

Top emerging technologies: Nanogenerators and nanopiezotronics

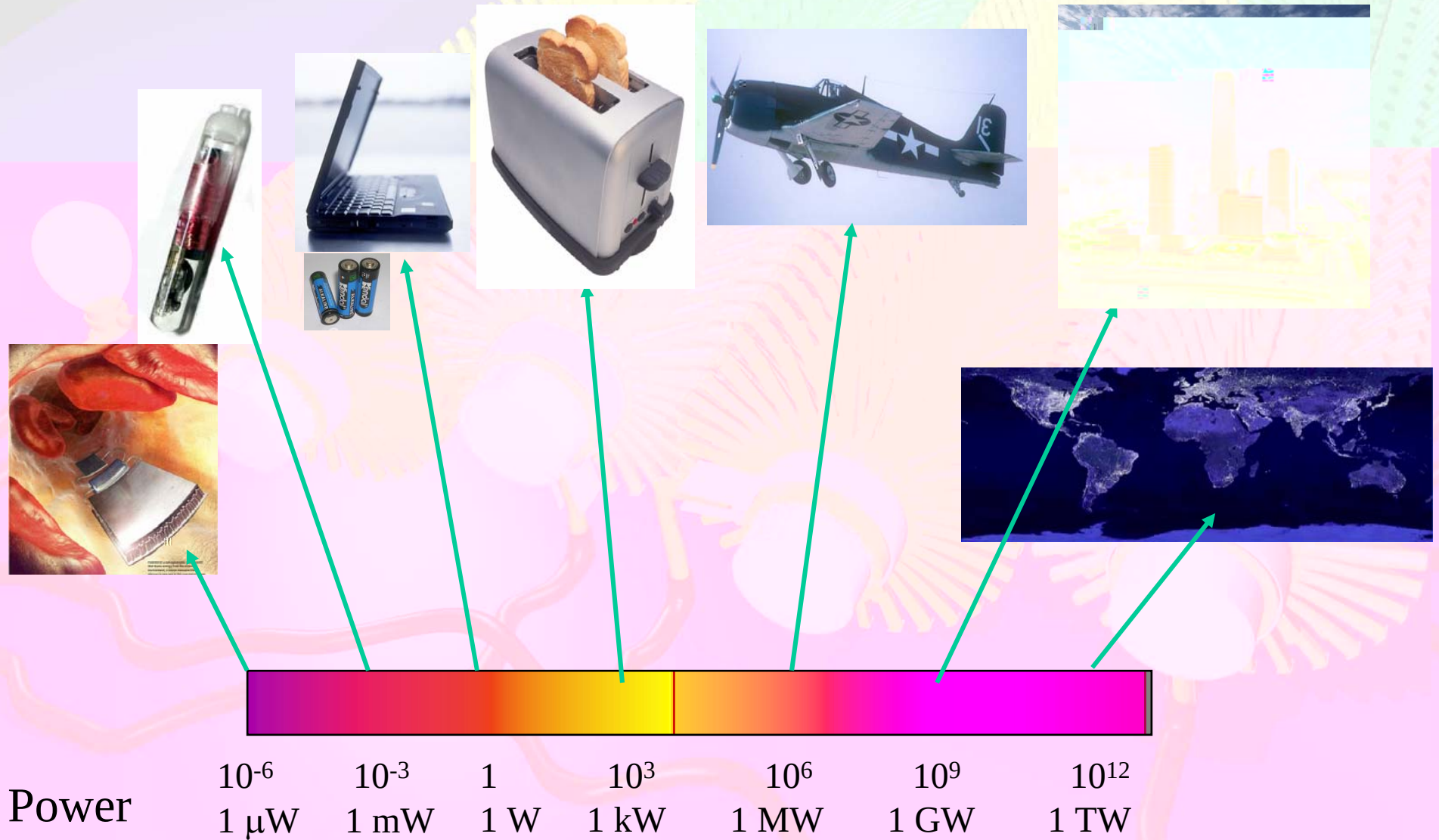
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www.nanoscience.gatech.edu/zlwang**

