Top emerging technologies: Nanogenerators and nanopiezotronics

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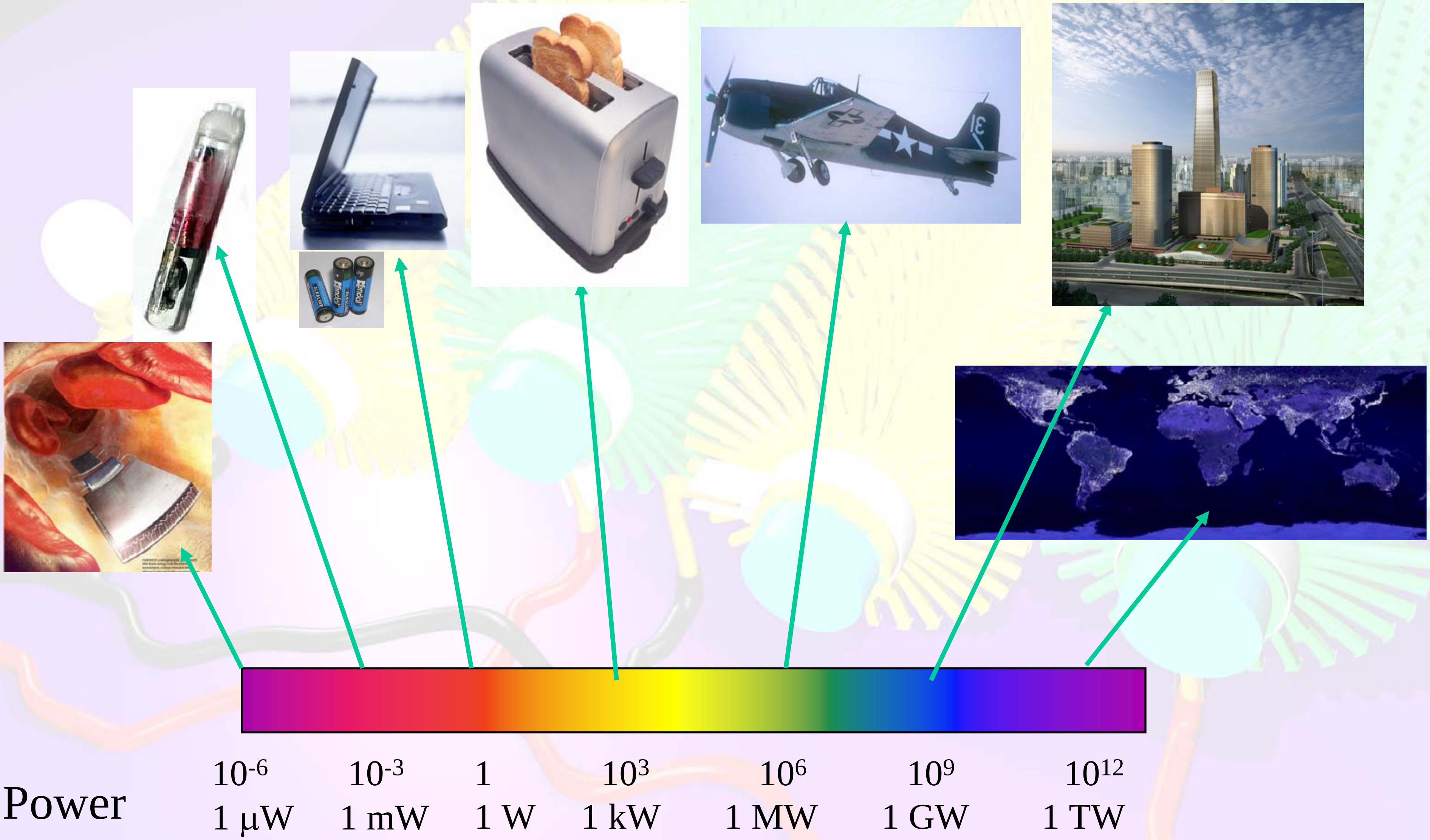
Research supported by DARPA, NASA, NSF, DOE

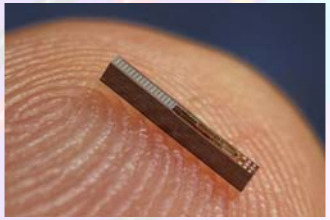
Magnitude of power scale

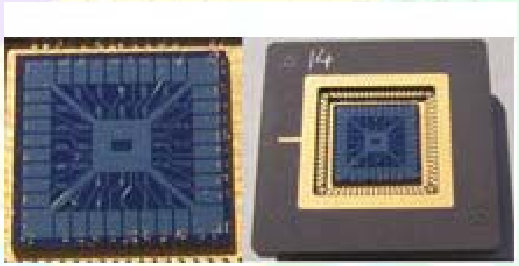


Energy Sources for Micro/Nanorobots

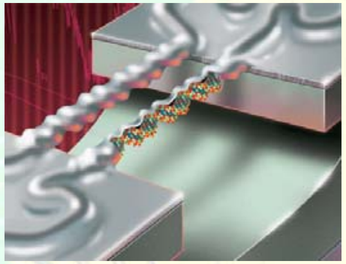
Microfabricated Solar Cells, Micro Fuel Cells, Thin-Film Batteries

Energy Harvesting Methods for Micro/Nano-Devices

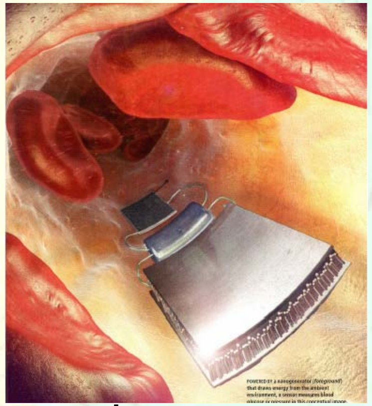




Nanosensors

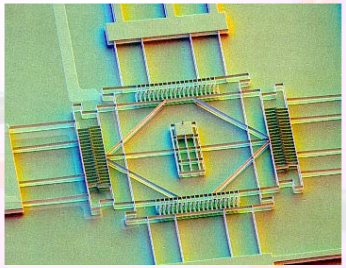


Nanodevices

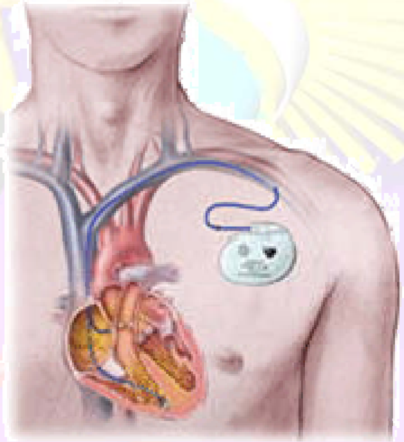


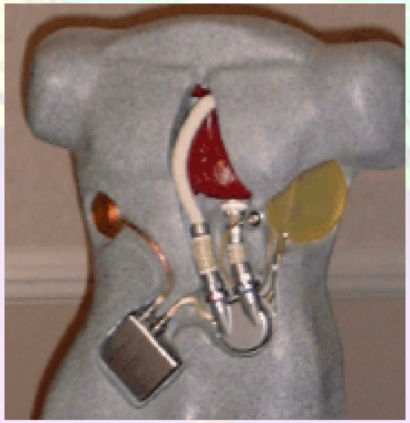
Biosensor

Micro-robot



MEMS

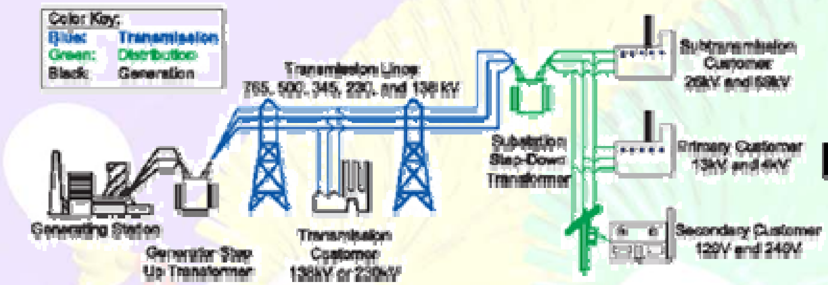




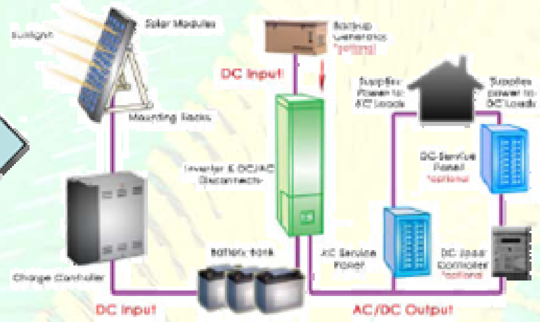
Medical devices

Size and magnitude matters!

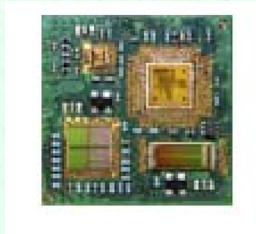
Macro-Grid

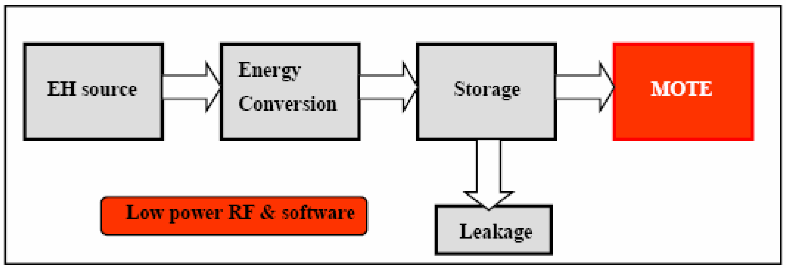


Micro-Grid

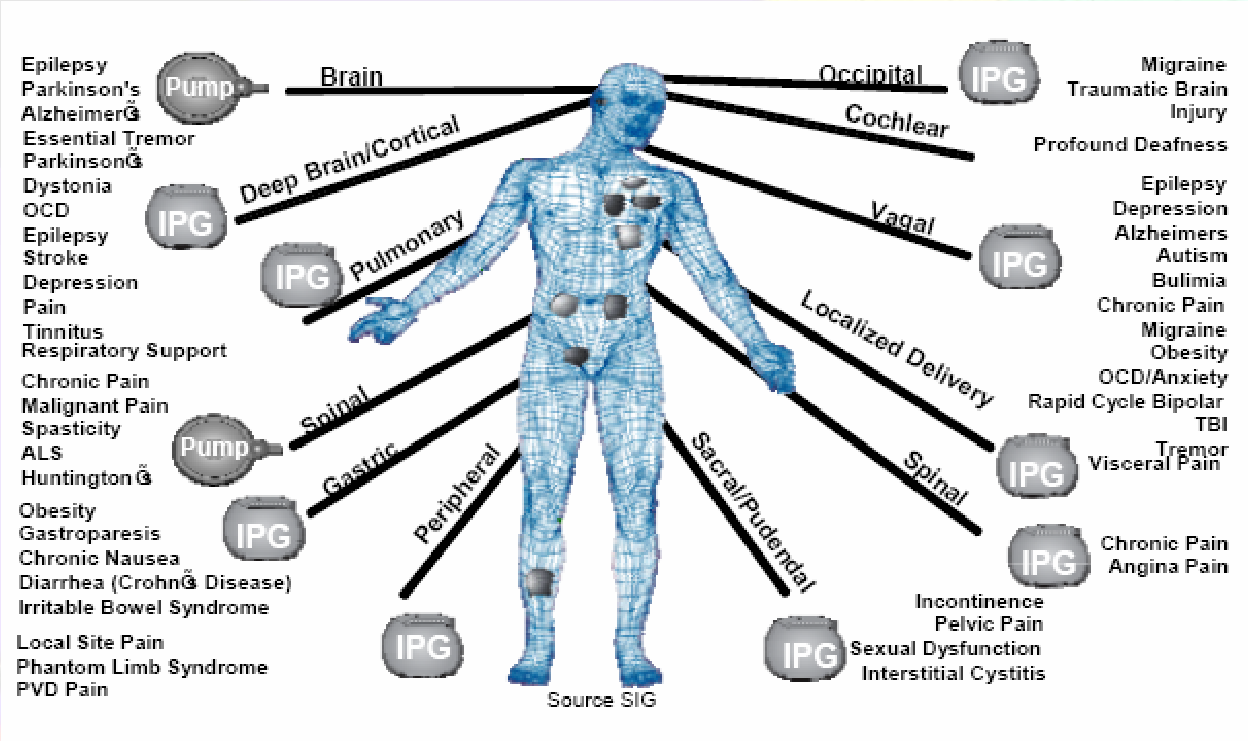


Nano-Grid





Wireless biosensor networks: complete monitoring

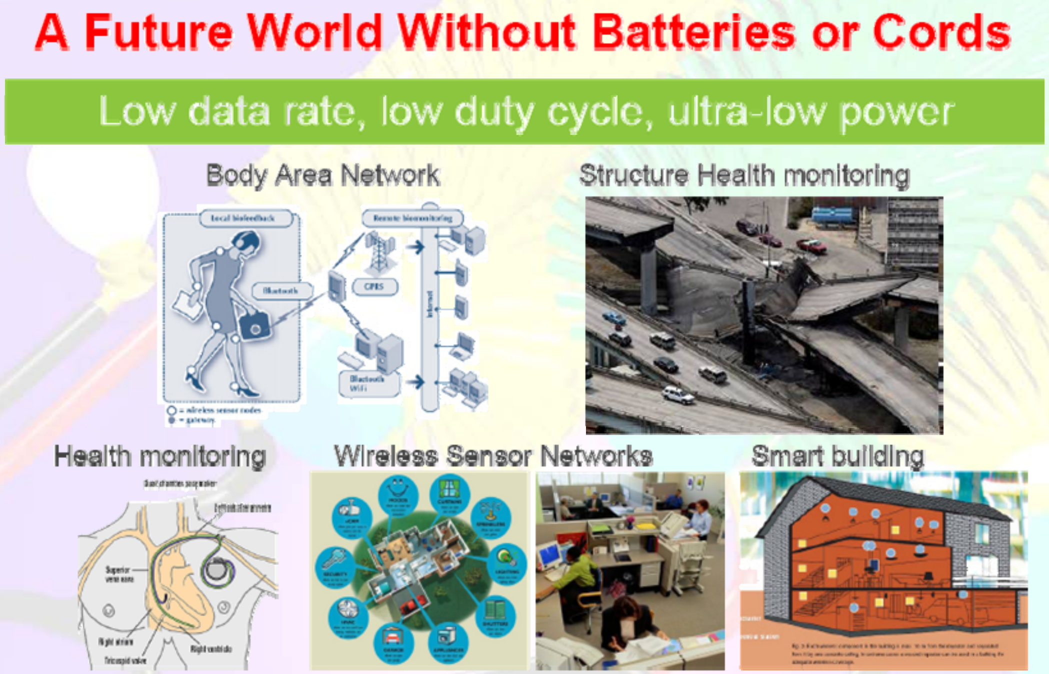


How much energy does each of us have?

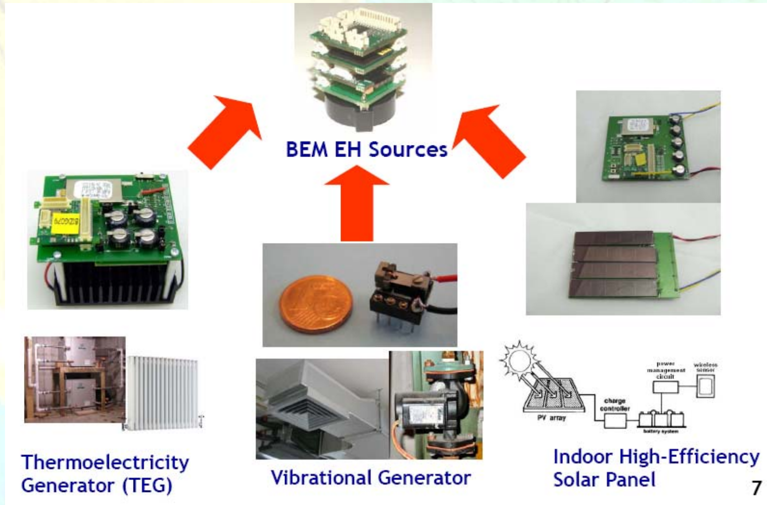
Table 1. Mechanical energy from typical body motions and the expected electrical energy can be generated.

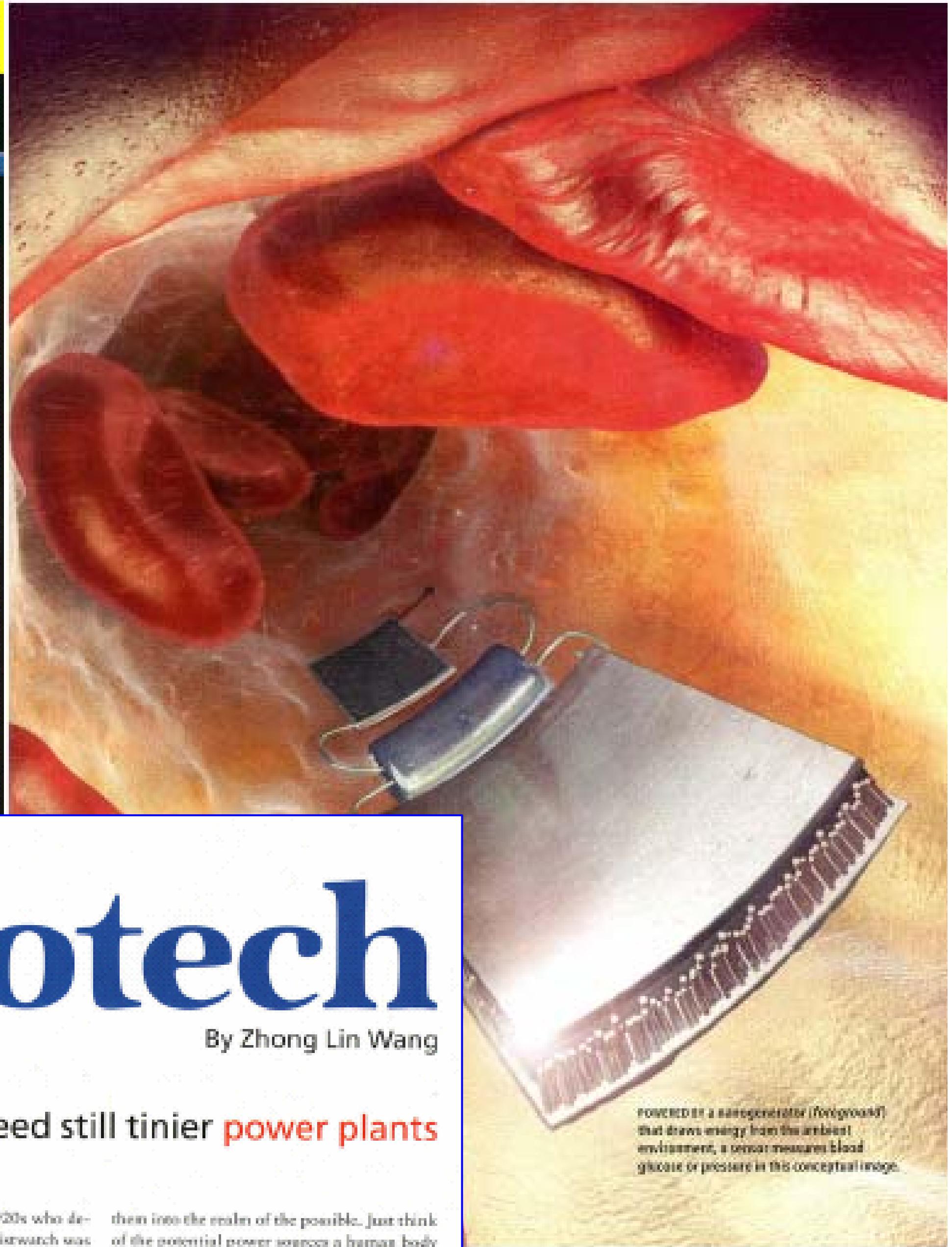
Activity	Mechanical Energy	Electrical energy available	Electrical energy per movement
Blood flow	0.93W	0.16W	0.16J
Exhalation	1.00W	0.17W	1.02J
Breath	0.83W	0.14W	0.84J
Upper limbs	3.00W	0.51W	2.25J
Fingers type	6.9-19mW	1.2-3.2mW	226-406 μ J
Walk	67.00W	11.39W	18.9J

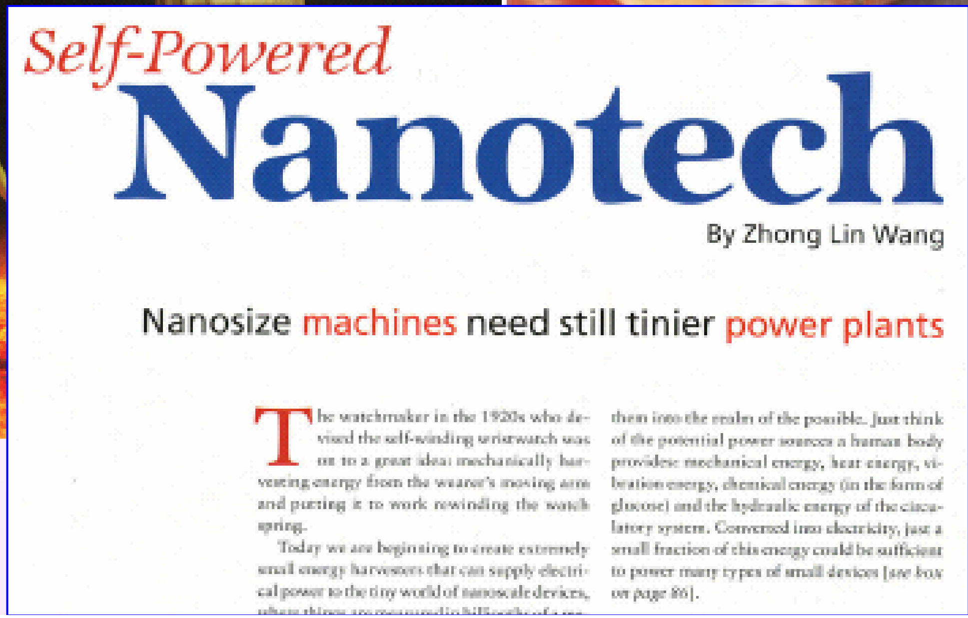
Wireless health and environmental monitoring



Energy harvesting







Self-Powered

Nanotech

By Zhong Lin Wang

Nanosize machines need still tinier power plants

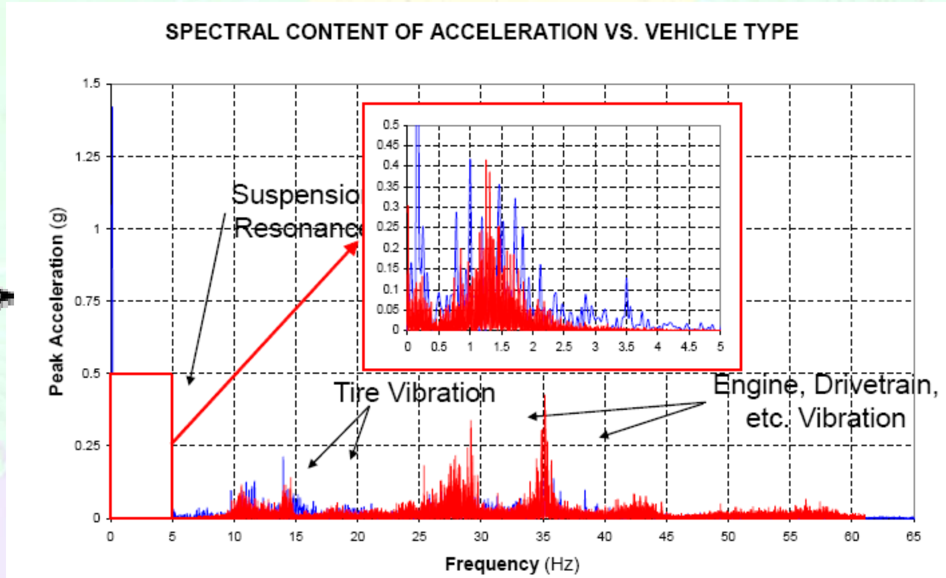
The watchmaker in the 1920s who devised the self-winding wristwatch was on to a great idea: mechanically harvesting energy from the wearer's moving arm and putting it to work rewinding the watch spring.

Today we are beginning to create extremely small energy harvesters that can supply electrical power to the tiny world of nanoscale devices, ...

them into the realm of the possible. Just think of the potential power sources a human body provides: mechanical energy, heat energy, vibration energy, chemical energy (in the form of glucose) and the hydraulic energy of the circulatory system. Converted into electricity, just a small fraction of this energy could be sufficient to power many types of small devices [see box on page 86].

January, 2008

Mechanical energy harvesting

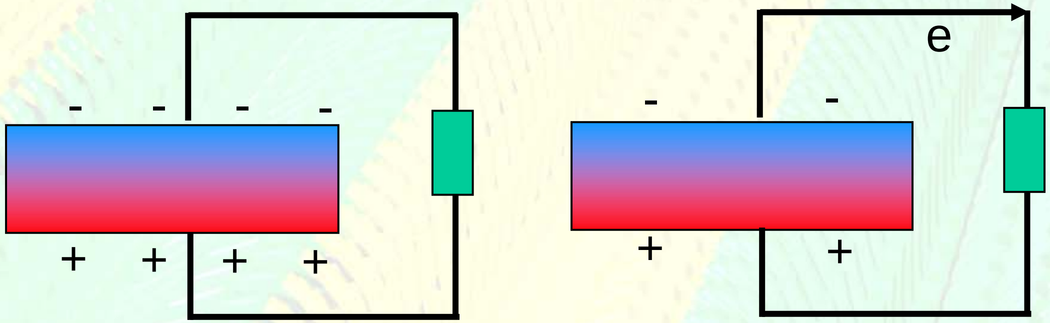


Energy harvesting – a new industry!

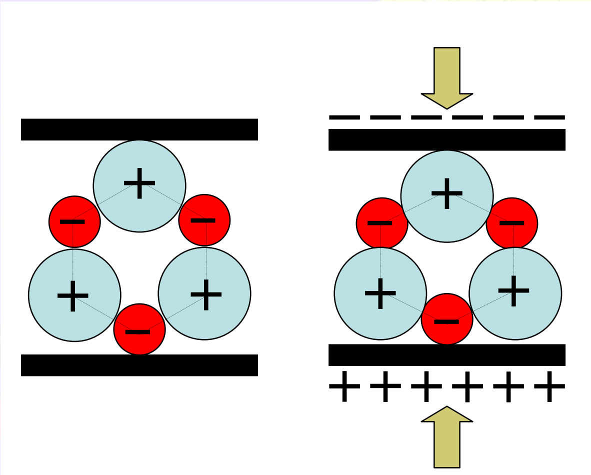
Characteristics:

1. Low frequencies;
2. Large frequency range;
3. Time-dependent;
4. Irregular amplitude

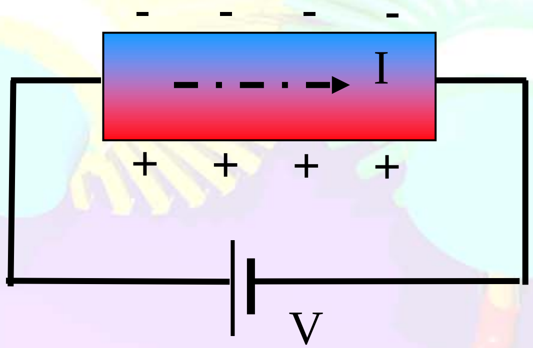
Electricity generation



Piezoelectric effect



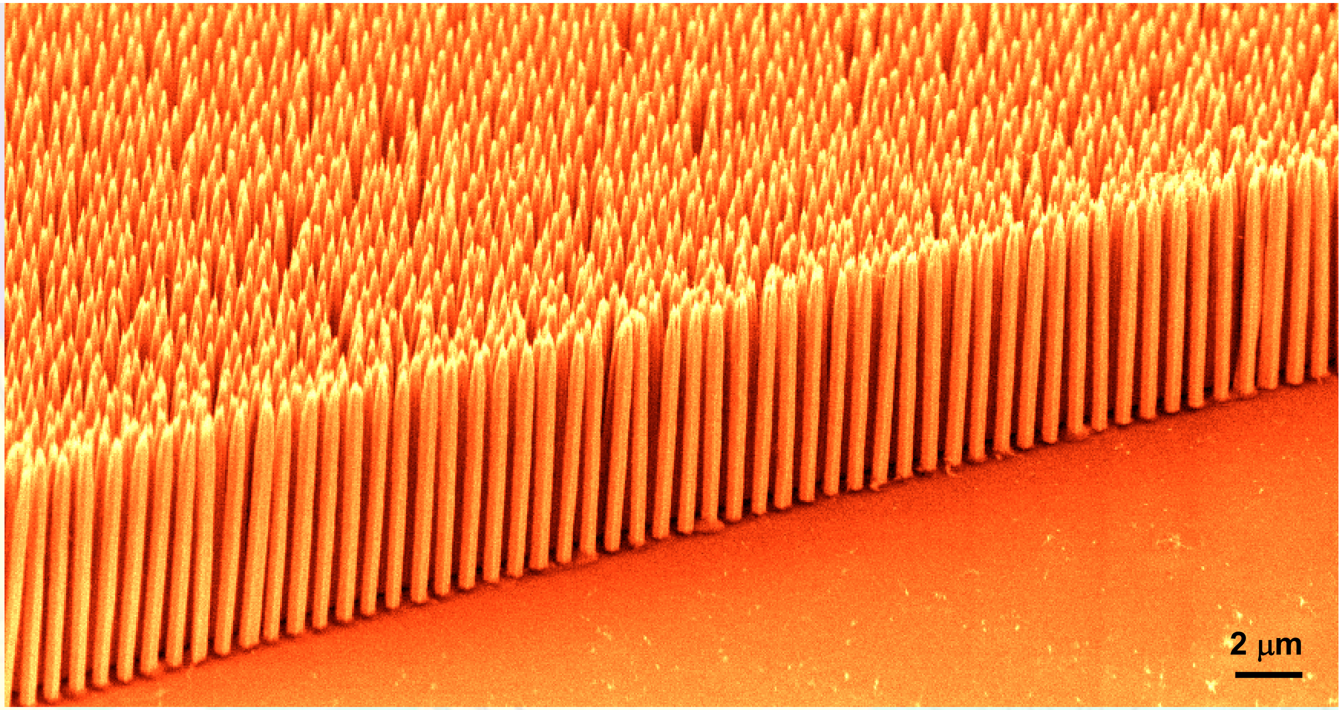
Piezotronics

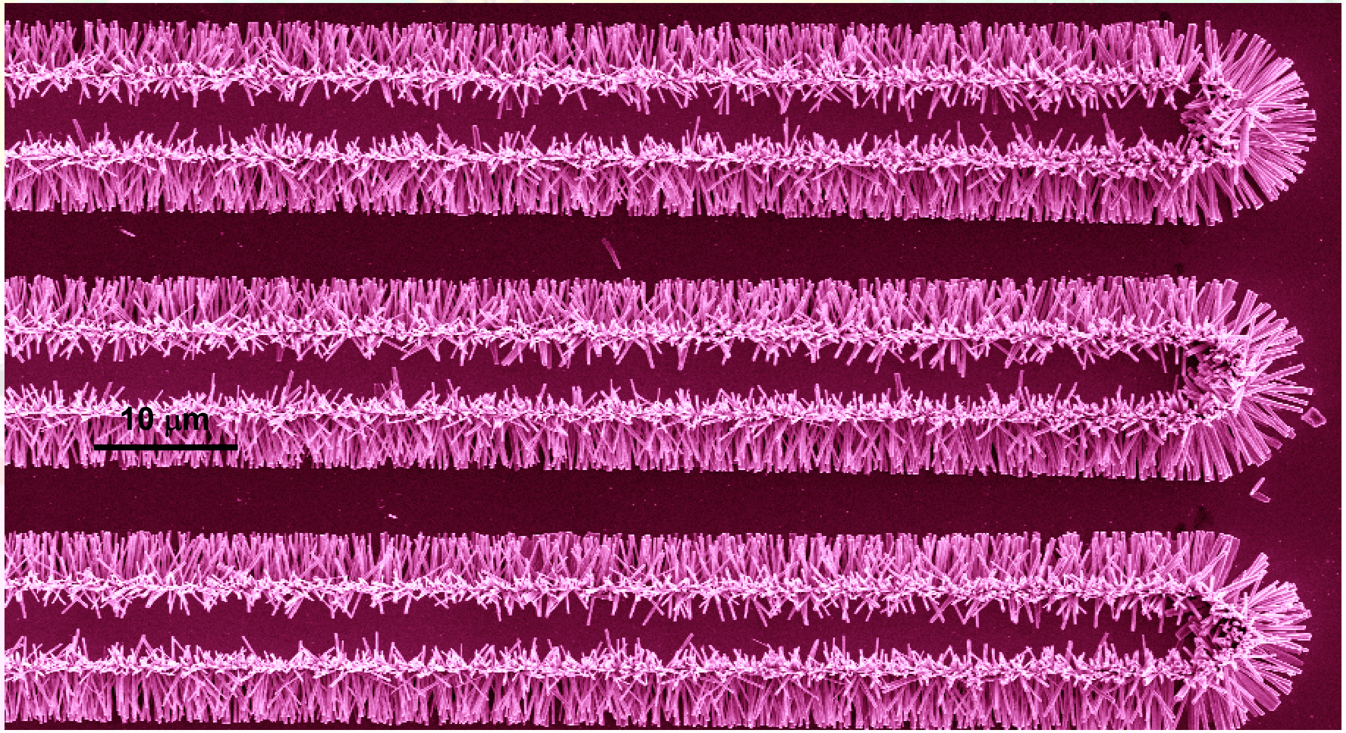


- Piezoelectric potential;
- Lower doping;
- Partial screening effect

Monday Symposium E 1:40PM

Controlled growth of ZnO nanowires





Xu et al. JACS, *130* (2008) 14958;

