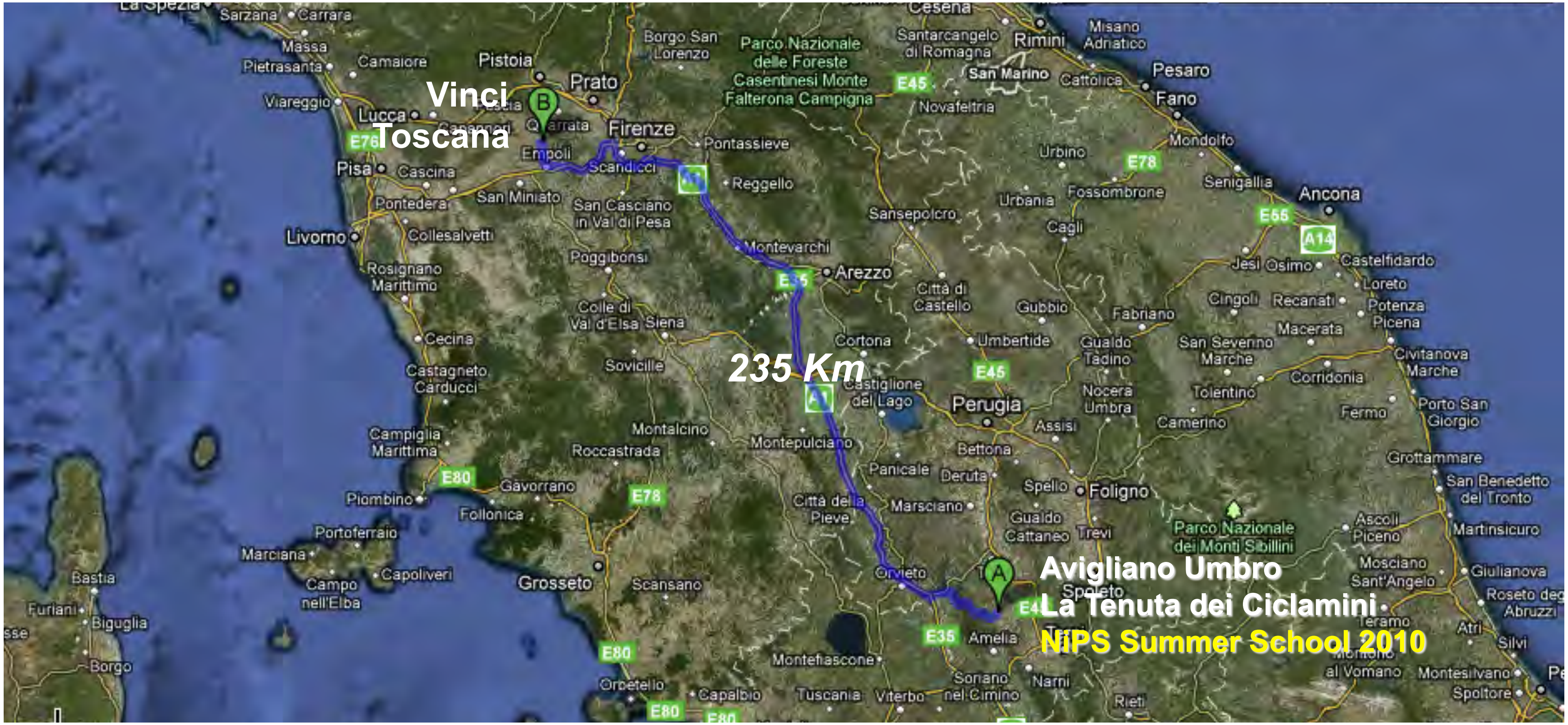
NiPS Laboratory
Noise in Physical Systems

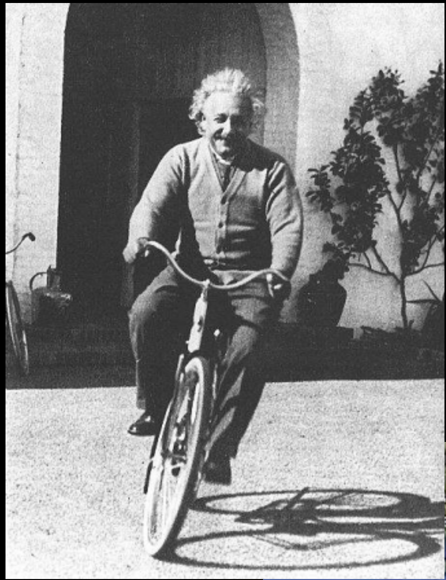
UAB
Universitat Autònoma de Barcelona

Dynamic NEMS based energy harvesting

Gabriel Abadal Berini
Departament d'Enginyeria Electrònica
Escola d'Enginyeria
Universitat Autònoma de Barcelona
Bellaterra (Barcelona). SPAIN

NiPS Summer School 2010. *Energy Harvesting at micro and nanoscale*, August 1-6, 2010
La Tenuta dei Ciclamini, Avigliano Umbro (TR) - Italy


Vinci
Toscana
235 Km
Avigliano Umbro
La Tenuta dei Ciclamini
NiPS Summer School 2010



1890

*…was **FASCINATED** by the incredible speed of the electricity circulating through an electrical wire and light propagating through the space…*

1480

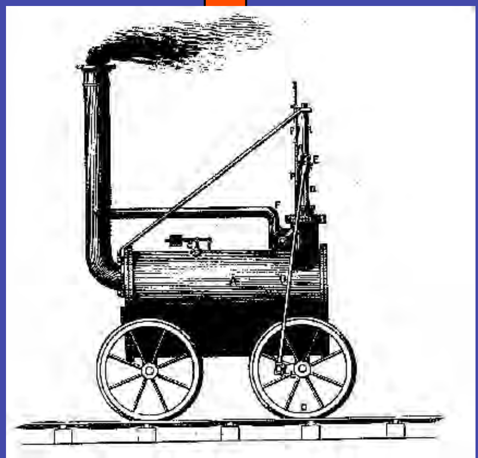
*…among others, he had a big **PASSION**: design and fabricate a flying machine…*

To know more about this story: COSMOS by Carl Sagan, chapter VIII

Technology Revolutions

19th Century

Energy



Movement

20th Century

Electronics

ICTs

21st Century ?

Technology Revolutions

21st Century

Energy → **ICT** future devices

Recycle

Efficiency

Movement

Which is our particular DREAM?

What is the idea that we are FASCINATED by?

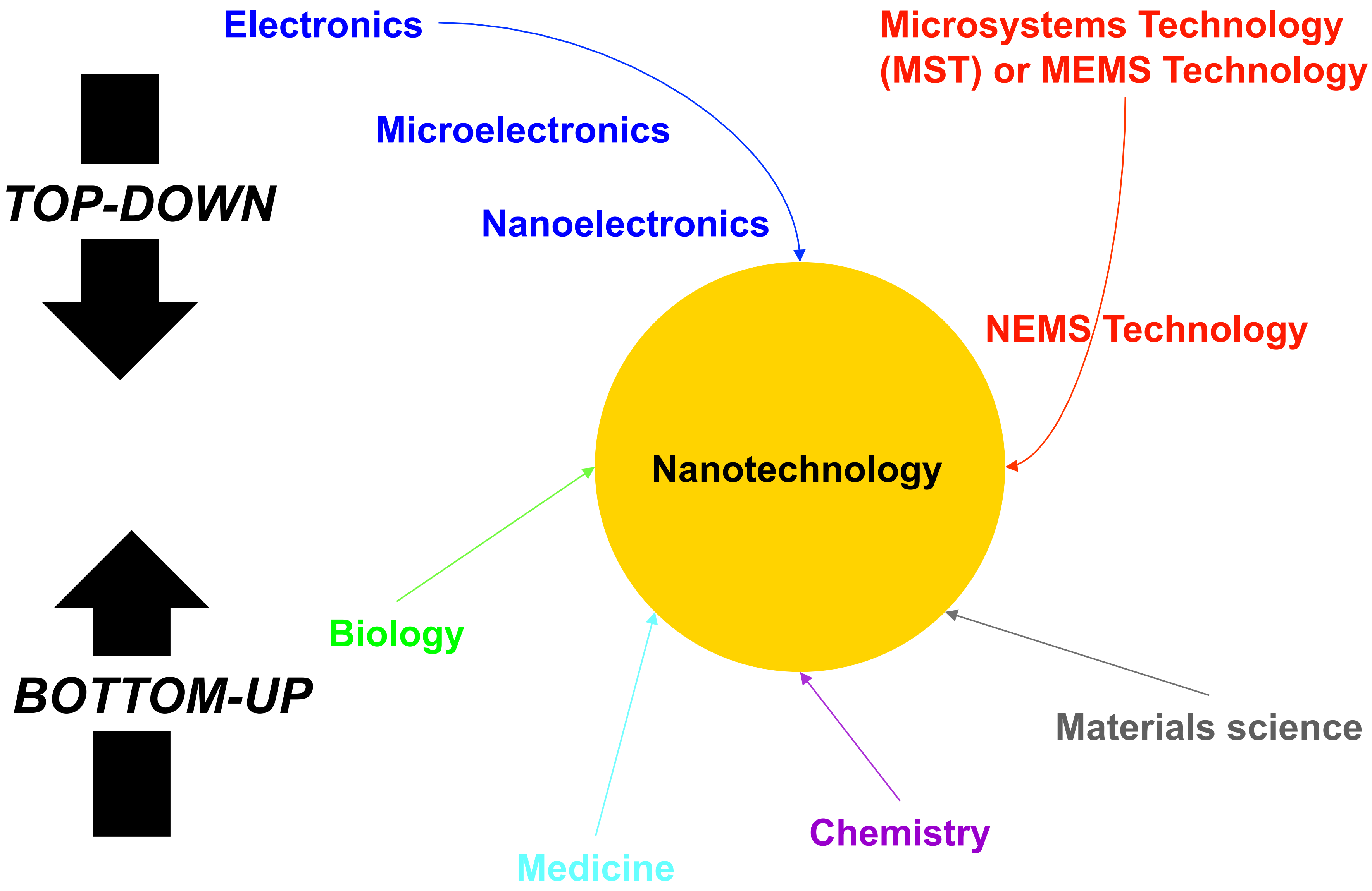
In which topic we are PASSIONATELY working?

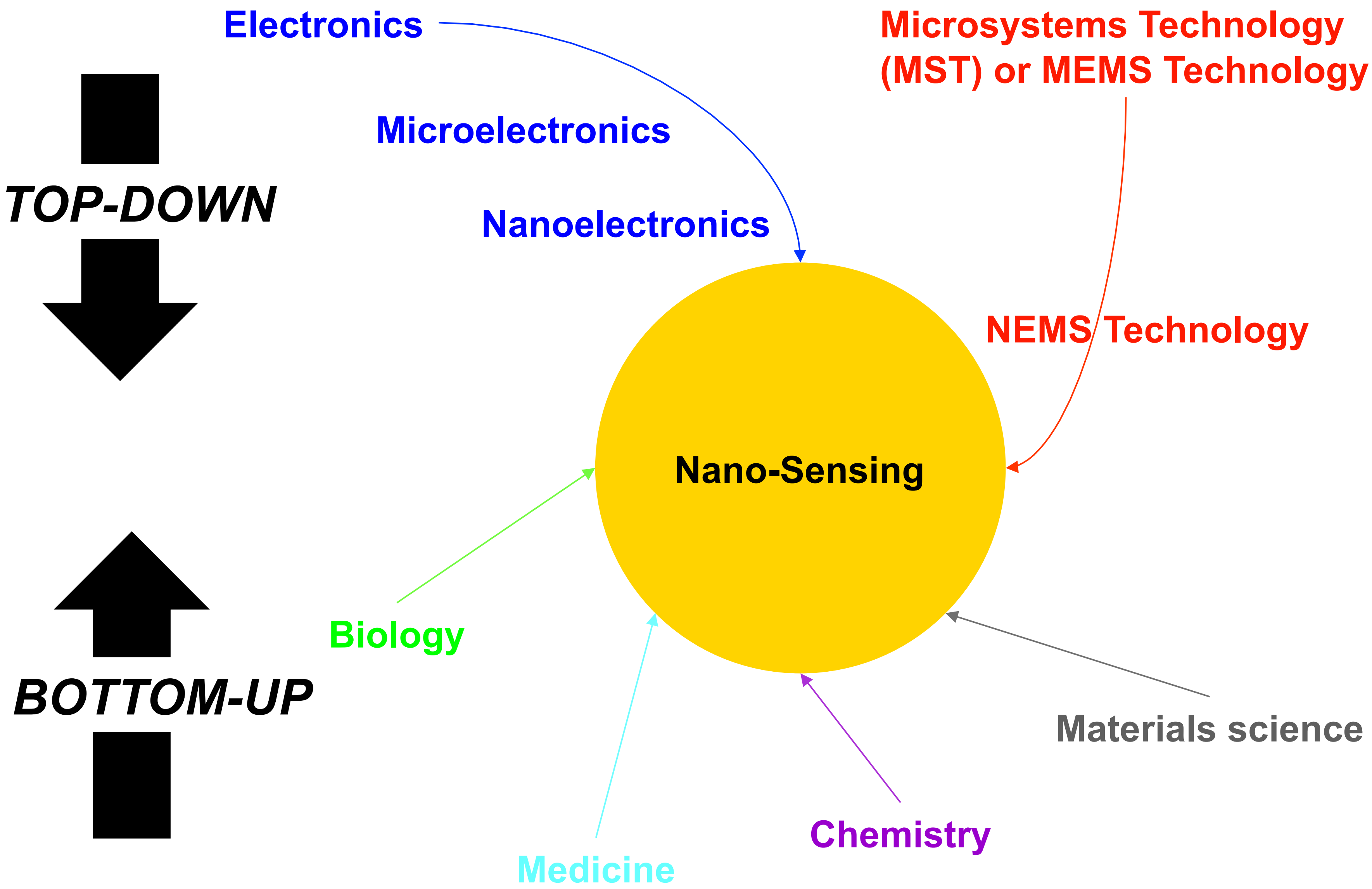
Comming back to the present at 21st century…
Comming back to the italian Umbria at this summer school…
and envisaging the future…

The aim of this lecture is none other than try to inspire new dreams, new ideas, new passions related to the topic of

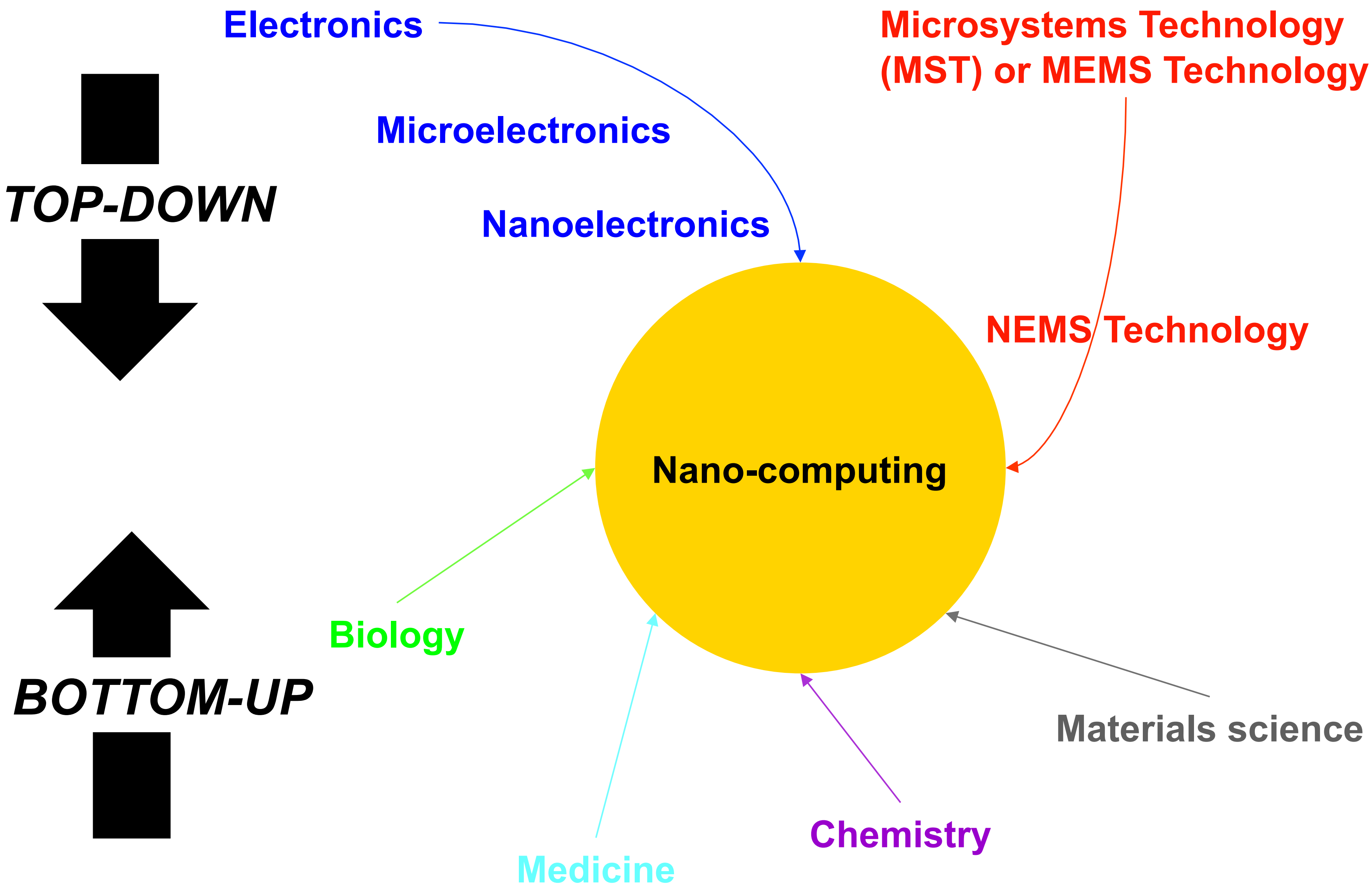
ENERGY HARVESTING

Nanotechnology


Electronics
Microsystems Technology
(MST) or MEMS Technology
Microelectronics
TOP-DOWN
Nanoelectronics
NEMS Technology
Nanotechnology
Biology
BOTTOM-UP
Materials science
Chemistry
Medicine