Research supported by DARPA, NASA, NSF, DOE

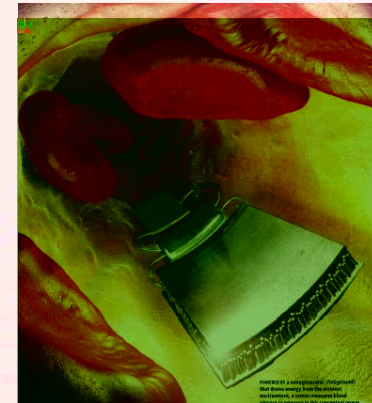
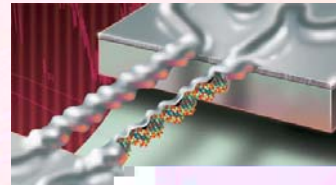
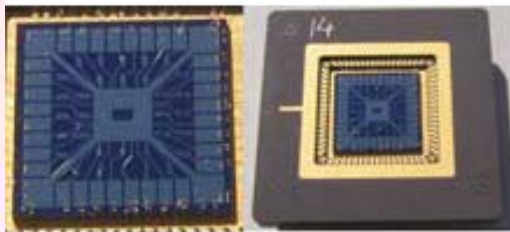
Magnitude of power scale



Energy Sources for Micro/Nanorobots

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

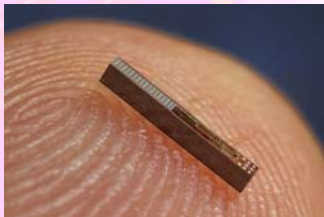
Energy Harvesting Methods for Micro/Nano-Devices



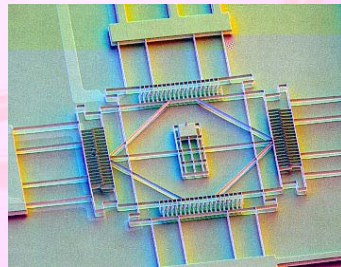
Nanosensors

Nanodevices

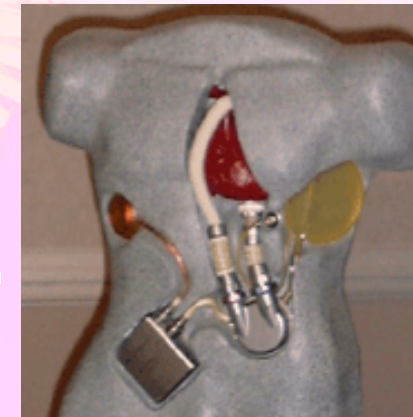
Biosensor



Micro-robot

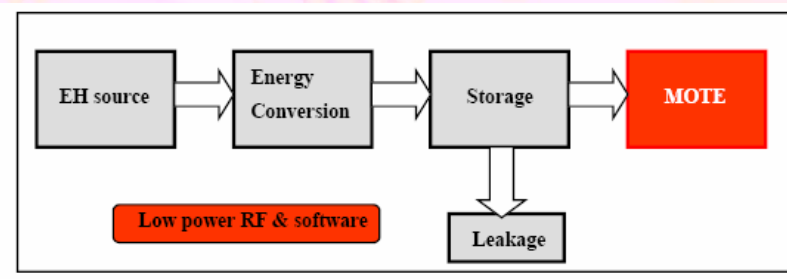


MEMS



Medical devices

Size and magnitude matters!