Qin et al. J. Physical Chemistry C, 112 (2008) 18734

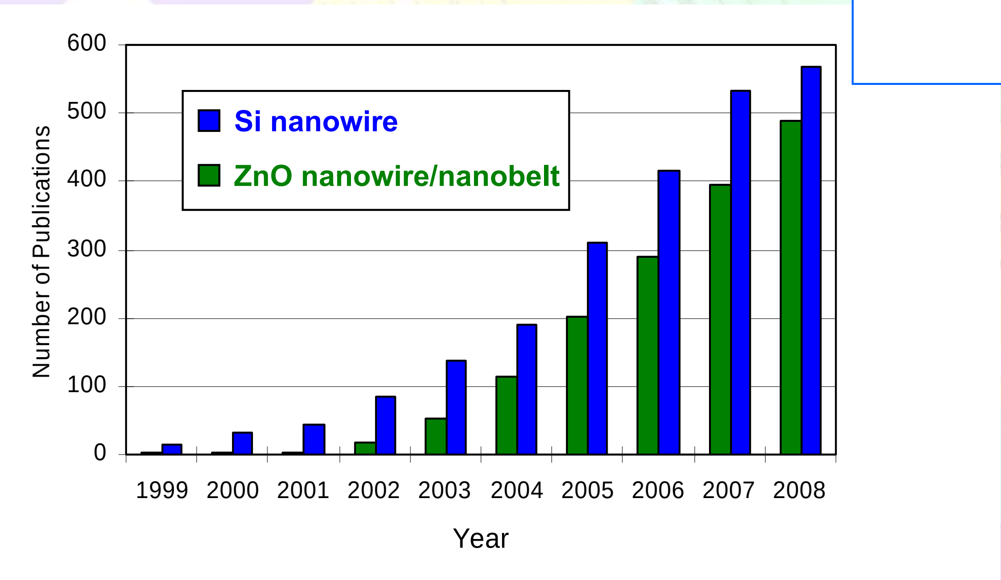
Zn(NO3)2·6H2O and (HMTA)

Publication statistics on one-dimensional nanostructures for ZnO and Si

Nanobelts of Semiconducting Oxides

Zheng Wei Pan,[1] Zu Rong Dai,[1] Zhong Lin Wang[1,2*]

Science 291 (2001) 1947.
Cited for 2450 times



Splendid One-Dimensional Nanostructures of Zinc Oxide: A New Nanomaterial Family for Nanotechnology

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School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0245

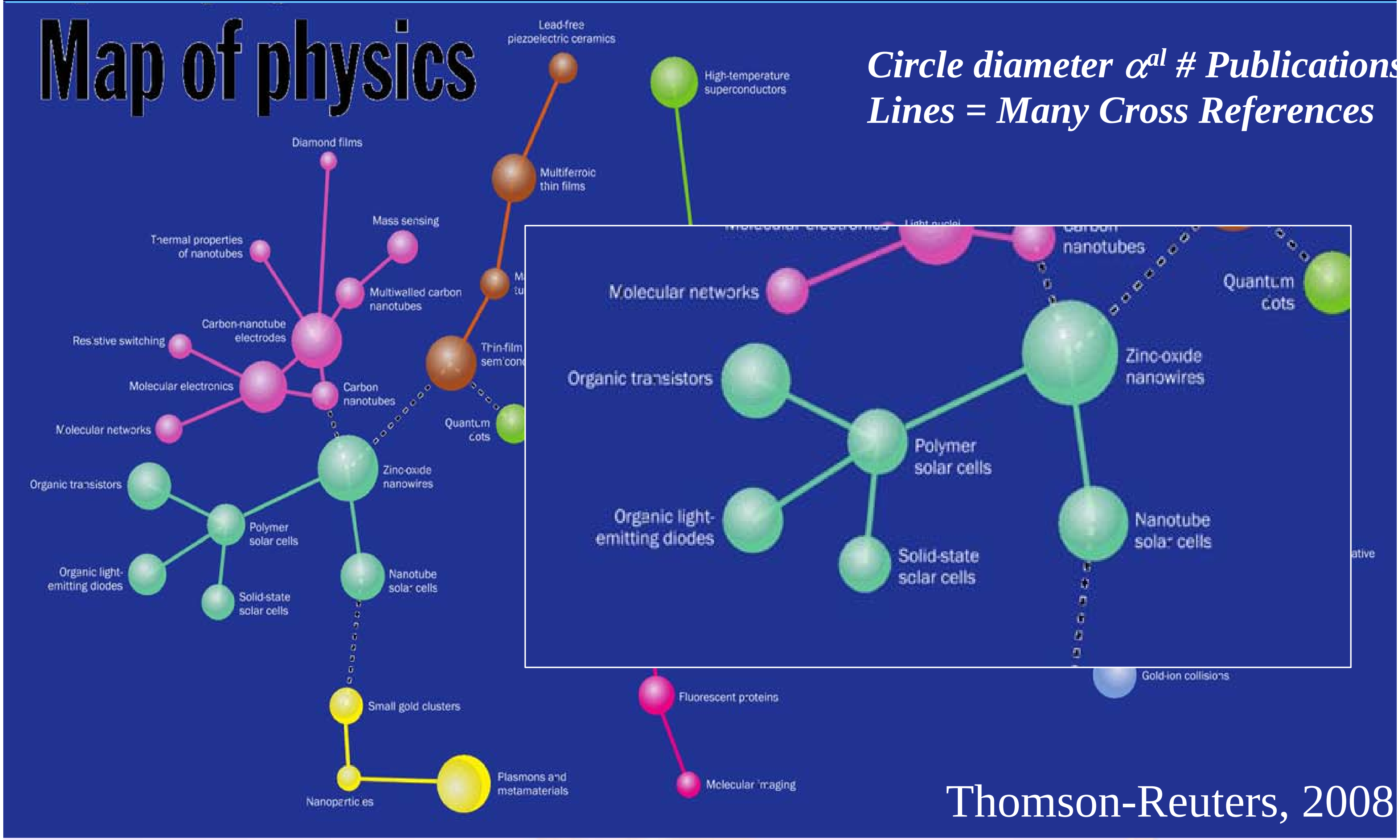
PERSPEC

ACS Nano, online

ZnO nanowires and nanobelts have equal importance as silicon nanowires and carbon nanotubes!

Nano ZnO Research

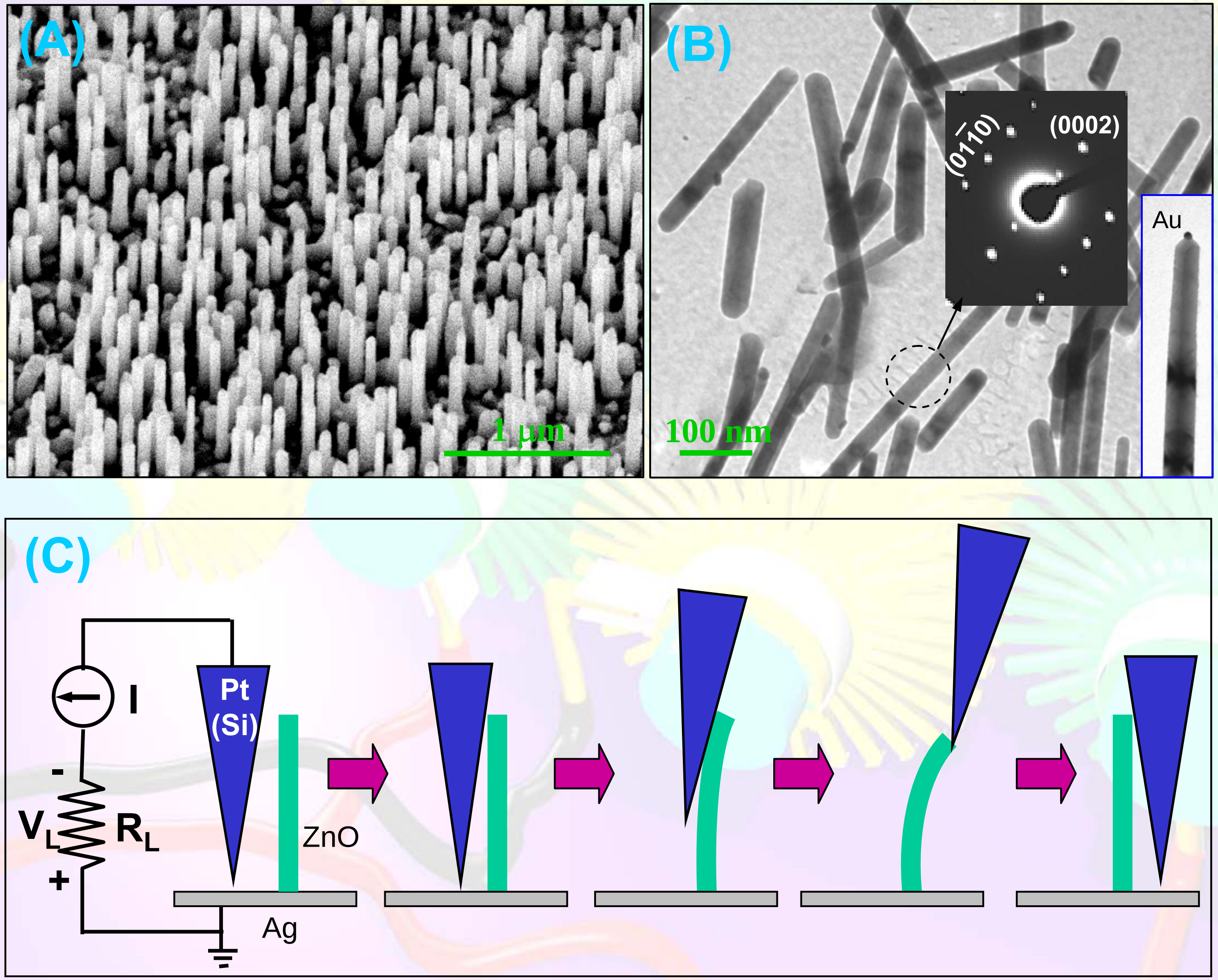
Circle diameter α^{al} # Publications
Lines = Many Cross References



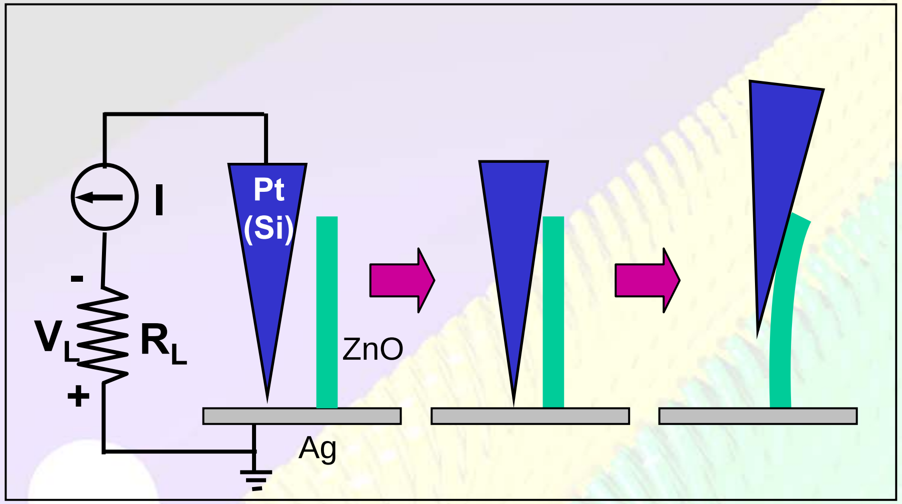
Thomson-Reuters, 2008

Based on bibliometric data from information-services provider Thomson Reuters, this map reveals "core areas" of physics, shown as coloured circular nodes, and the relationship between these subdisciplines, shown as lines. From *Physics World*, October (2008) 36-37.

Converting mechanical energy into electricity energy by piezoelectric ZnO nanowires

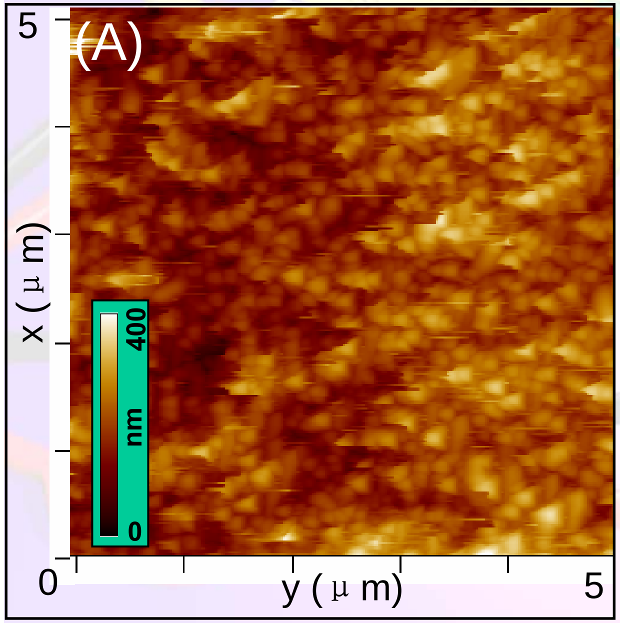


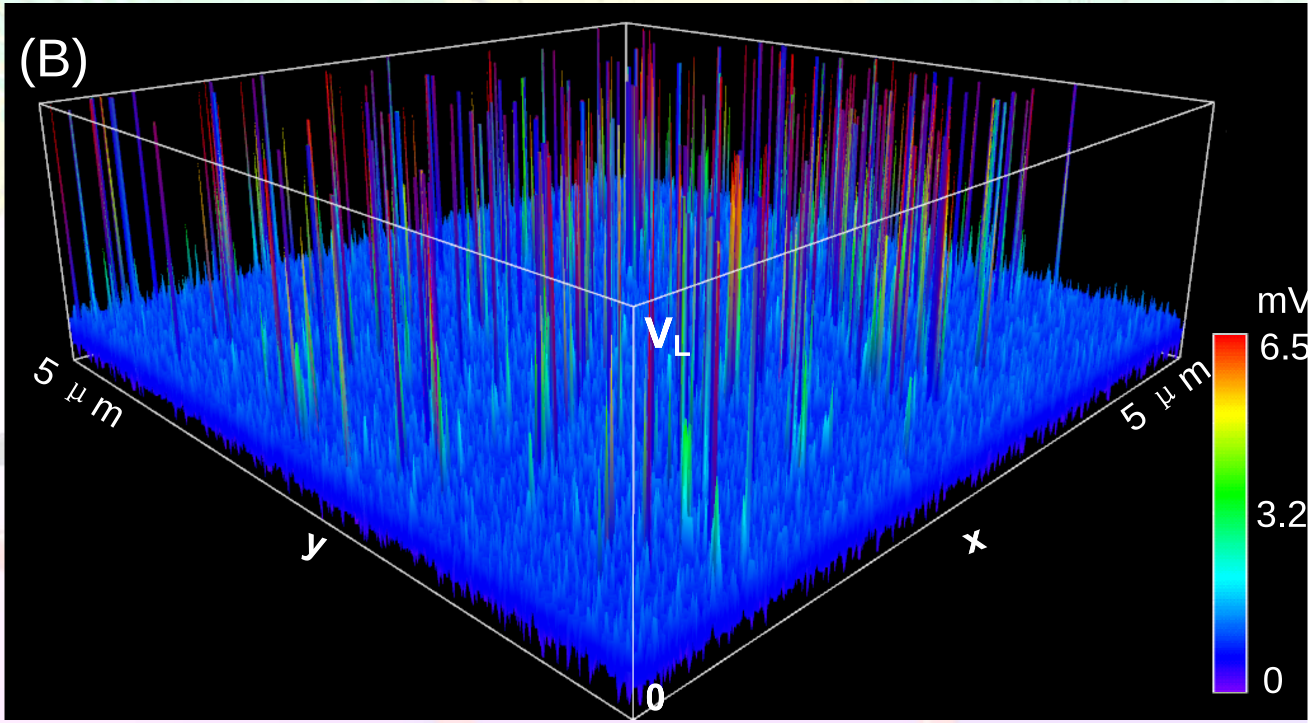
Wang and Song, Science 312 (2006) 242.



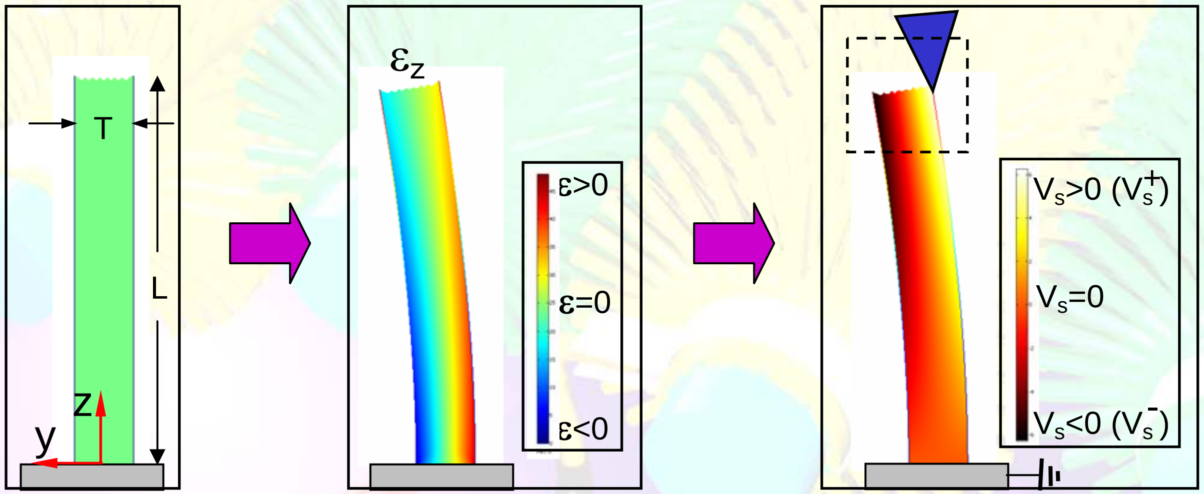
Piezo-electric nano-generator using ZnO nanowires

Wang and Song, Science 312 (2006) 242.



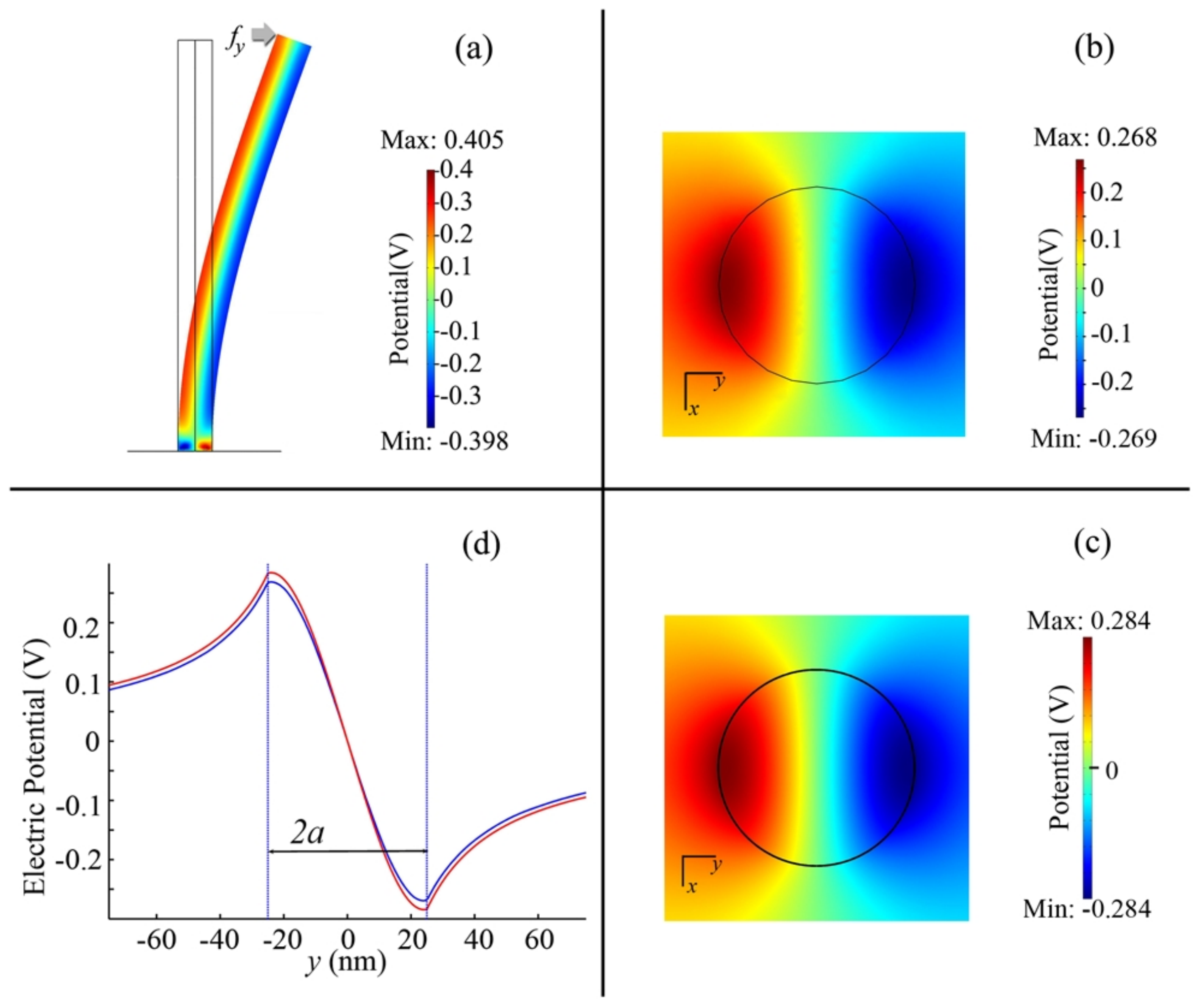


Converting mechanical energy into electricity energy by a piezoelectric ZnO nanowire: mechanism



Wang and Song, Science 312 (2006) 242.

Piezoelectric Potential, a = 25nm

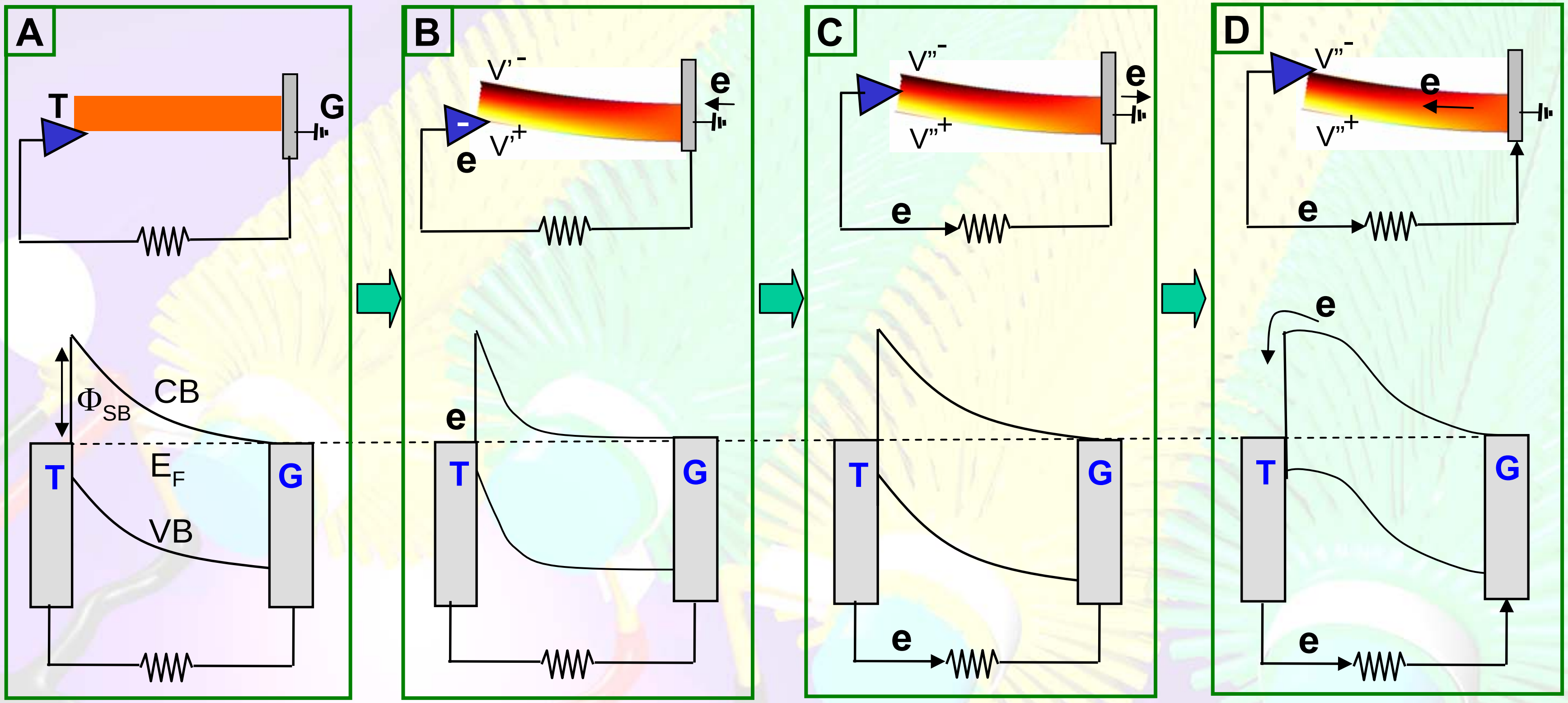


$$\varphi_{\max}^{(T,C)} \sim \frac{f_y}{Ea} \sim \frac{a^3}{l^3} v_{\max}$$

The piezoelectric potenital is much largter than kT (25 mV), and is strong enough to drive the Schottky diode

Nano Letters, 7 (2007) 2499-2505;   Nano Letters, 9 (2009) 1103

Working principle of piezoelectric nanogenerator



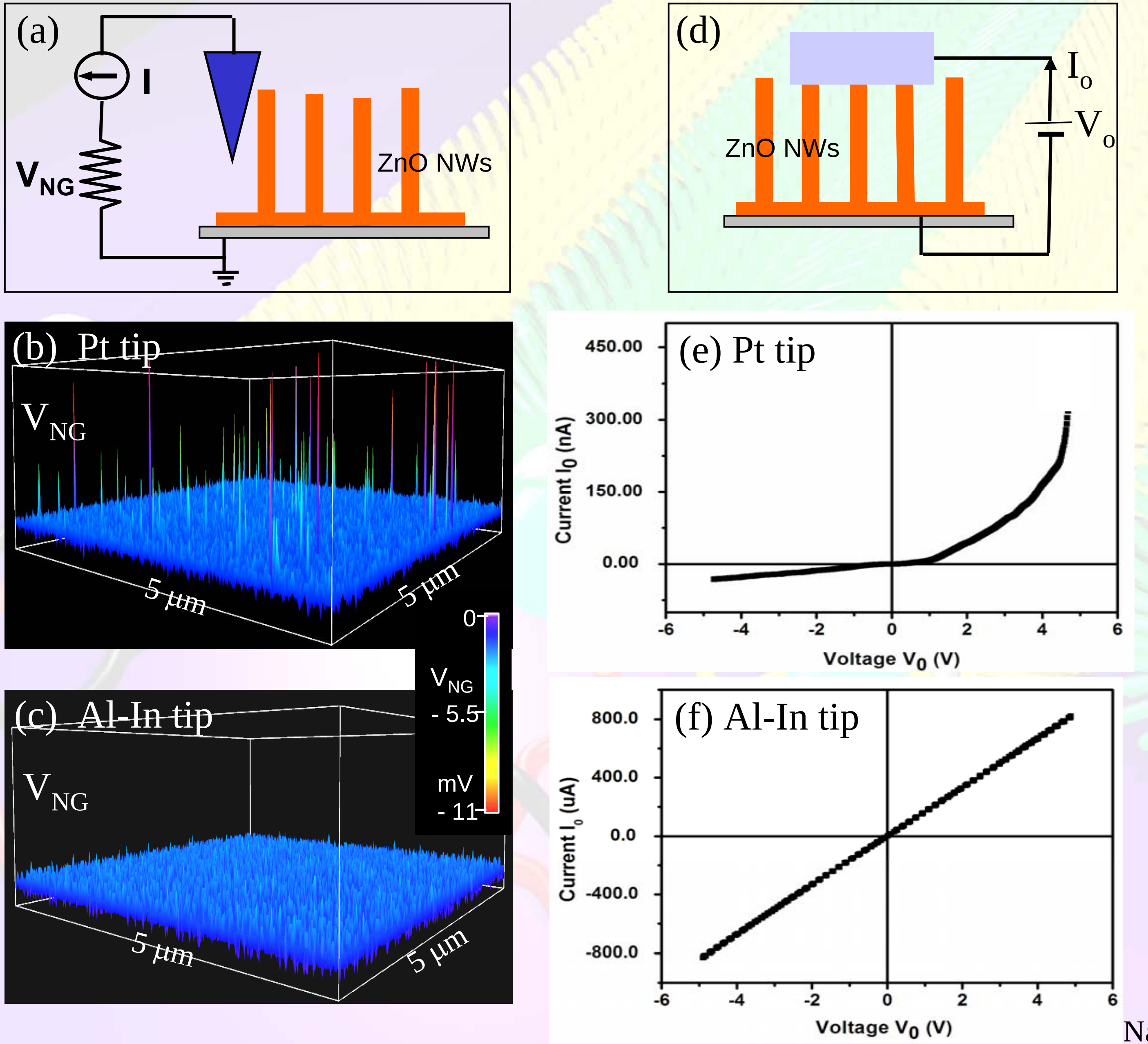
- Piezoelectric charges are ionic charges from the polarization of atoms;
- Piezoelectric charges cannot be quickly depleted by free electrons, although screening is possible;
- Piezoelectric potential preserves to tens of seconds if strain is maintained;
- Piezoelectric potential quickly disappears after strain is released.

Current generation processes:

- Charge pump driving flow of external electrons;
- Piezopotential driving charge carrier

Wang , Adv. Functional Mater.

The key role played by Schottky barrier in nanogenerator

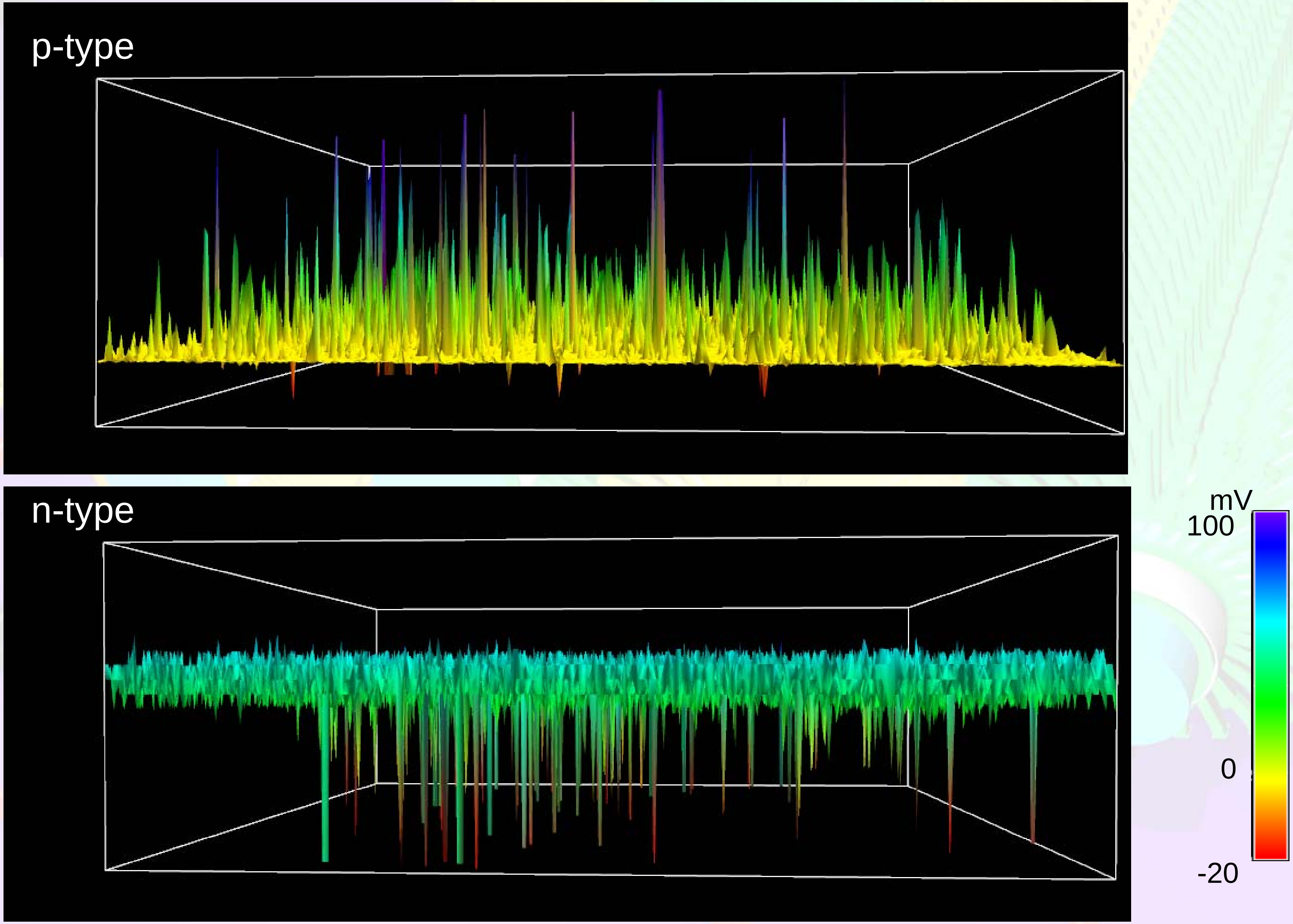


- **Schottky barrier is the key for NG:**

charge accumulation
charge releasing

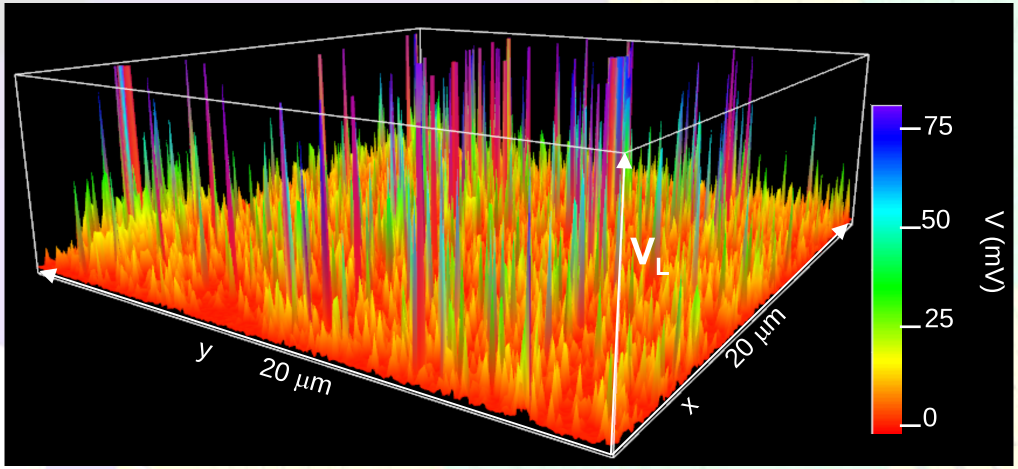
Nano Letters, 8 (2008) 328-332

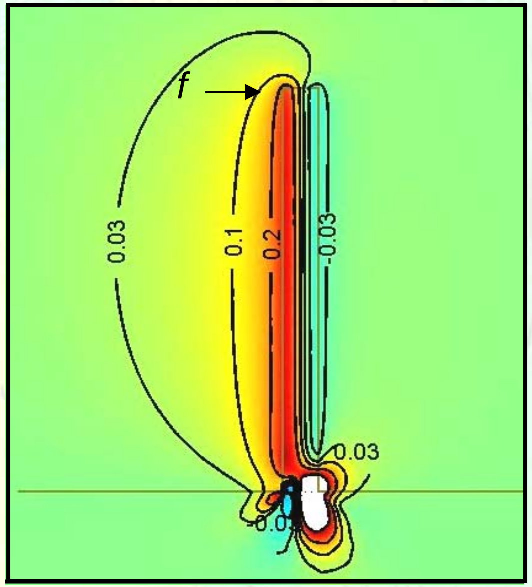
Energy generation using p-type and n-type nanowire arrays measured using the same equipment and same AFM tip