Electronics
Microsystems Technology
(MST) or MEMS Technology
Microelectronics
TOP-DOWN
Nanoelectronics
NEMS Technology
Nano-Sensing
Biology
BOTTOM-UP
Materials science
Chemistry
Medicine


Electronics
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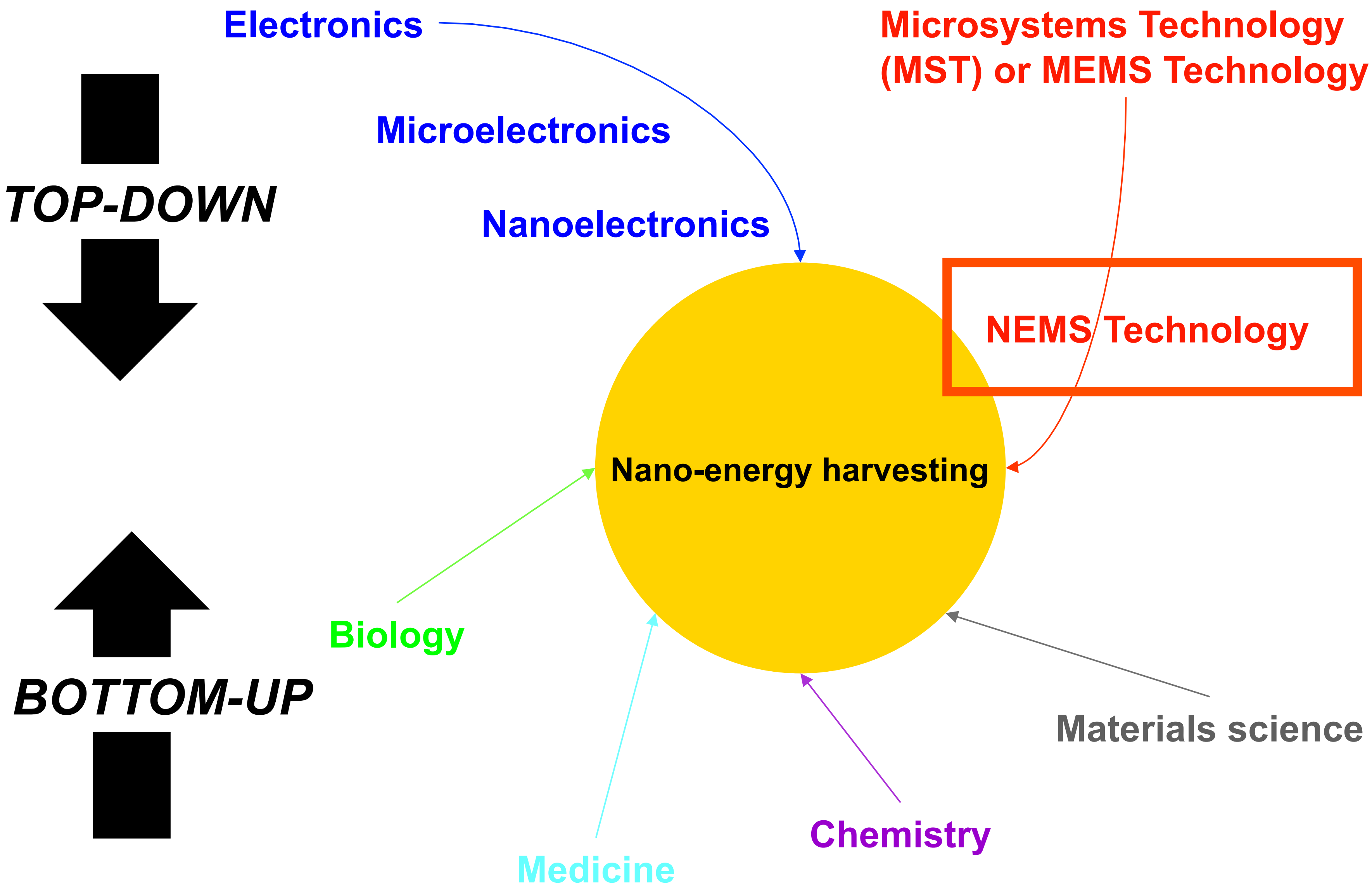
TOP-DOWN
BOTTOM-UP
Nano-computing
Biology
Medicine
Chemistry
Materials science



Electronics
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Nanoelectronics
Microsystems Technology
(MST) or MEMS Technology
TOP-DOWN
NEMS Technology
Nano-energy harvesting
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Biology
Medicine
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Which is our particular DREAM?

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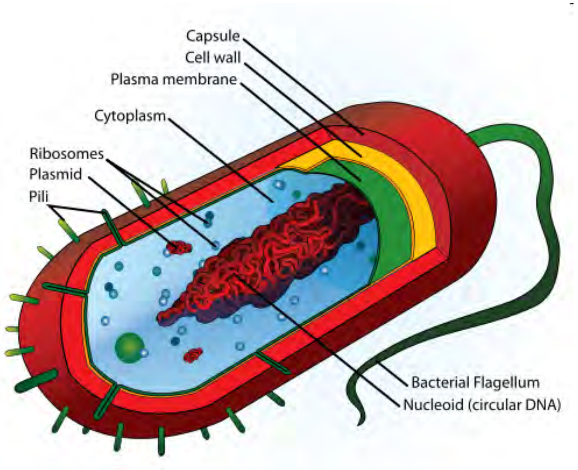
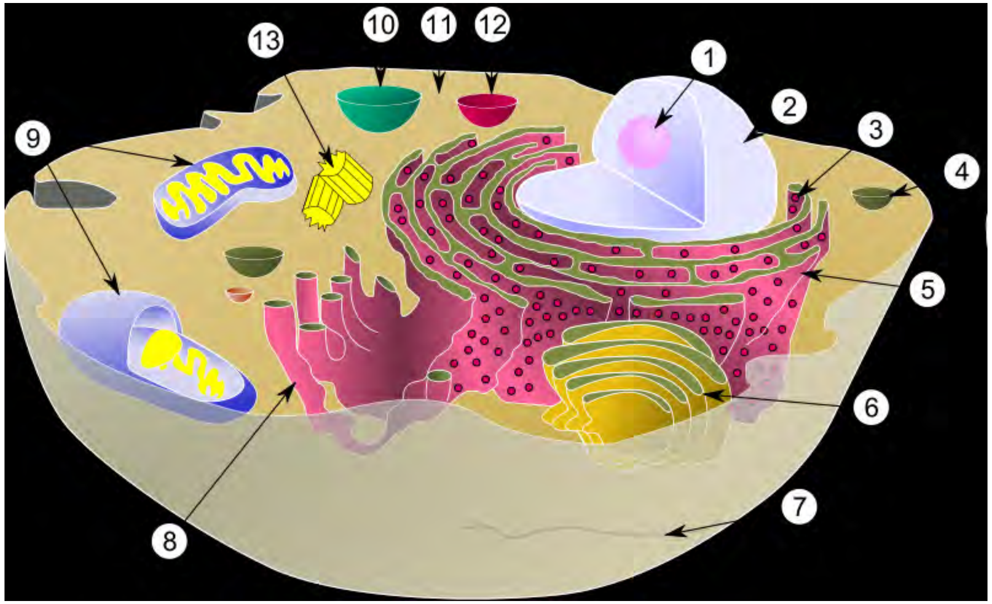


Prokaryotic cell

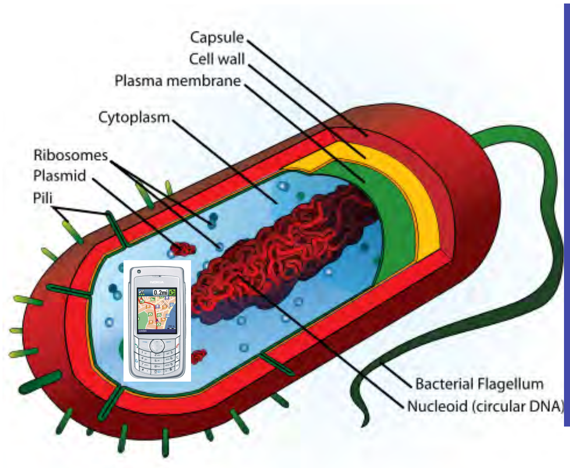
1-10 μm

Eukaryotic cell

10-100 μm



Talk and listen to a cell



Miniaturization to the nanoscale

NANODEVICE

In particular:

Miniaturization of the BATTERY

1-10 μm

10 cm

Tracking cells

small

Cell tracking

Intracellular Polysilicon Barcodes for Cell Tracking

Elisabet Fernandez-Rosas, Rodrigo Gómez, Elena Ibañez, Leonardo Barrios, Marta Duch, Jaume Esteve, Carme Nogués, and José Antonio Plaza**

During the past decade, diverse types of barcode have been designed in order to track living cells in vivo or in vitro, but none of them offer the possibility to follow an individual cell up to ten or more days. Using silicon microtechnologies a barcode sufficiently small to be introduced into a cell, yet visible and readily identifiable under an optical microscope, is designed. Cultured human macrophages are able to engulf the barcodes due to their phagocytic ability and their viability is not affected. The utility of the barcodes for cell tracking is demonstrated by following individual cells for up to ten days in culture and recording their locomotion. Interestingly, silicon microtechnology allows the mass production of reproducible codes at low cost with small features (bits) in the micrometer range that are additionally biocompatible.

Keywords:
- barcodes
- cell tracking
- micromachining
- optical microscopy
- polysilicon

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small 2009, 5, No. 21, 2433–2439

Tracking cells

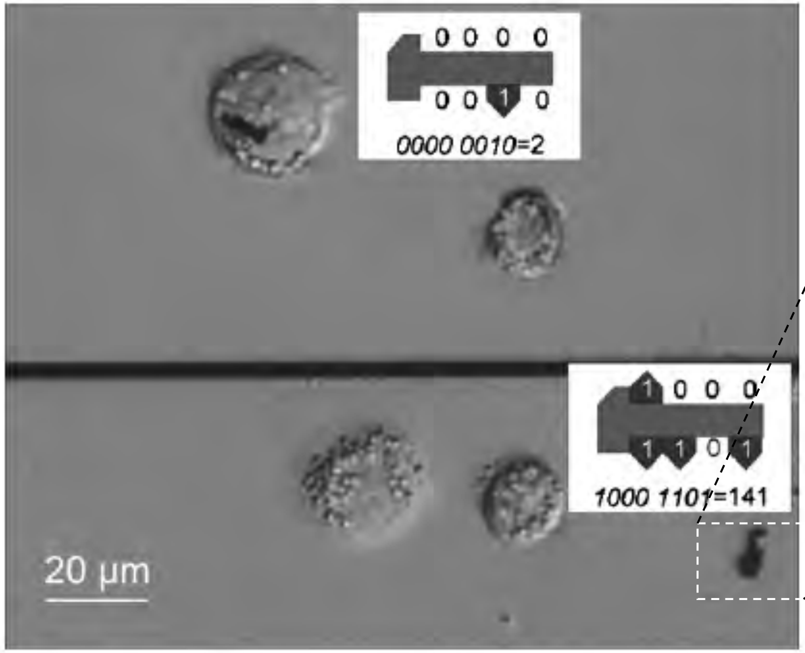
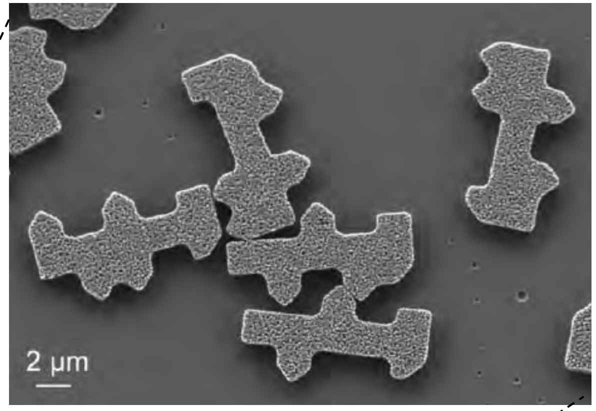


Figure 5. Light microscope micrograph of an in vitro culture of macrophage cells with polysilicon barcodes. Cells with (upper left insert) and without barcodes, as well as an isolated barcode are shown. The picture was taken with a 40 × objective on an inverted optical microscope.



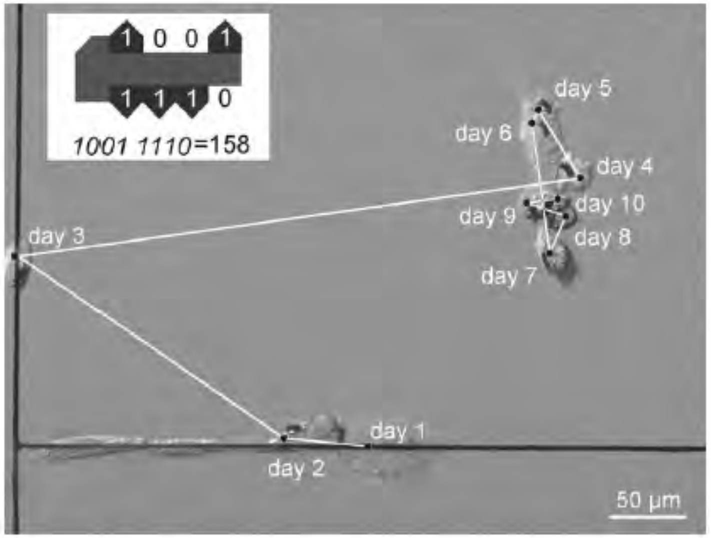
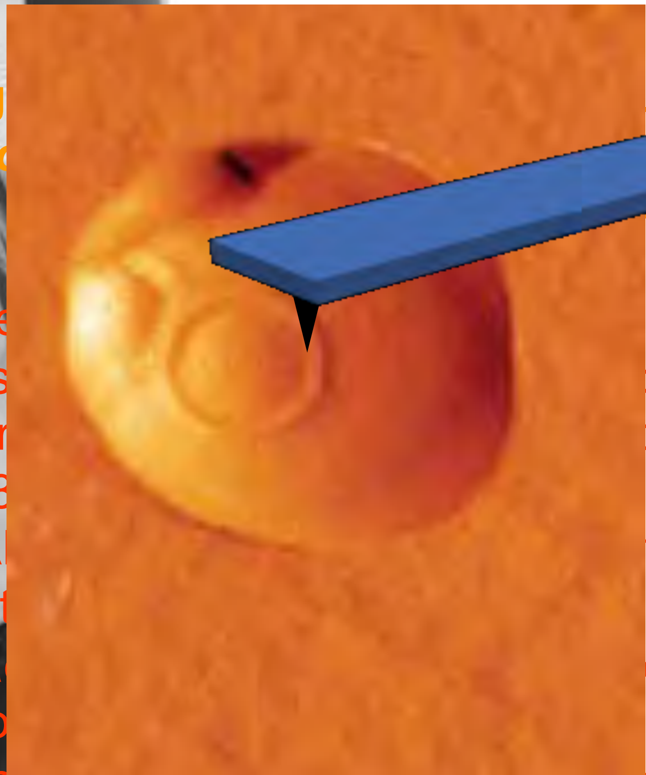
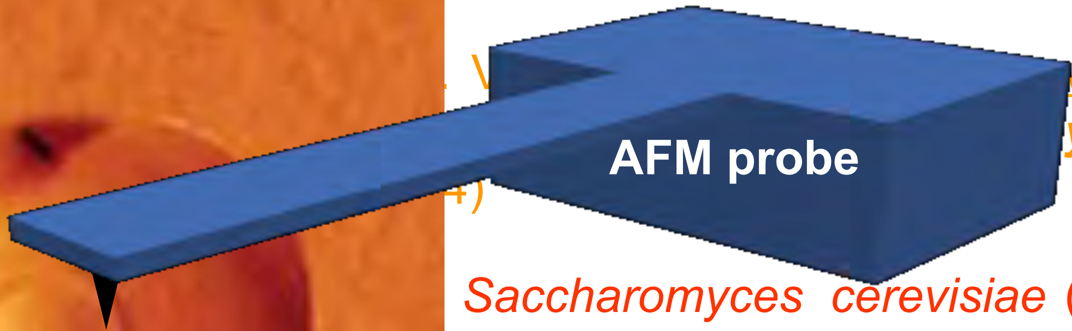


Figure 10. Daily movements of encoded macrophage-158 during 10 days in culture. Pictures were taken daily with an inverted light microscope. The picture shown is a composition of the daily micrographs taken and the white line indicates the cell trajectory throughout the 10 days. Macrophage 158 has travelled a total of 697 µm.