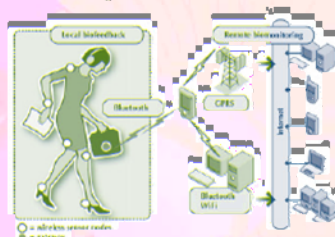


Wireless health and environmental monitoring

A Future World Without Batteries or Cords

Low data rate, low duty cycle, ultra-low power

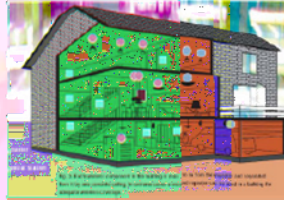
Body Area Network



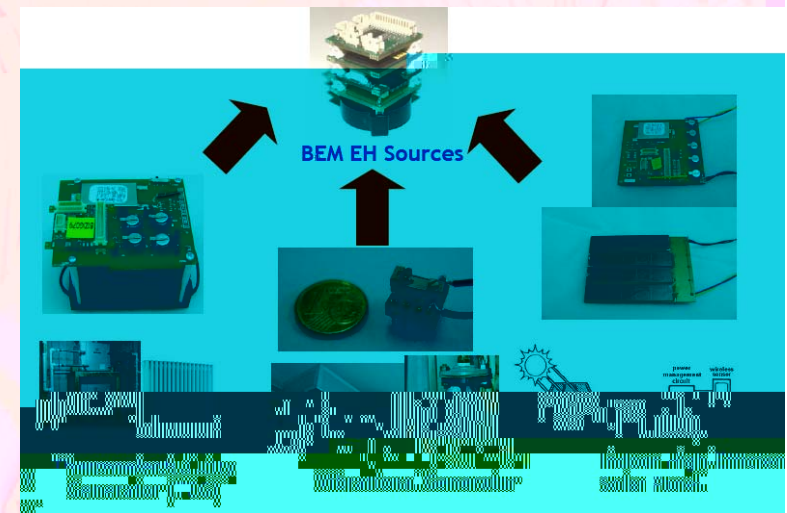
Structure Health monitoring



Smart building



Energy harvesting





January, 2008

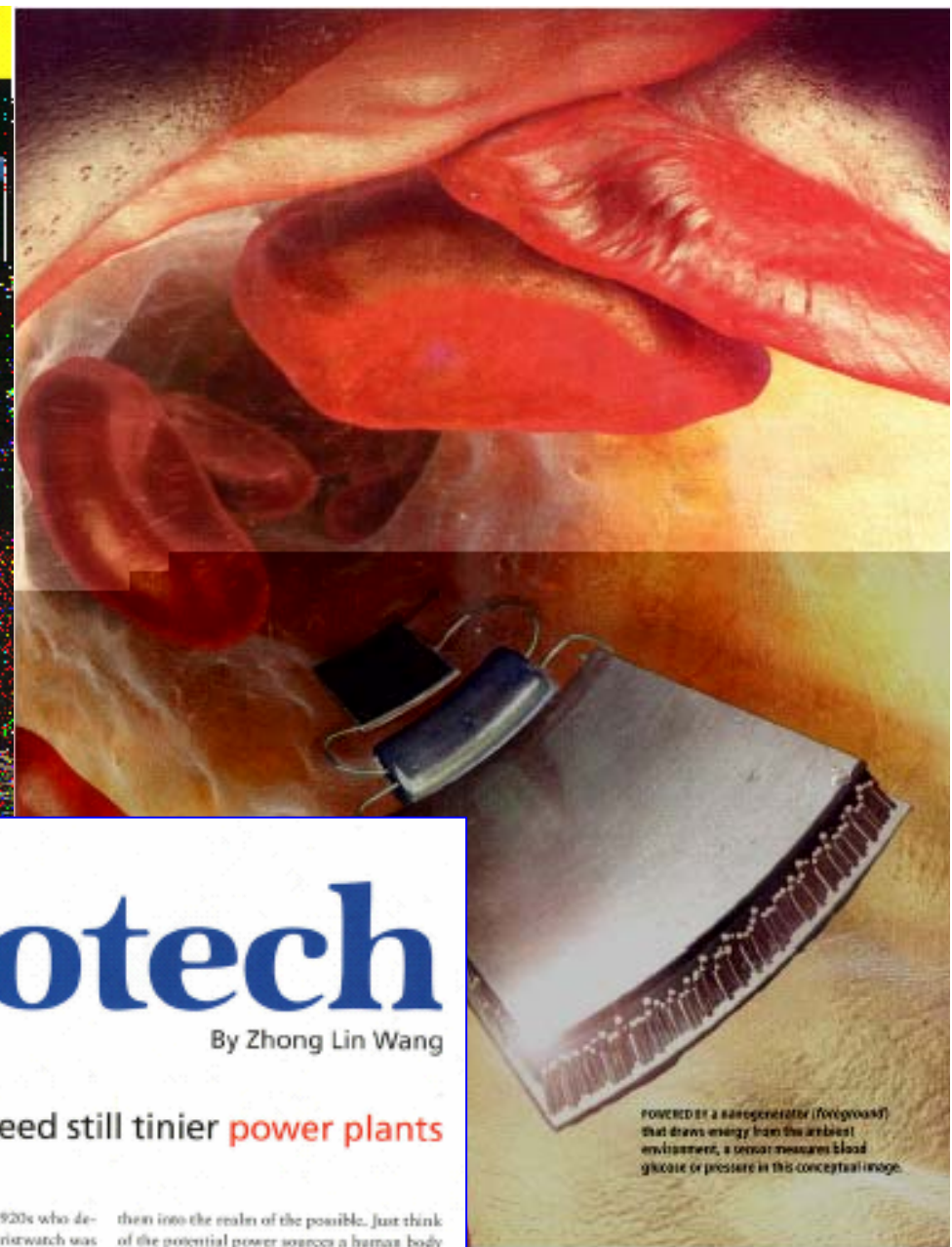
Self-Powered Nanotech

By Zhong Lin Wang

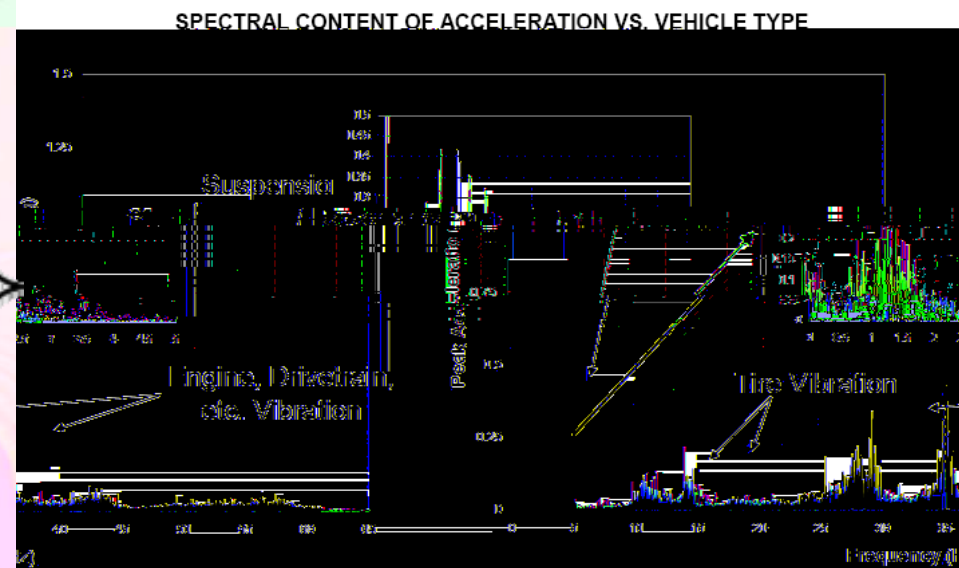
Nanosize machines need still tinier power plants

The watchmaker in the 1920s who devised the self-winding wristwatch was on to a great idea: mechanically harvesting energy. Now, with a nanoscale wristwatch, we can make something like that.