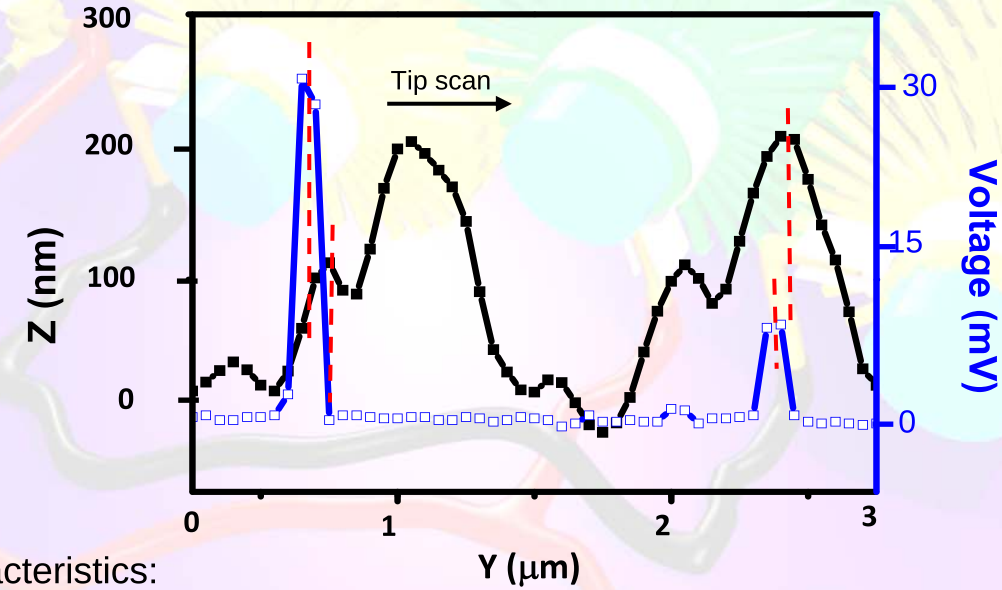


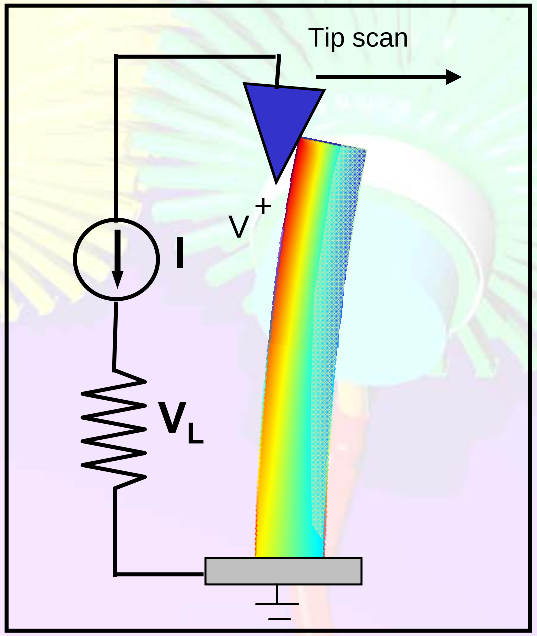
Nano Letters, 9 (2009) 1223

Piezoelectric power generation using the p-type ZnO NW arrays





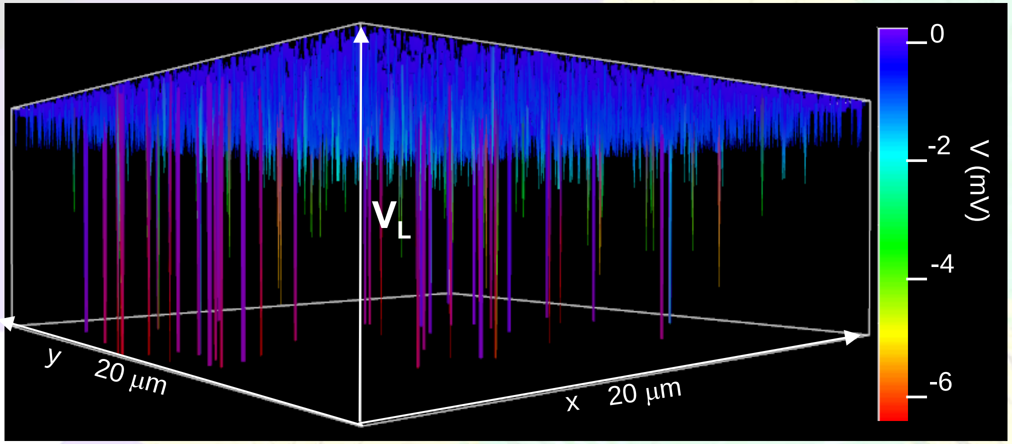


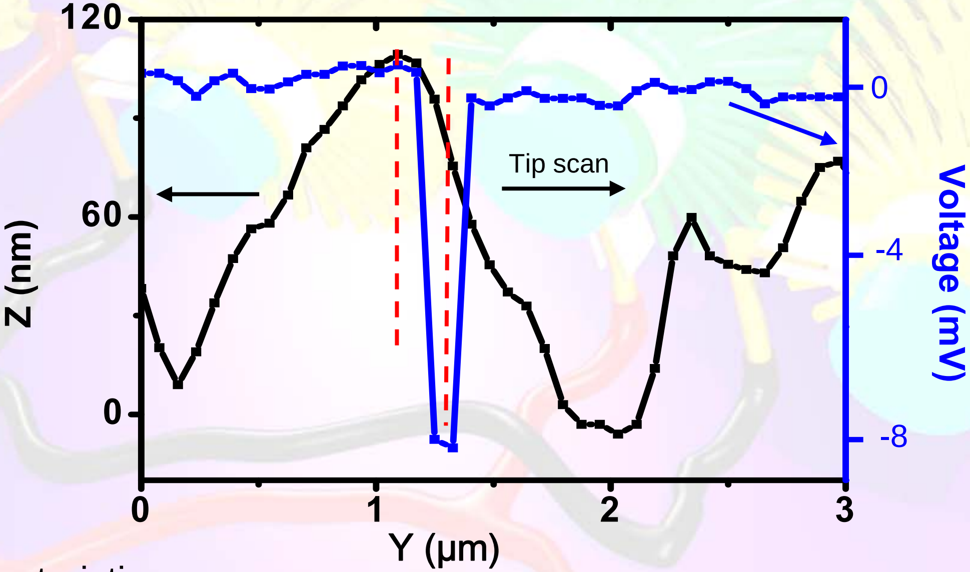


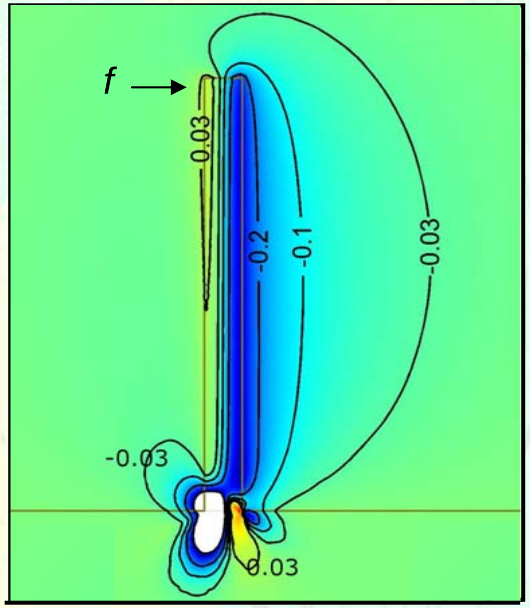
Characteristics:
- positive output voltage;
- output is created when the tip touches the stretched side of the NW

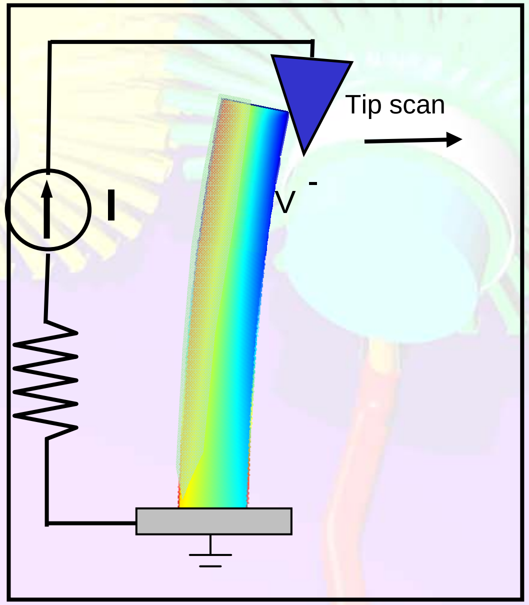
Nano Letters, 9 (2009) 1223

Piezoelectric power generation using the n-type ZnO NW arrays









Characteristics:

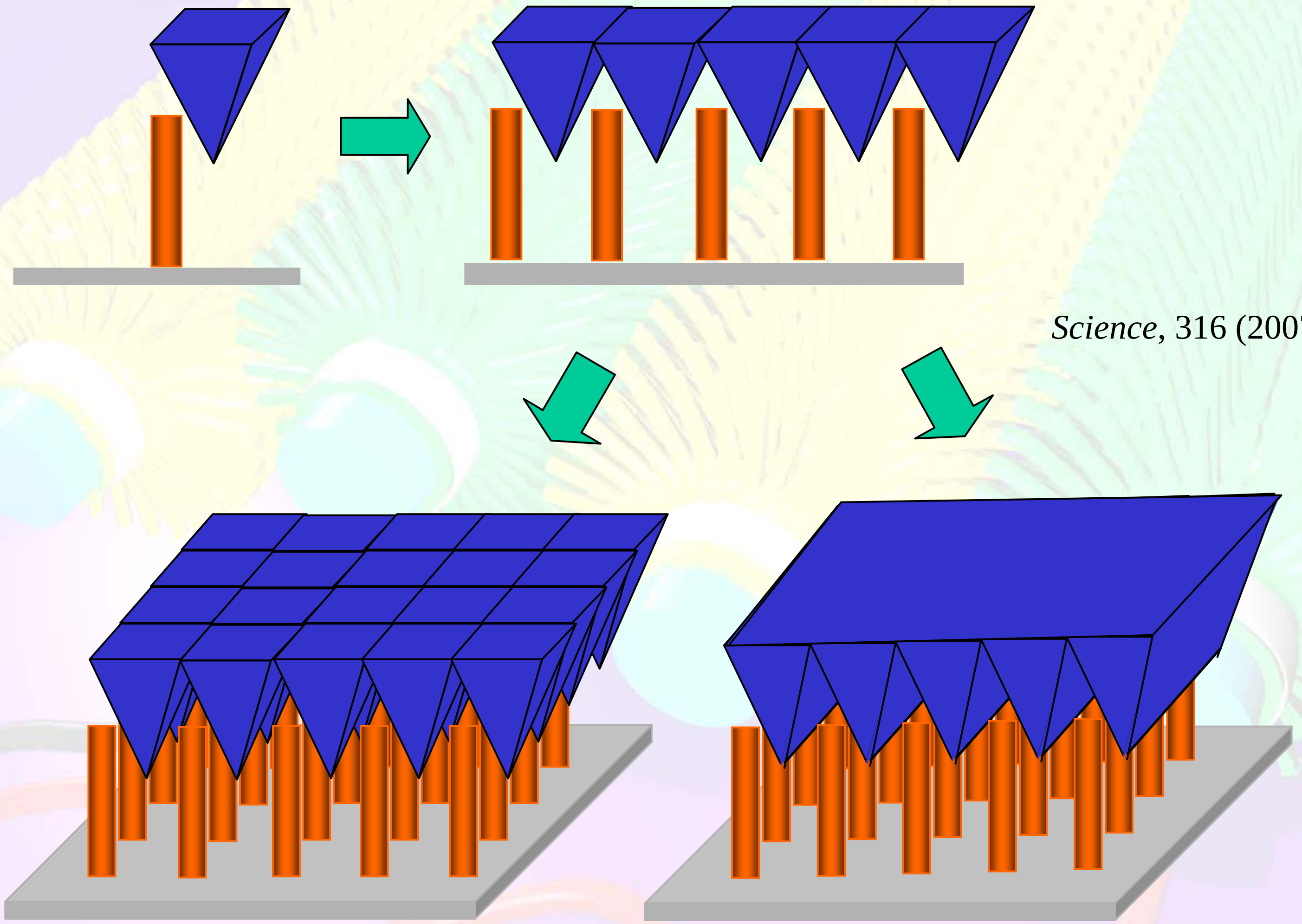
- negative output voltage;
- output is created when the tip touches the compressed side of the NW

Nano Letters, 9 (2009) 1223

For applications in wireless nanorobotics, remote sensing, implantable biomedical devices and MEMS what do we need?

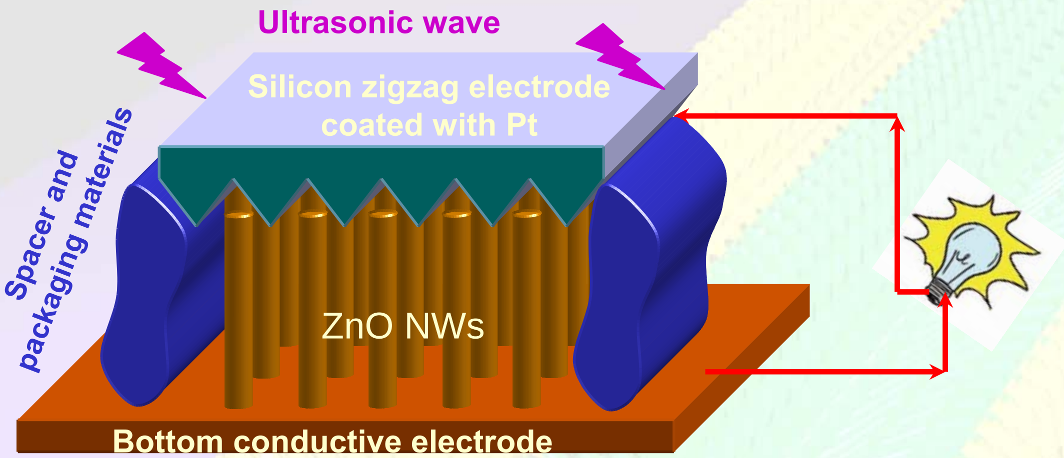
- we must eliminate the use of AFM for making the mechanical deformation of the NWs so that the power generation can be achieved by an adaptable, mobile and cost-effective approach over a larger scale.
- All of the NWs are required to generate electricity simultaneously and continuously, and all the electricity can be effectively collected and output.
- The energy to be converted into electricity has to be provided in a form of wave/vibration from the environment, so the nanogenerator can operate “independently” and wirelessly.

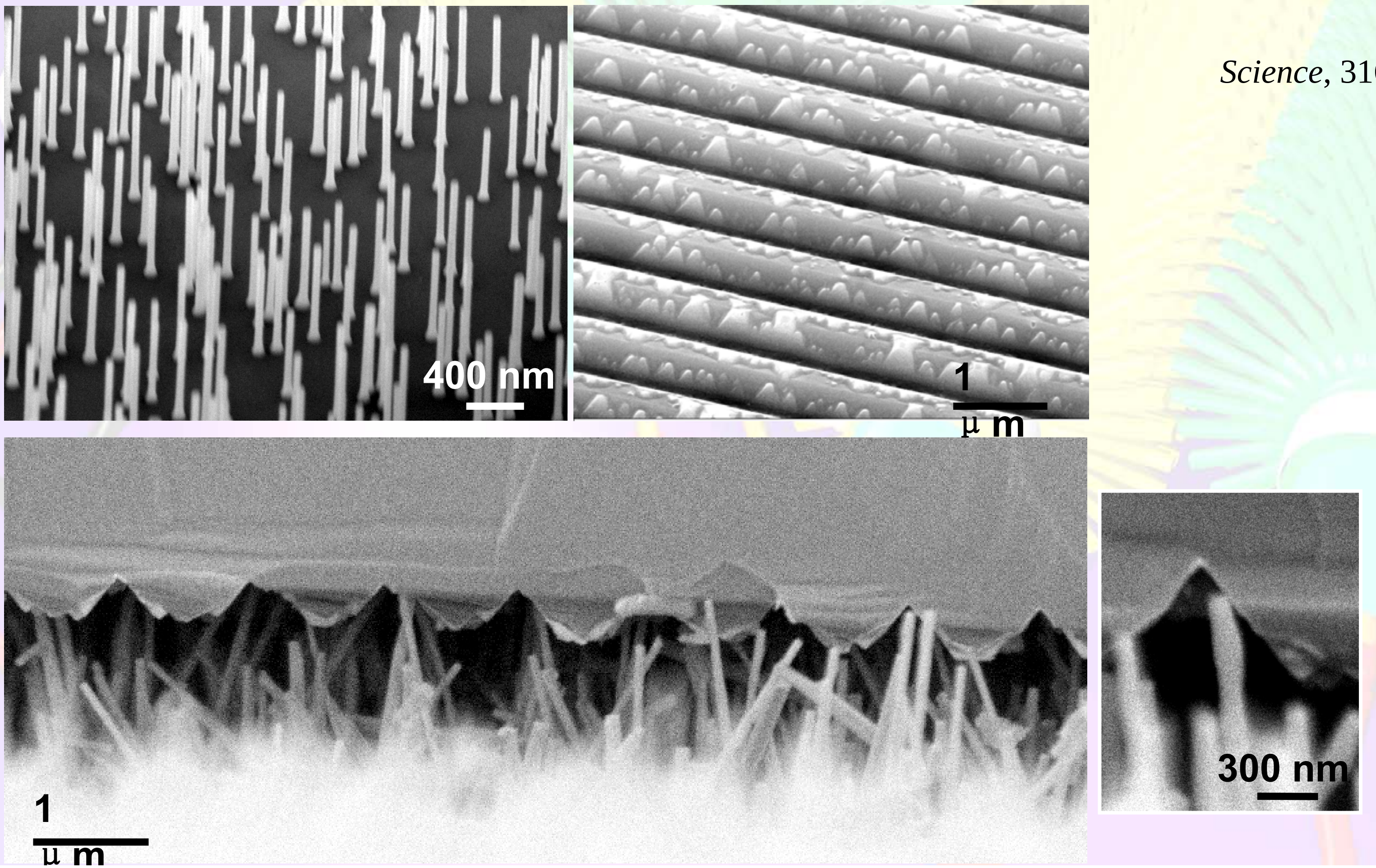
From a single scanning AFM tip to an array of integrated tips to trentches



Science, 316 (2007) 102-105

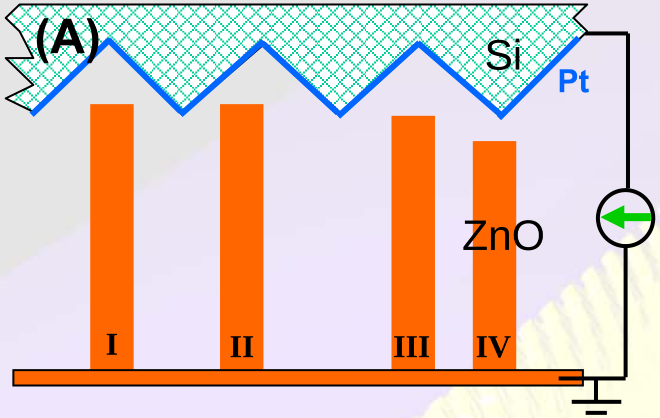
Fabrication of ultrasonic wave driven DC nanogenerator

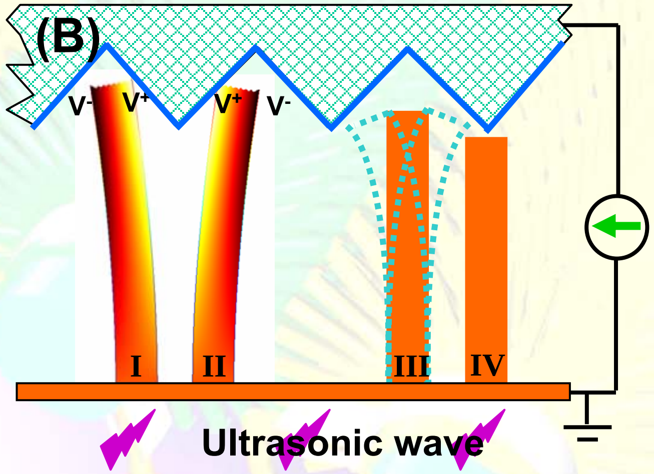




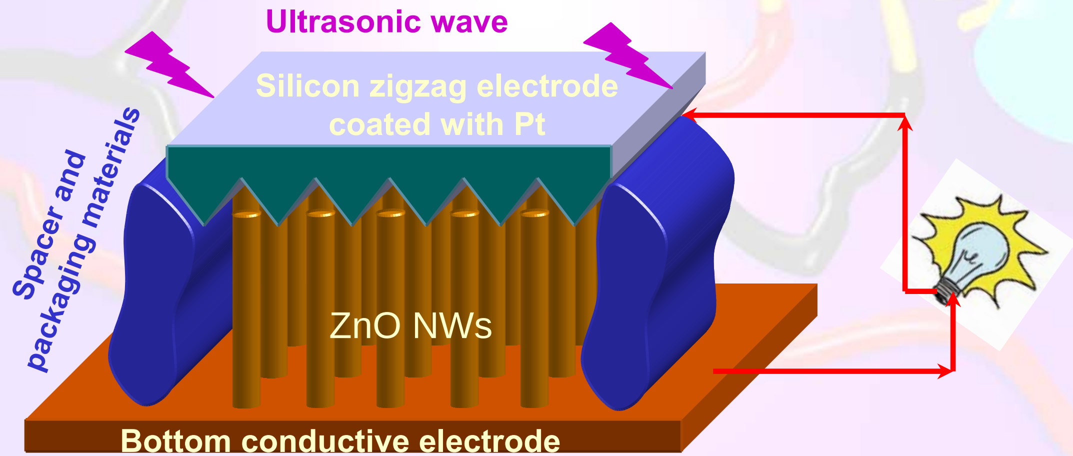
Science, 316 (2007) 102-105

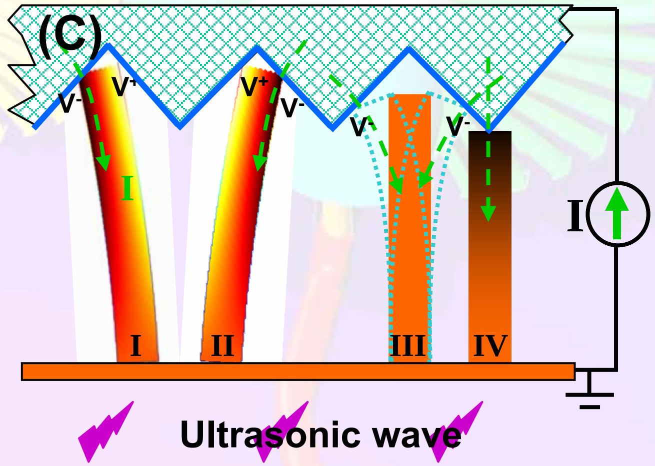
Processes for generating the charges



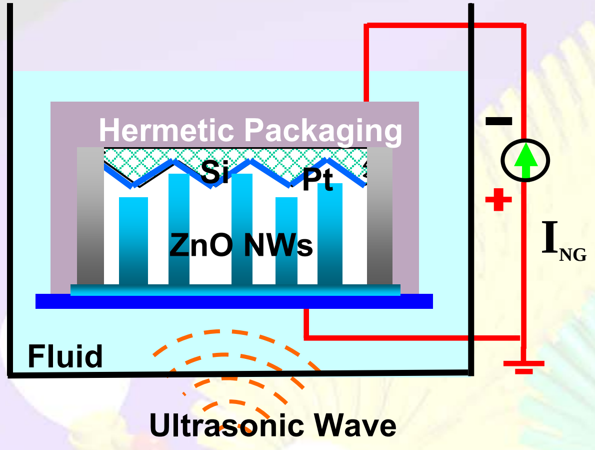


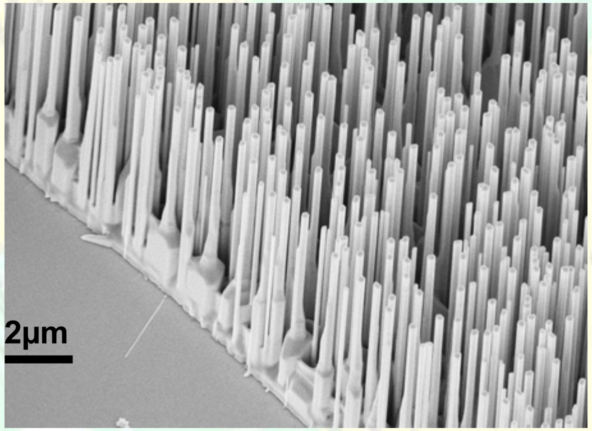
Science, 316 (2007) 102-105

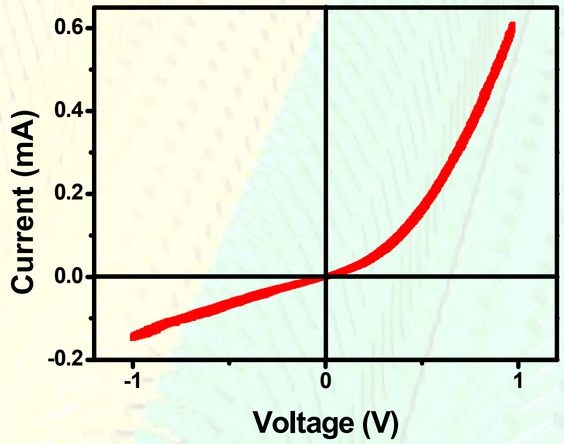


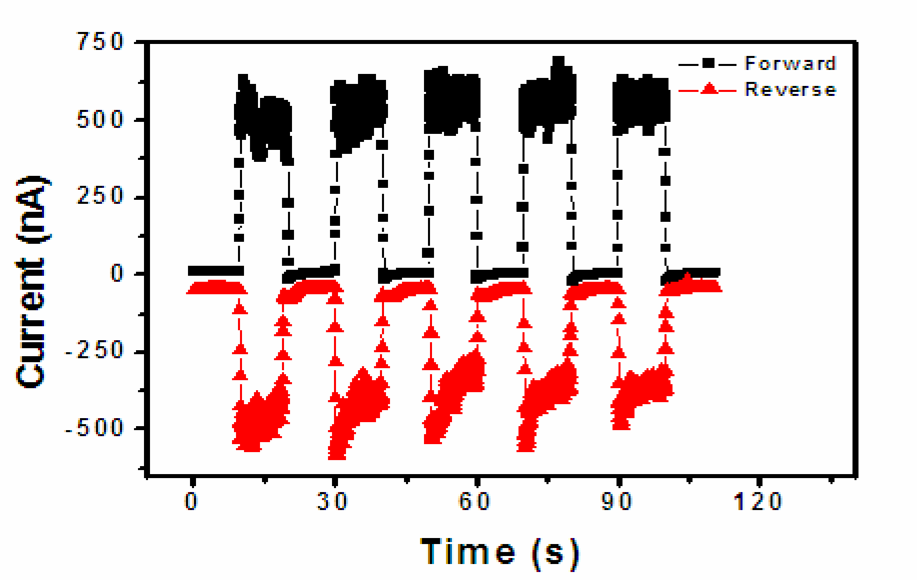


Performance of a packaged nanogenerator when periodically excited by ultrasonic wave

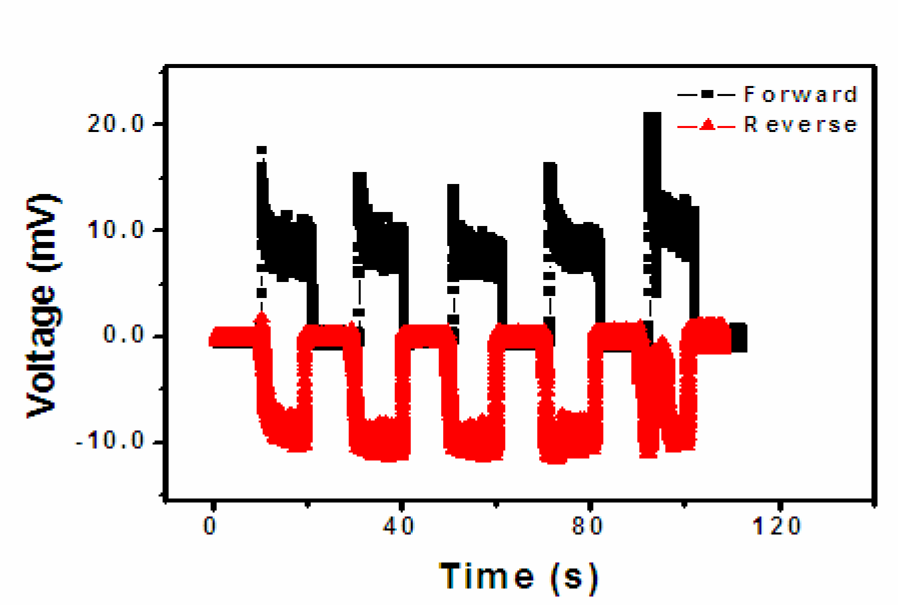






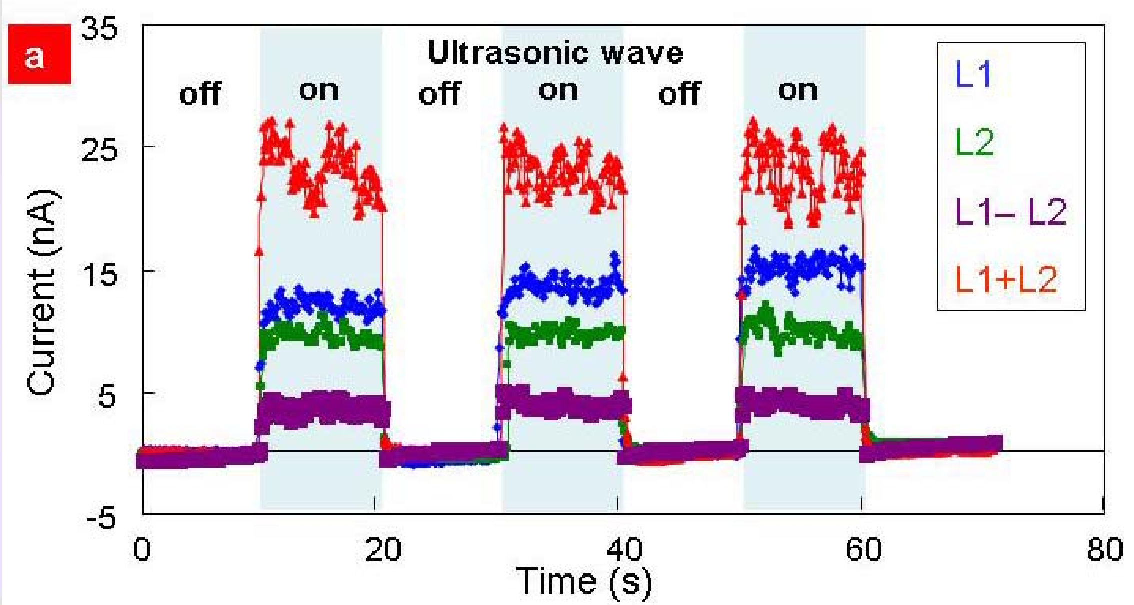


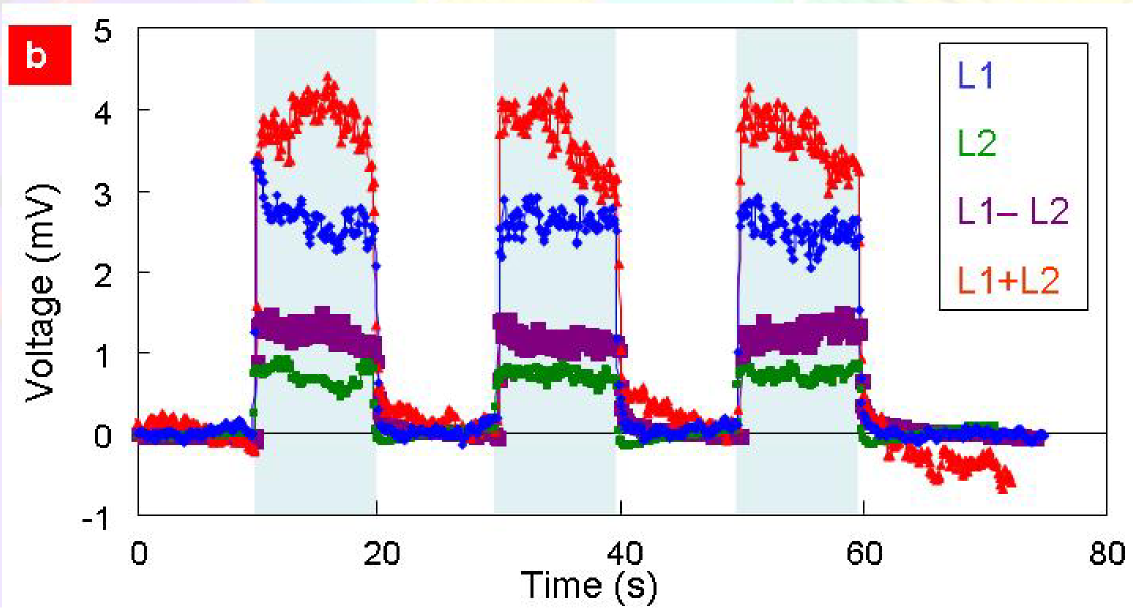
6 mm²

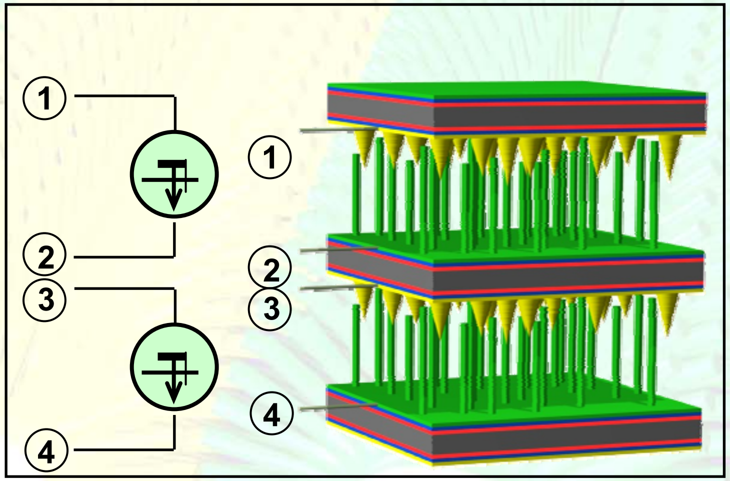


Appl. Phys. Letts., 92 (2008) 173105

Output current and voltage signals by connecting two single-layered NGs in parallel and anti-parallel, and serial and anti-serial, illustrating the 3D integration of the NGs for raising output power