Listen to yiest cell sound

Prof. JAMES K. GIMZEWSKI
UCLA Chemistry & Biochemistry Department

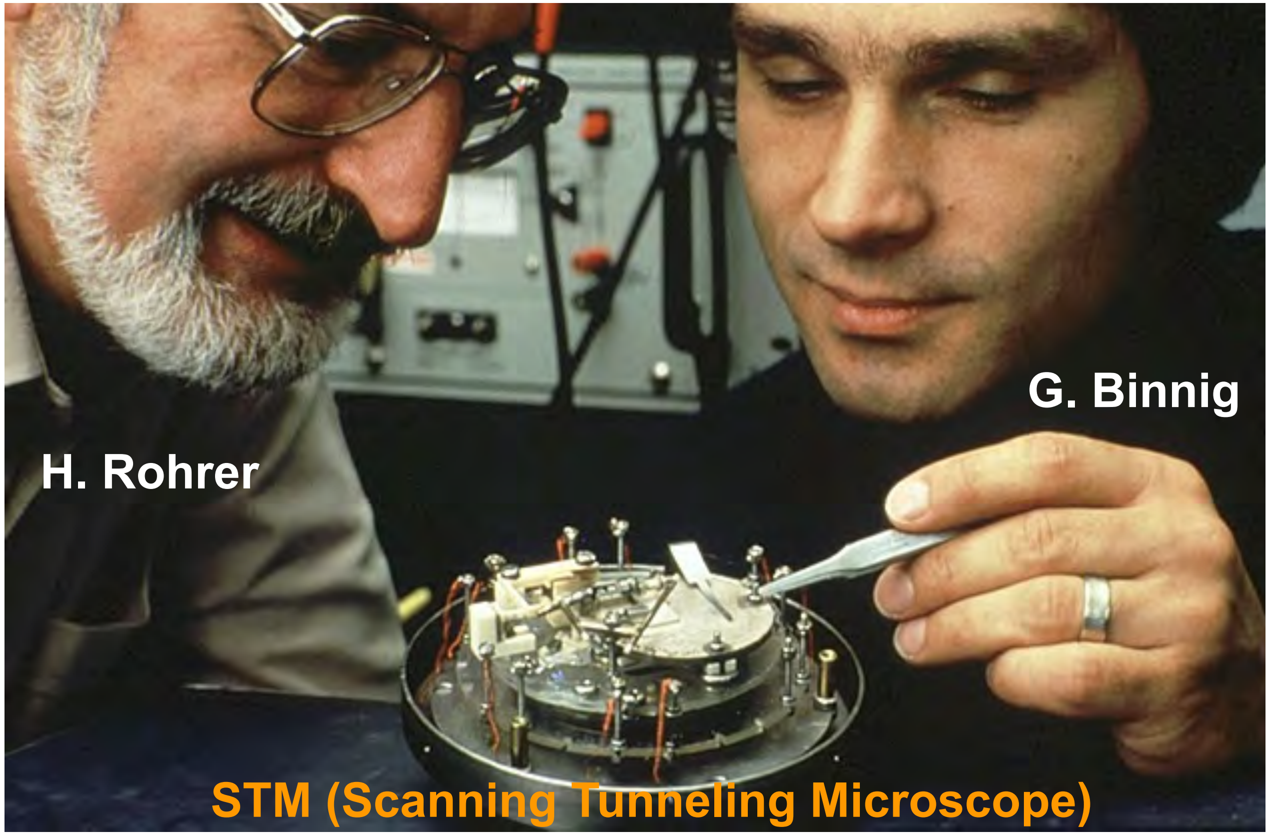




A. E. Pelling ... V ... wski,
"Local Nano ... yces
cerevisiae," ... 4)

We demonstrate ... *Saccharomyces cerevisiae* (**baker's yeast**) exhibits ... dent **nanomechanical motion at characteristic** fr ... ons in the range of 0.8 to 1.6 kHz with amplitudes of 3 ... the cantilever of an **atomic force microscope** (Al ... to a metabolic inhibitor causes the periodic motion t ... quency dependence on temperature, we derive an a ... l, which is consistent with the cell's metabolism invo ... as kinesin, dynein, and myosin. The magnitude of the forces observed (10 nN) suggests concerted nanomechanical activity is operative in the cell.

Physics Nobel Prize 1986



VOLUME 50, NUMBER 2 PHYSICAL REVIEW LETTERS 10 JANUARY 1983

7 × 7 Reconstruction on Si(111) Resolved in Real Space

G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel
IBM Zurich Research Laboratory, 8803 Rüschlikon-ZH, Switzerland
(Received 17 November 1982)

The 7×7 reconstruction on Si(111) was observed in real space by scanning tunneling microscopy. The experiment strongly favors a modified adatom model with 12 adatoms per unit cell and an inhomogeneously relaxed underlying top layer.

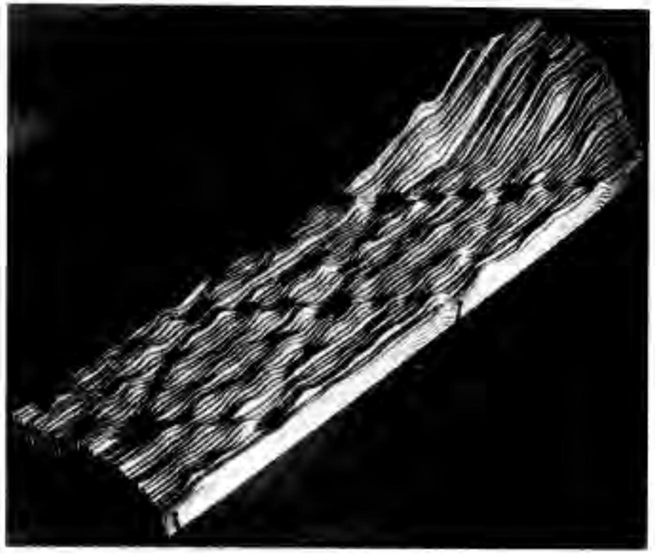


FIG. 1. Relief of two complete 7×7 unit cells, with nine minima and twelve maxima each, taken at 300 °C. Heights are enhanced by 55%; the hill at the right grows to a maximal height of 15 Å. The [211] direction points from right to left, along the long diagonal.

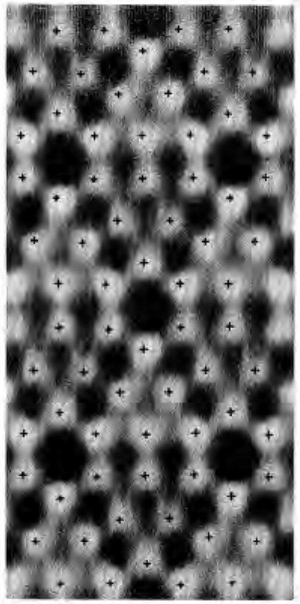


FIG. 2. Top view of the relief shown in Fig. 1 (the hill at the right is not included) clearly exhibiting the sixfold rotational symmetry of the maxima around the rhombohedron corners. Brightness is a measure of the altitude, but is not to scale. The crosses indicate adatom positions of the modified adatom model (see Fig. 3) or "milk-stool" positions (Ref. 5).

VOLUME 56, NUMBER 9 PHYSICAL REVIEW LETTERS 3 MARCH 1986

Atomic Force Microscope

G. Binnig[a] and C. F. Quate[b]
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305
and
Ch. Gerber[c]
IBM San Jose Research Laboratory, San Jose, California 95193
(Received 5 December 1985)

The scanning tunneling microscope is proposed as a method to measure forces as small as 10^{-18} N. As one application for this concept, we introduce a new type of microscope capable of investigating surfaces of insulators on an atomic scale. The atomic force microscope is a combination of the principles of the scanning tunneling microscope and the stylus profilometer. It incorporates a probe that does not damage the surface. Our preliminary results *in air* demonstrate a lateral resolution of 30 Å and a vertical resolution less than 1 Å.

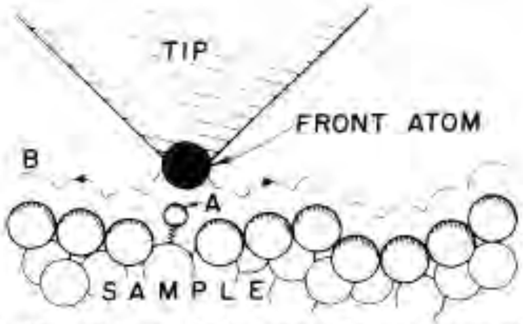


FIG. 1. Description of the principle operation of an STM as well as that of an AFM. The tip follows contour *B*, in one case to keep the tunneling current constant (STM) and in the other to maintain constant force between tip and sample (AFM, sample, and tip either insulating or conducting). The STM itself may probe forces when a periodic force on the adatom *A* varies its position in the gap and modulates the tunneling current in the STM. The force can come from an ac voltage on the tip, or from an externally applied magnetic field for adatoms with a magnetic moment.

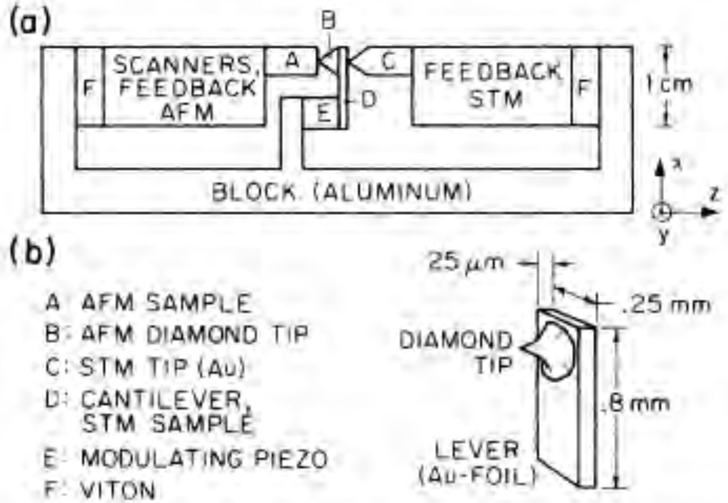
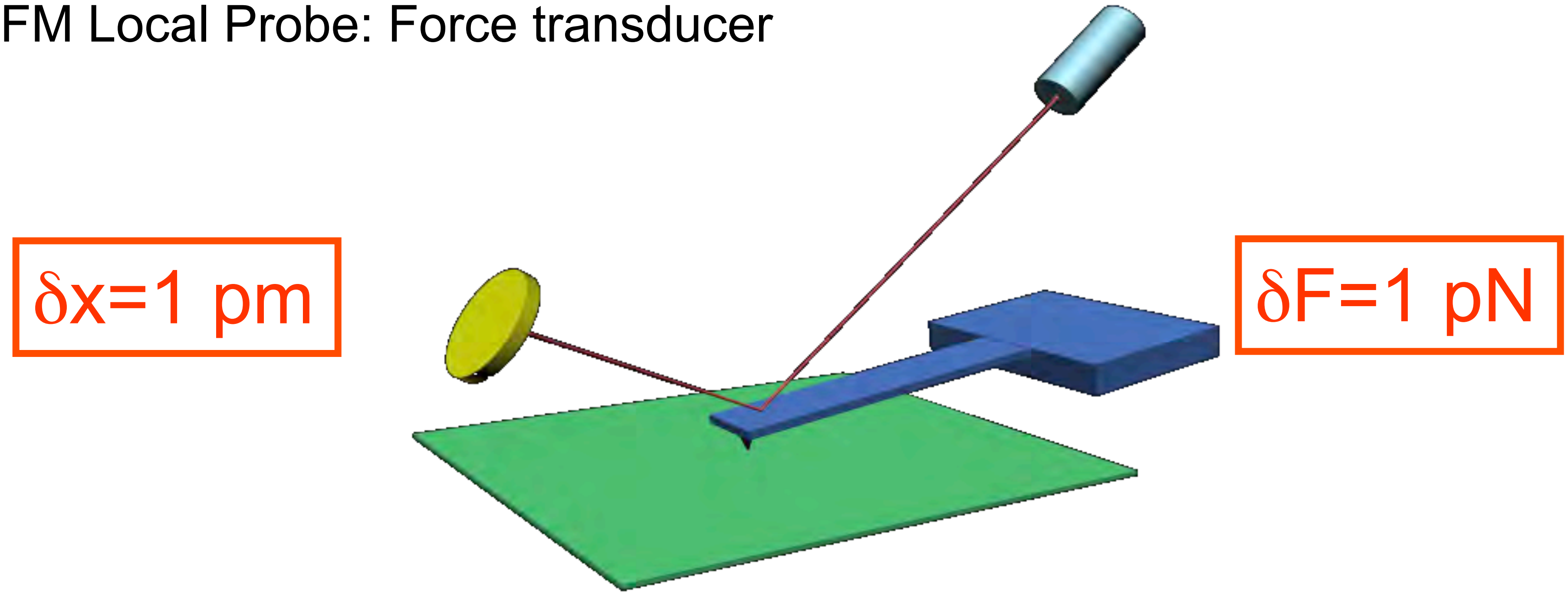


FIG. 2. Experimental setup. The lever is not to scale in (a). Its dimensions are given in (b). The STM and AFM piezoelectric drives are facing each other, sandwiching the diamond tip that is glued to the lever.

AFM (Atomic Force Microscopy)
G.Binnig, C.F. Quate, Ch. Gerber, *Phys Rev. Lett.* **56**, 930 (1986)

AFM Local Probe: Force transducer

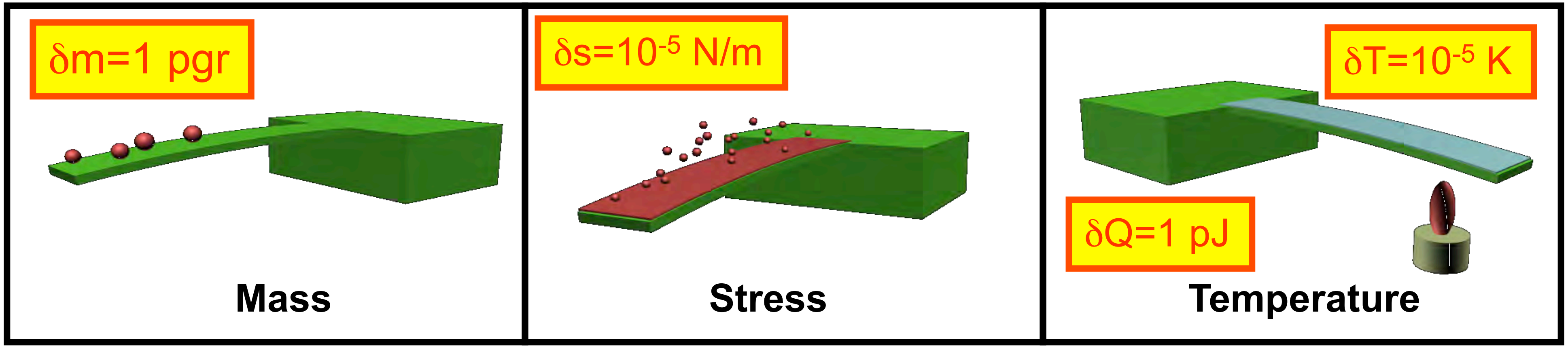


T.R. Albrecht, C.F. Quate, *J. Vac. Sci. Technol.* A **6**, 271 (1988).
O. Wolter, Th Bayer, J. Greschner, *J. Vac. Sci. Technol. B* **9**, 1353 (1991).

R. Berger, Ch. Gerber, H.P. Lang, J.K. Gimzewski

Micromechanics: A Toolbox for Femtoscale Science: "Towards a Laboratory on a Tip"

Microelectronic Engineering **35**, 373-379 (1997)



"...almost every signal domain can be transduced into a micromechanical actuation detected with picometer resolution."

NANO
LETTERS

Zeptogram-Scale Nanomechanical Mass Sensing

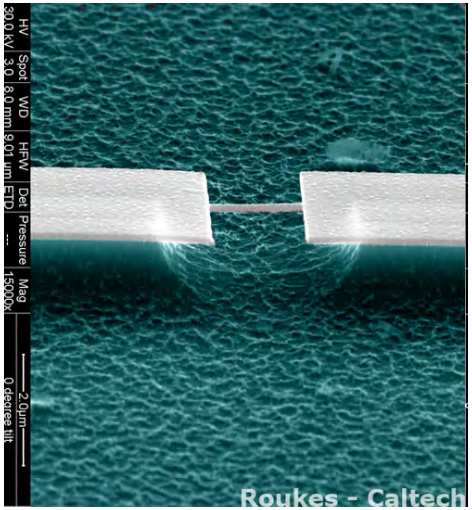
Y. T. Yang,† C. Callegari,‡ X. L. Feng, K. L. Ekinci,§ and M. L. Roukes*

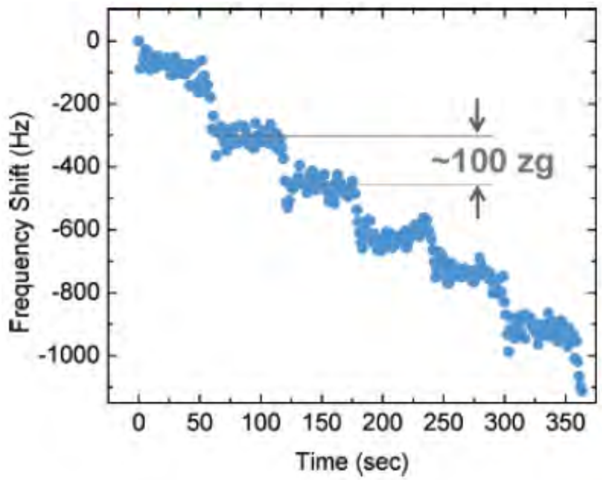
Kavli Nanoscience Institute, California Institute of Technology, Mail Code 114-36, Pasadena, California 91125

Received October 29, 2005; Revised Manuscript Received February 5, 2006

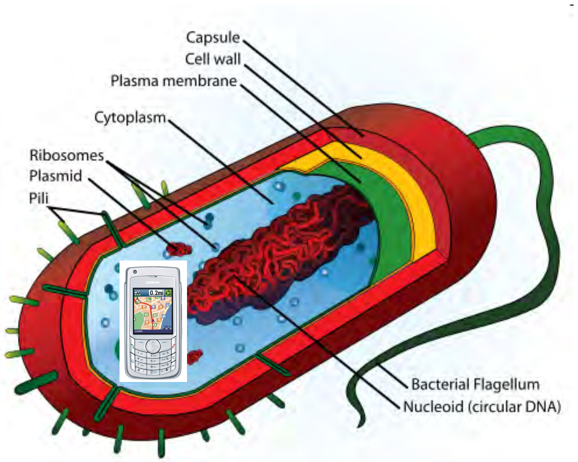
ABSTRACT

Very high frequency (VHF) nanoelectromechanical systems (NEMS) provide unprecedented sensitivity for inertial mass sensing. We demonstrate *in situ* measurements in *real time* with mass noise floor ~20 zg. Our best mass resolution corresponds to ~7 zg, equivalent to ~30 xenon atoms or the mass of an individual 4 kDa molecule. Detailed analysis of the ultimate sensitivity of such devices based on these experimental results indicates that NEMS can ultimately provide inertial mass sensing of individual intact, electrically neutral macromolecules with single-Dalton (1 amu) resolution.