then into the realm of the possible. Just think of the potential power sources a human body provides: mechanical energy, heat energy, vibration, and so on. We have already shown that a nanoscale wristwatch can harvest energy from the ambient environment, a sensor measures blood glucose or pressure in this conceptual image.



Mechanical energy harvesting

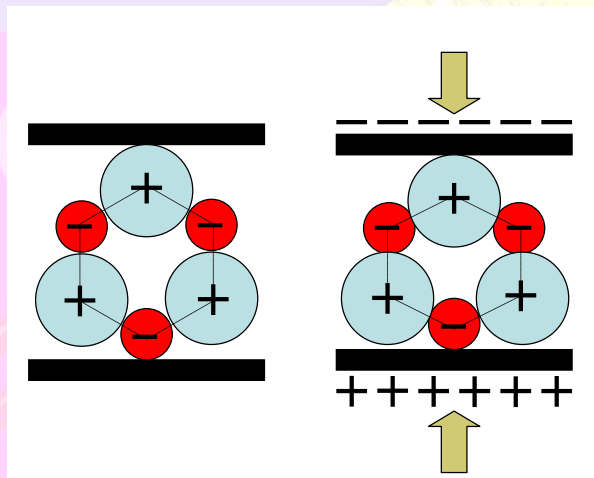


Characteristics:

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

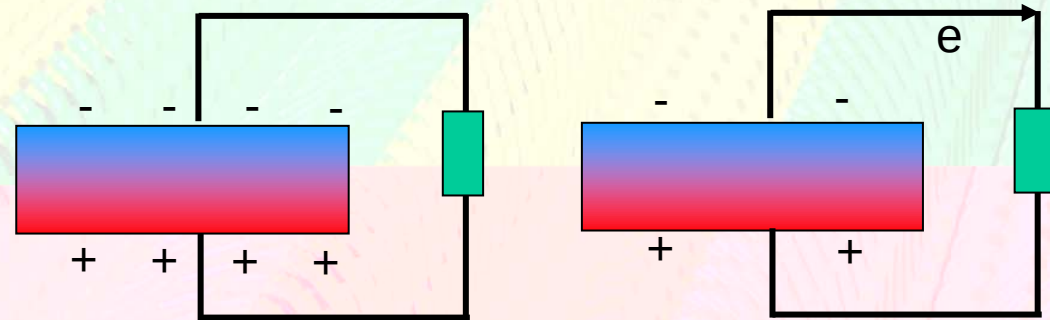
Energy harvesting – a new industry!