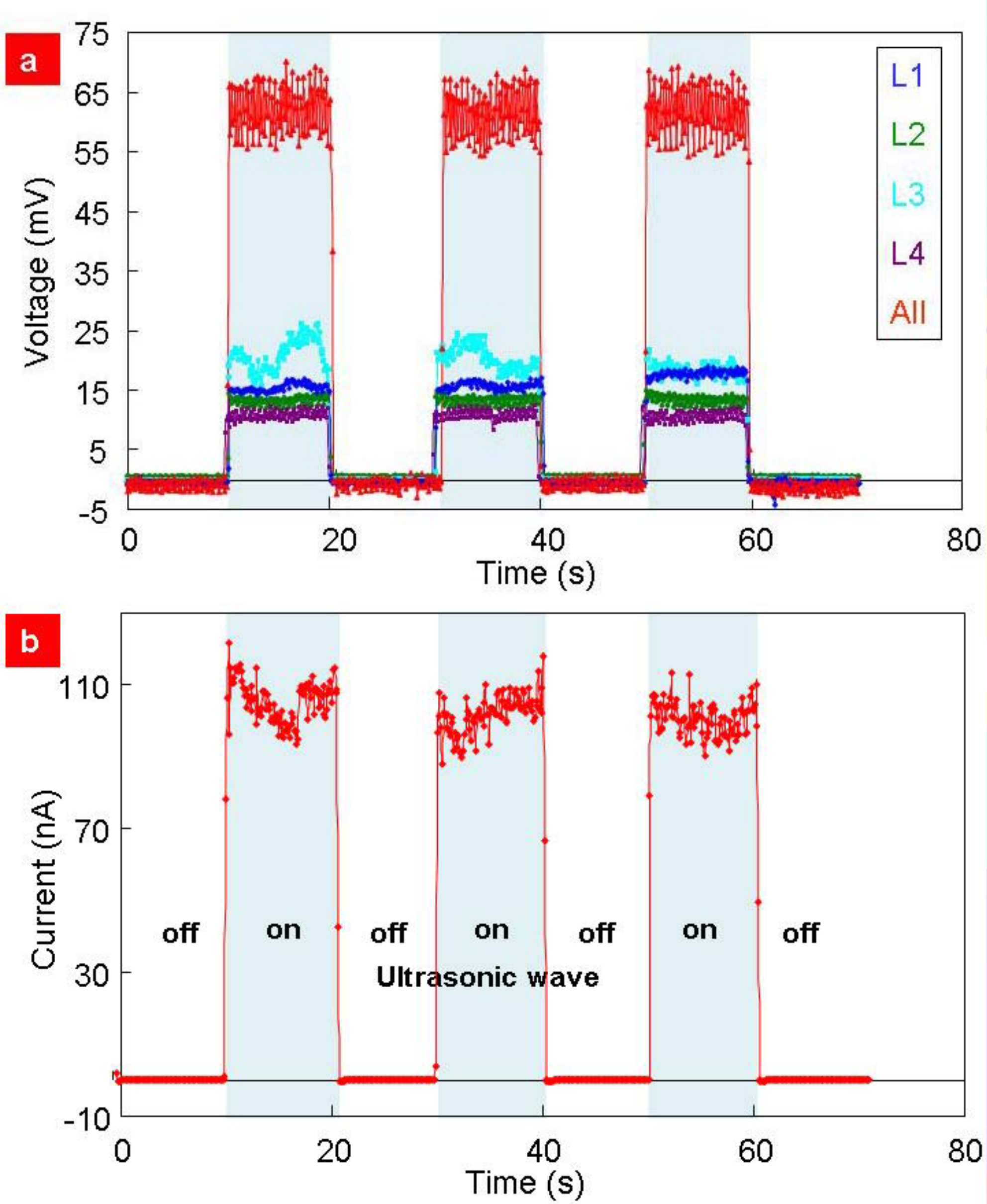


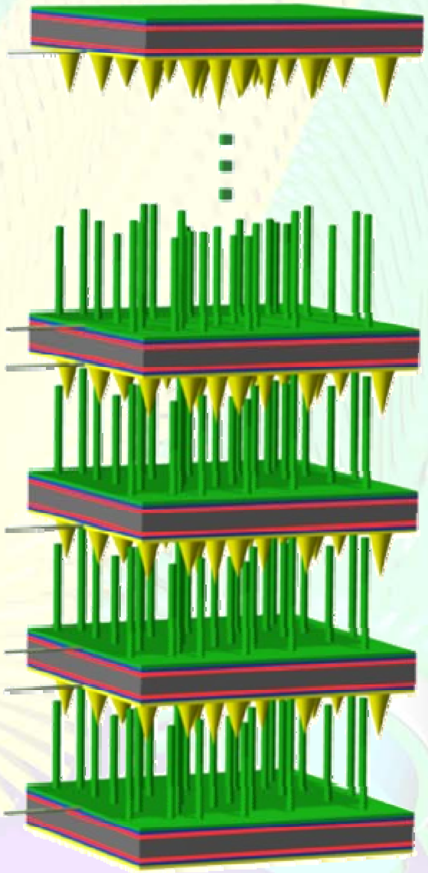




Nano Letters, 8 (2008) 4027

Open circuit voltage and short circuit current output measured from serially connected four-layer integrated NG.





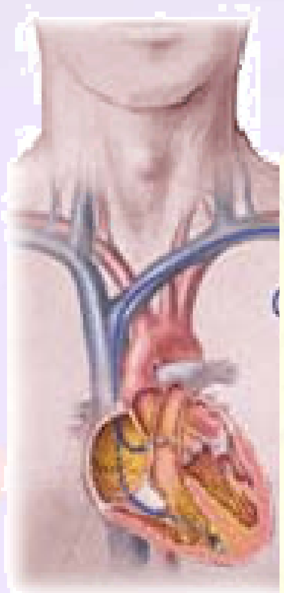
Power density 0.11 uW/cm^2 at 62 mV

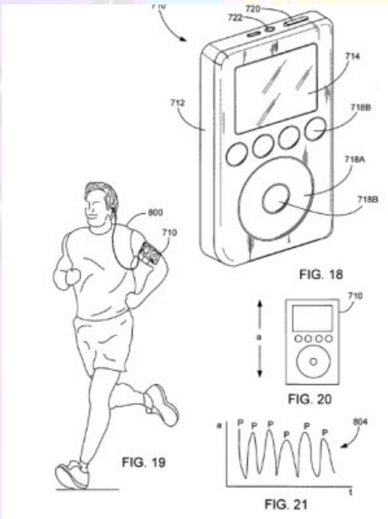
Nano Letters, 8 (2008) 4027

Textile-fiber based nanogenerator; “power shirt”

Qin, Wang and Wang, Nature 451 (2008) 809

Low frequency nanogenerator in muscles/fabrics





Applications:

- In-vivo biosensing (brain sensor, blood pressure, blood sugar..)
- Pacemaker
- Remote environmental monitoring
- Defense technology
- Energy harvesting from environment
- Personal electronics

- Low frequency:
muscle movement/contraction, heart beating, blood flow, air flow, foot steps

- **Flexible/foldable soft materials as substrates of any shape/curvature**

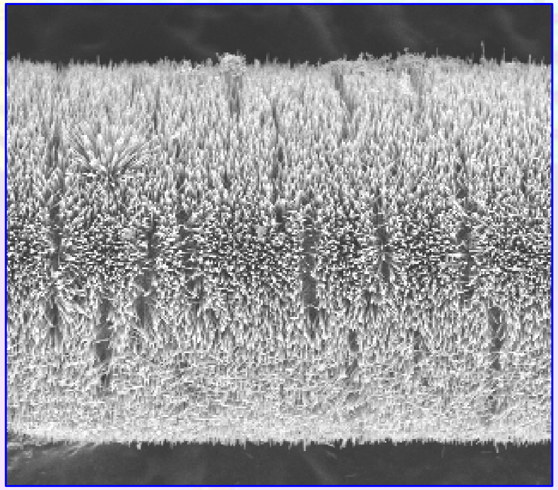
- **Vibration driven in medium/air**

- **Materials growth at low temperature**

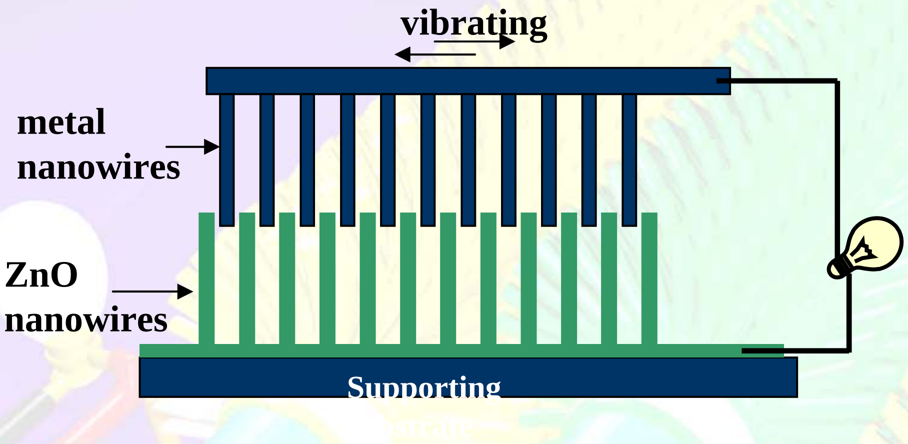
Textile fiber based nanogenerators

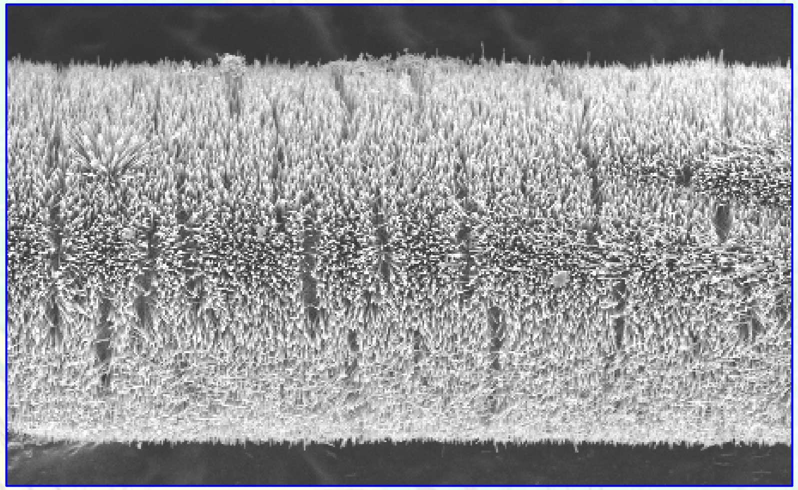


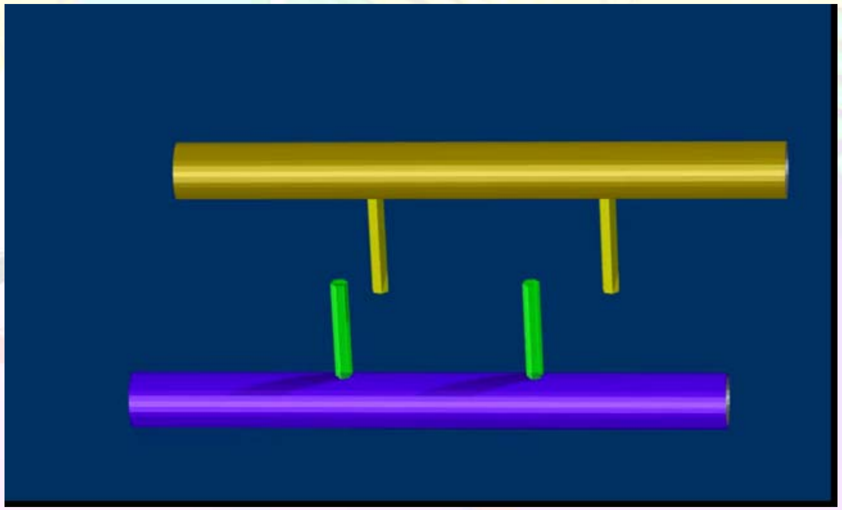


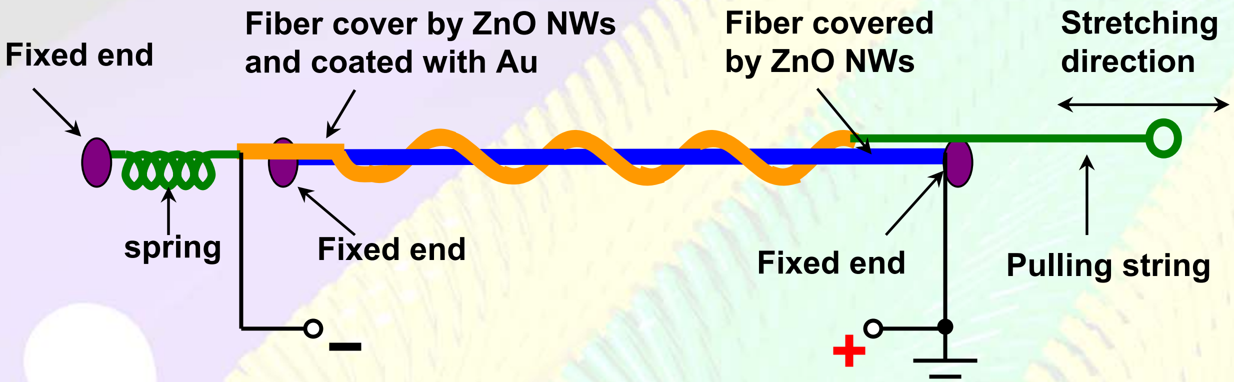
Textile fiber based nanogenerators

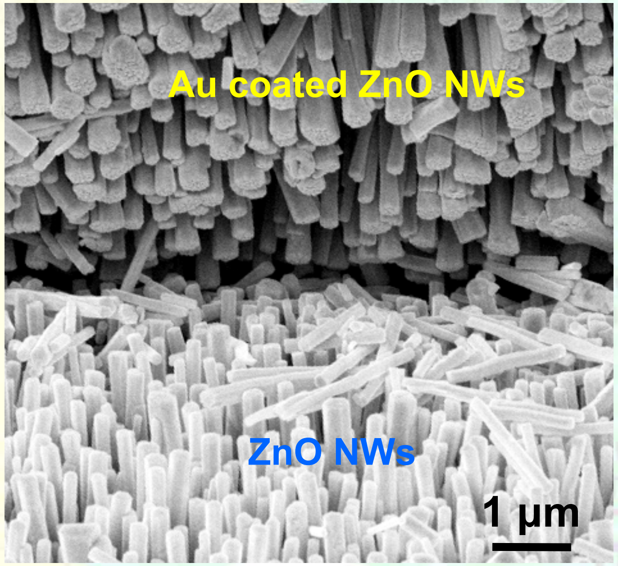


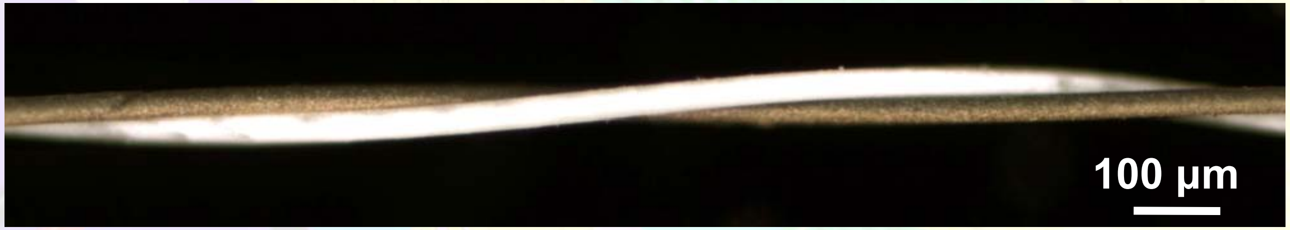


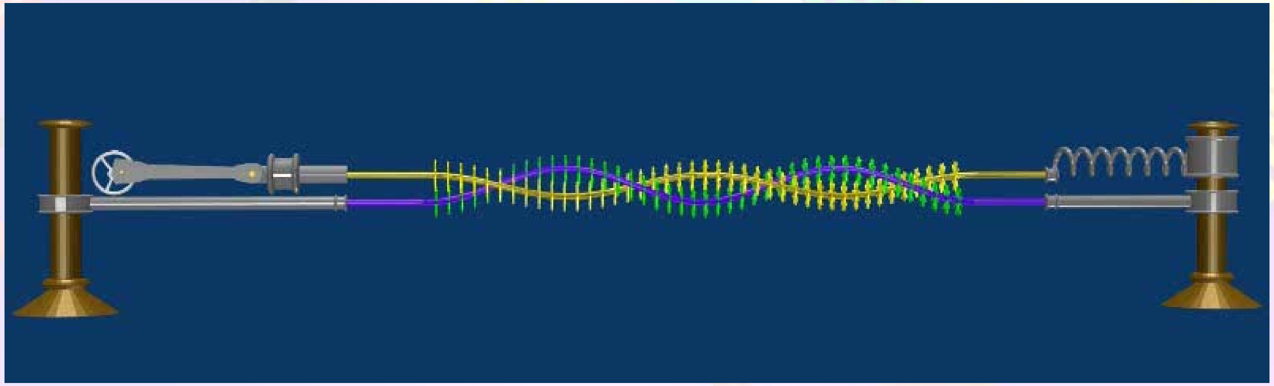


Textile fiber based nanogenerator



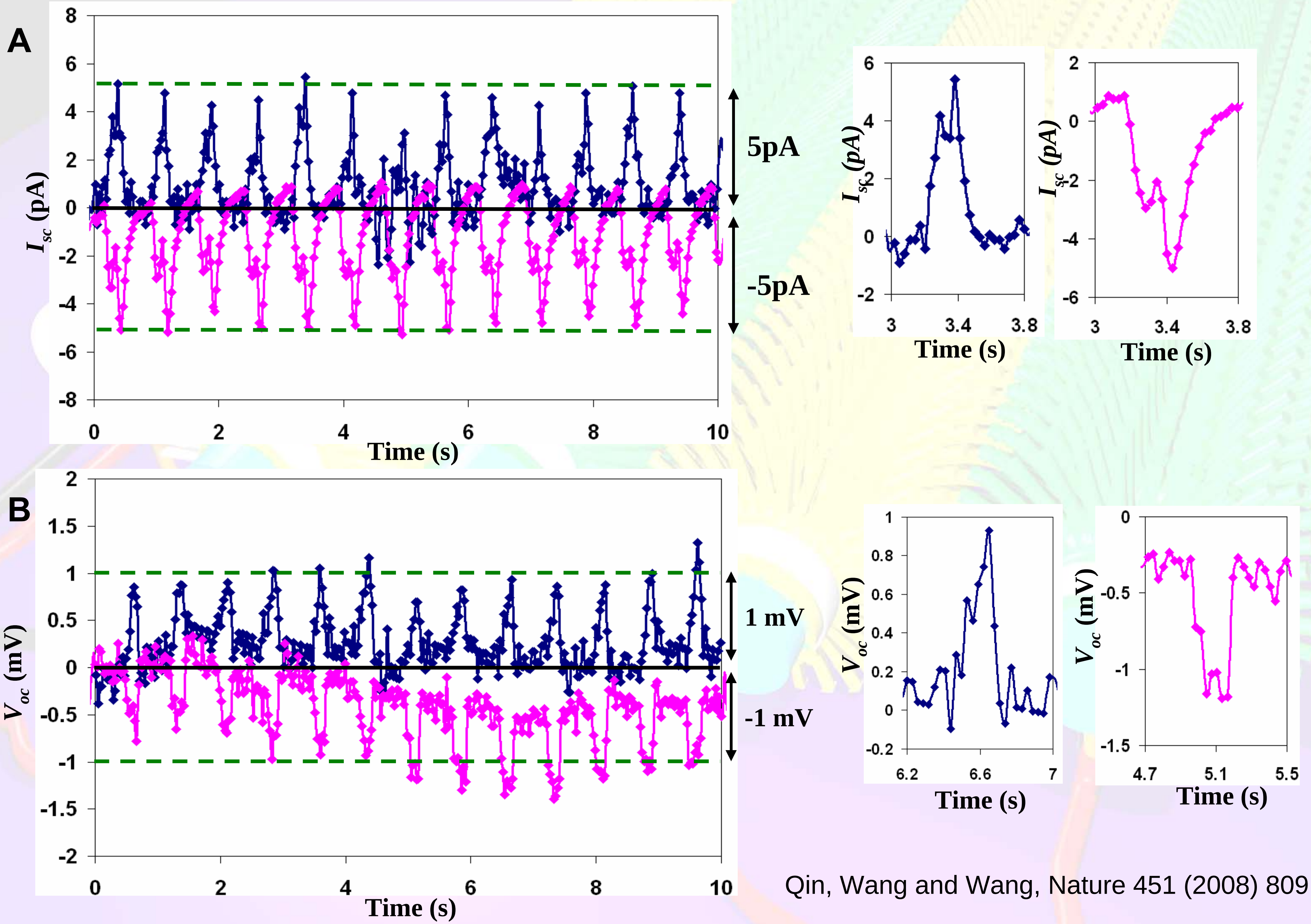






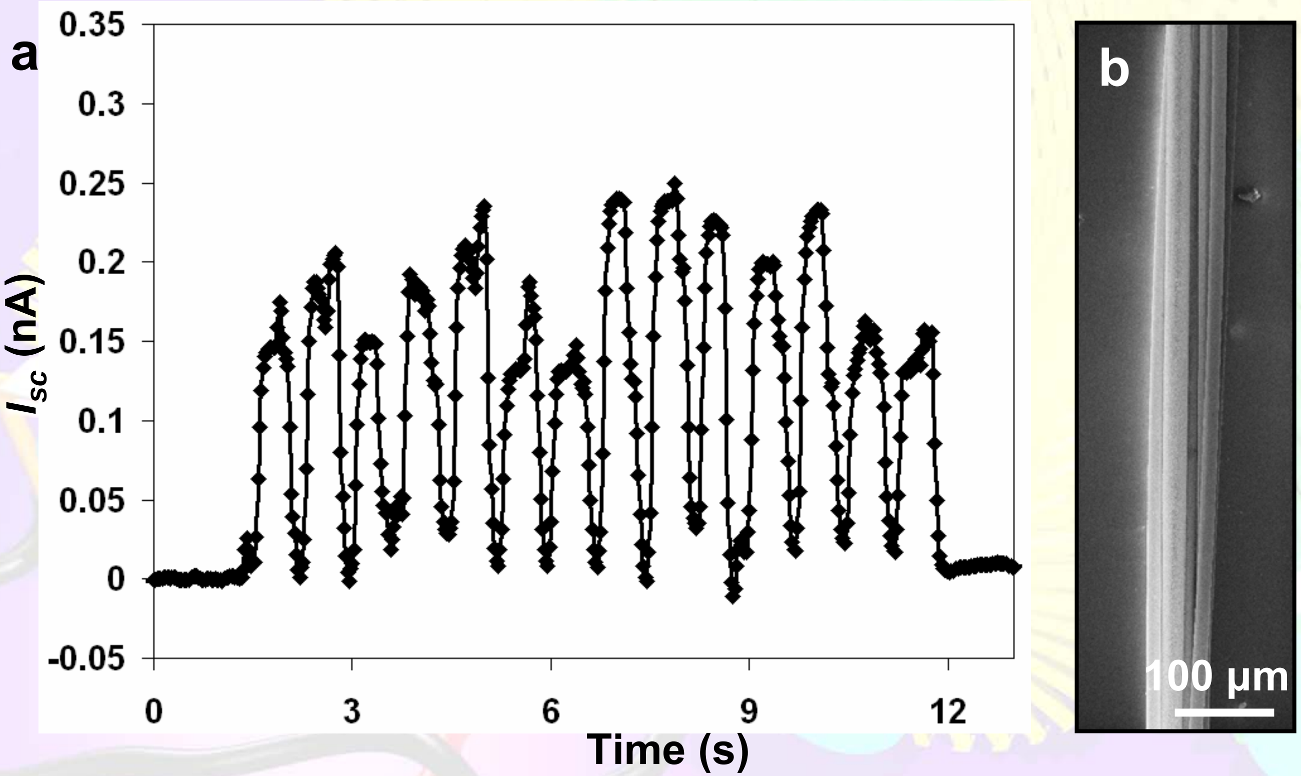
Qin, Wang and Wang, Nature 451 (2008) 809

Current and voltage output - reversed polarity testing

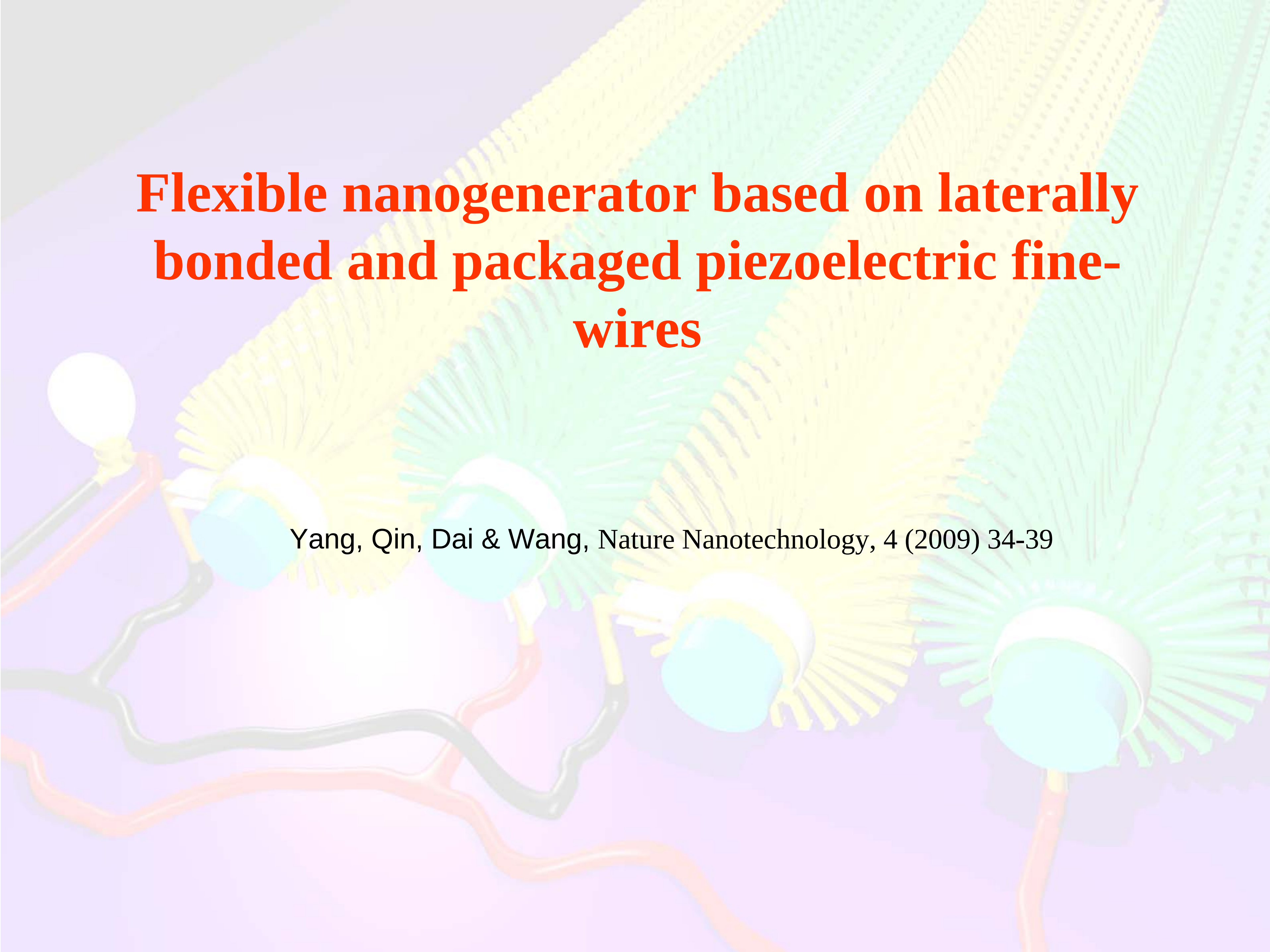


Qin, Wang and Wang, Nature 451 (2008) 809

Raising the output power by multiple fibers



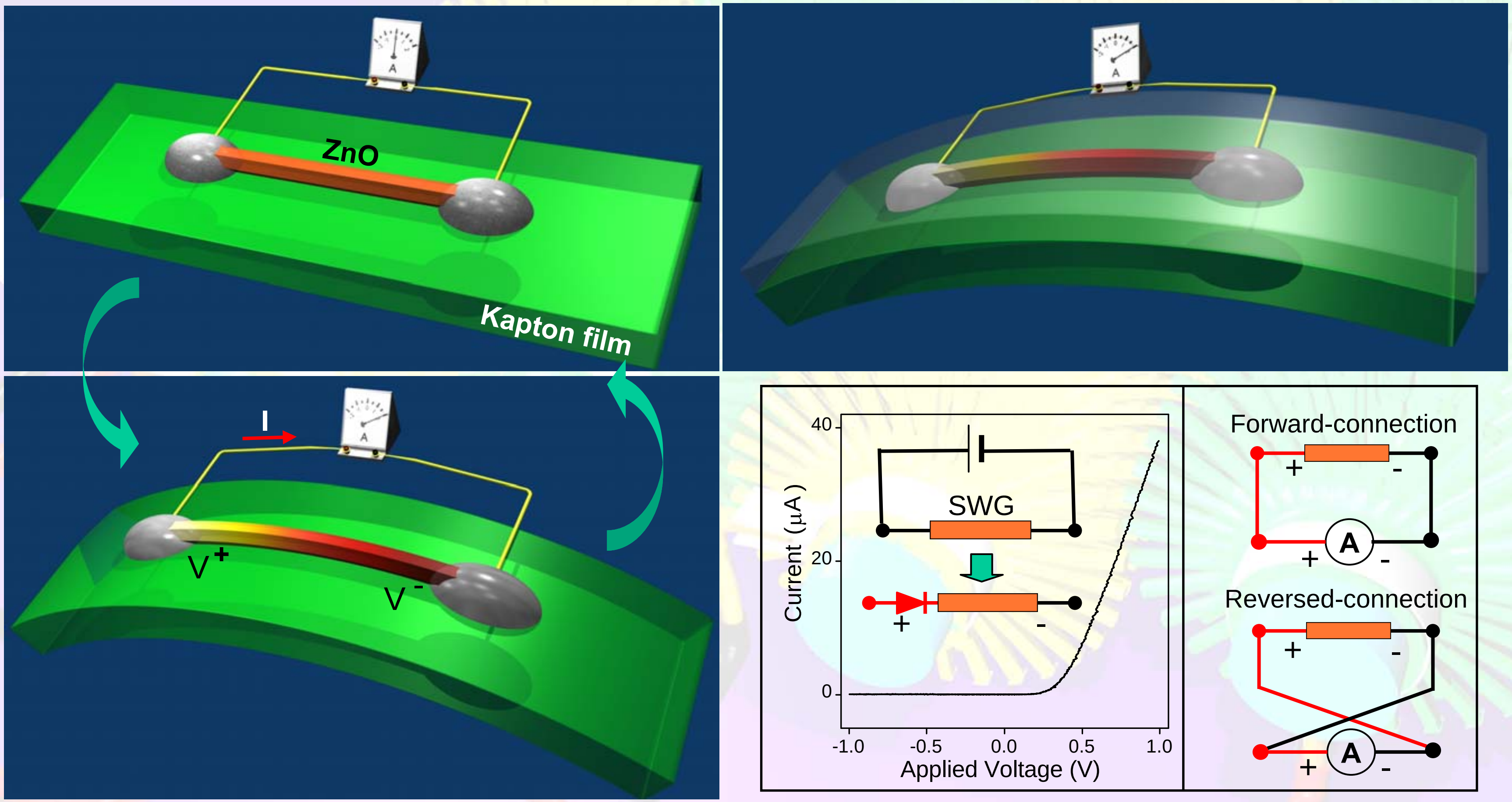
Qin, Wang and Wang, Nature 451 (2008) 809



Flexible nanogenerator based on laterally bonded and packaged piezoelectric fine-wires