Talk and listen to a cell



1-10 μm

Miniaturization to the nanoscale

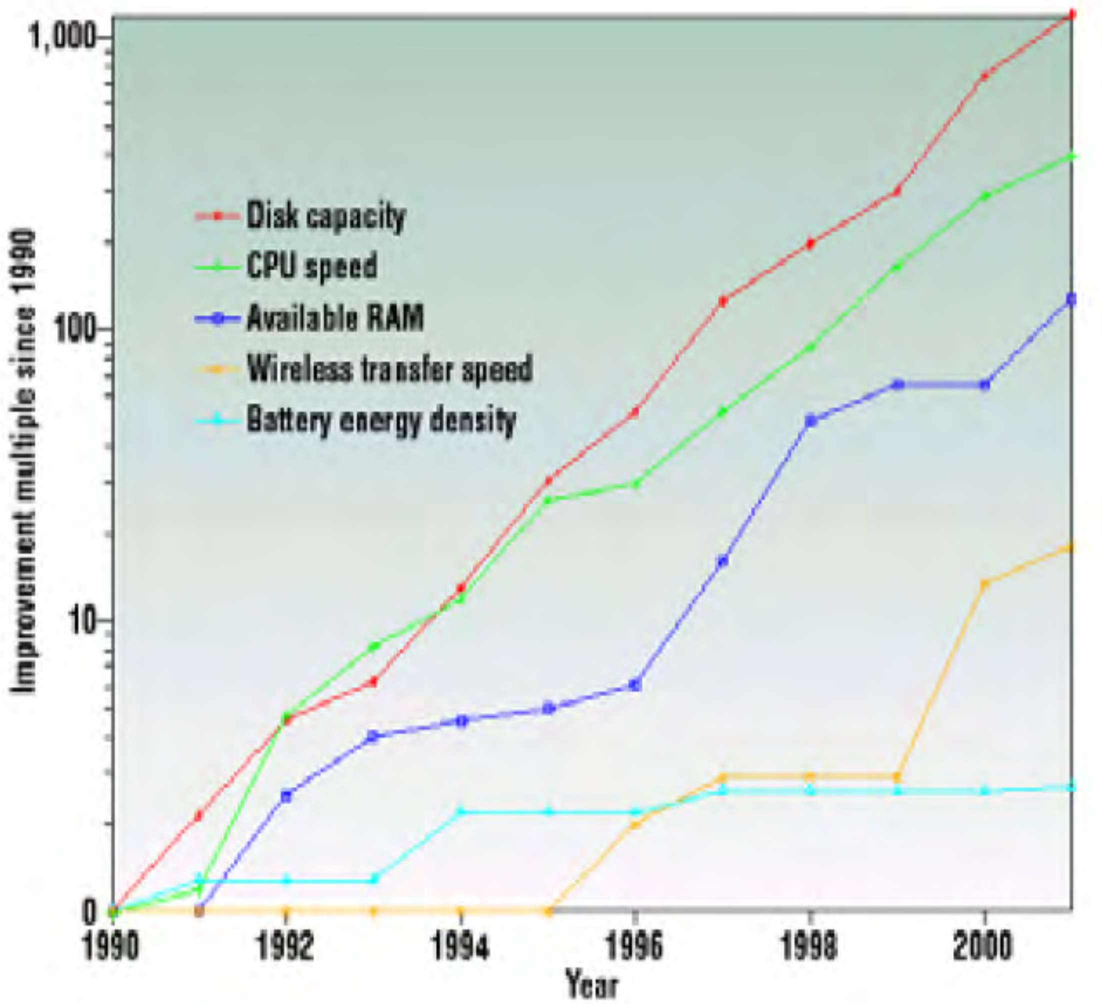
NANODEVICE

In particular:

Miniaturization of the BATTERY

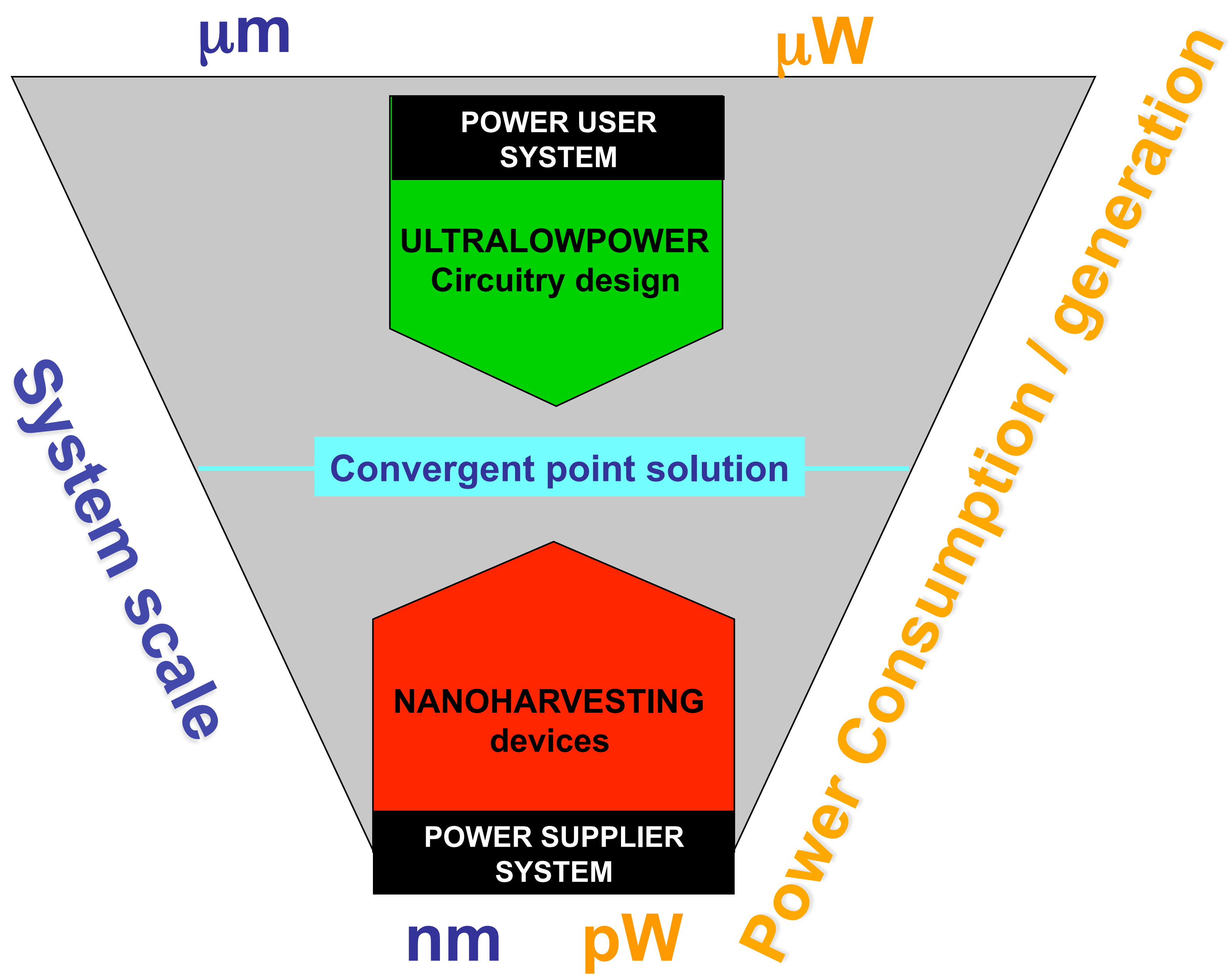
10 cm

Electrochemical battery evolution vs. ICT technologies

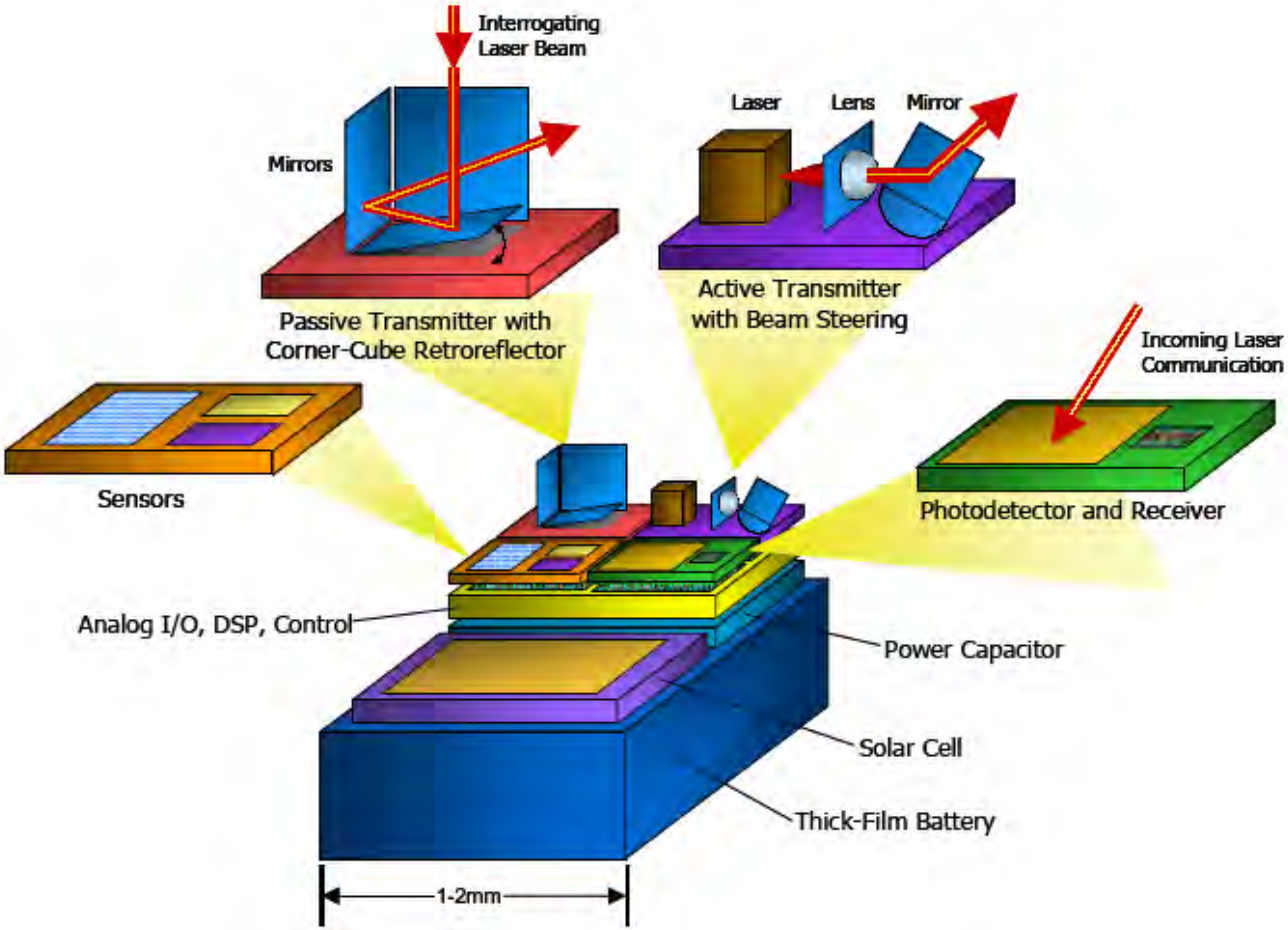


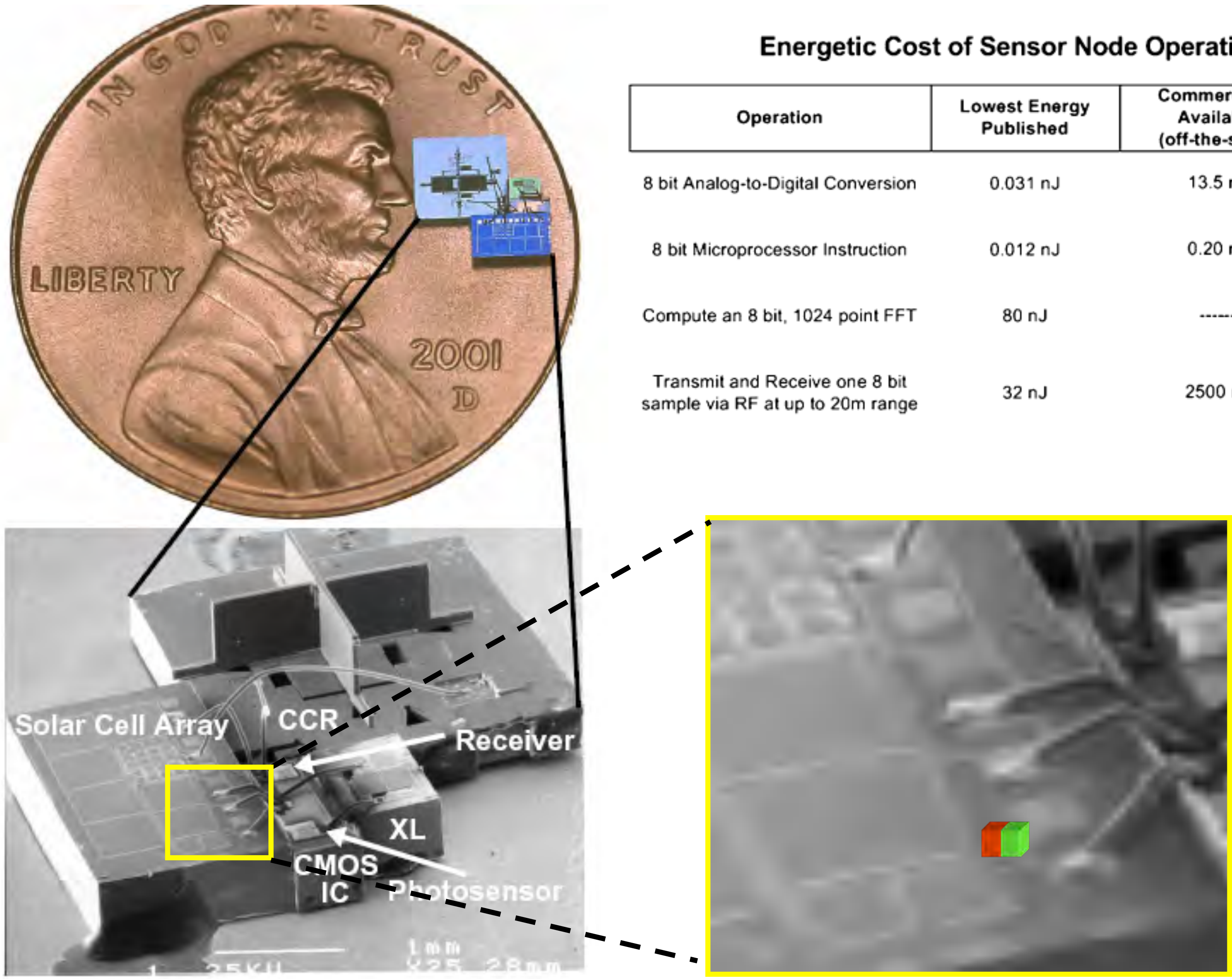
Main drawbacks:

- Size
- Only for energy storage
- Recharge / Replaceability


µm
µW
POWER USER SYSTEM
ULTRALOWPOWER Circuitry design
System scale
Convergent point solution
Power Consumption / generation
NANOHARVESTING devices
POWER SUPPLIER SYSTEM
nm
pW