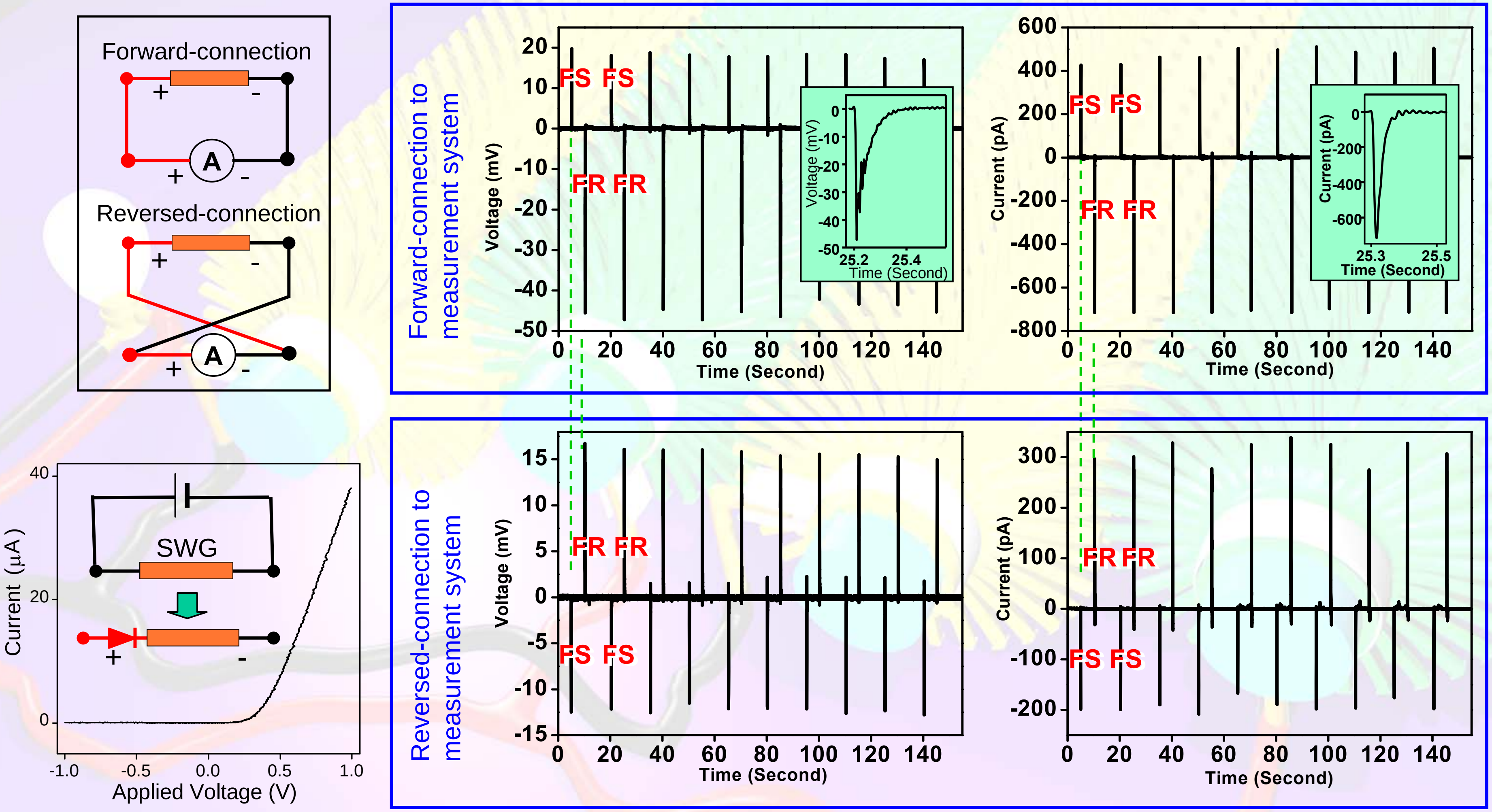
Yang, Qin, Dai & Wang, Nature Nanotechnology, 4 (2009) 34-39

Experimental set up and the polarity test

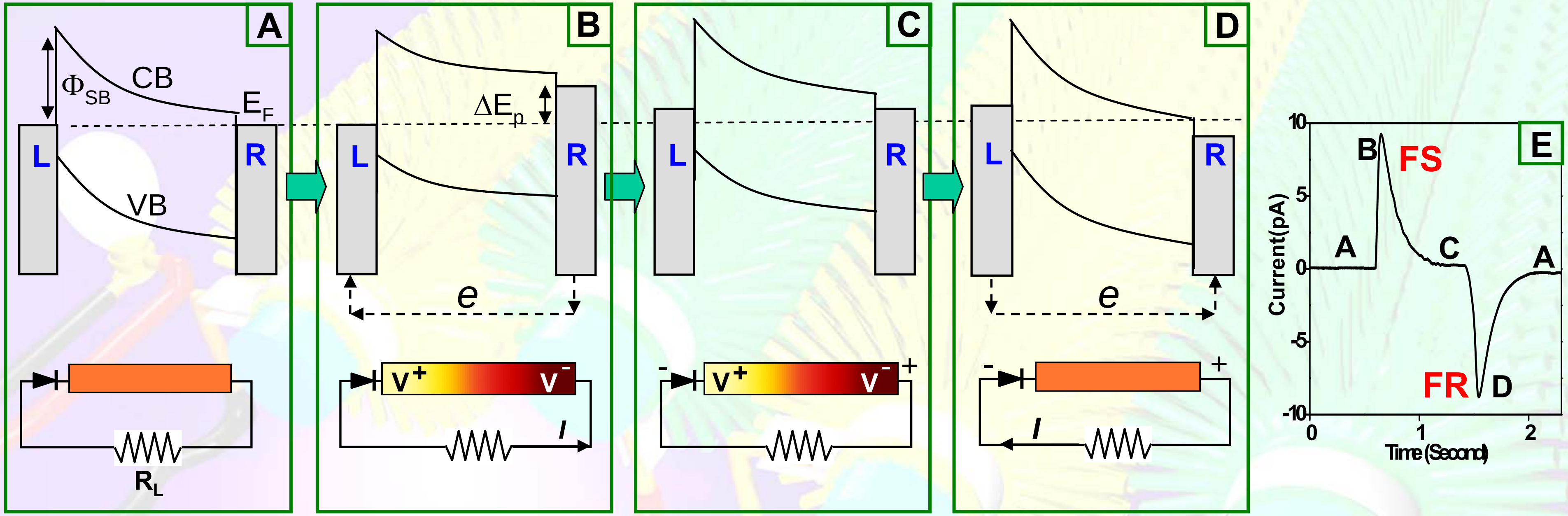


Nature Nanotechnology, 4 (2009) 34-39

Non-symmetric Schottky contacts and polarity test

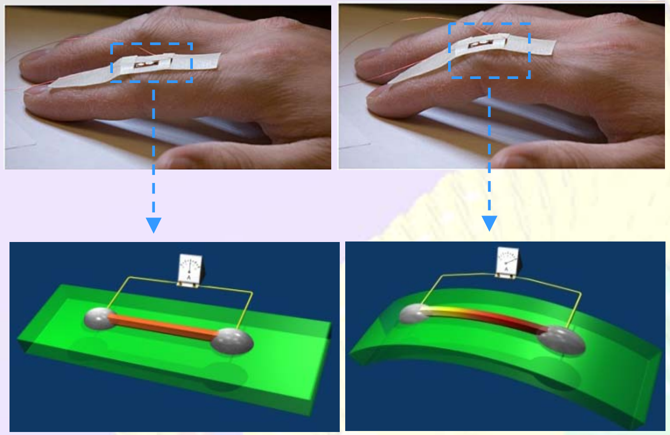


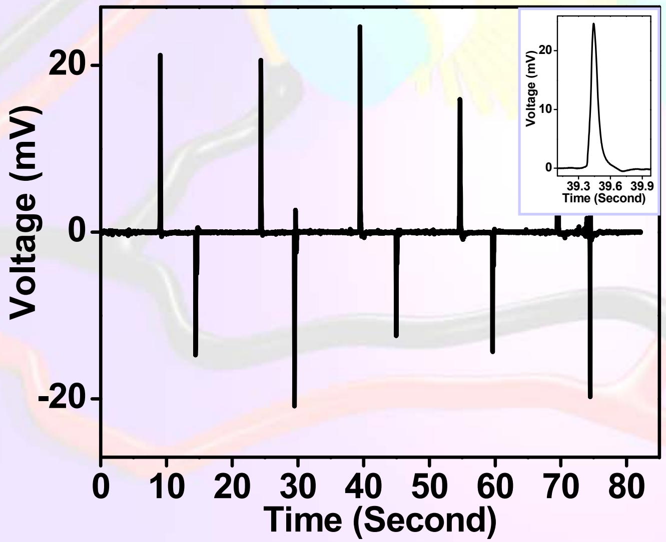
Mechanism of the AC generator

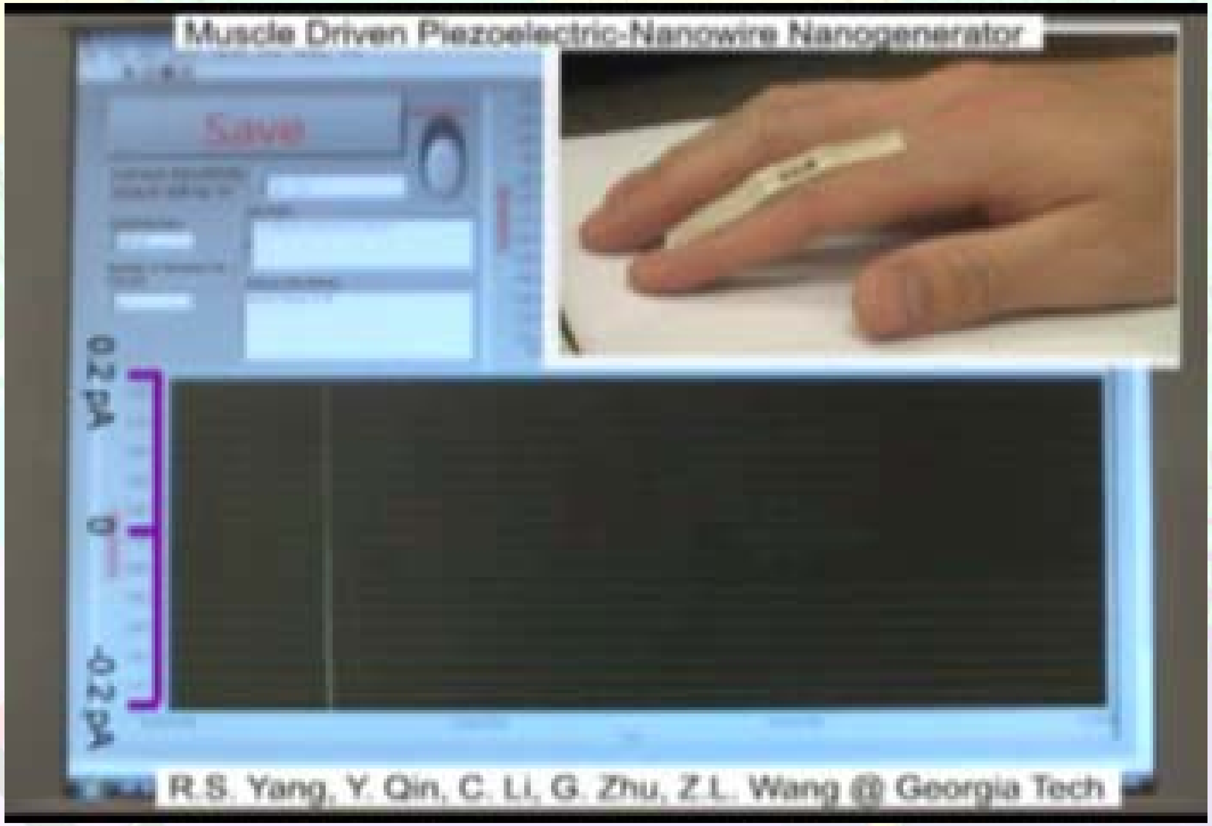


Nature Nanotechnology, 4 (2009) 34-39

Electricity generation by finger movement

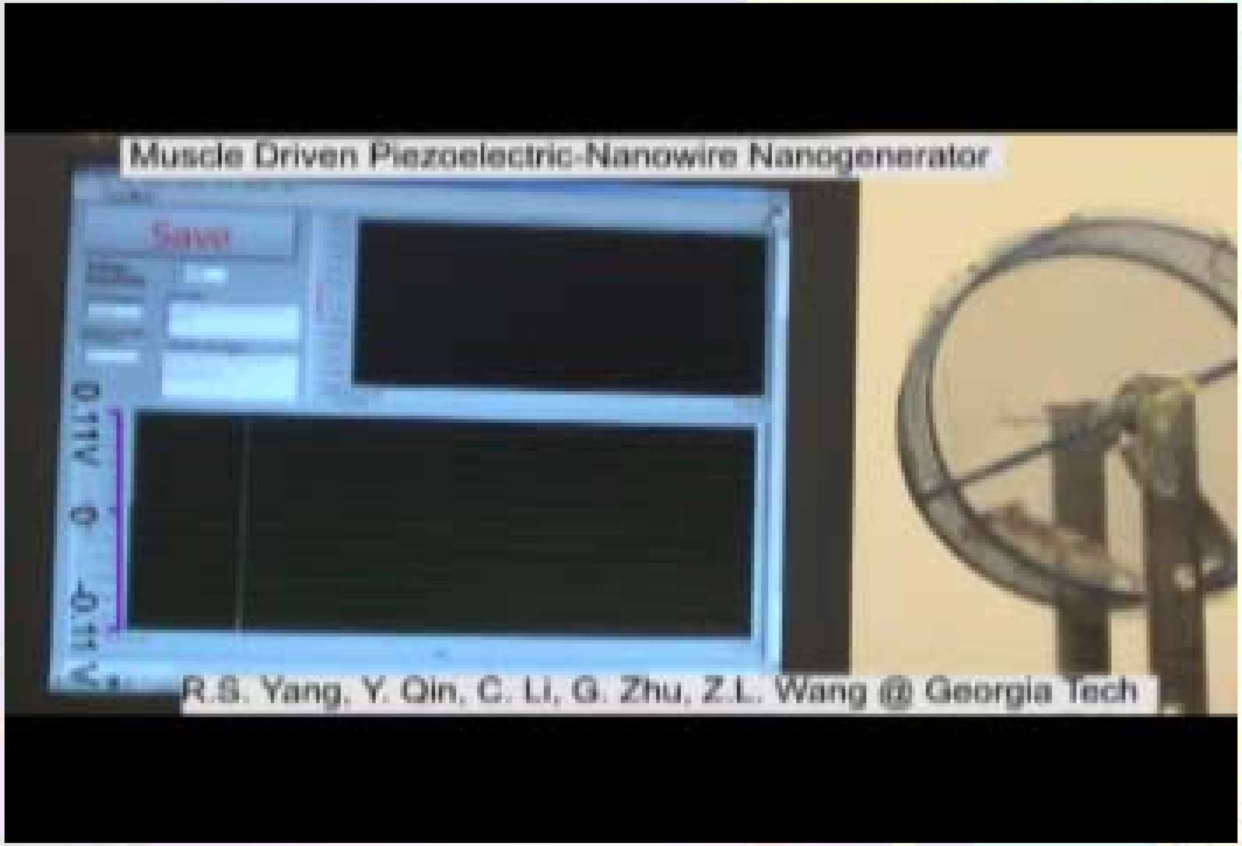


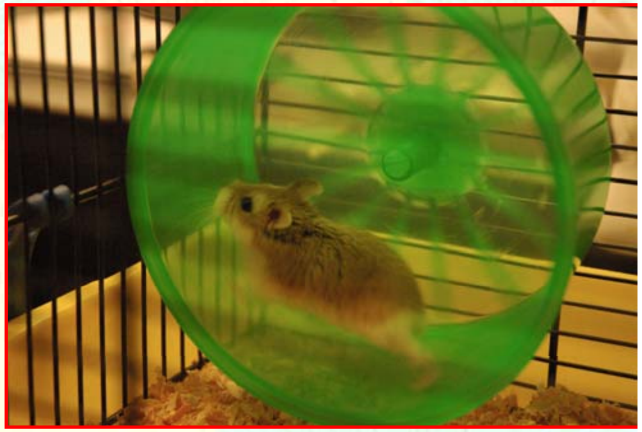


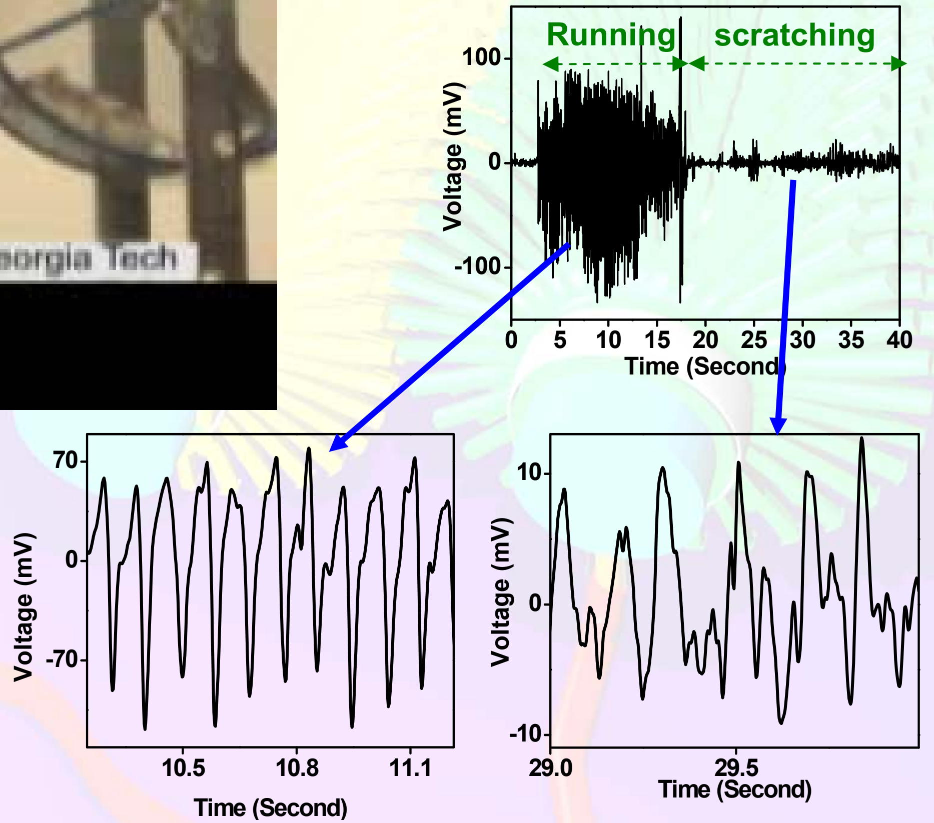


Nano Letters, 9 (2009) 1201

Electricity generation by a running hamster

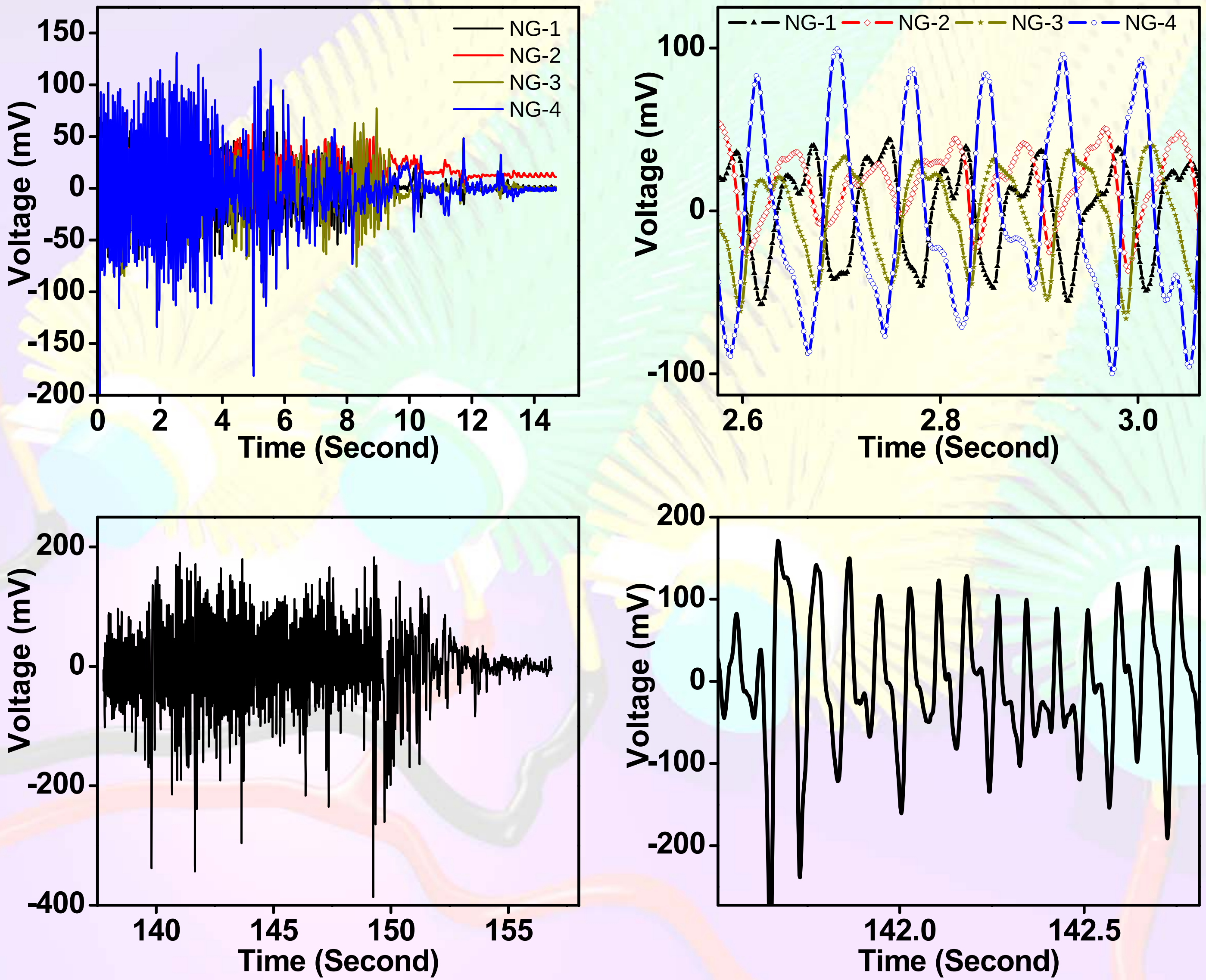






Nano Letters, 9 (2009) 1201

Four nanogenerators drive by a running hamster – out of synchronization



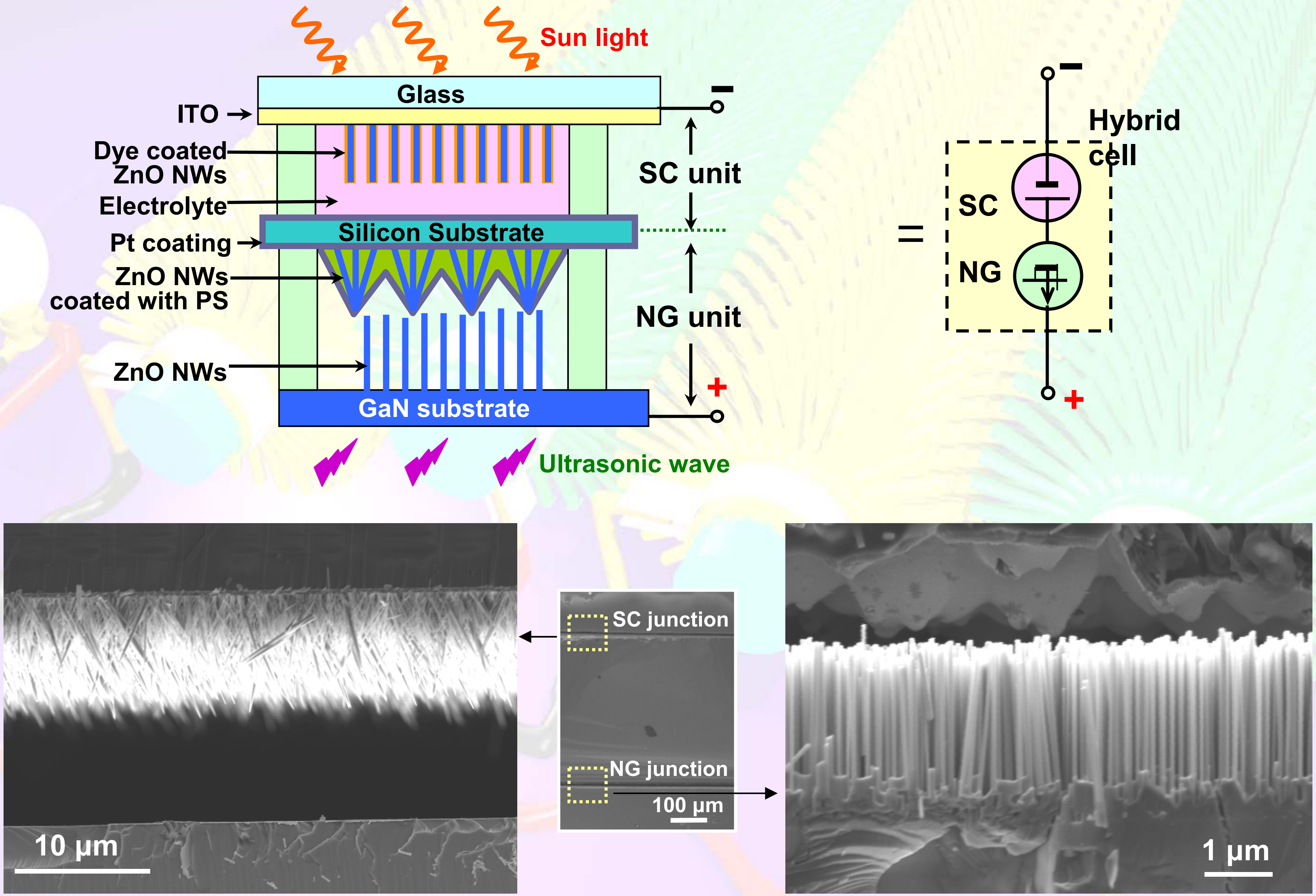
Nano Letters, 9 (2009) 1201

Hybrid cell for simultaneous harvesting of solar and mechanical energies

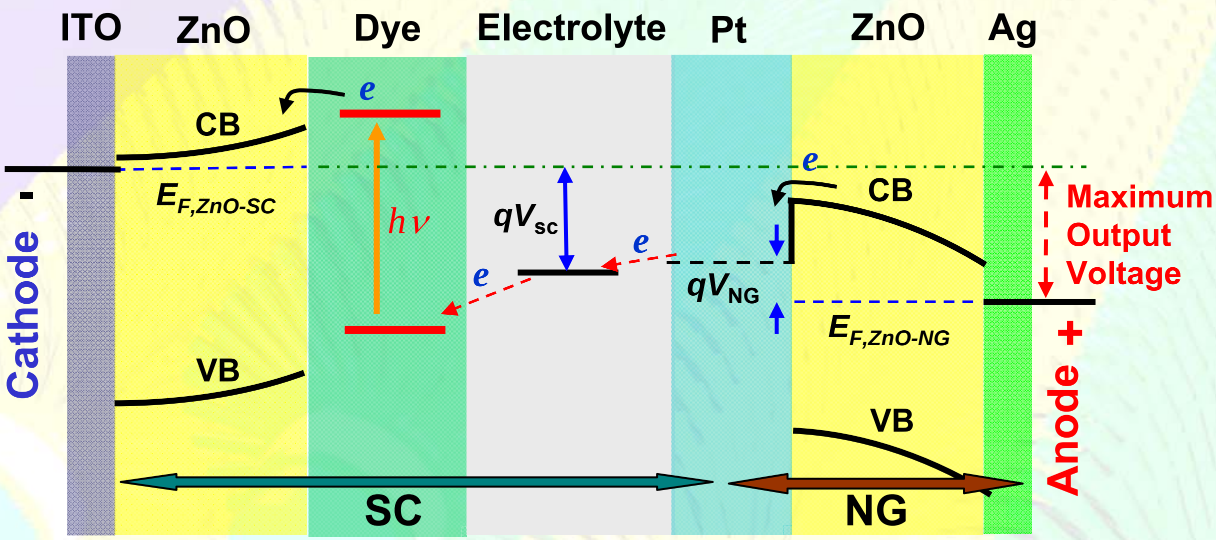
Xu, Wang and Wang, JACS, published online

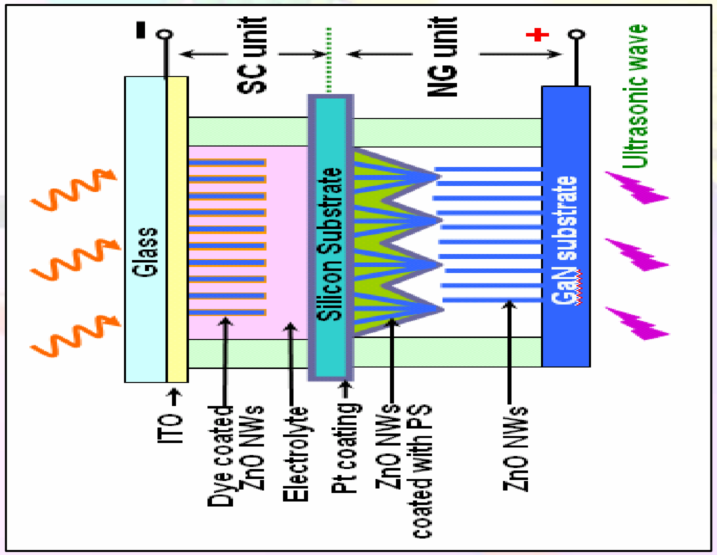
The concept of hybrid cell

Design and fabrication of a hybrid cell composed of serially integrated SC and NG

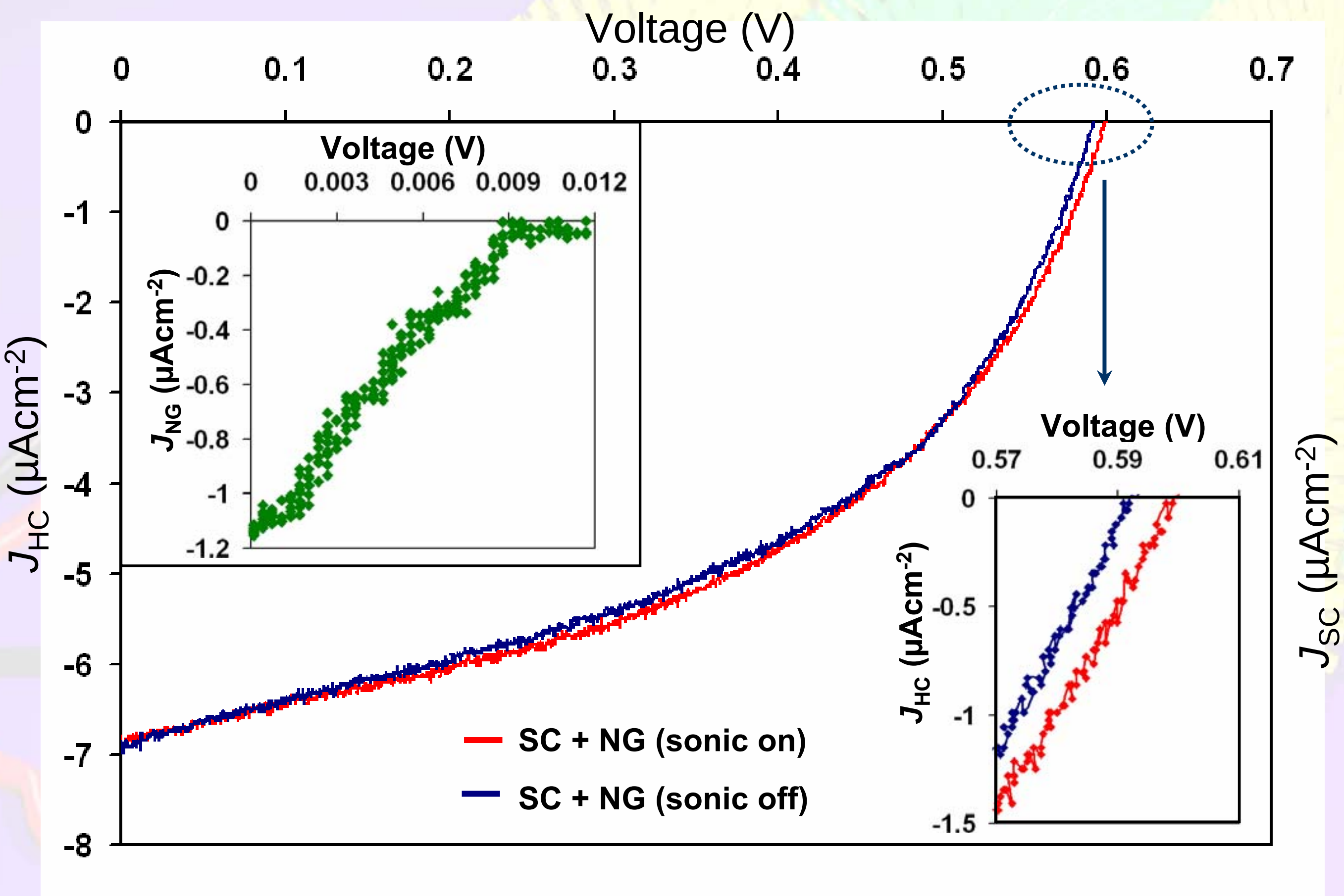


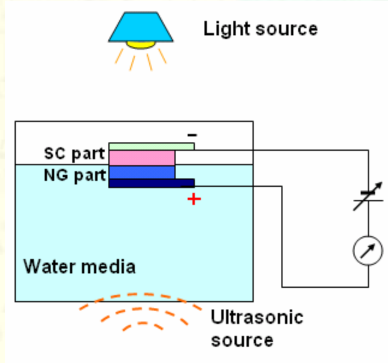
Working principle of a hybrid cell composed of serially integrated SC and NG

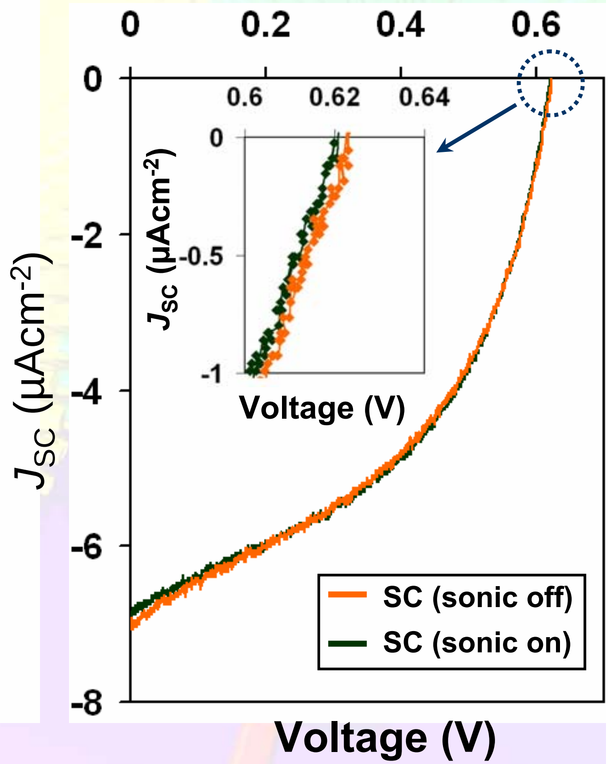




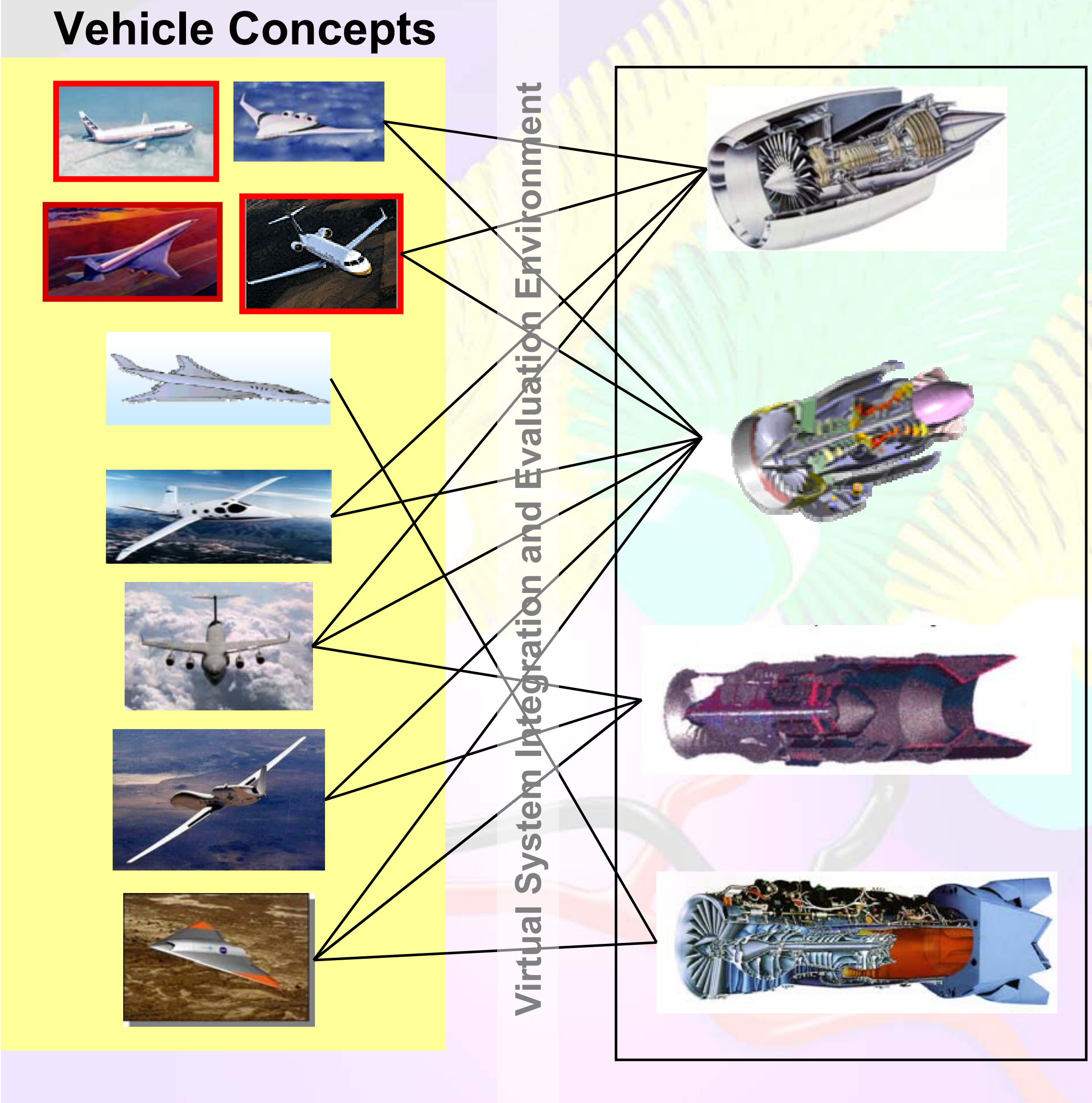
Performance of the hybrid cell composed of serially integrated SC and NG



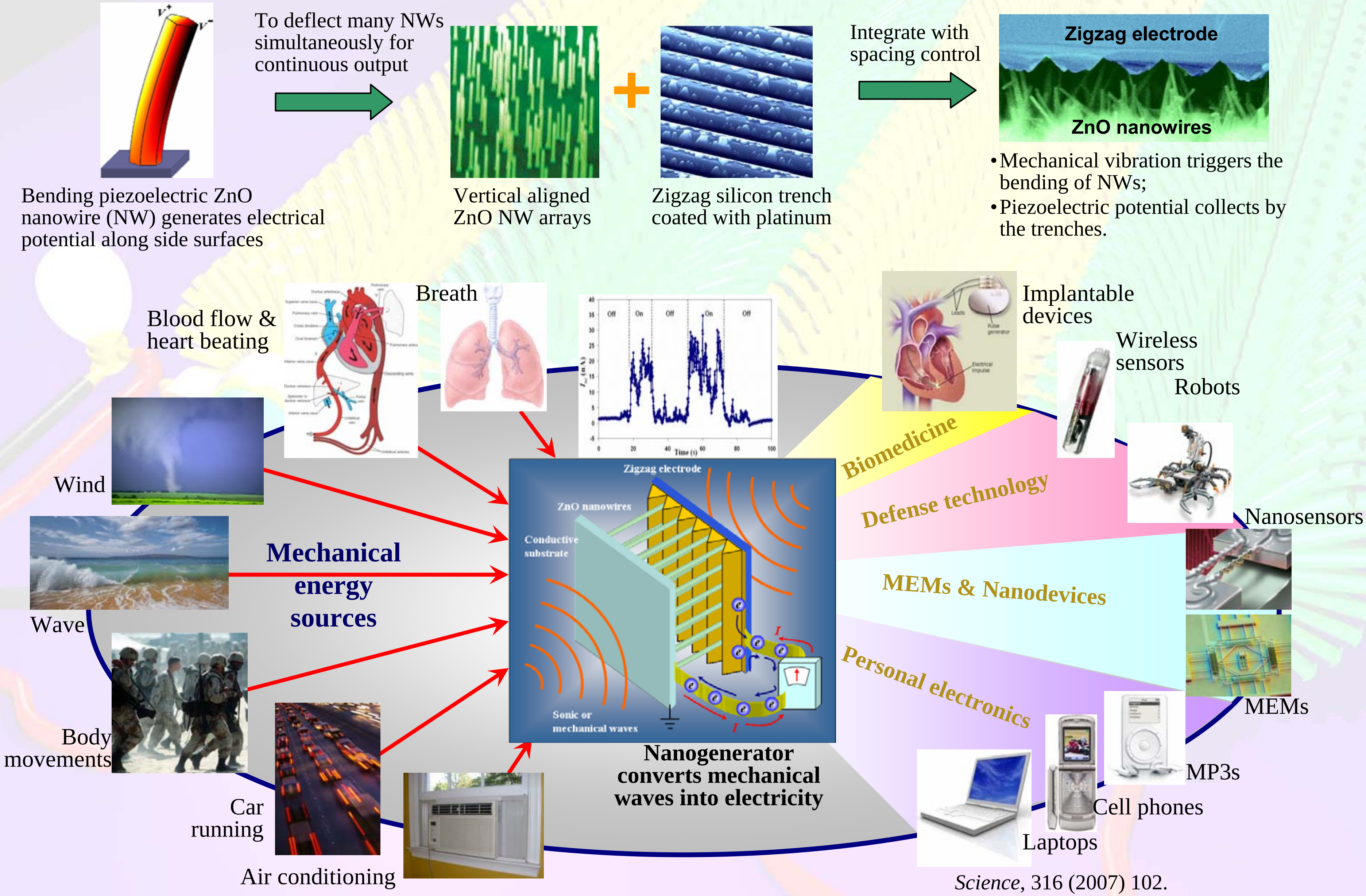




Harvesting multi-type energies



Perspectives of Piezoelectric Nanogenerator



Science, 316 (2007) 102.

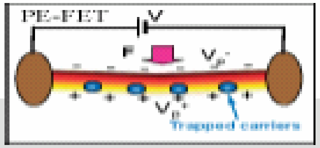
Nano-Piezotronics, what is it about? What can it be used for?

ADVANCED MATERIALS

DOI: 10.1002/adma.200602918

Nanopiezotronics**

By *Zhong Lin Wang**



This article introduces the fundamental principle of nanopiezotronics, which utilizes the coupled piezoelectric and semiconducting properties of nanowires and nanobelts for designing and fabricating electronic devices and components, such as field-effect transistors and diodes. The physics of nanopiezotronics is based on the principle of a nanowire nanogenerator that converts mechanical energy into electric energy. It is anticipated to have a wide range of applications in electromechanical coupled electronics, sensing, harvesting/recycling energy from the environment, and self-powered nanosystems.

Adv. Mater., 19 (2007) 889-992
Materials Today, 10 (2007) 20-28;

ENERGETIC MATERIALS

Flexible approach pays off

Researchers have managed to extract electrical energy from environmental noise by exploiting the piezoelectric properties of zinc oxide nanowires with a device that could herald a new generation of local power sources.

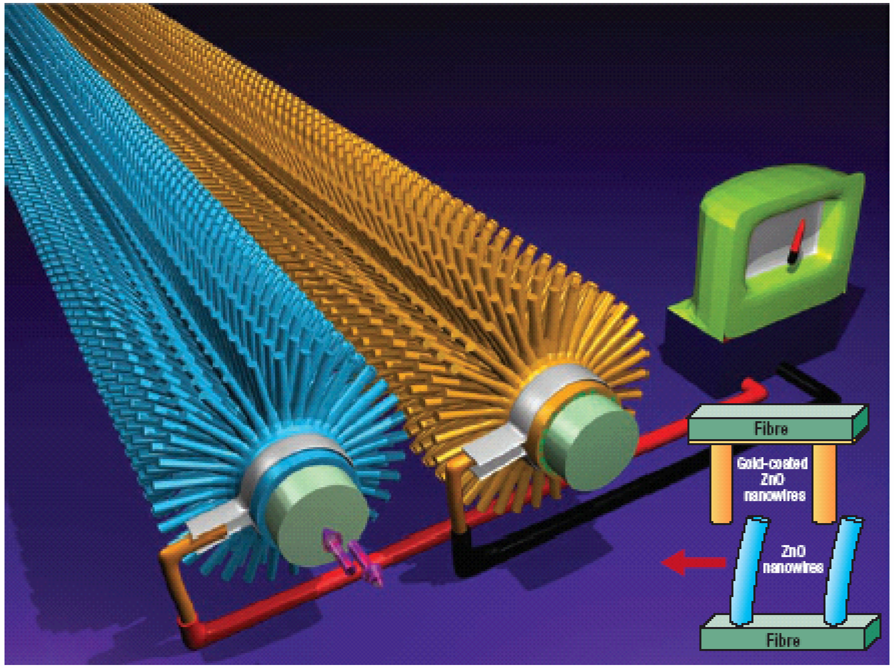
resulting electrical polarization of ZnO was converted into electricity through a combination of piezotronic effects[6] and the piezoelectric–semiconducting coupling process[7]. Although this work demonstrated the potential of piezoelectric nanowires, a

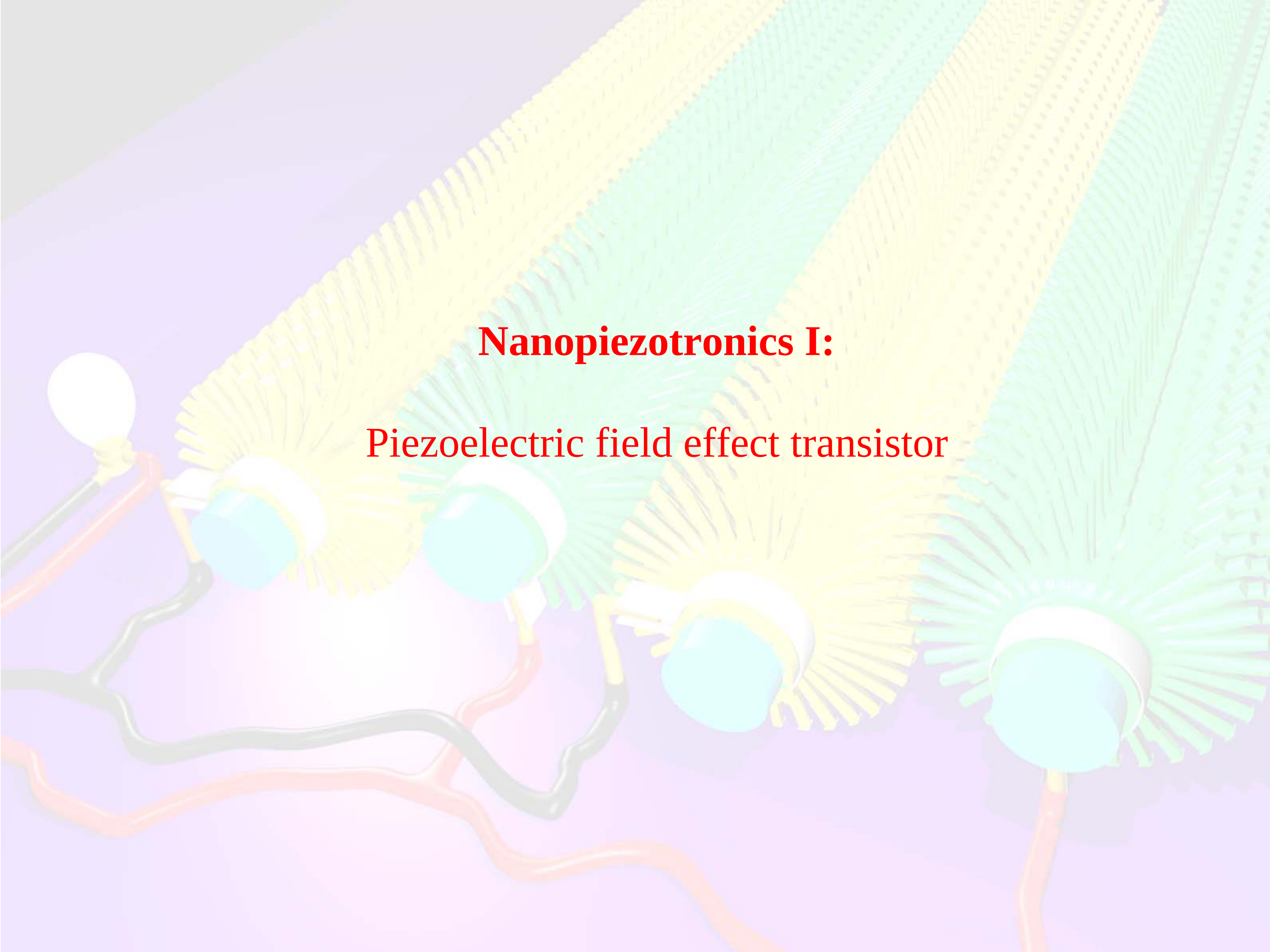
dge,

.gov

and storage of electrical energy for mobile devices and systems is one of the most urgent challenges in science and engineering today. Micro- and nanoscale devices — such as ultrasensitive chemical and biomolecular sensors, nanorobotics, microelectromechanical systems (MEMS), environmental sensors and other personal electronic devices — have energy requirements that are not fully met by available technologies such as batteries.

Although the energy requirements of these micro- and nanoscale devices are

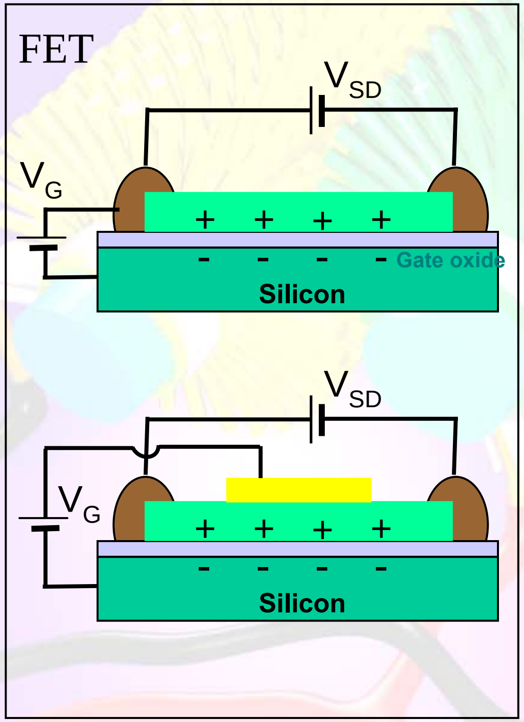


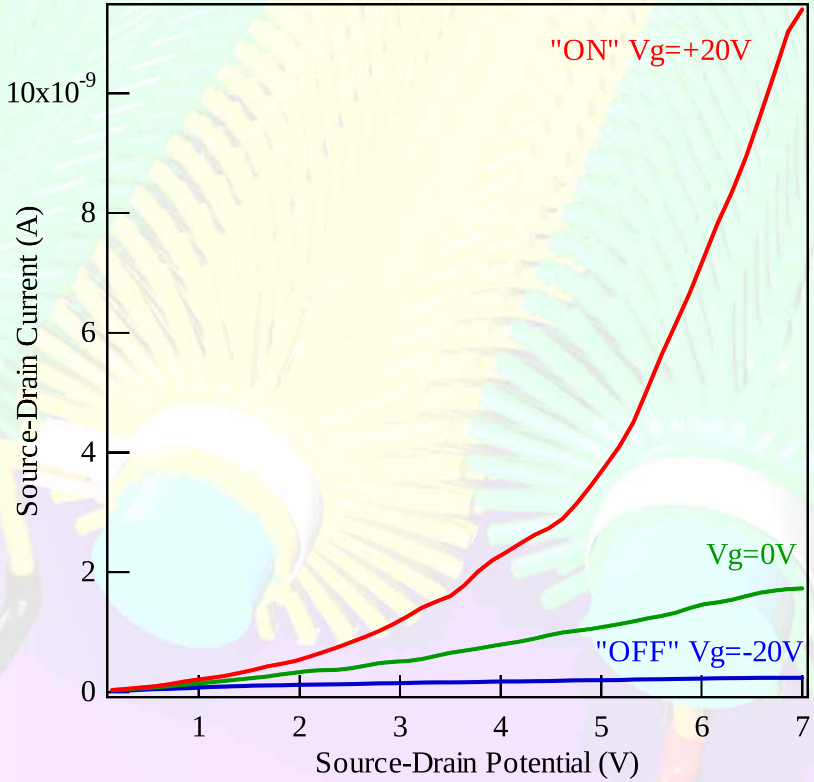


Nanopiezotronics I:

Piezoelectric field effect transistor

Nanobelt based FET





Piezoelectric potential at the surface of a ZnO nanowire

- No free charge inside the wire:

$$\nabla \cdot \vec{D} = 0$$

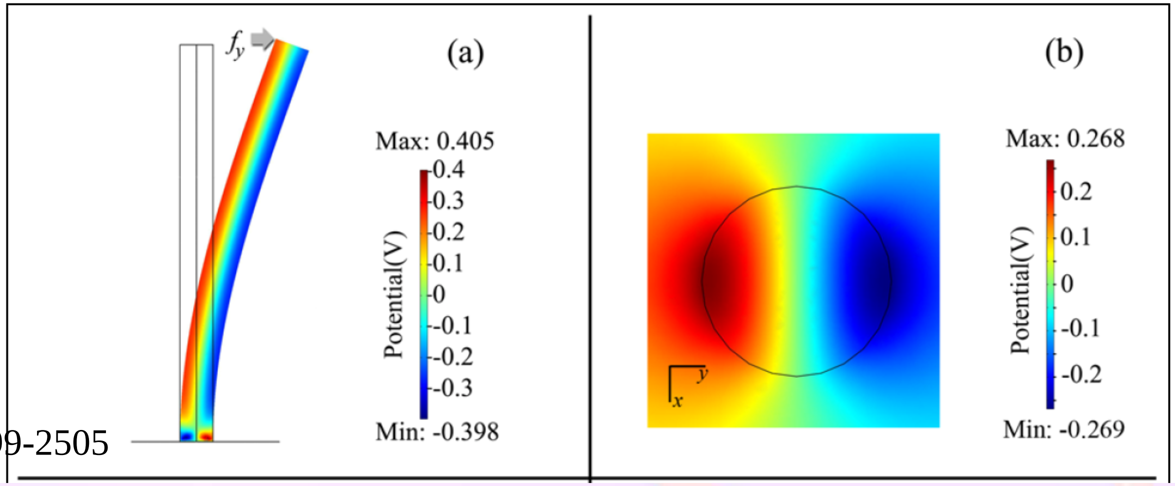
- No external body force:

$$\nabla \cdot (\sigma_{ij} + T_{ij}) = 0$$

  – Maxwell's stress tensor T_{ij} is small and can be neglected

- Constitutive Equations:

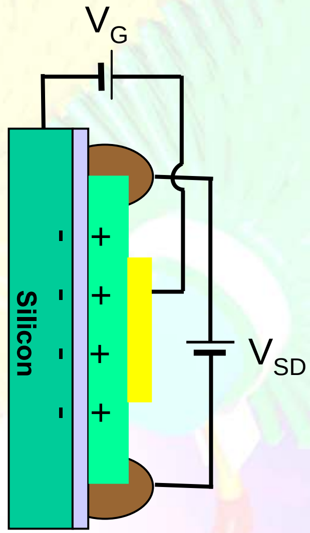
$$\begin{cases} \sigma_{ij} = c_{ijkl}\varepsilon_{kl} - e_{mij}E_m \\ D_n = e_{nij}\varepsilon_{ij} + \kappa_{nm}E_m \end{cases}$$

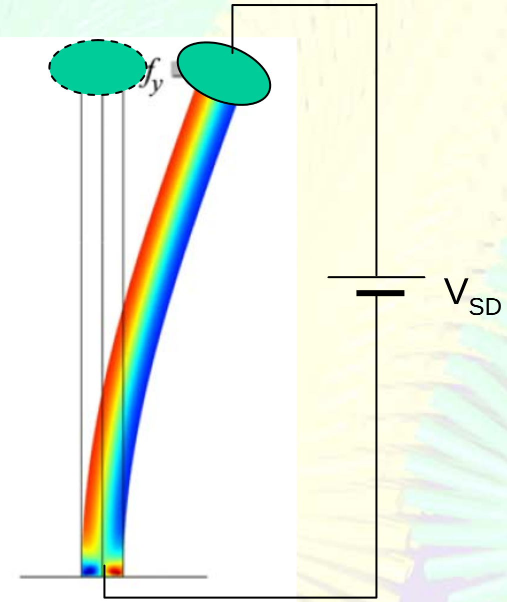


Nano Letters, 7 (2007) 2499-2505

Piezoelectric FET

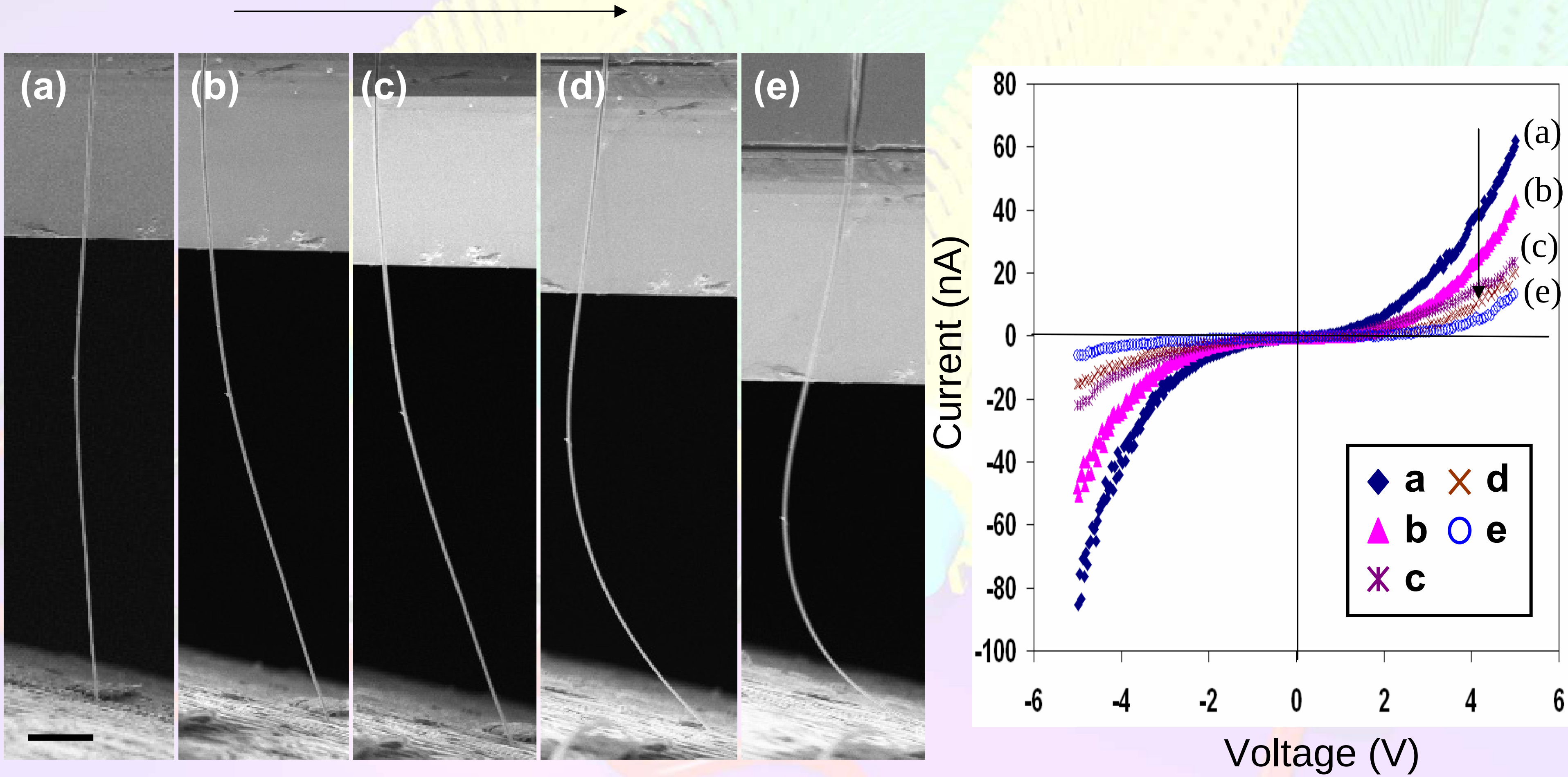
FET





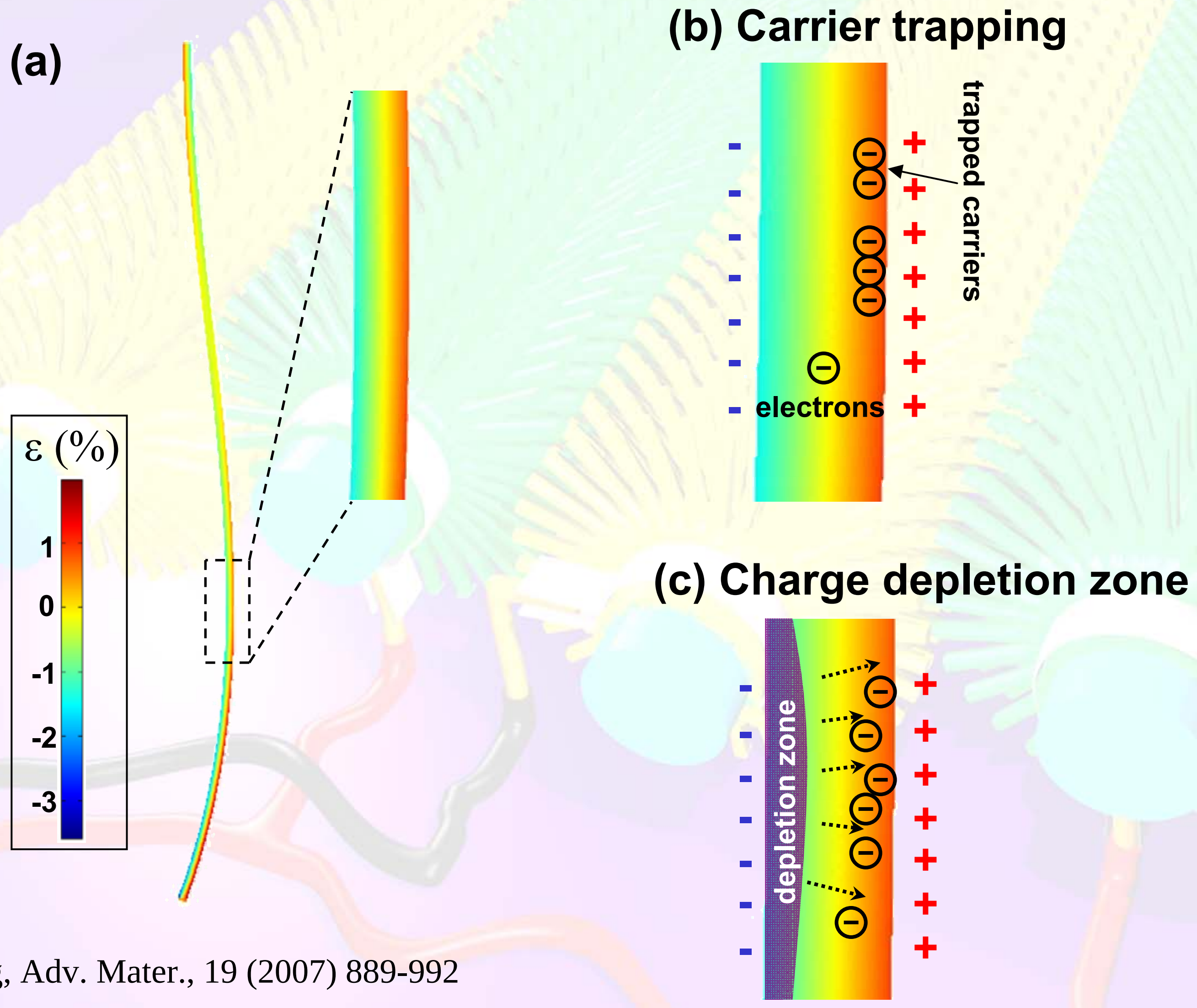
Wang, Adv. Mater., 19 (2007) 889-992

I-V characteristics of the ZnO nanowire based piezoelectric-field effect transistor (PE-FET)



Nano Letters, 6 (2006) 2768

Mechanisms of the P-FET



Wang, Adv. Mater., 19 (2007) 889-992

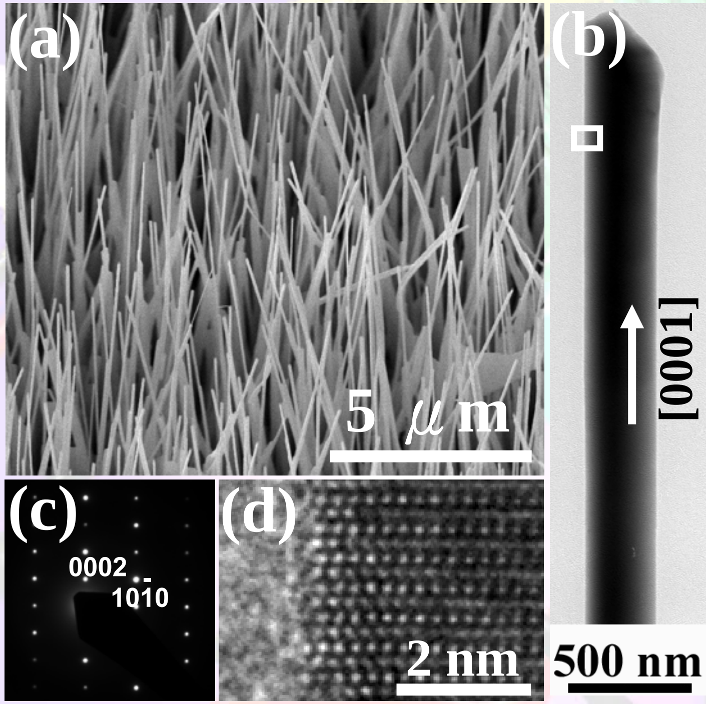
Nanopiezotronics II:

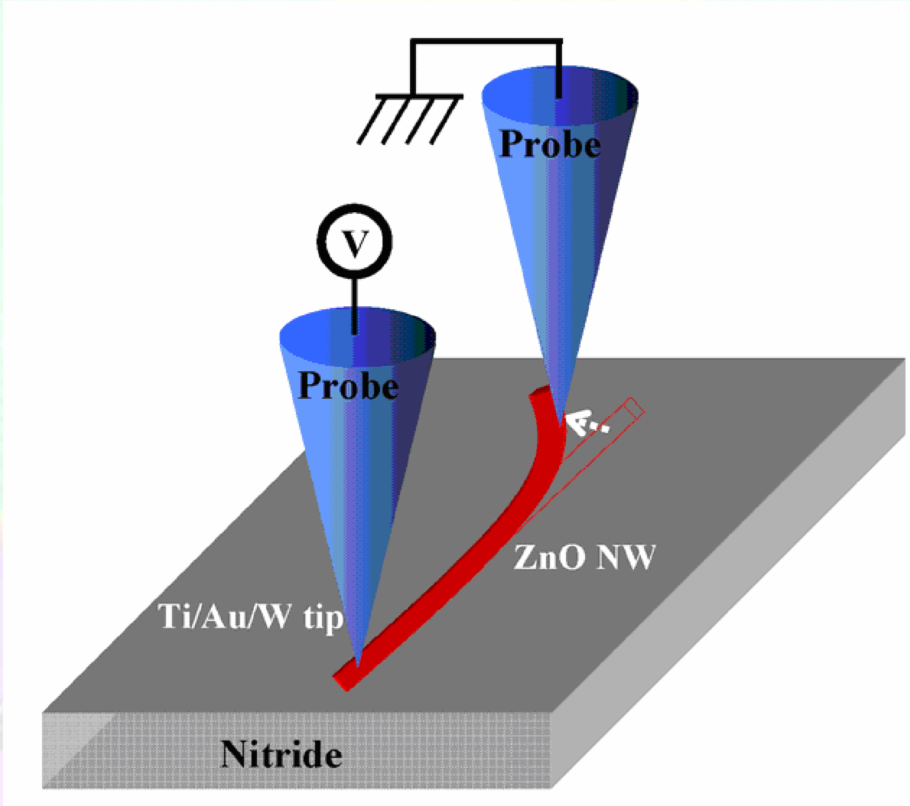
Piezoelectric diode/switch and sensor

He, Chen and Wang, *Adv. Mater.*, 19 (2007) 781.

Zhou, Fei, Gu, Mai, Gao, Yang, Bao, Wang* , Nano Letters, 8 (2008) 3973.