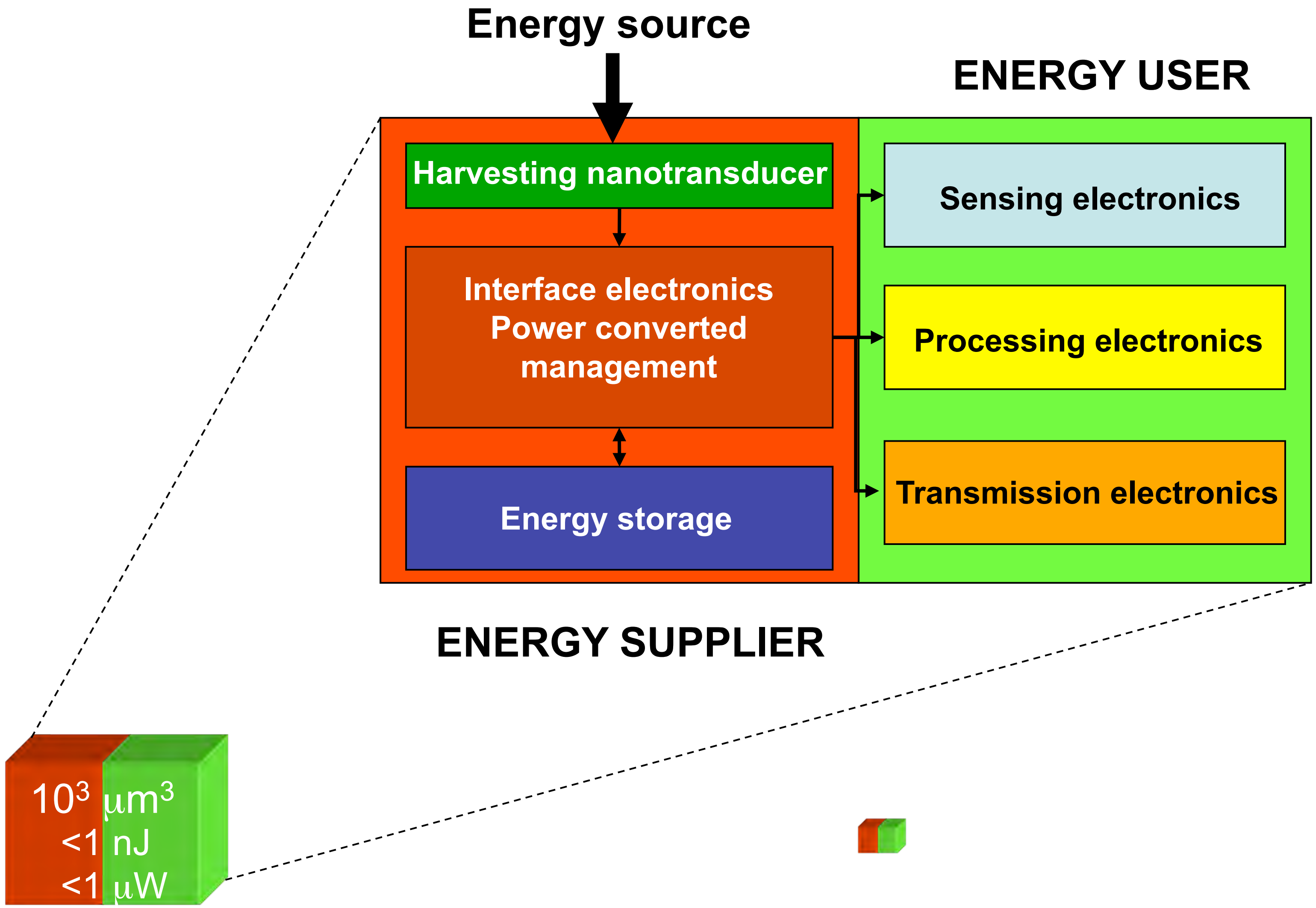
Smart Dust US project (2002)

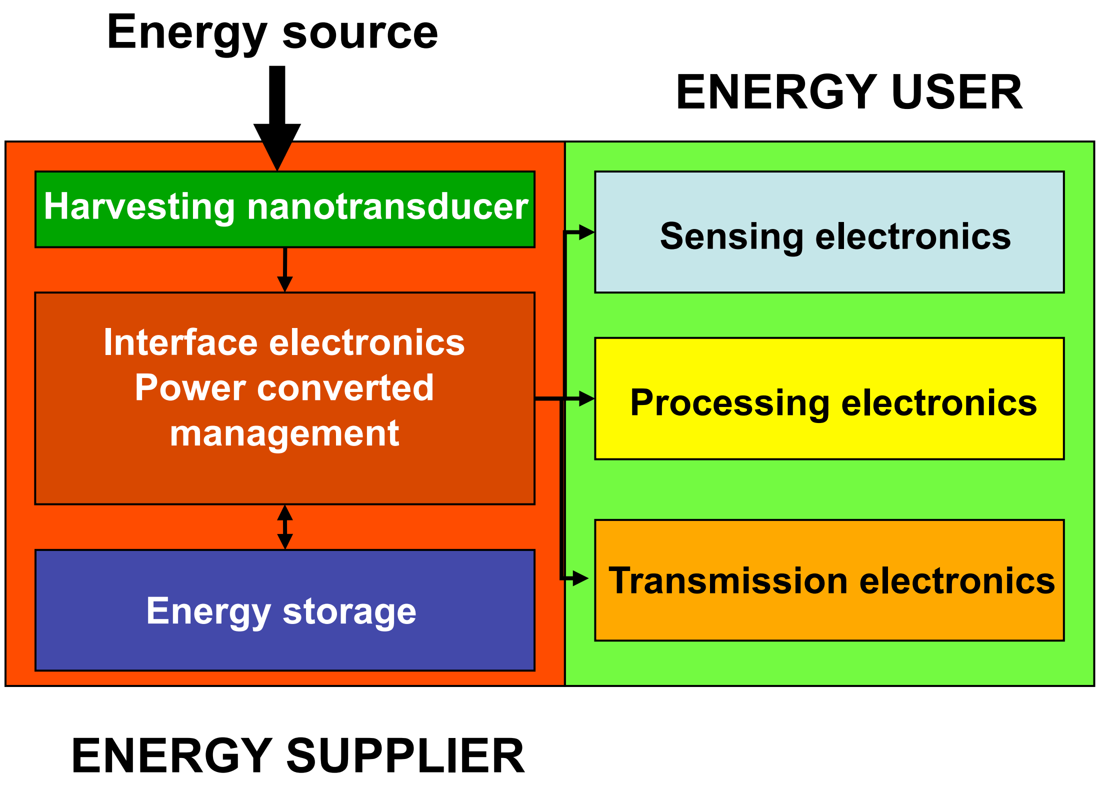




Energetic Cost of Sensor Node Operations

Operation	Lowest Energy Published	Commercially Available (off-the-shelf)
8 bit Analog-to-Digital Conversion	0.031 nJ	13.5 nJ
8 bit Microprocessor Instruction	0.012 nJ	0.20 nJ
Compute an 8 bit, 1024 point FFT	80 nJ	------
Transmit and Receive one 8 bit sample via RF at up to 20m range	32 nJ	2500 nJ


Energy source
ENERGY USER
Harvesting nanotransducer
Interface electronics
Power converted
management
Energy storage
Sensing electronics
Processing electronics
Transmission electronics
ENERGY SUPPLIER
10³ μm³
<1 nJ
<1 μW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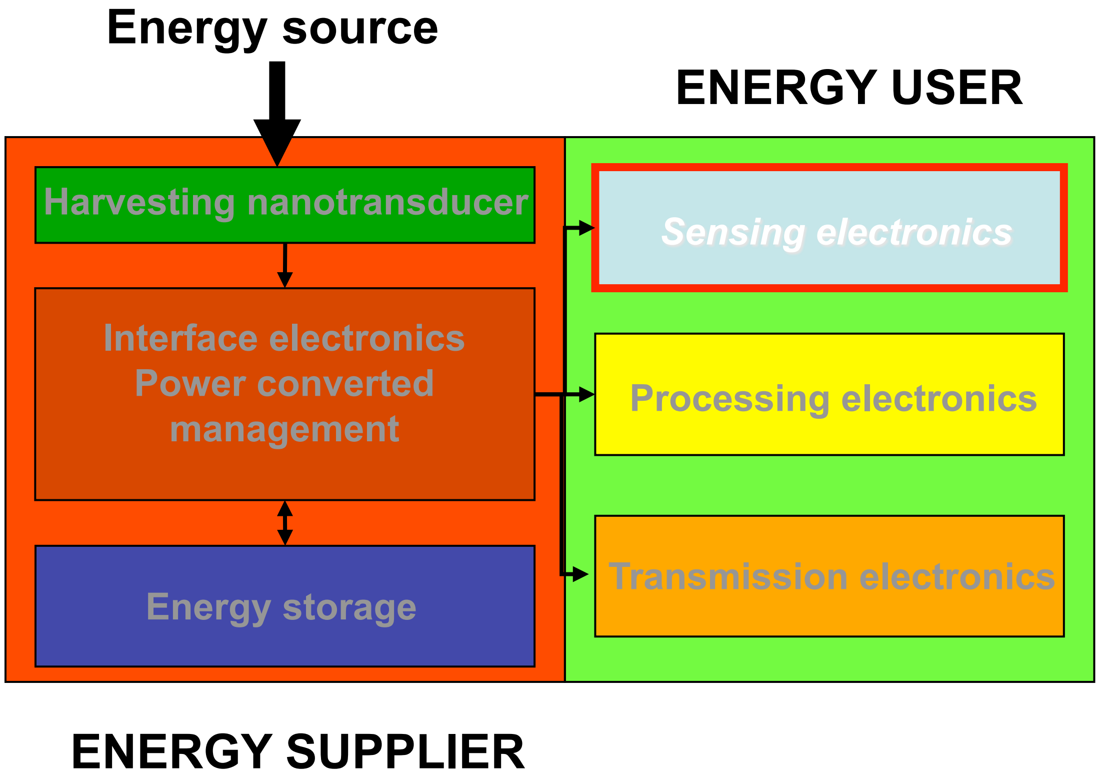
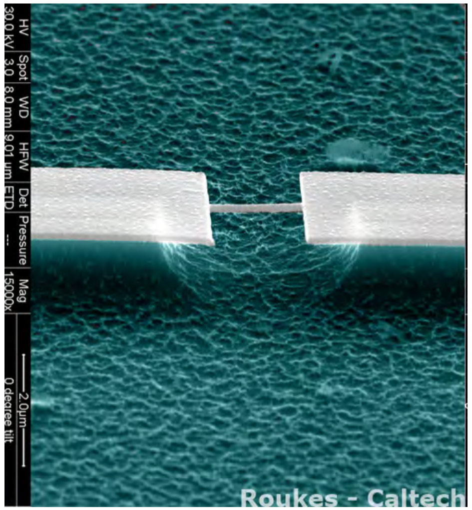
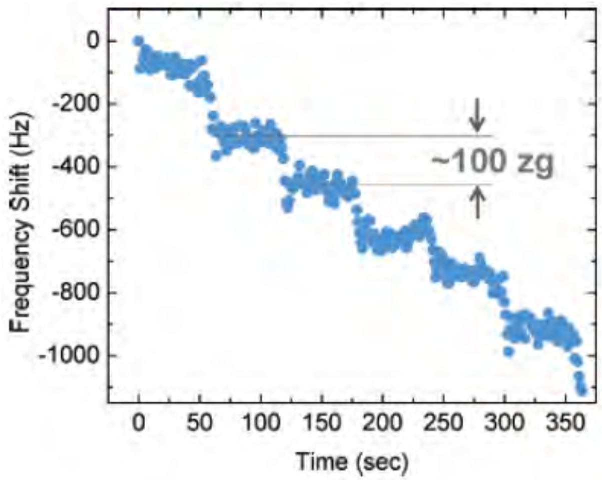
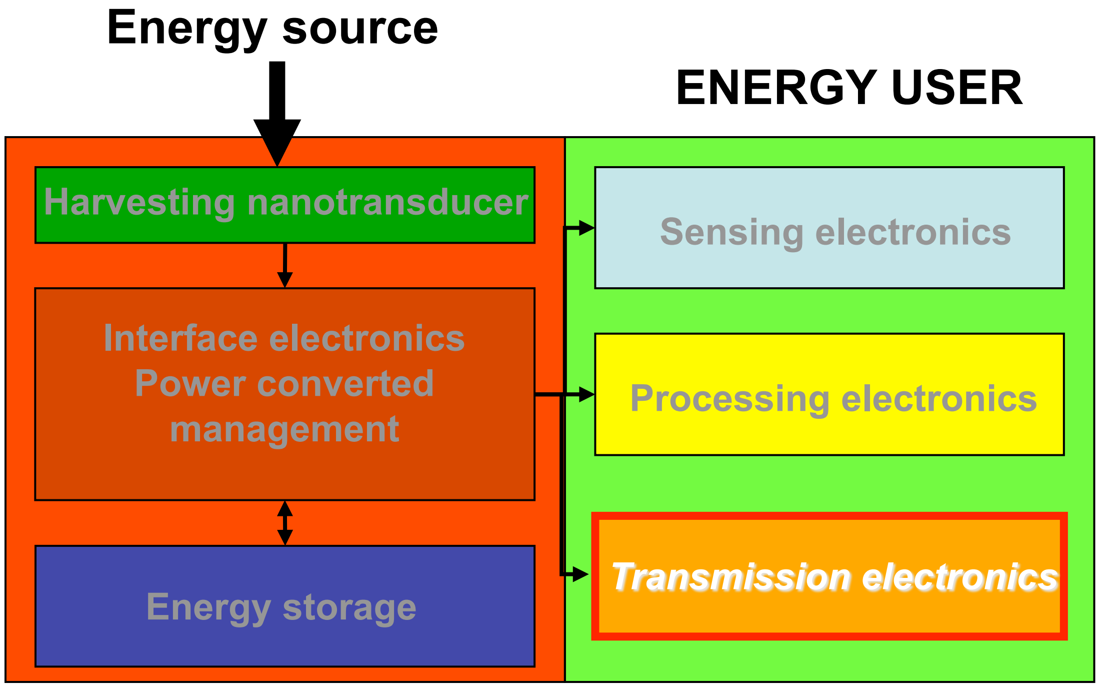