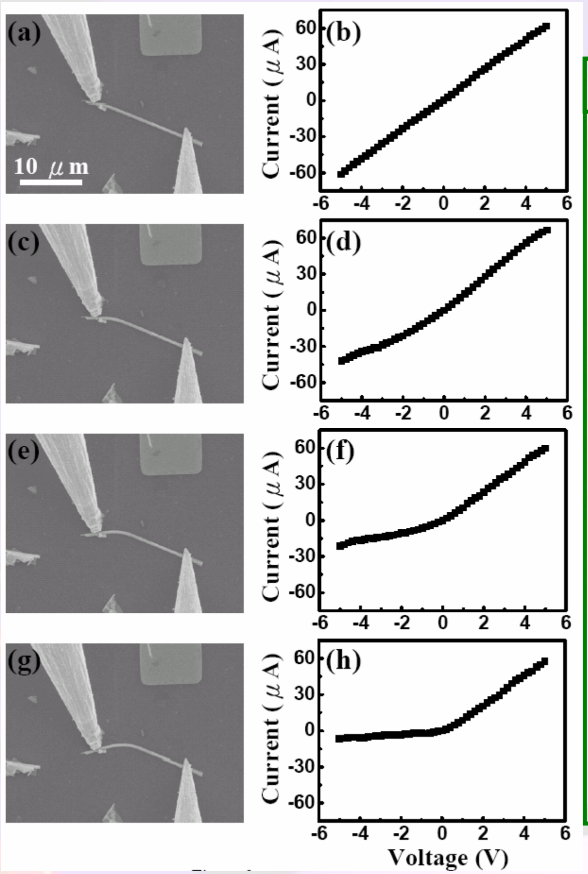
Piezoelectric diode

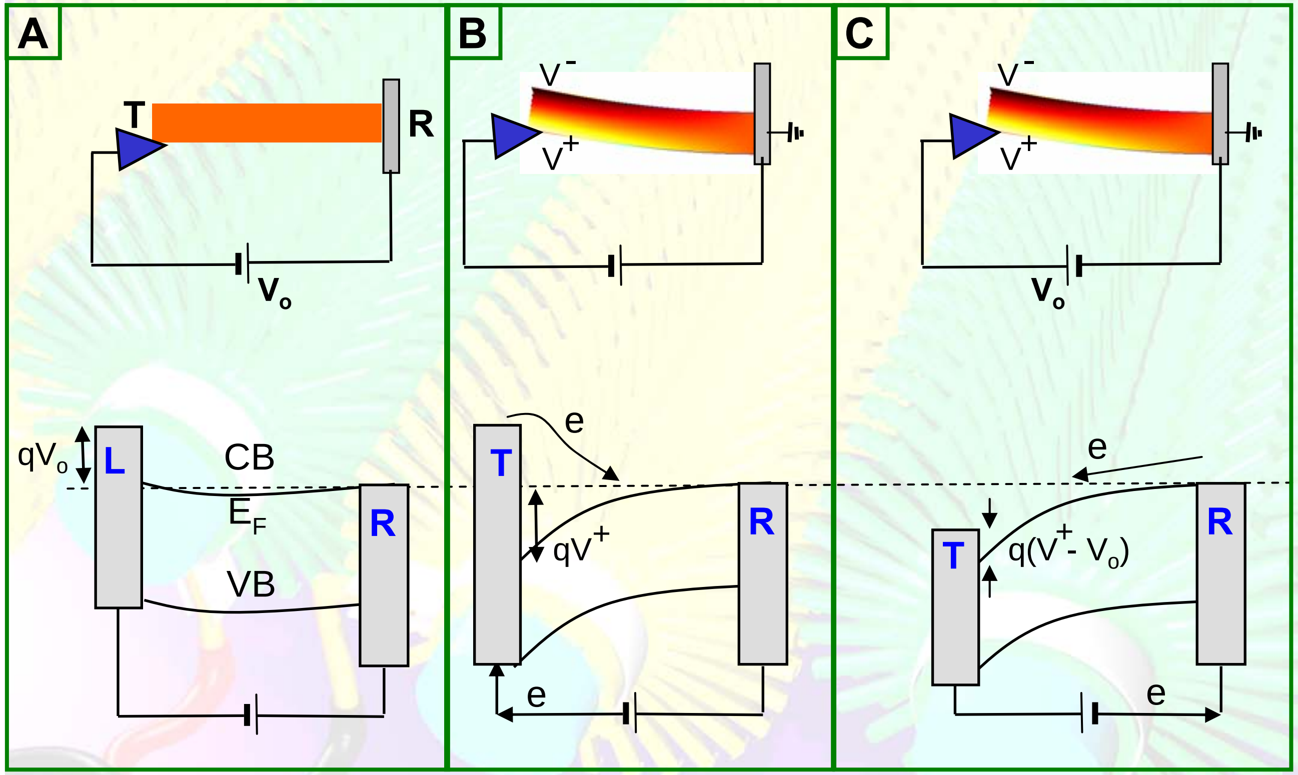




Adv. Mater., 19 (2007) 781.

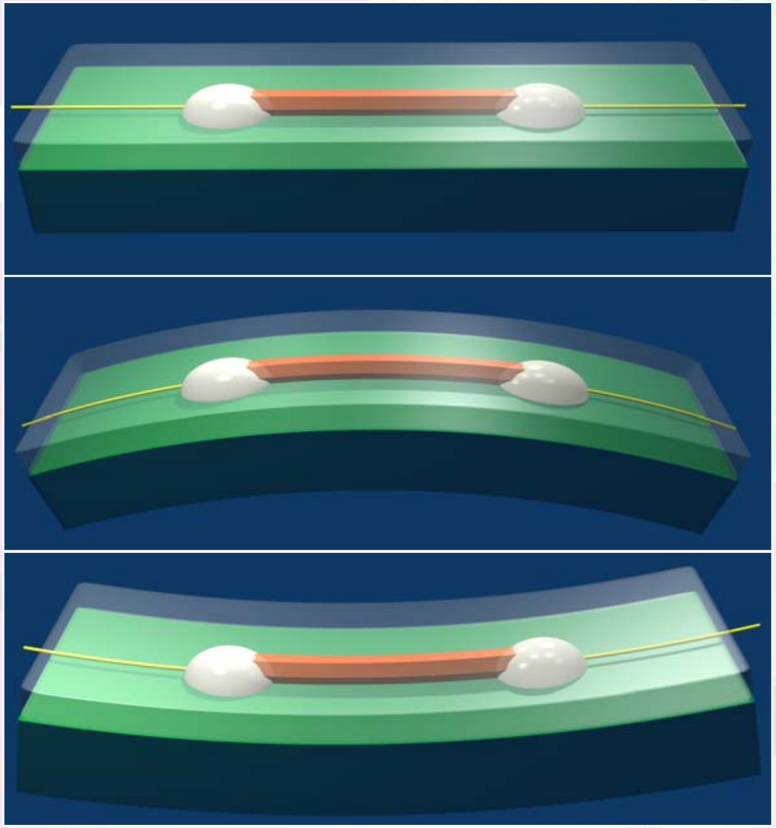
Piezoelectric diode

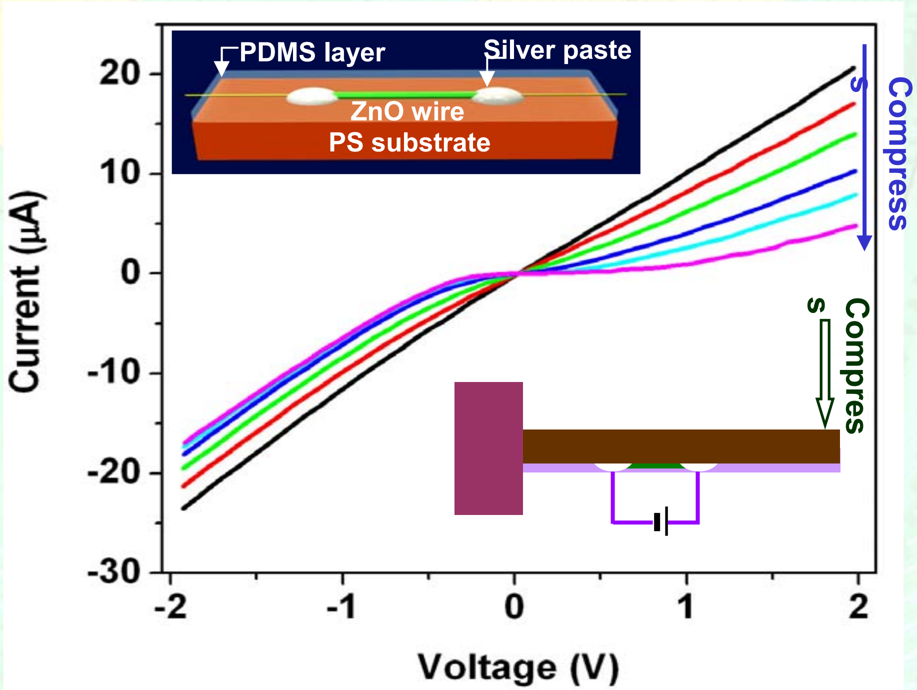


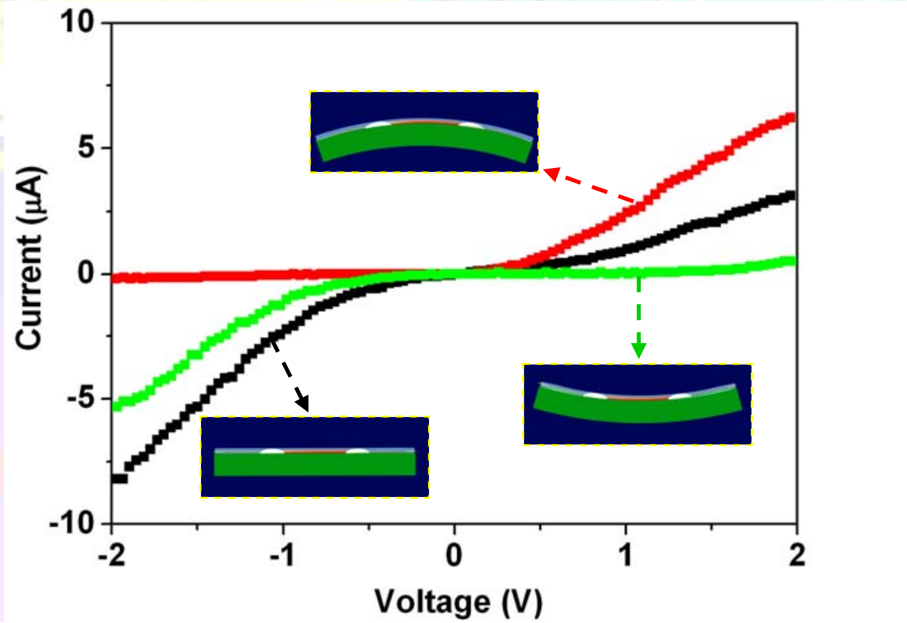


Adv. Mater., 19 (2007) 781.

Flexible and packaged piezotronic diode/switch device based on ZnO wire

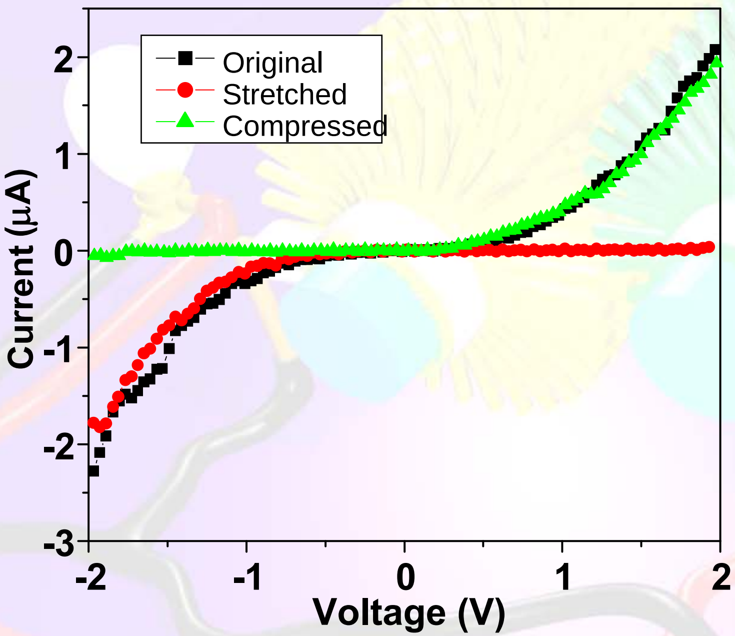


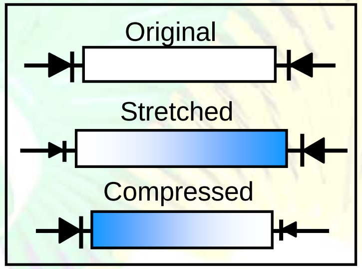


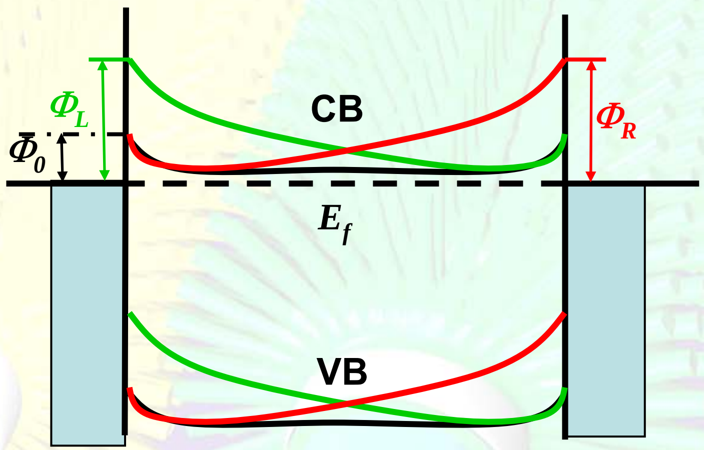


Nano Letters, 8 (2008) 3973.

Strain induced change of I-V characteristic from symmetric to asymmetric (diode) of a ZnO nanowire FET

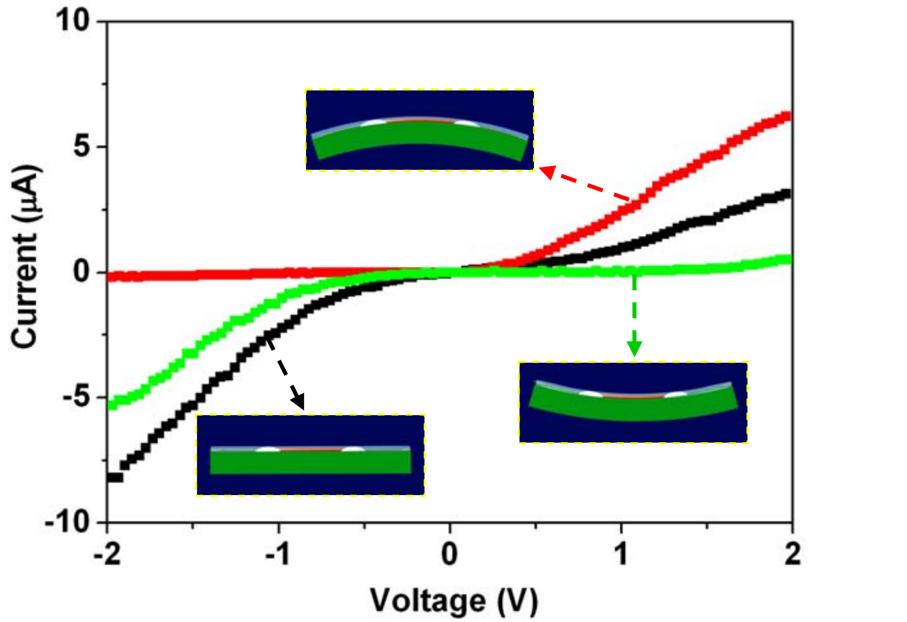


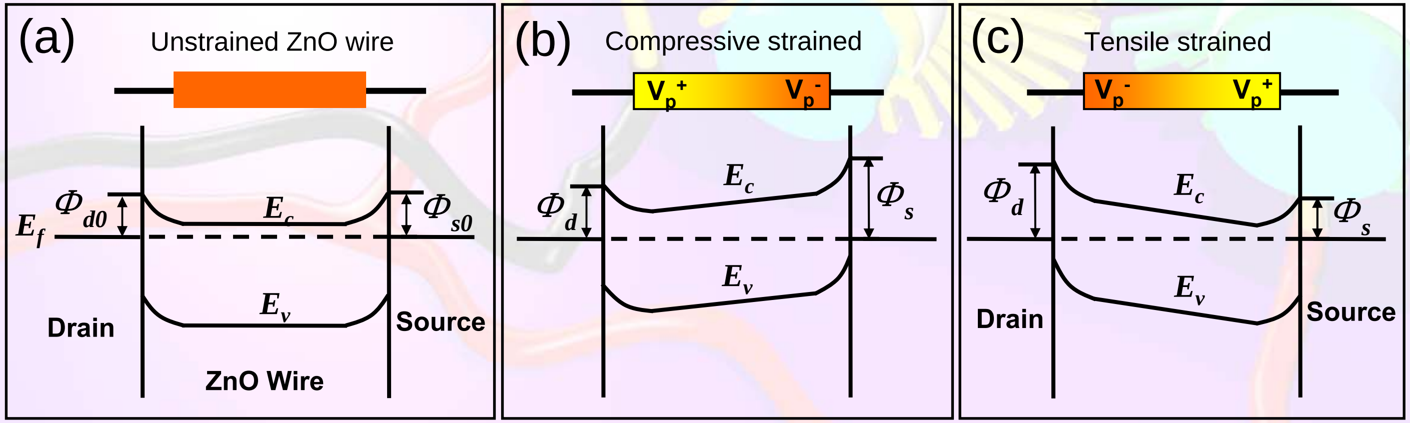




Gao, Zhou … Wang, J. Appl. Phys.

Flexible and packaged piezotronic diode/switch device based on ZnO wire





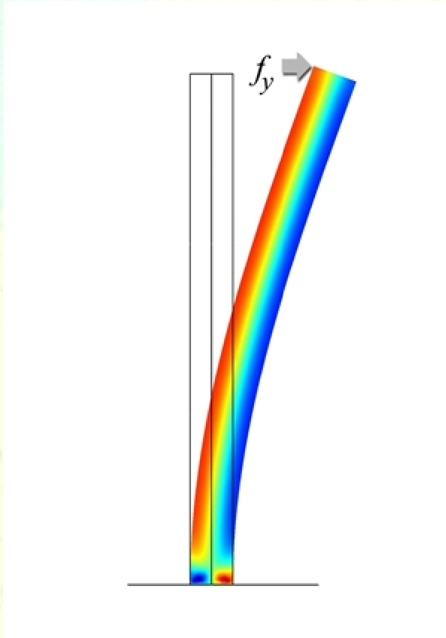
Nanopiezotronics III:

Free-standing FET based piezoelectric force/flow sensor

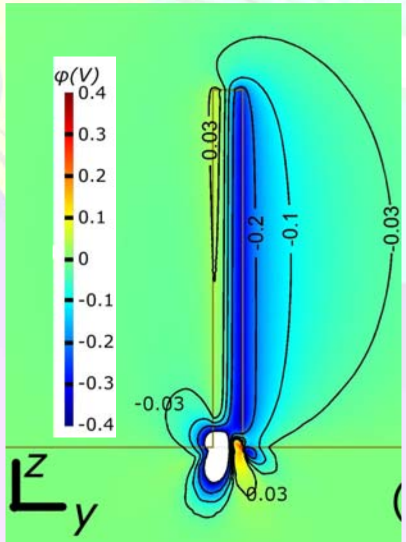
Fei, Huang, Wang* , Nano Letters, submitted

Piezoelectric potential at the root of a free-standing nanowire

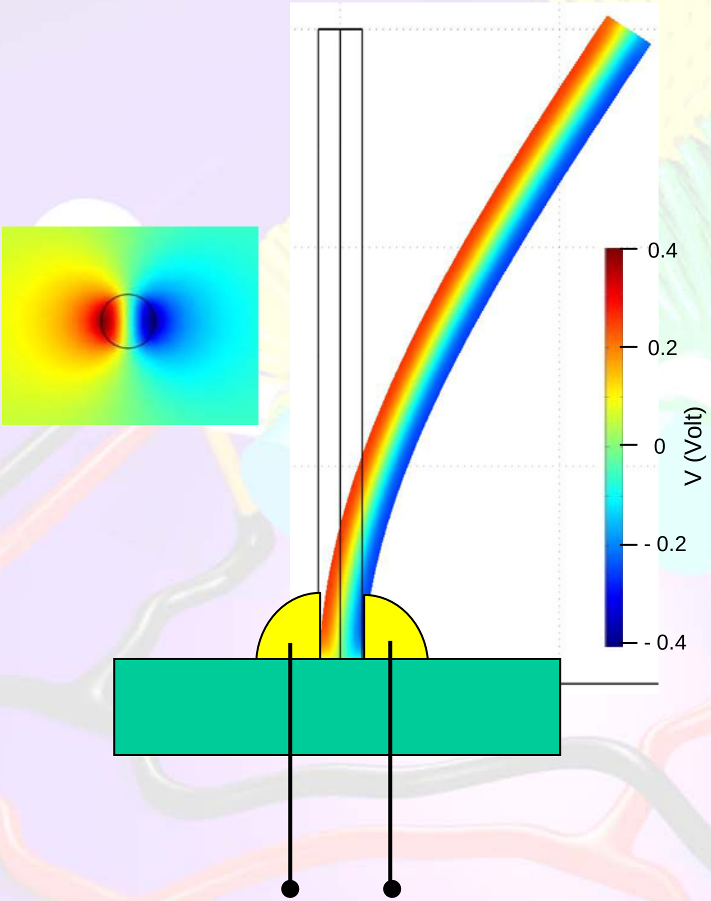
Gao and Wang “Electrostatic Potential in a Bent Piezoelectric Nanowire – The Fundamental Theory of Nanogenerator and Nanopiezotronics”, Nano Letters, 7 (2007) 2499-2505.

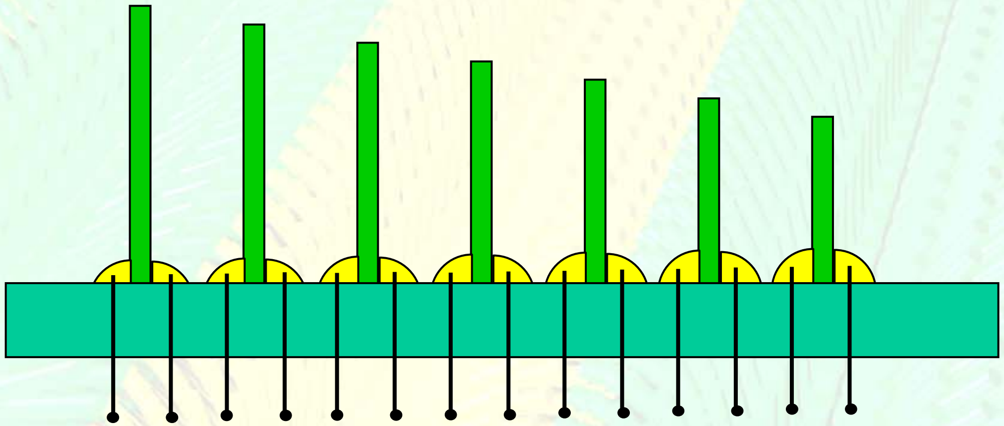


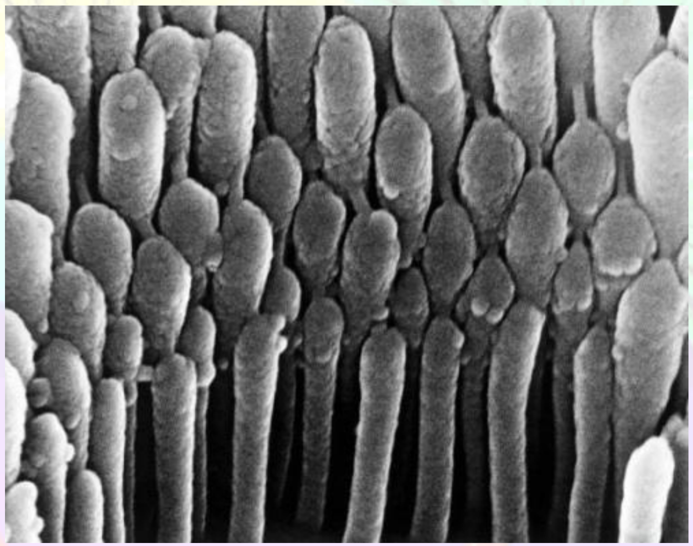
Gao and Wang* “Equilibrium Potential of Free Charge Carriers in a Bent Piezoelectric Semiconductive Nanowire”, Nano Letters, 9 (2009) 1103 - 1110.



Design idea of hearing aid

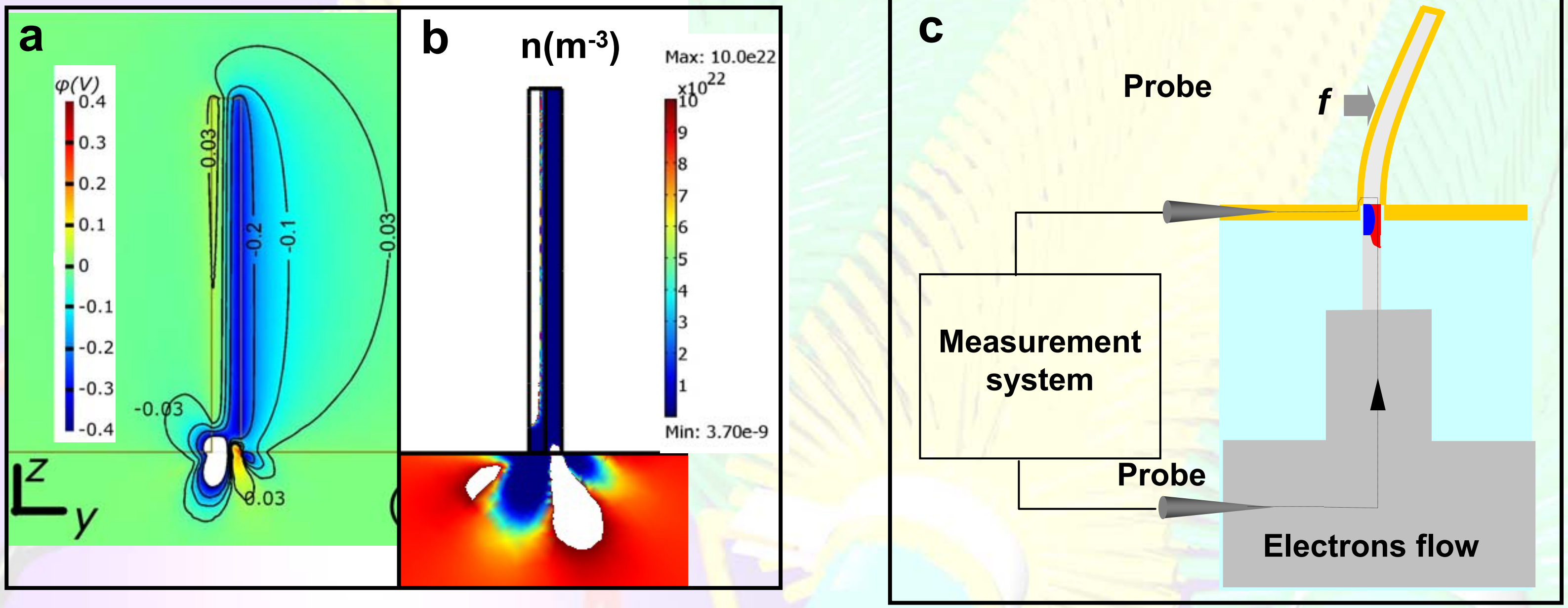




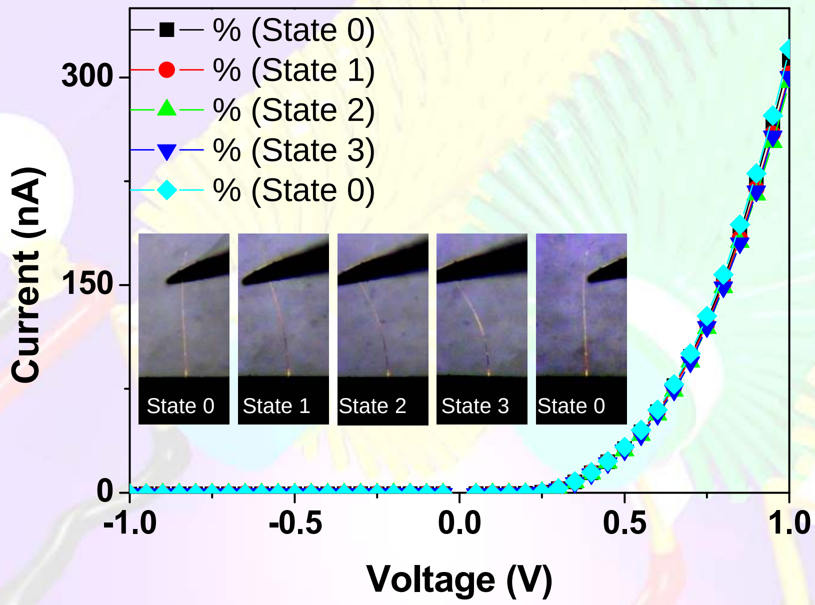


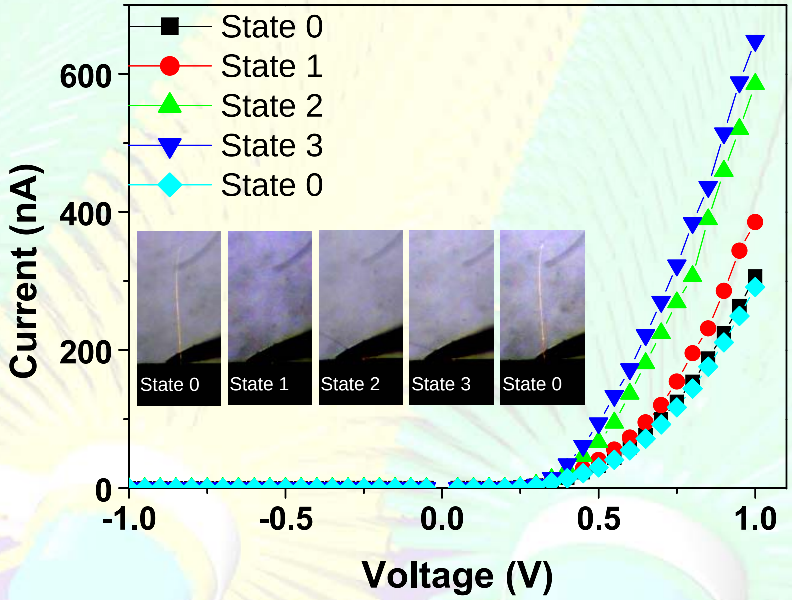
Inner year cell

Theoretical basis of free-standing nanowire nanosensors

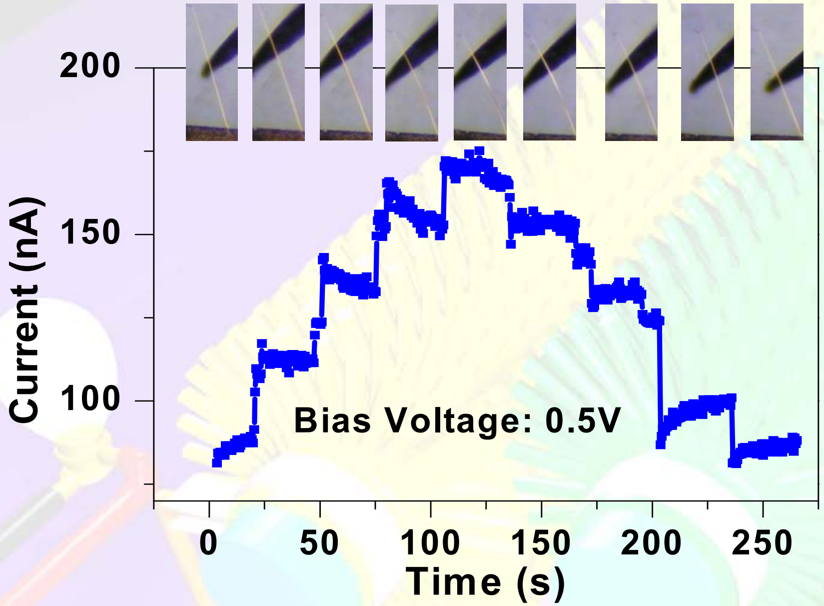


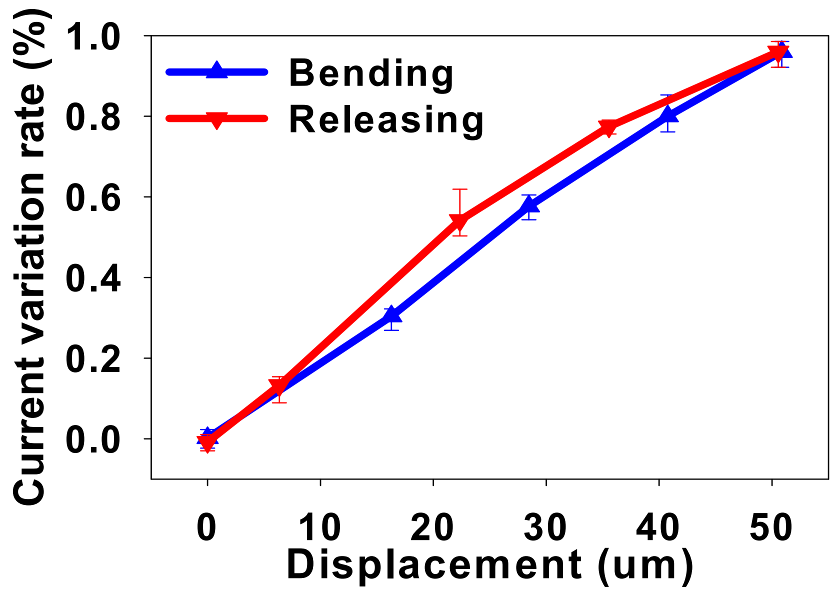
Experimental testing about the pieozopotential at the nanowire root