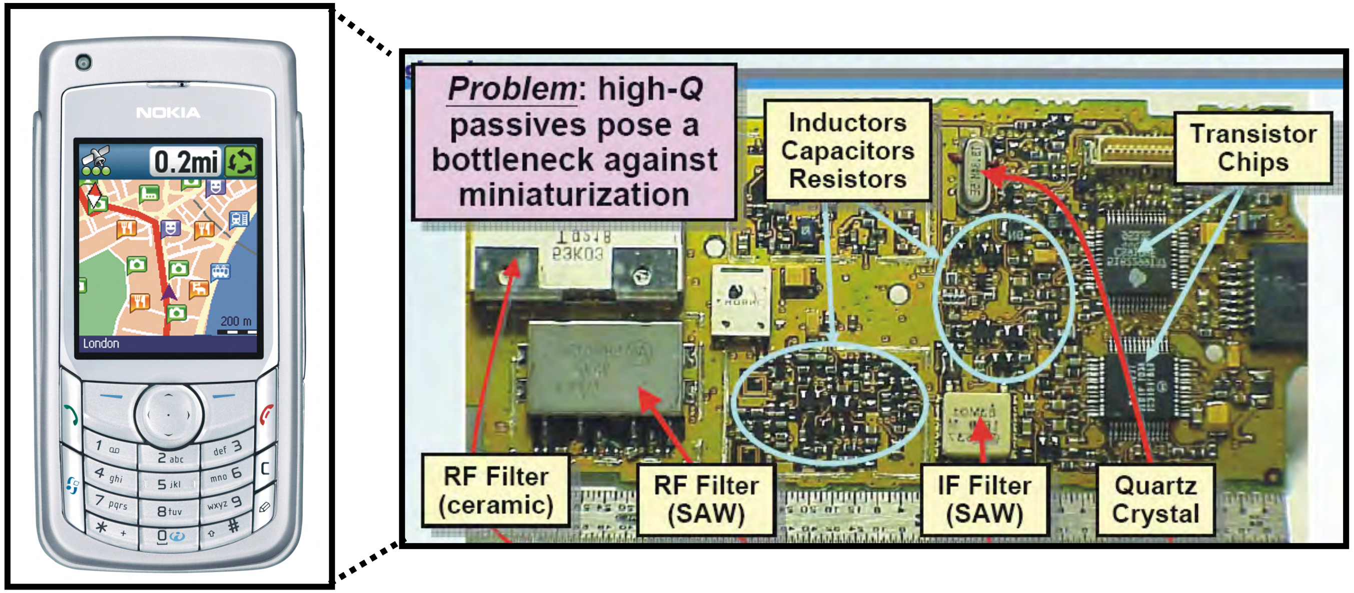
Prof. M.L. Roukes

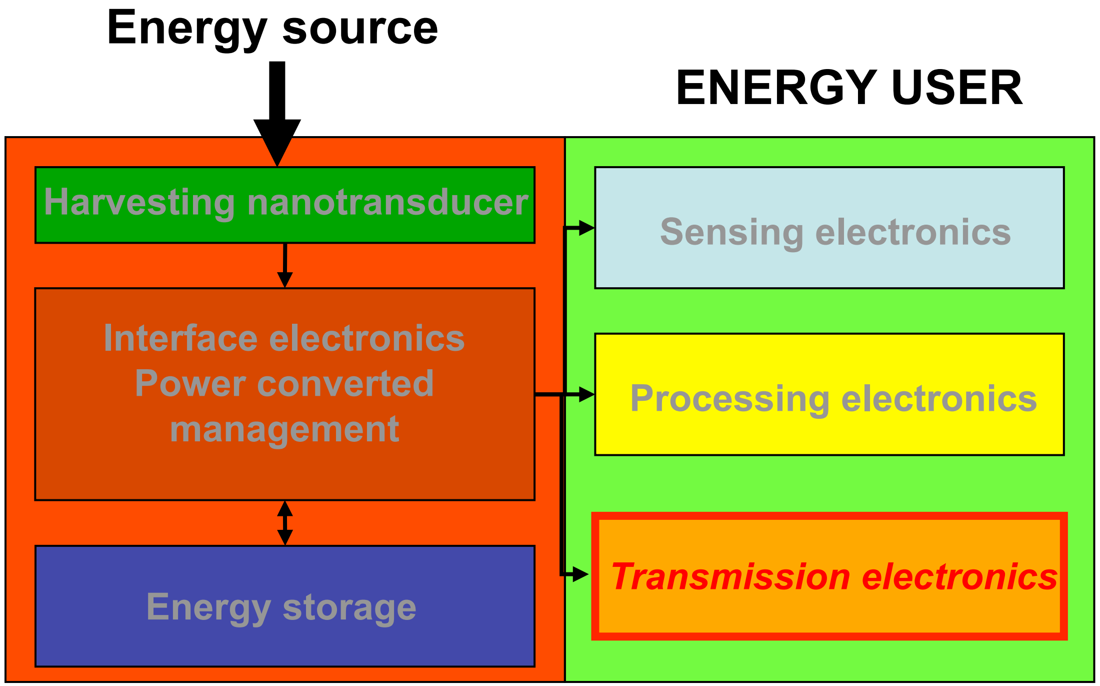




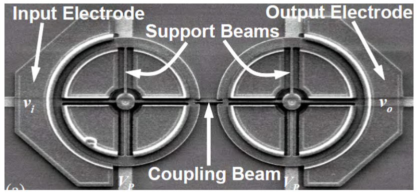


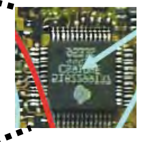
Prof. C.T.-C. Nguyen





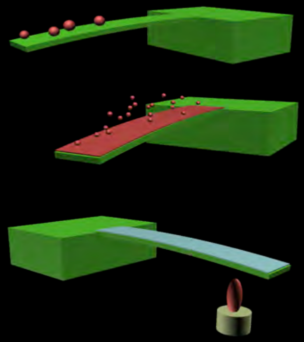
Prof. C.T.-C. Nguyen



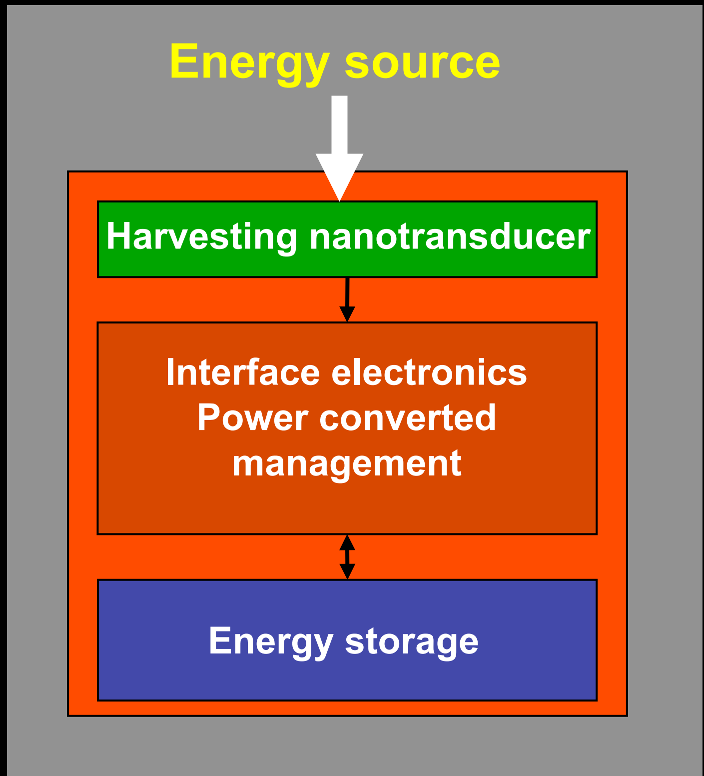


Solution: Replacement of these external elements by **integrated high-Q RF-MEMS resonators capacitively transduced**.

Precedents:



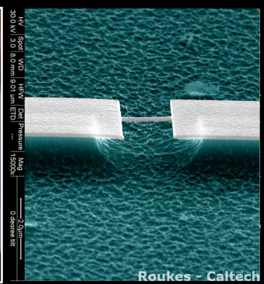
“...almost every signal domain can be transduced into a micromechanical actuation detected with picometer resolution.”

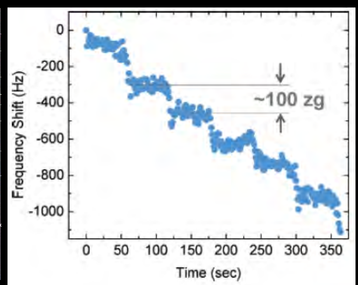


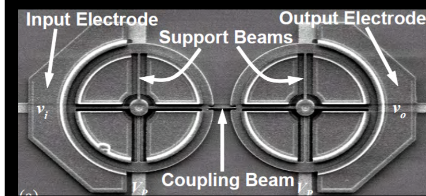
Thesis:

NEMS can satisfy the needed requirements in nanoscale EH:

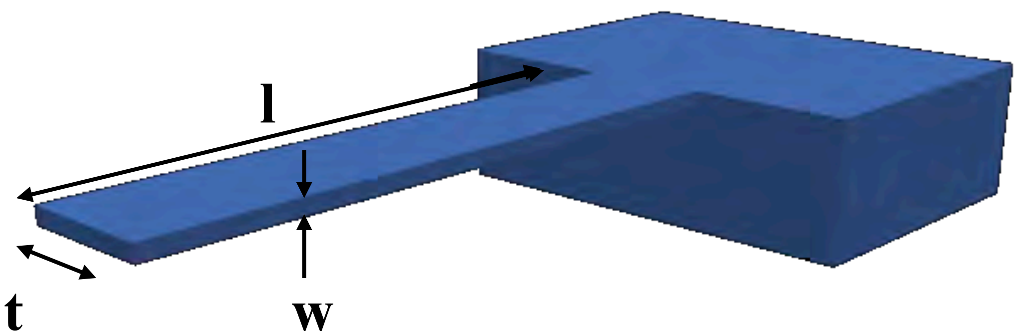
- Ultrasmall volume
- Adapted to low energy levels
- Multidomain energy source
- Other…?







Some basics on NEMS. Mechanical characteristics



$$k = \frac{E}{4} \cdot \frac{w^3 \cdot t}{l^3} \quad \text{(N/m)}$$

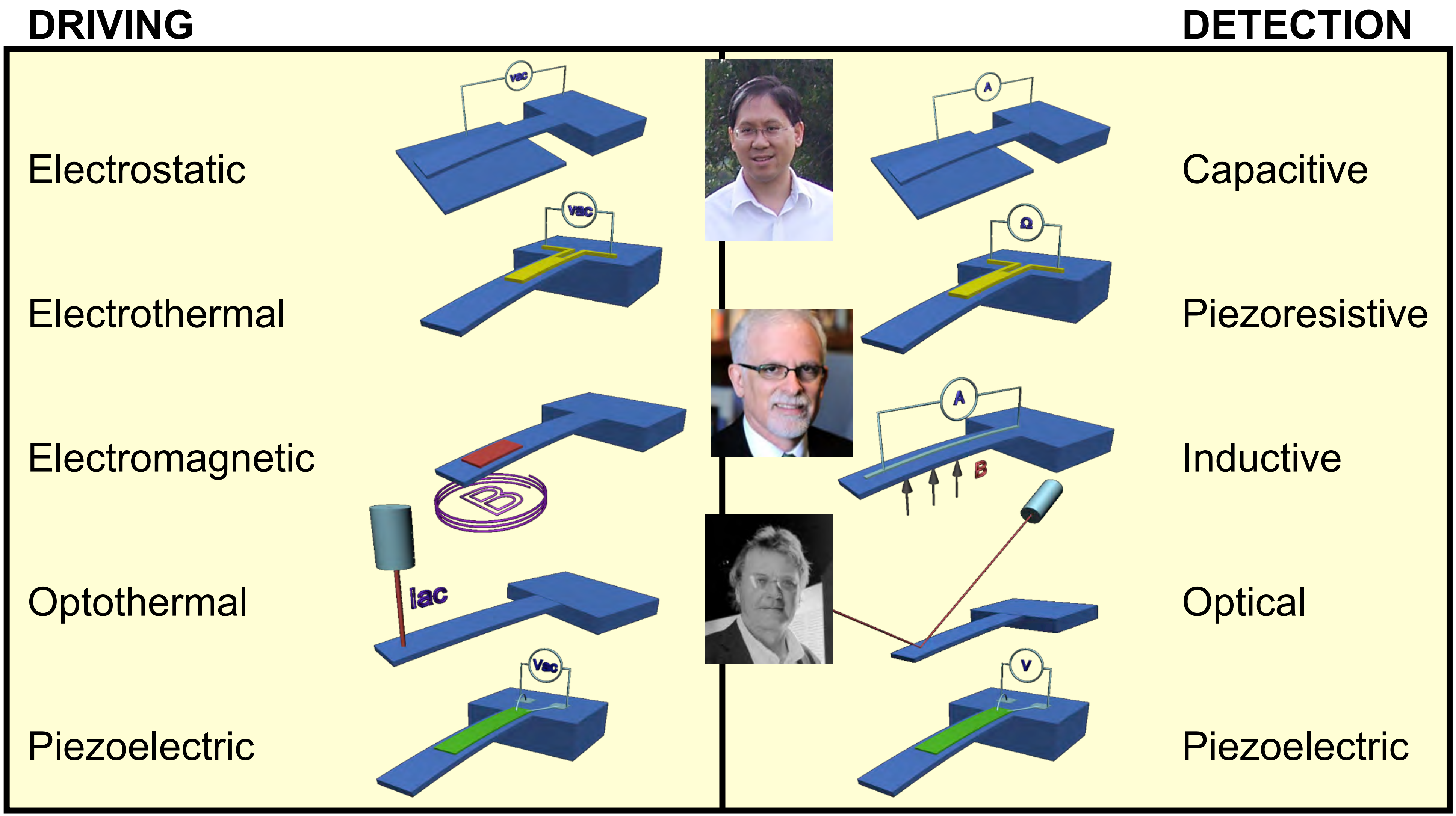
$$f_{res} = 0.162 \cdot \sqrt{\frac{E}{\rho} \cdot \frac{w}{l^2}} \quad \text{(Hz)}$$

Young modulus: E_{Si}=1.79·1011 N/m^2
Density: ρ_{Si}=2.33·103 kg/m^3

$$m = \frac{k}{f_{res}^{\ 2}} \quad \text{(kg)}$$

	l(um)	t(um)	w(um)	k(N/m)	fres(kHz)	m(gr)
MEMS	450	50	2	0.2	14	10^{-6}
MEMS	125	30	4	44	364	$3 \cdot 10^{-7}$
NEMS	10	0.48	0.1	0.02	$1.4 \cdot 10^{3}$	10^{-11}

Some basics on NEMS. Transduction techniques



Some basics on NEMS. Modelization tools

Finite elements commercial softwares

ANSYS

Allows to analyze **macro and microsistems**. Multidomain: mechanics, thermal, fluidics, etc…

COMSOL

Multiphysics. Allows to co-simulate several domains: MEMS, electromagnetics, heat transfer, etc…

CoventorWare

MEMS oriented. Allows the design of MEMS elements from the fabrication process and their simulation. Also multidomain at the microscale.

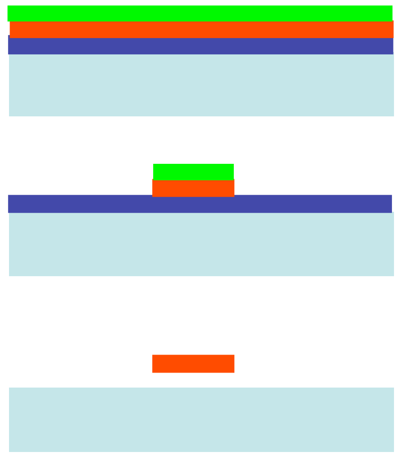
Some basics on NEMS. Fabrication technologies

TOP-DOWN APPROACH

Bulk micromachining

- Two sides accessibility
- Crystal Si structure
- Complex process

Surface micromachining



- Simple process
- Polysilicon structure
- Residual stress
- Adhesion to the substrate

Some basics on NEMS. Fabrication technologies

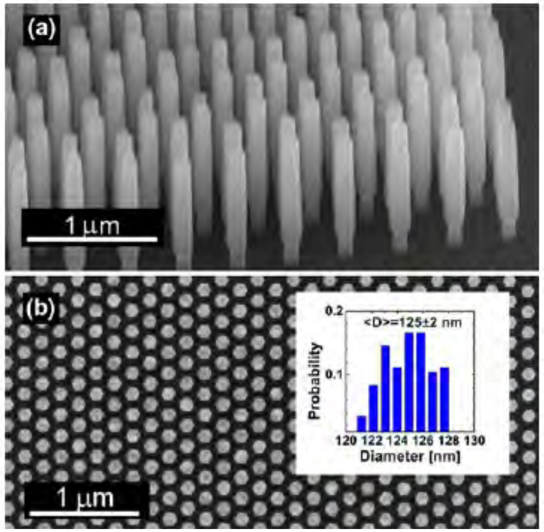
BOTTOM-UP APPROACH

Nanoscale Res Lett (2009) 4:699–704
DOI 10.1007/s11671-009-9302-1

NANO EXPRESS

Highly Uniform Epitaxial ZnO Nanorod Arrays for Nanopiezotronics

J. Volk · T. Nagata · R. Erdélyi · I. Bársony · A. L. Tóth · I. E. Lukács · Zs. Czigány · H. Tomimoto · Y. Shingaya · T. Chikyow



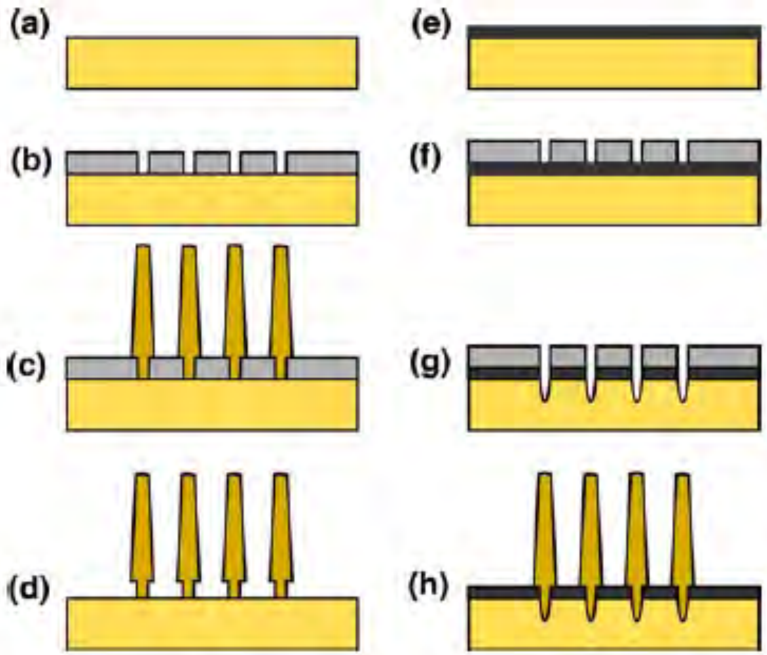
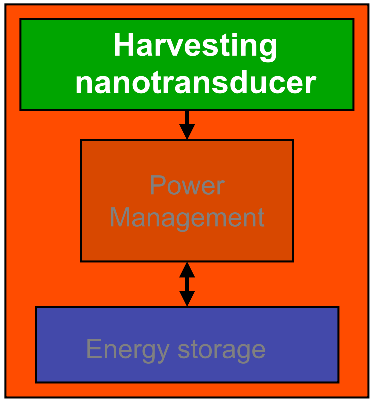


Fig. 1 Schematic process flow of all-ZnO (**a**–**d**) and anchored (**e**–**h**) nanorod arrays. The processing steps for all-ZnO structure are: surface treatment of ZnO substrates (**a**), pattern generation in PMMA by e-beam lithography (**b**), chemical nanowire growth (**c**), and PMMA removal (**d**). Processing steps for the anchored ZnO array are: Ru thin film deposition (**e**), e-beam lithography (**f**), Ar^{+} ion milling (**g**), and chemical nanorod growth after PMMA removal (**h**)



Energy source: Thermomechanical noise (thermal fluctuations)

Attonewton force detection using ultrathin silicon cantilevers

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(Received 14 May 1997; accepted for publication 14 May 1997)

A measured force resolution of 5.6×10^{-18} N/$\sqrt{\text{Hz}}$ at 4.8 K in vacuum using a single-crystal silicon cantilever only 600 Å thick is demonstrated. The spring constant of this cantilever was 6.5×10^{-6} N/m, or more than 1000 times smaller than that of typical atomic force microscope cantilevers. The cantilever fabrication includes the integration of in-line tips so that the cantilever can be oriented perpendicular to a sample surface. This orientation helps suppress cantilever snap-in so that high force sensitivity can be realized for tip-sample distances less than 100 Å. © *1997 American Institute of Physics.* [S0003-6951(97)04628-7]

$$F_{\min}=S_F^{1/2}B^{1/2}\approx\left(\frac{wt^2}{lQ}\right)^{1/2}(E\rho)^{1/4}(k_BTB)^{1/2}$$

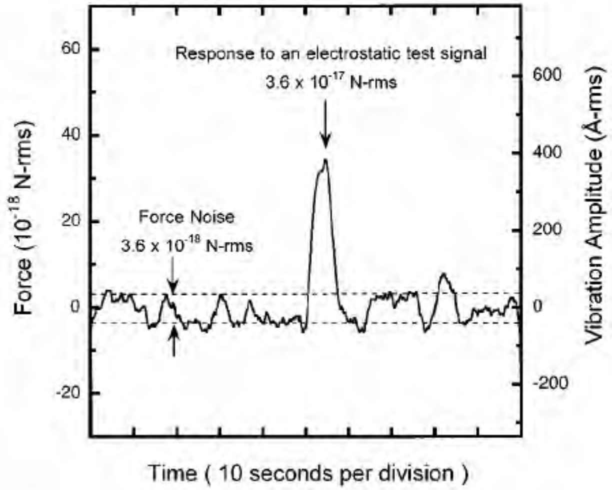
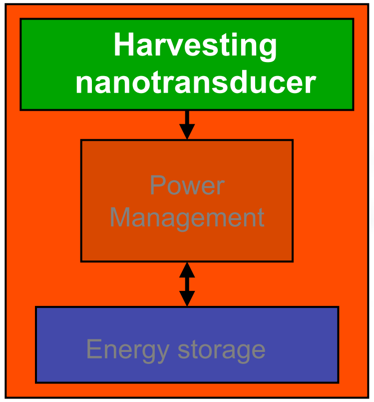


FIG. 3. Time trace of the cantilever vibration amplitude showing noise and a response to an oscillating 36 aN rms electrostatic force. The right hand scale shows the cantilever vibration amplitude and the left hand scale shows the corresponding force amplitude. From the measured noise level, a force resolution of 3.6 aN was estimated. The bandwidth of the measurement was set by the natural bandwidth of the cantilever (equivalent noise bandwidth, $B=\pi f_0/2Q=0.4$ Hz).



Energy source: Thermomechanical noise (thermal fluctuations)

JOURNAL OF APPLIED PHYSICS VOLUME 92, NUMBER 5 1 SEPTEMBER 2002

Noise processes in nanomechanical resonators

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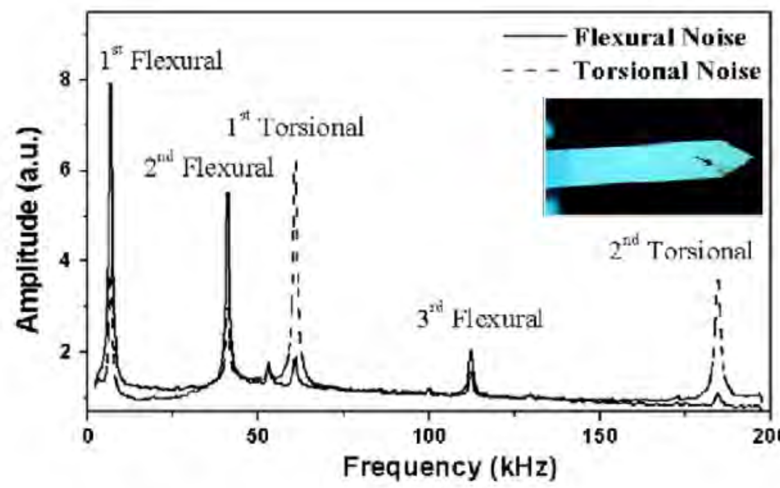
TABLE IV. Expressions for the various spectral noise densities worked out for different representations of the same noise, as well as for noise associated with different fundamental processes.

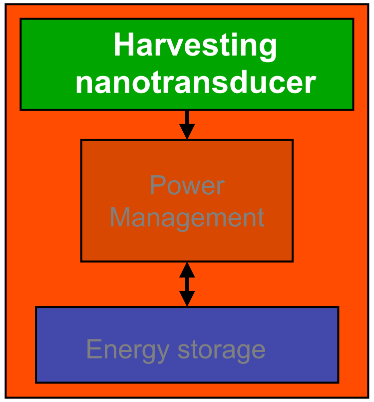
Type of noise	Symbol	Expression	Equation
Force noise, mode n	$S_{f_n}(\omega)$	$\frac{2k_BTM\Omega_n}{\pi Q L^2}$	(23)
Amplitude noise, mode n	$S_{a_n}(\omega)$	$\frac{\Omega_n}{(\Omega_n^2-\omega^2)^2+(\Omega_n^2/Q)^2}\frac{2k_BT}{\pi M L^2 Q}$	(24)
On-resonance amplitude noise, mode n	$S_{a_n}(\Omega_n)$	$\frac{2k_BTQ}{\pi M L^2\Omega_n}$	(24)
Off-resonance phase noise, mode $n=1$	$S_\phi(\omega)$	$\frac{k_BT}{8\pi P_c Q^2}\left(\frac{\Omega_1}{\omega}\right)^2$	(34)
Off-resonance fractional frequency noise, $n=1$	$S_y(\omega)$	$\frac{k_BT}{8\pi P_c Q^2}$	(42)
Allan variance, $n=1$	$\sigma_A(\tau_A)$	$\sqrt{\frac{k_BT}{8P_cQ^2\tau_A}}$	(49)
Temperature fluctuations	$S_T(\omega)$	$\frac{4}{\pi}\frac{k_BT^2/g}{1+\omega^2\tau_T^2}$	(55)
Allan variance, temperature fluctuations	$\sigma_A(\tau_A)$	$(2.25\times10^{-4}/K^2)\sqrt{k_BT^2/g\tau_A}$	(61)
Allan variance, adsorption desorption	$\sigma_A(\tau_A)$	$\sqrt{\frac{2N_a\tau_r}{\tau_A}}\frac{\sigma_{occ}m}{M}$	(66)
Allan variance, defect motion	$\sigma_A(\tau_A)$	$\sqrt{\frac{2\sigma_\omega^2}{\langle\Omega\rangle^2}}\sqrt{\frac{\tau_d}{\tau_A}}$	(68)

blication 18 June 2002)

ed to achieve high natural resonance frequencies,
xcess of 10^4. These resonators are candidates for use
ion on-chip clocks. Some fundamental and some
limits to the performance of such resonators. These
hnson noise, and adsorption–desorption noise; other
hermal fluctuations and defect motion-induced noise.
rmalism for treating these noise sources, and use it to
will have on the noise of a model nanoscale resonator.



D. Ramos et al. Nanotechnology (2008)



Energy source: Thermomechanical noise (thermal fluctuations)

JOURNAL OF APPLIED PHYSICS VOLUME 95, NUMBER 5 1 MARCH 2004

Ultimate limits to inertial mass sensing based upon nanoelectromechanical systems

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Y. T. Yang and M. L. Roukes[b)]
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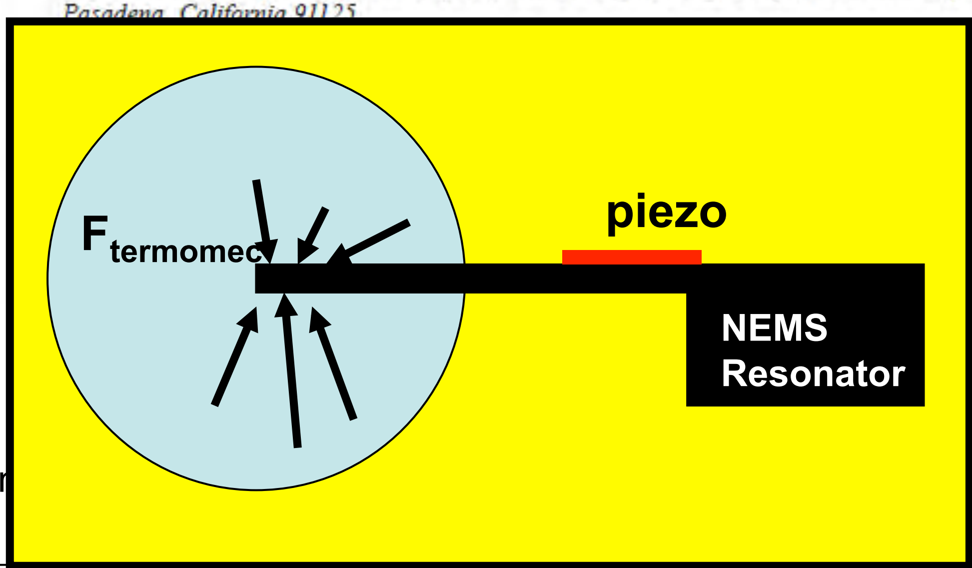
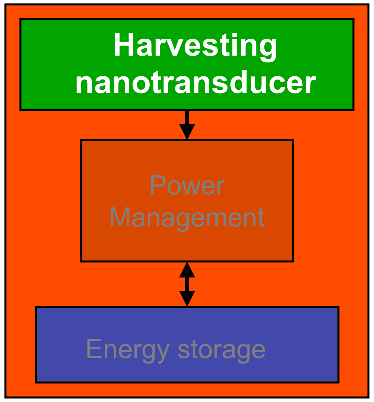


Mass resolution

$$\delta M \approx -2\frac{M_{eff}}{\omega_0}\delta\omega_0$$

$$\delta\omega_0 \approx \left[\int_{\omega_0-\pi\Delta f}^{\omega_0+\pi\Delta f} S_\omega(\omega)\,d\omega\right]^{1/2}$$

Spectral density of frequency fluctuations



Energy source: Thermomechanical noise (thermal fluctuations)

Efficient non-linear NEMS based energy harvesting from thermomechanical noise

M. López-Suárez[1], G. Murillo[1], J. Agustí[1], H. Vocca[2], L. Gammaitoni[2] and G. Abadal[1]

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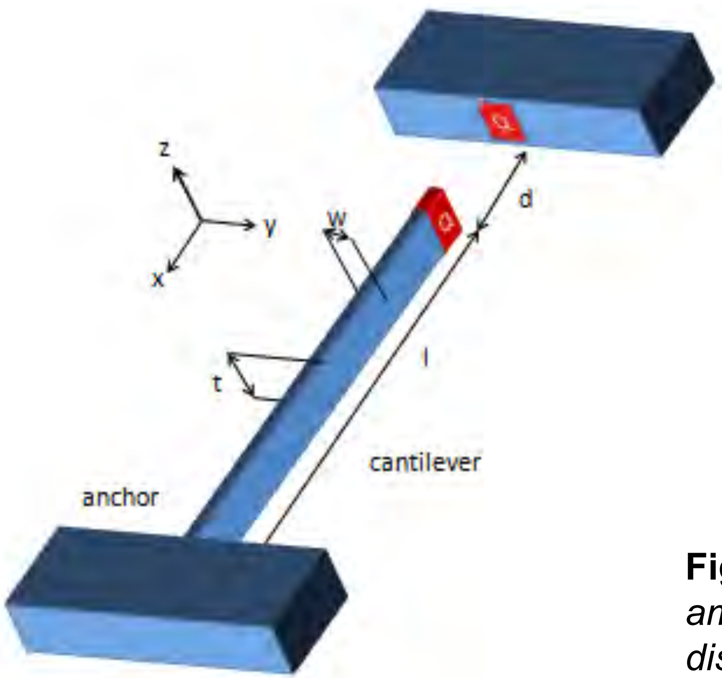
2 *NiPS Laboratory, Dipartimento di Fisica, Universitá di Perugia, 06100 Perugia, Italy and INFN Sezione di Perugia, 06100 Perugia, Italy*



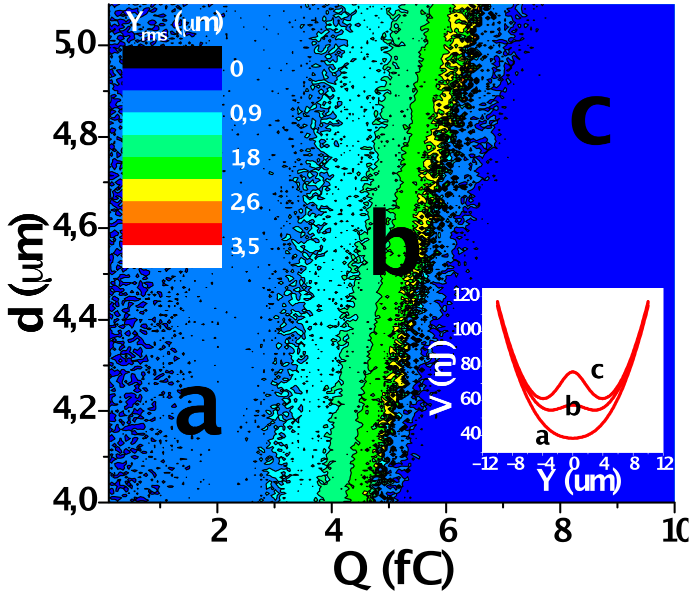
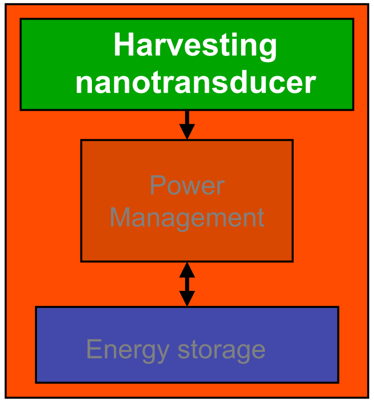
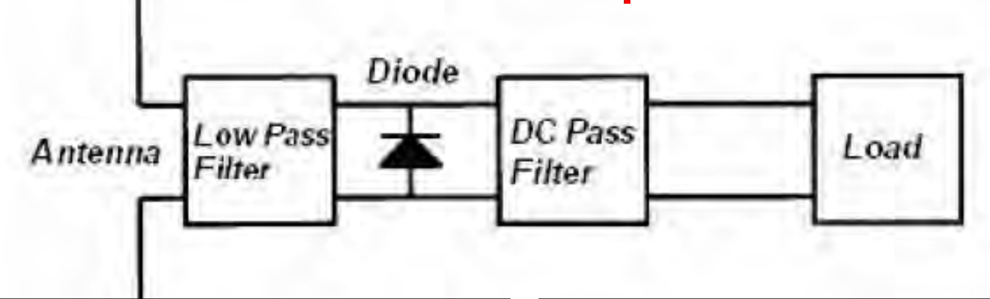


Figure 2: *Color map of the cantilever on-plane vibration amplitude for different conditions of charge, Q, and electrode distance, d. Inset: potential energy at the regions of low interaction (a), maximum hoping (b) and strong interaction (c). Cantilever dimensions: l=28um; w=0.1um; t=1.0um; QF=1000, material: silicon. T=300K and B=1MHz*

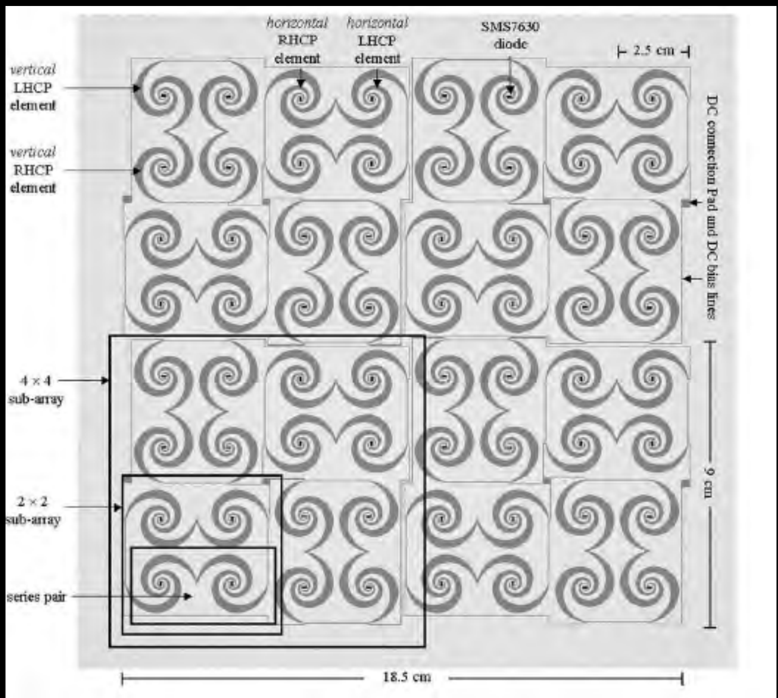


Energy source: Electromagnetic radiation

Rectenna concept

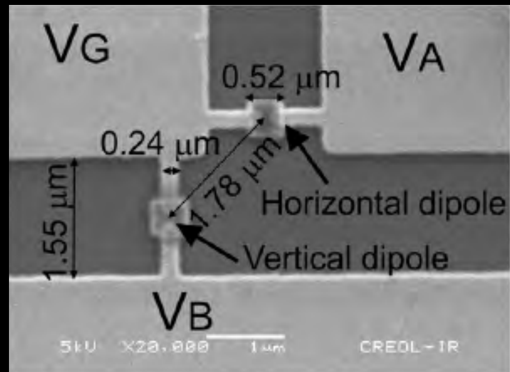


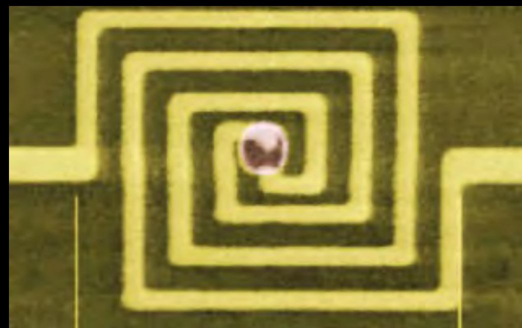
GHz rectenna



Hagerty et al., "IEEE Trans on MTT", (2004)

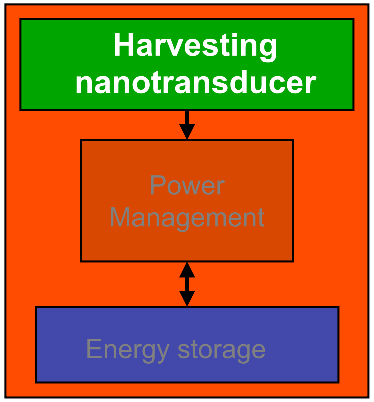
THz optical rectenna





Alda et al. Opt. Lett. (2009)