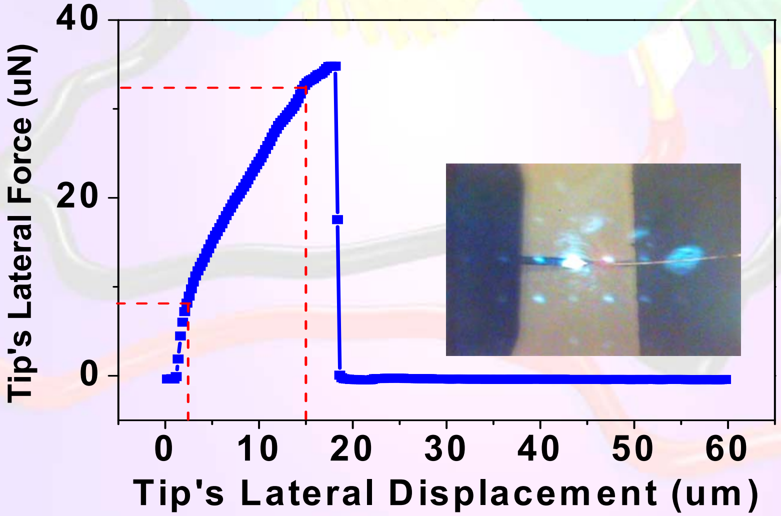


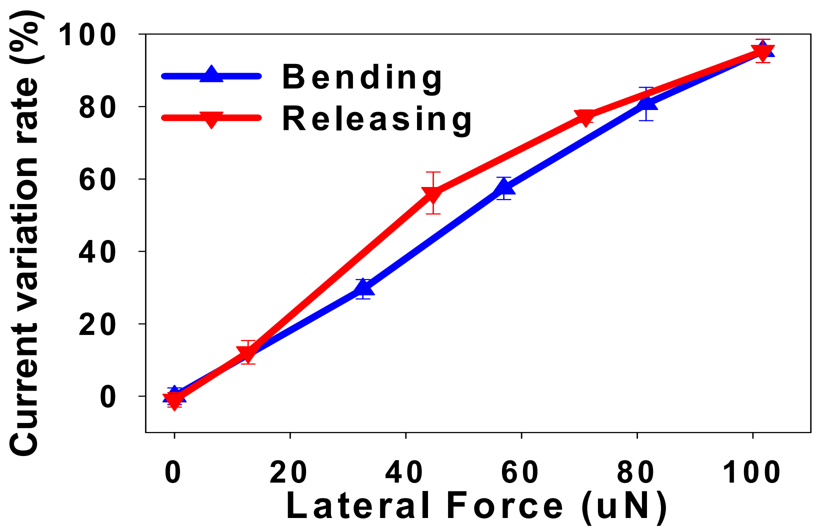


Quantification of the response of the force/flow sensor

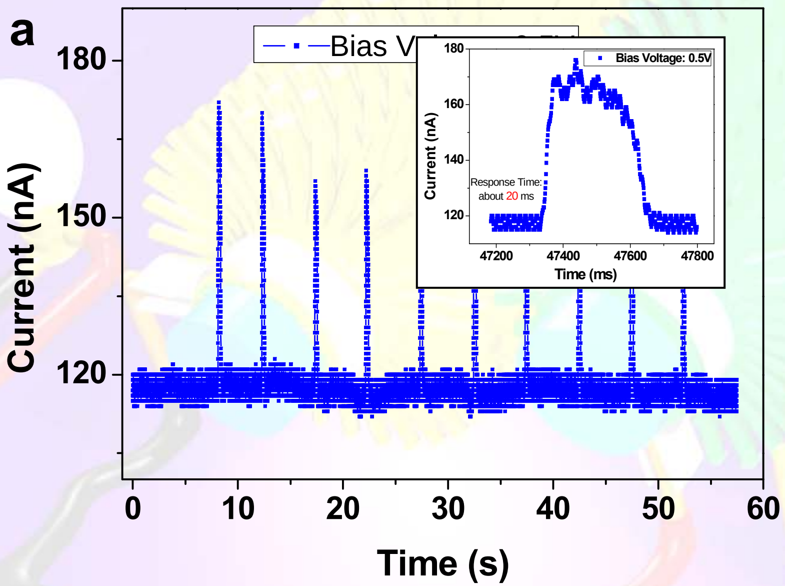


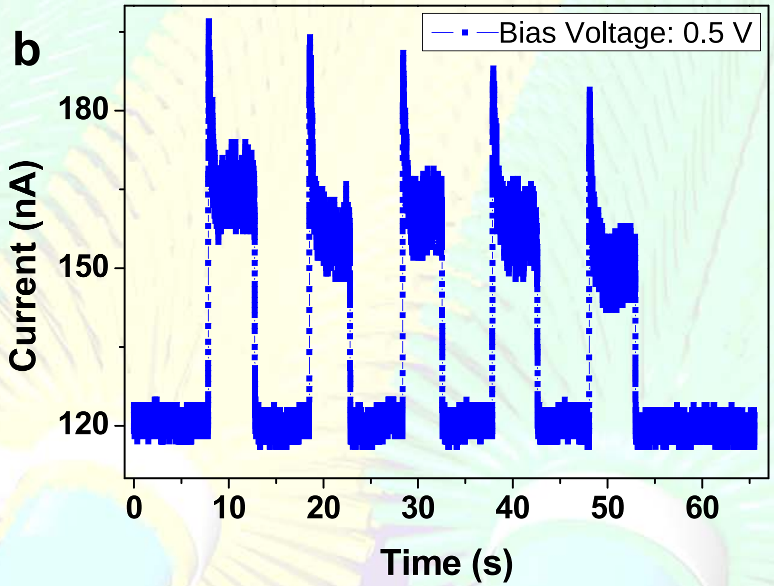






Response of the force/flow sensor to pulsed gas flow

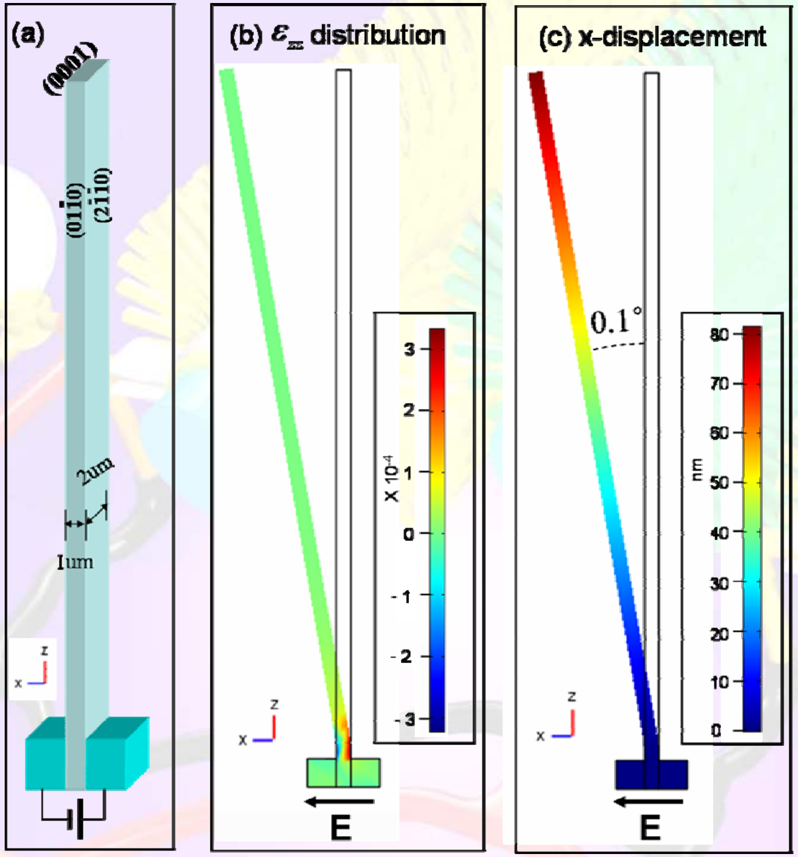




Converse piezoelectric sensor/transducer using free-standing nanowires

Hu, Wang, Nano Letters, in press

Converse piezoelectric effect induced transverse deflection of a free-standing ZnO microbelt



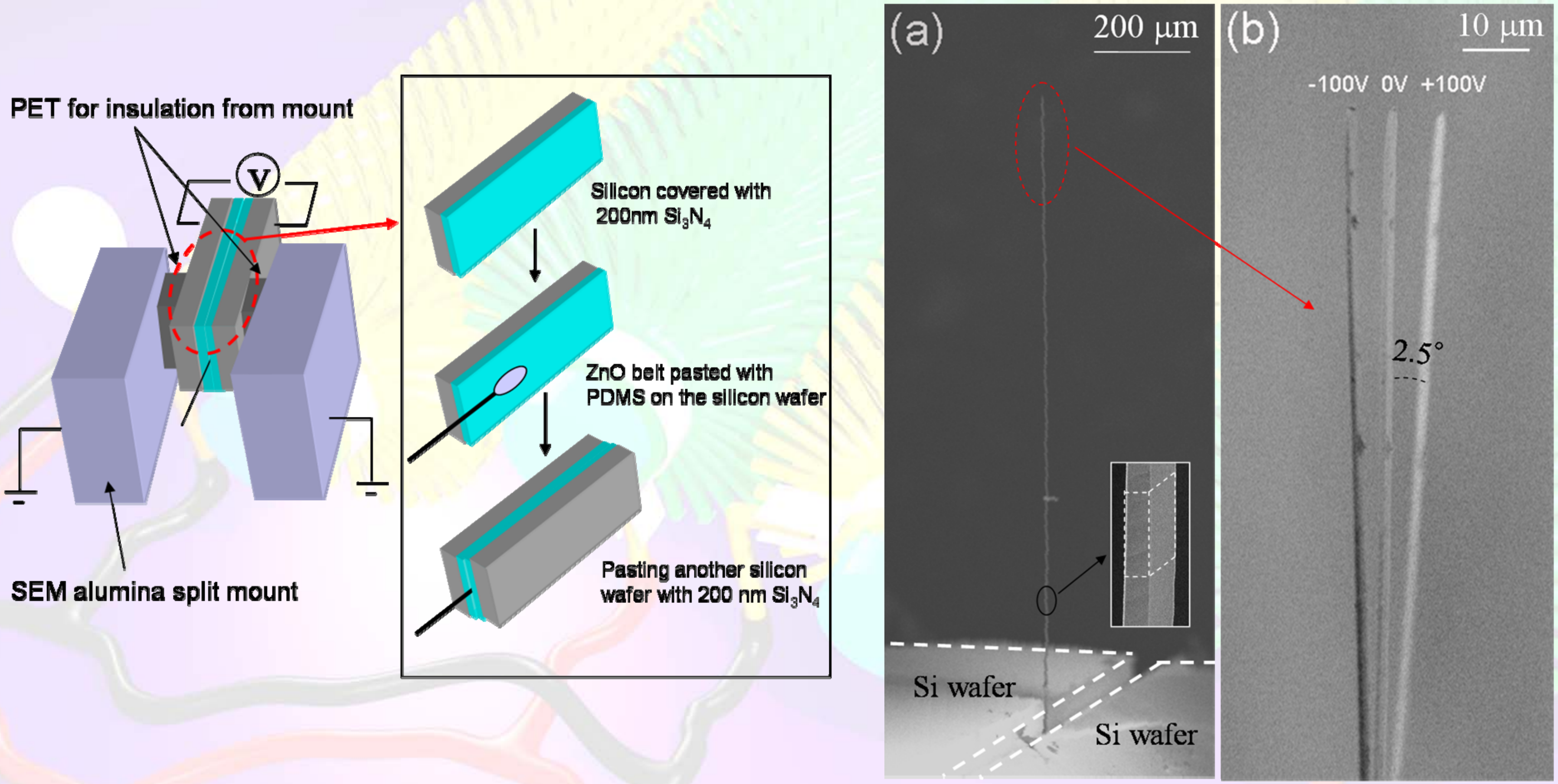
Piezoelectric equations

$$\begin{cases} \sigma_p = c_{pq}\varepsilon_q - e_{kp}E_k \\ D_i = e_{iq}\varepsilon_q + \kappa_{ik}E_k \end{cases}$$

Piezoelectric tensor

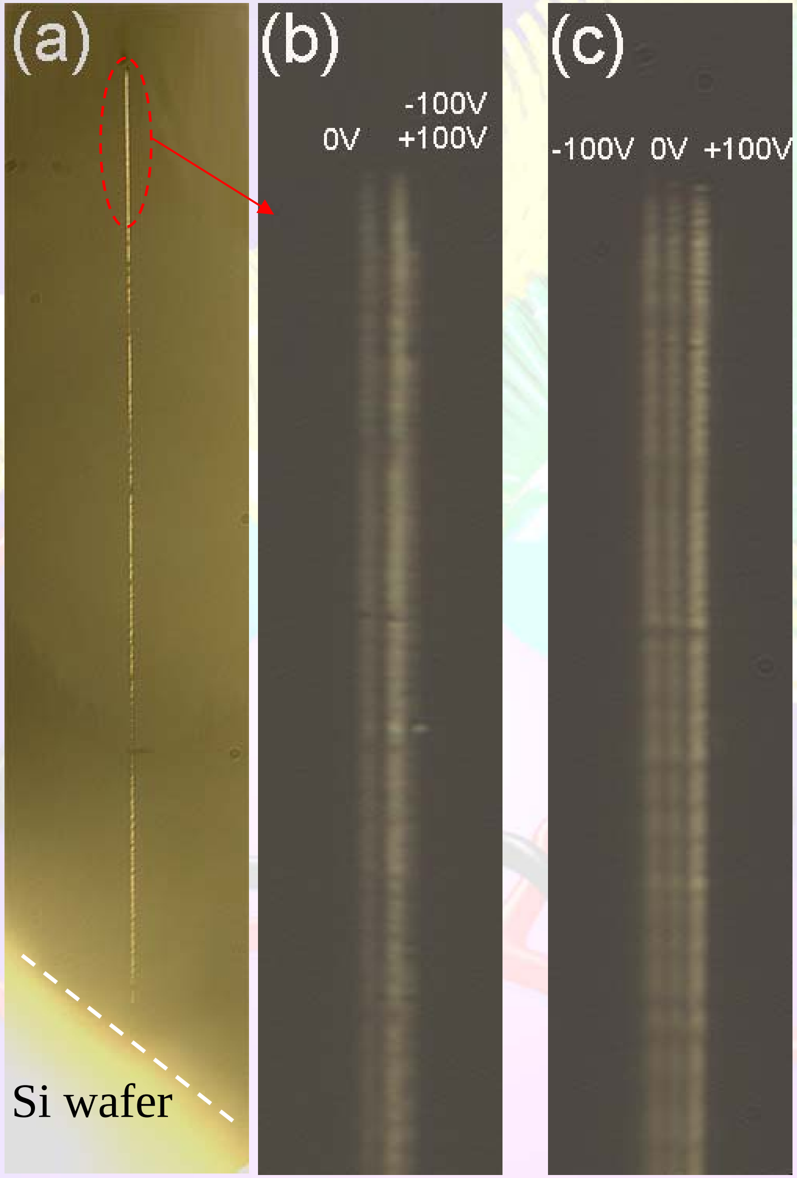
$$e_{iq} = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix}$$

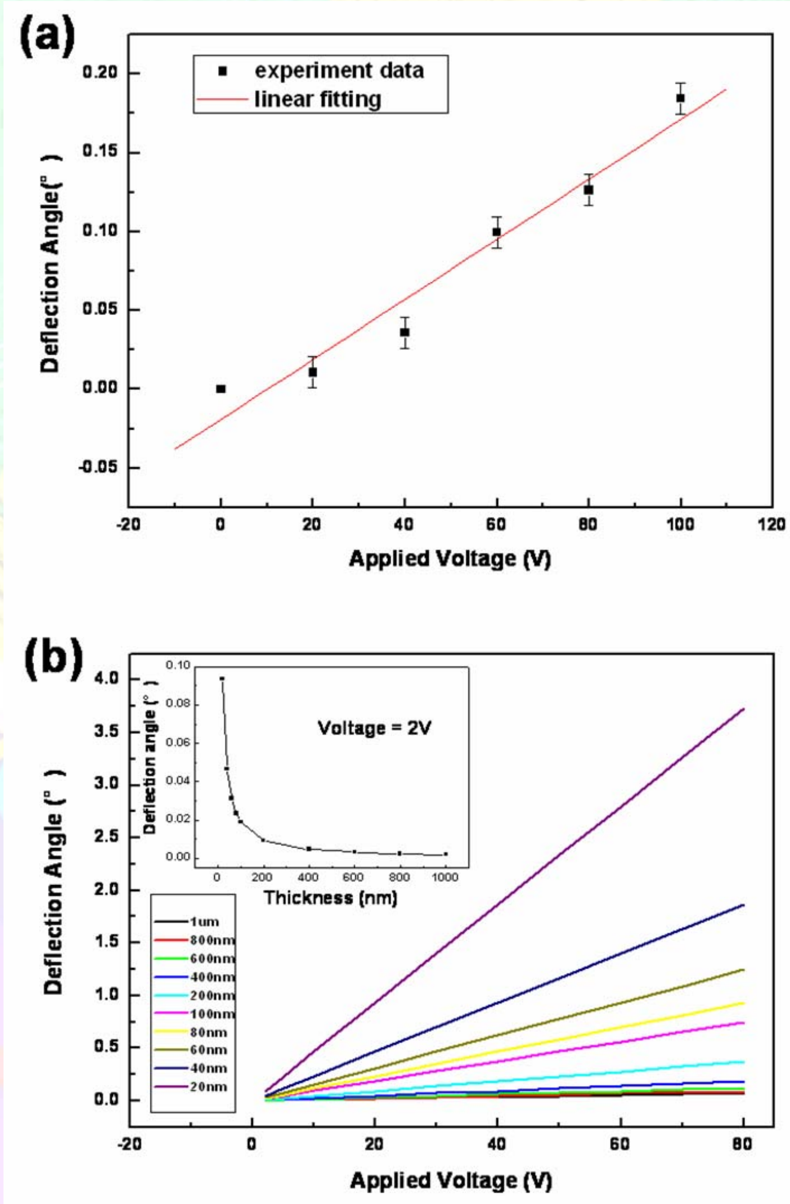
Experimental design and first observation



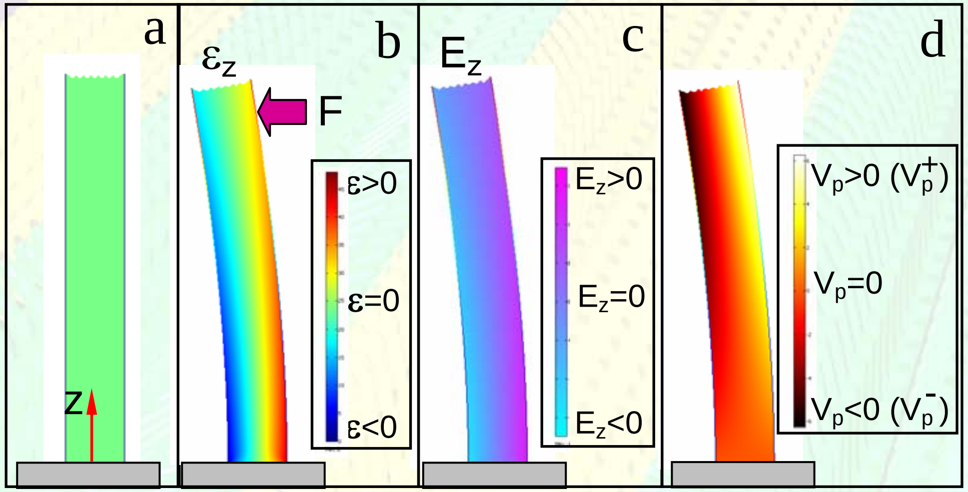
Performance of the devices

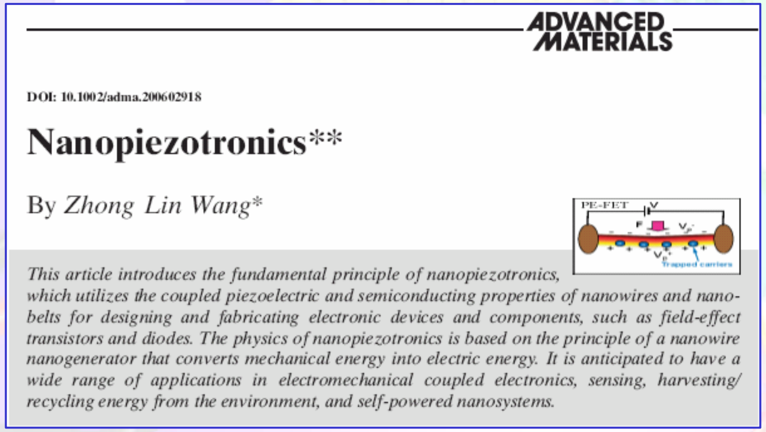
Deflection in responding to applying 100V (b) before and (c) after Au coating across the width of the microbelt.





Nano-Piezotronics



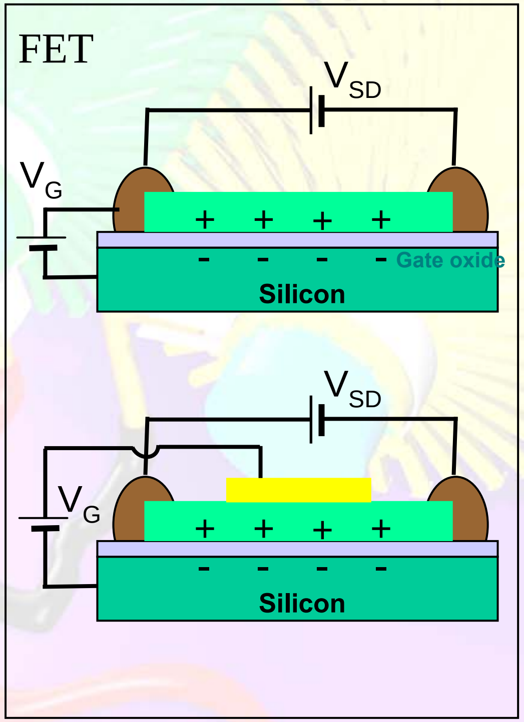

ADVANCED MATERIALS

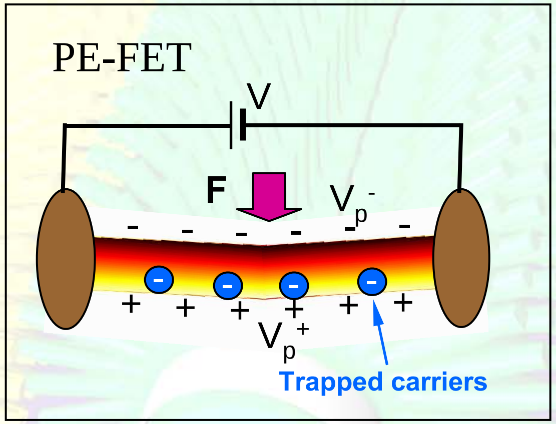
DOI: 10.1002/adma.200602918

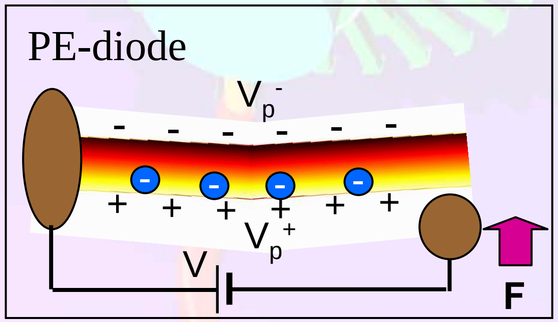
Nanopiezotronics**

By *Zhong Lin Wang**

This article introduces the fundamental principle of nanopiezotronics, which utilizes the coupled piezoelectric and semiconducting properties of nanowires and nanobelts for designing and fabricating electronic devices and components, such as field-effect transistors and diodes. The physics of nanopiezotronics is based on the principle of a nanowire nanogenerator that converts mechanical energy into electric energy. It is anticipated to have a wide range of applications in electromechanical coupled electronics, sensing, harvesting/recycling energy from the environment, and self-powered nanosystems.





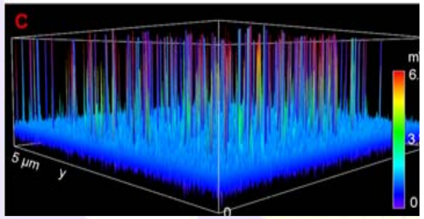


Materials Today, 10 (2007) 20-28;
Adv. Mater., 19 (2007) 889-992

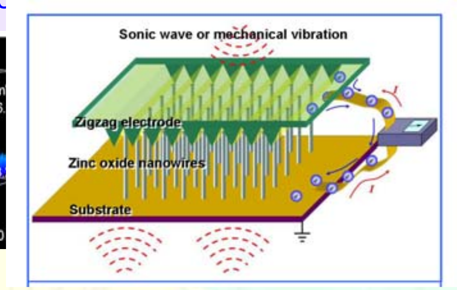
Nano-Piezotronics

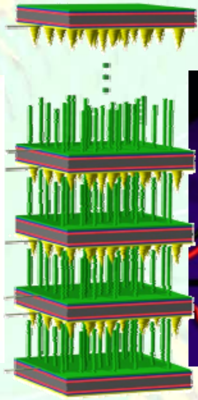
➢**Piezotronics** is a field of using piezoelectric-semiconducting coupled properties/effects for creating/fabricating novel and unique electronic devices and components (ZLW).

1. Piezoelectric nanogenerator

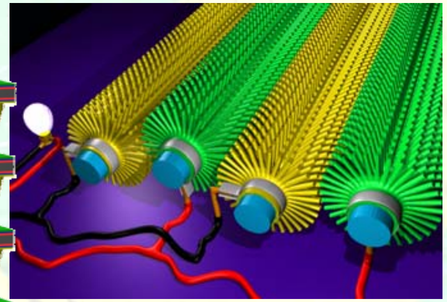


2. DC nanogenerator

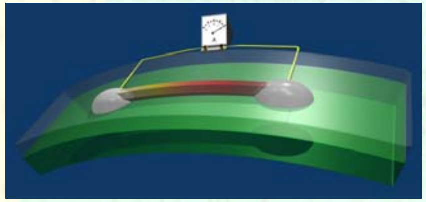




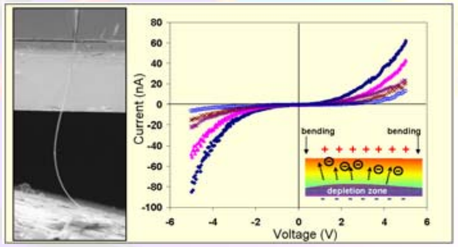
3. Fiber nanogenerator



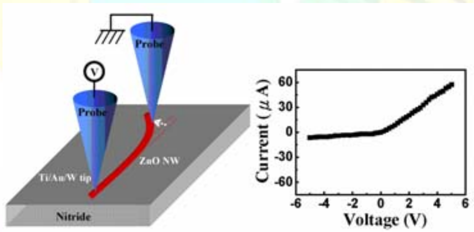
4. Lateral and packaged NG



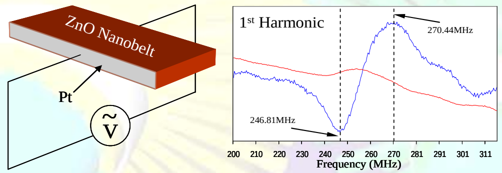
Piezoelectric-field effect transistor



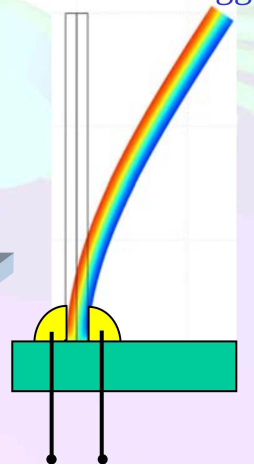
Piezoelectric diode



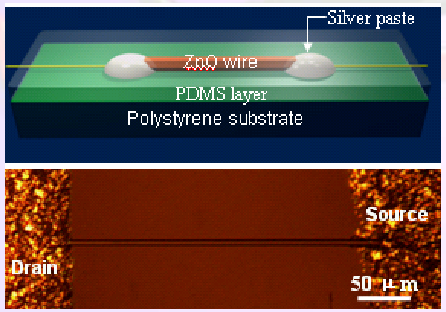
Piezoelectric resonator



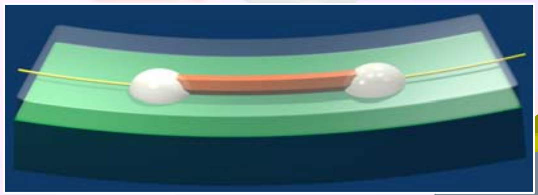
Force sensor/trigger



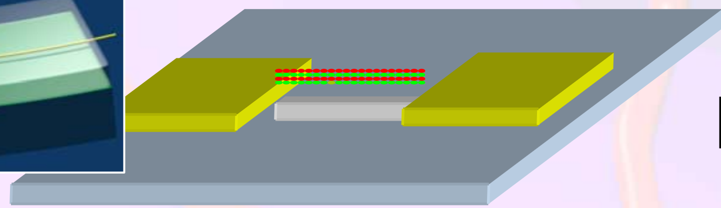
Strain/force/pressure sensor



Piezo-diode



Piezoelectric FET sensors



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Ten sci-fi devices that could soon be in your hand

26 January 2009

Magazine issue 2692. Subscribe and ge

NewScientist

Darwin was wrong

Cutting down the tree of life

4 Spider vs gecko

Peter Parker makes it look easy, but replicating his rooftop antics is so difficult it has had researchers climbing the walls for years. The problem is clear: the gloves and shoes of any Spider-Man suit must be able to support the weight of an average person while dangling from the side of a skyscraper. And of course hands and feet must also peel off easily when required - superglue is not an option.

For inspiration, researchers have turned to geckos rather than spiders. In 2003, Andre Geim at the University of Manchester, UK, designed a material with microscopic hairs that mimic those found on geckos' feet. Intermolecular van der Waals forces, which take effect on tiny scales, encourage each hair to stick to the wall and, because a gecko's feet are coated with millions of these hairs

5 You power

Your cellphone is a marvel of the modern age. Yet no matter how sophisticated it is, it's useless the moment it runs out of juice. But what if you could dispense with batteries and simply gather all the energy your gadget needs from the world around you?

For a start, you could plug it into your shirt. In 2008, Zhong Lin Wang at the Georgia Institute of Technology in Atlanta wove a fabric made from zinc-oxide nanowires grown on strands of Kevlar. Each time the material is bent or squeezed, it generates a tiny current. Wang and his team found they could harvest it by coating each fibre with a film of metal.

Gadgets implanted inside your body, such as pacemakers, could be powered by you. David Tran's team at Stanford University, California, have devised a heart-powered electricity generator. The gadget produces electricity by forcing a small magnet back and forth through a tiny wire coil. The magnet is housed in a liquid-filled silicone tube with a balloon attached to each end, and the whole device is placed within the heart. As the heart beats, the balloons are squeezed in turn, forcing the liquid - and the magnet - back and forwards through the tube.

Adam Heller at the University of Texas, Austin, has built a fuel cell that can be implanted in an artery and which uses glucose in the blood as fuel.

Done

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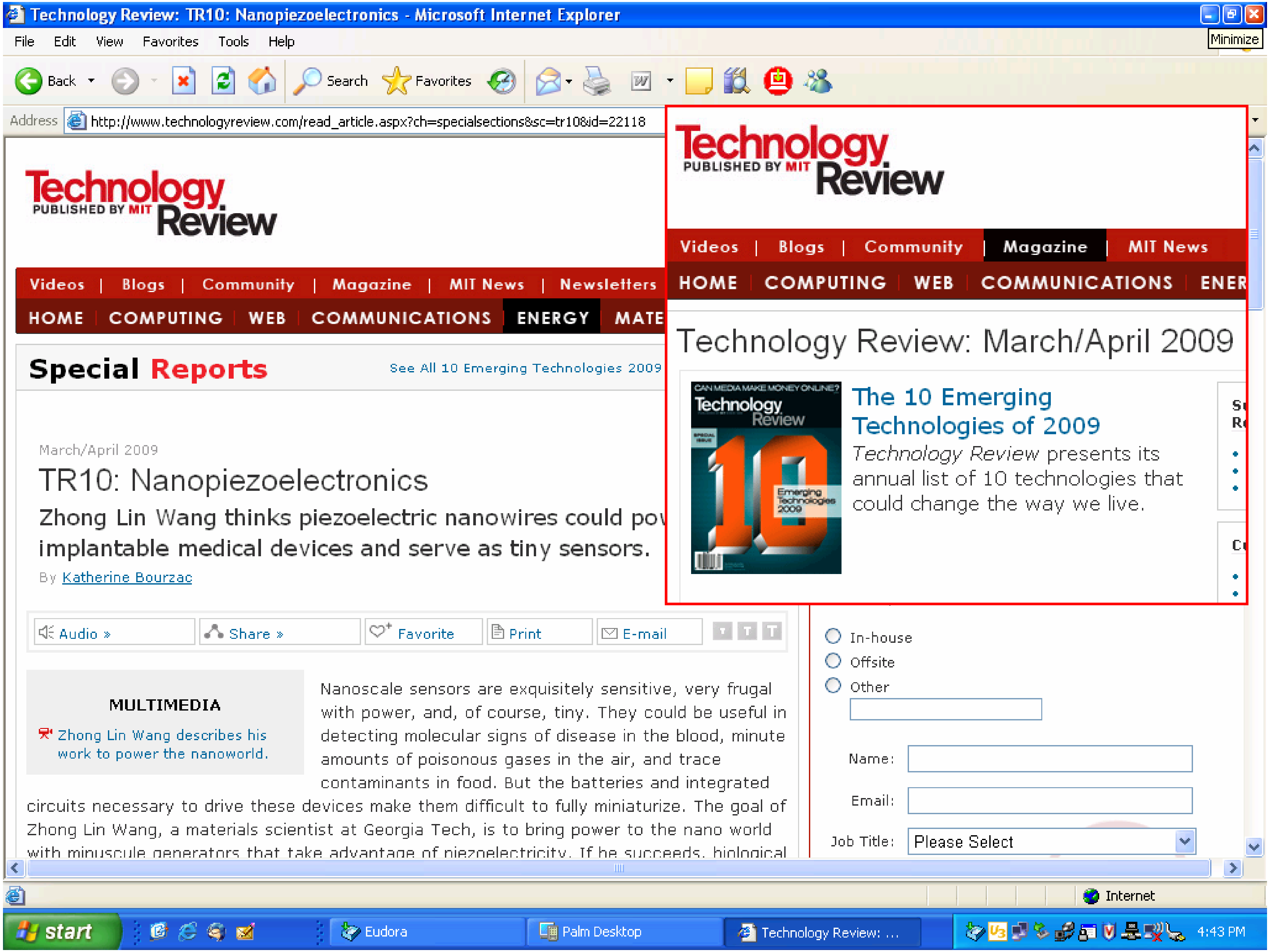

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March/April 2009

TR10: Nanopiezoelectronics

Zhong Lin Wang thinks piezoelectric nanowires could pow implantable medical devices and serve as tiny sensors.

By Katherine Bourzac

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Zhong Lin Wang describes his work to power the nanoworld.

Nanoscale sensors are exquisitely sensitive, very frugal with power, and, of course, tiny. They could be useful in detecting molecular signs of disease in the blood, minute amounts of poisonous gases in the air, and trace contaminants in food. But the batteries and integrated circuits necessary to drive these devices make them difficult to fully miniaturize. The goal of Zhong Lin Wang, a materials scientist at Georgia Tech, is to bring power to the nano world with minuscule generators that take advantage of piezoelectricity. If he succeeds, biological

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Technology Review: March/April 2009

The 10 Emerging Technologies of 2009

Technology Review presents its annual list of 10 technologies that could change the way we live.

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Piezoelectric nanogenerator

- Fundamental mechnism
- DC nanogenerators
- Fiber based nanogenerators
- Muscle driven nanogenerators
- Hybrid cell

Nano-Piezotronics

- Piezoelectric transistor
- Piezoelectric diode
- Piezoelectric force sensor/trigger