Energy source: Electromagnetic radiation



NANO LETTERS
2007
Vol. 7, No. 11
3508–3511

Nanotube Radio

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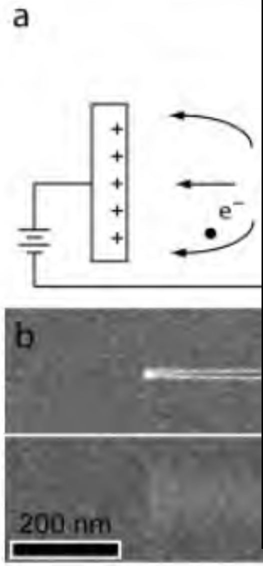
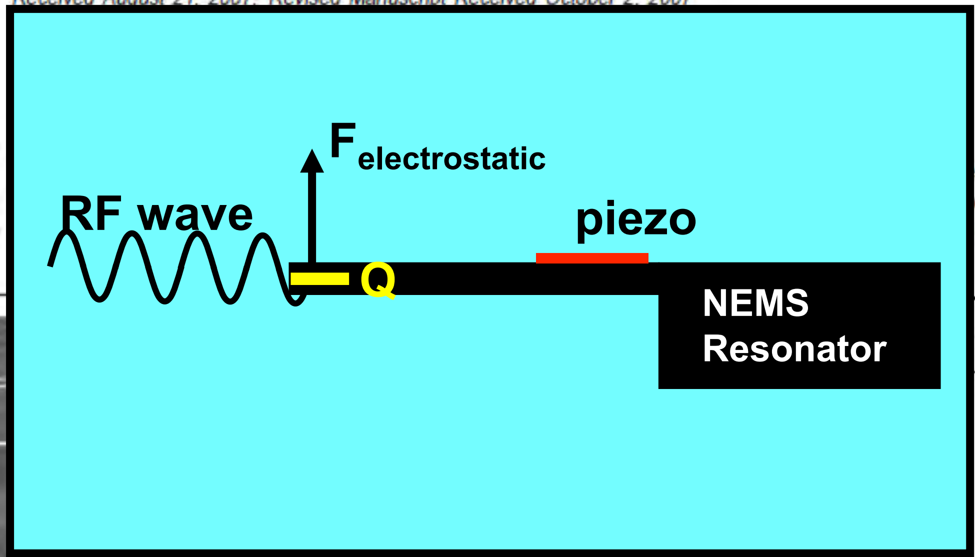
Received August 21, 2007; Revised Manuscript Received October 2, 2007





. The nanotube serves simultaneously as
direct current voltage source, as supplied
both frequency and amplitude modulation

trimming

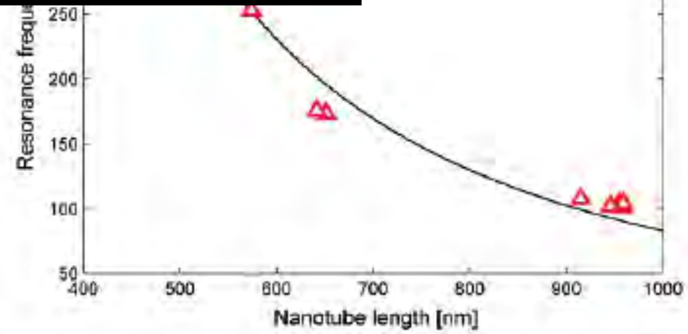
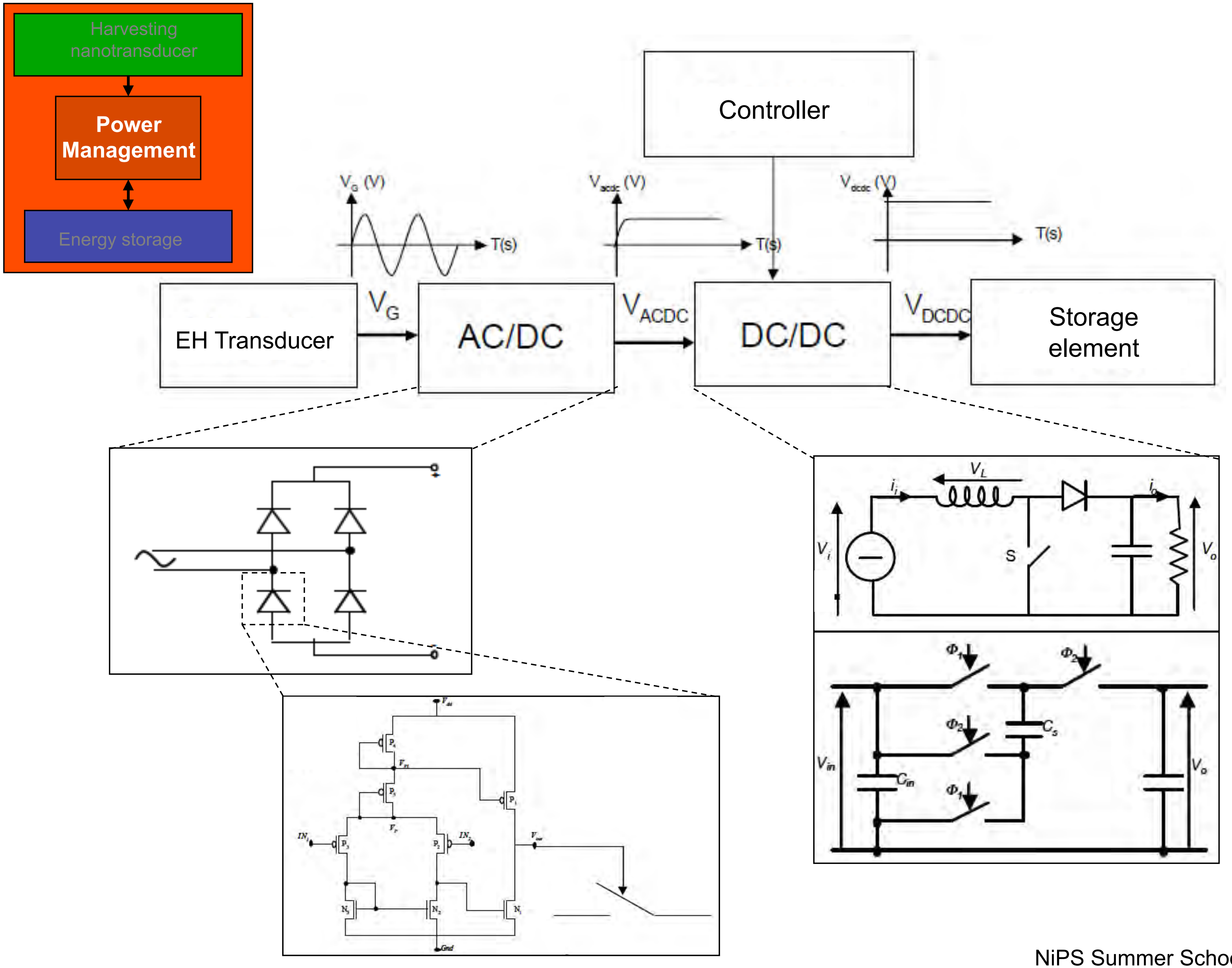
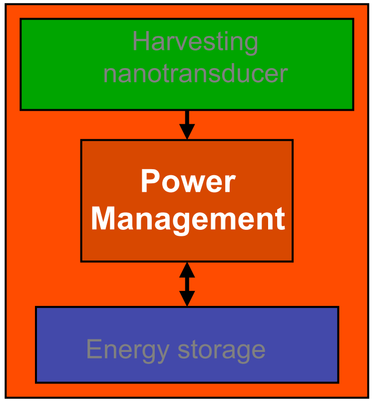
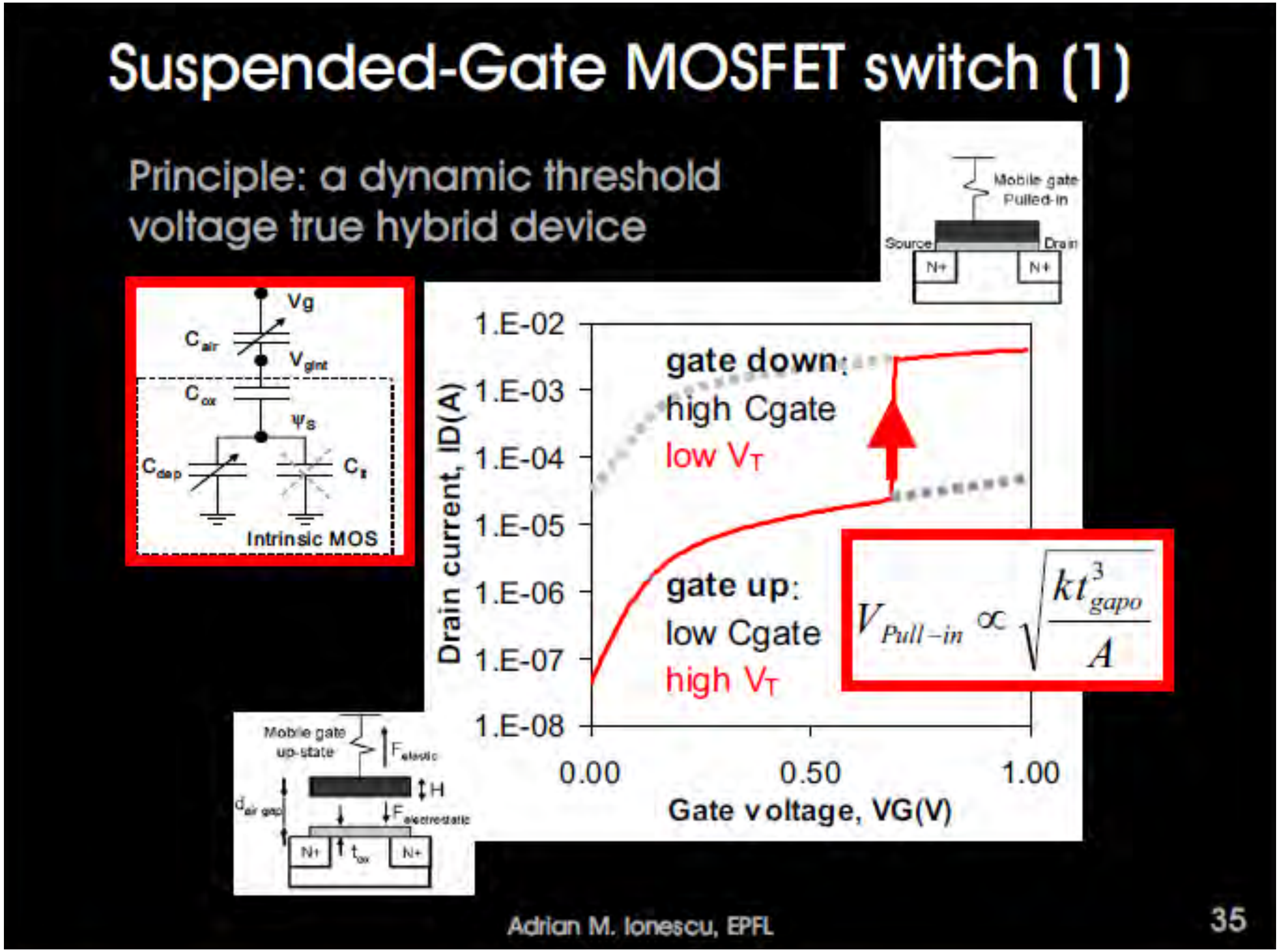


Figure 2. (a) Schematic of the nanotube radio. Radio transmissions tuned to the nanotube's resonance frequency force the charged nanotube to vibrate. Field emission of electrons from the tip of the nanotube is used to detect the vibrations and also amplify and demodulate the signal. A current measuring device, such as a sensitive speaker, monitors the output of the radio. (b) Transmission electron micrographs of a nanotube radio off and on resonance during a radio transmission.

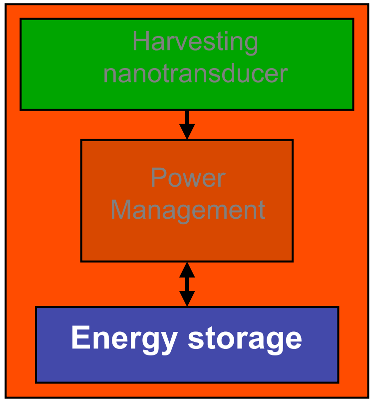


NiPS Summer School 2010





Europractice-STIMESI. MEMS and System Package Workshop – IMEC November 2007



IOP PUBLISHING JOURNAL OF MICROMECHANICS AND MICROENGINEERING

J. Micromech. Microeng. 19 (2009) 094015 (5pp) doi:10.1088/0960-1317/19/9/094015

Storing elastic energy in carbon nanotubes

F A Hill[1], T F Havel[1], A J Hart[2] and C Livermore[1]

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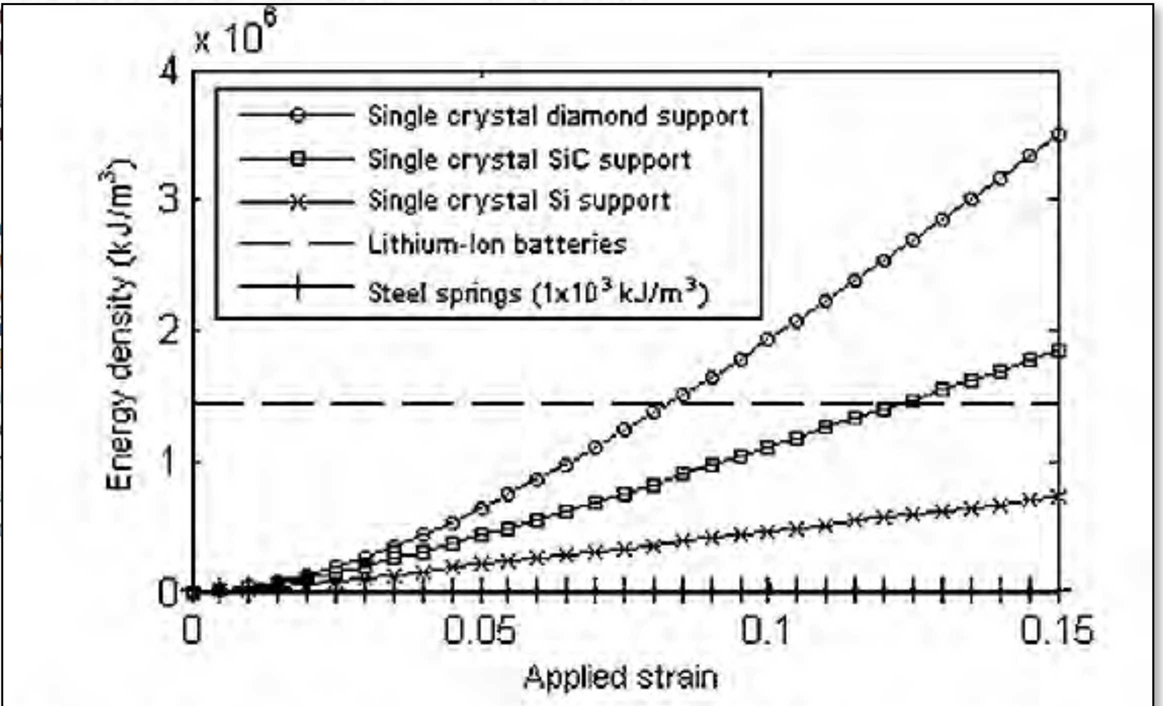
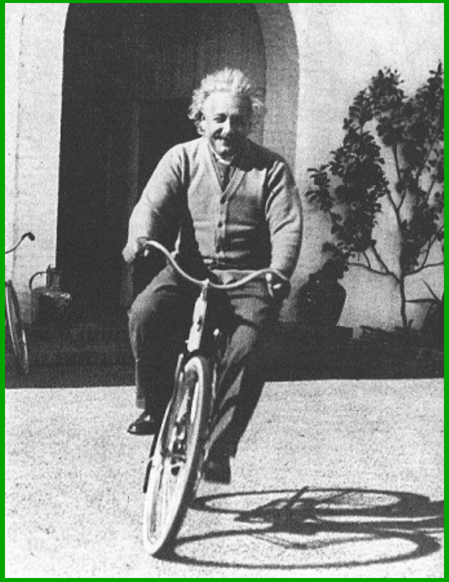


Figure 2. Energy density of SWCNT bundles under tensile loading with support structures made of single crystal diamond, silicon and silicon carbide.

"If at first, the idea is not absurd, then there is no hope for it"

ALBERT EINSTEIN



Abstract

Nanoelectromechanical systems, NEMS, have been investigated in the last decade with a special emphasis in the detection of fundamental magnitudes. NEMS, as a natural consequence of the MEMS downscaling, inherit their multi-domain response with a dramatic improvement in terms of sensitivity, resolution and energy consumption. The unique miniaturization and low-consumption opportunities that offer resonant NEMS have also been studied in the field of integrated radio communications.

In this lecture we will analyze the potential possibilities that NEMS also offer in the field of energy scavenging from ambient sources. Modeling and design issues, as well as their link to top-down and bottom-up technologies and fabrication processes will be introduced. A special emphasis will be dedicated to the linear resonance and non-linear mechanical characteristics of NEMS, as a key point in terms of energy efficiency in the transduction process. A complete self-powered system will be described, considering the transduction-management-storage chain of the energy, as well as the application subsystem that uses the harvested energy. NEMS role in the power management and storage blocs will also be introduced. Finally, the complementarity of NEMS based energy harvesters with ongoing sensing and communications NEMS based applications will be envisaged.