Piezoelectric effect

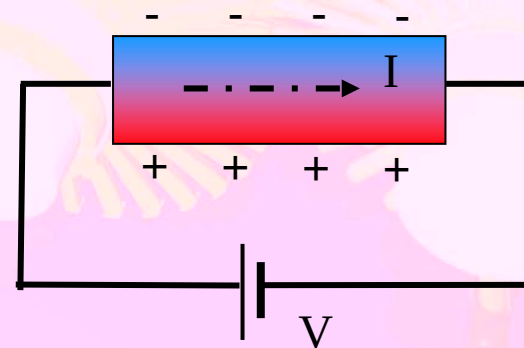


- Piezoelectric potential;
- Lower doping;
- Partial screening effect

Electricity generation



Piezotronics

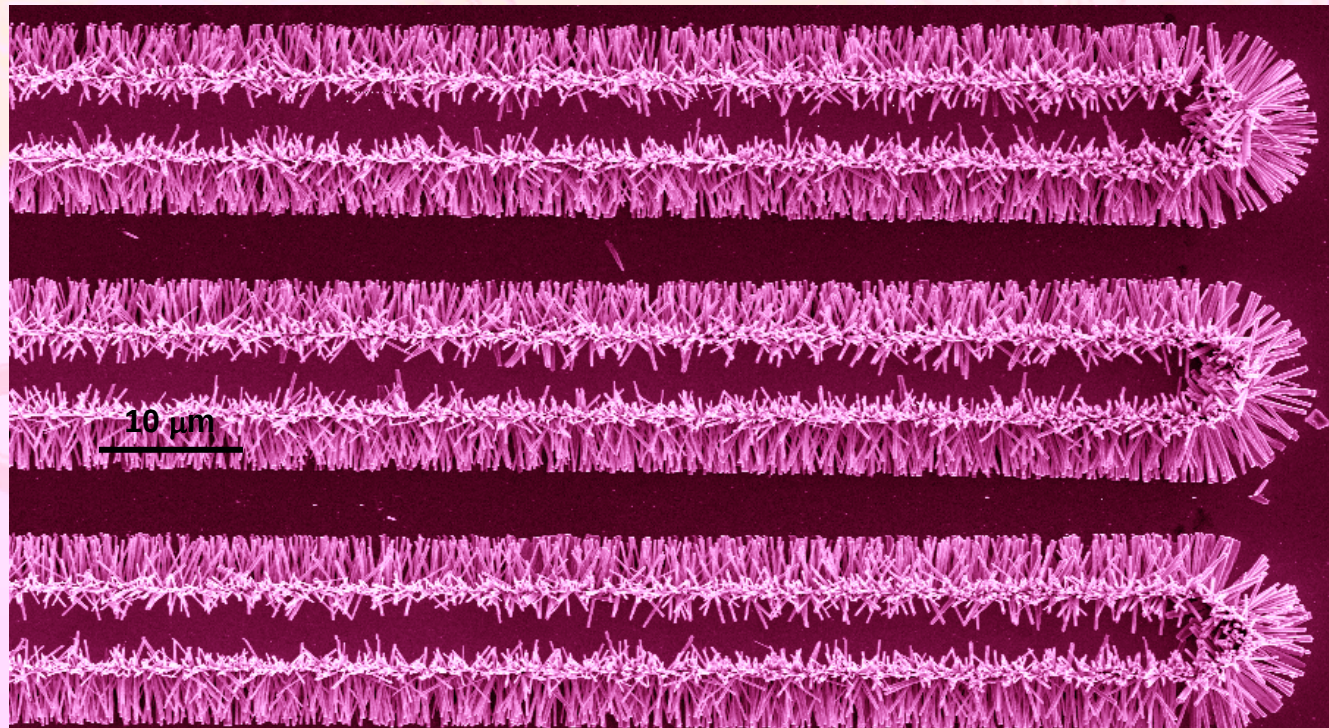
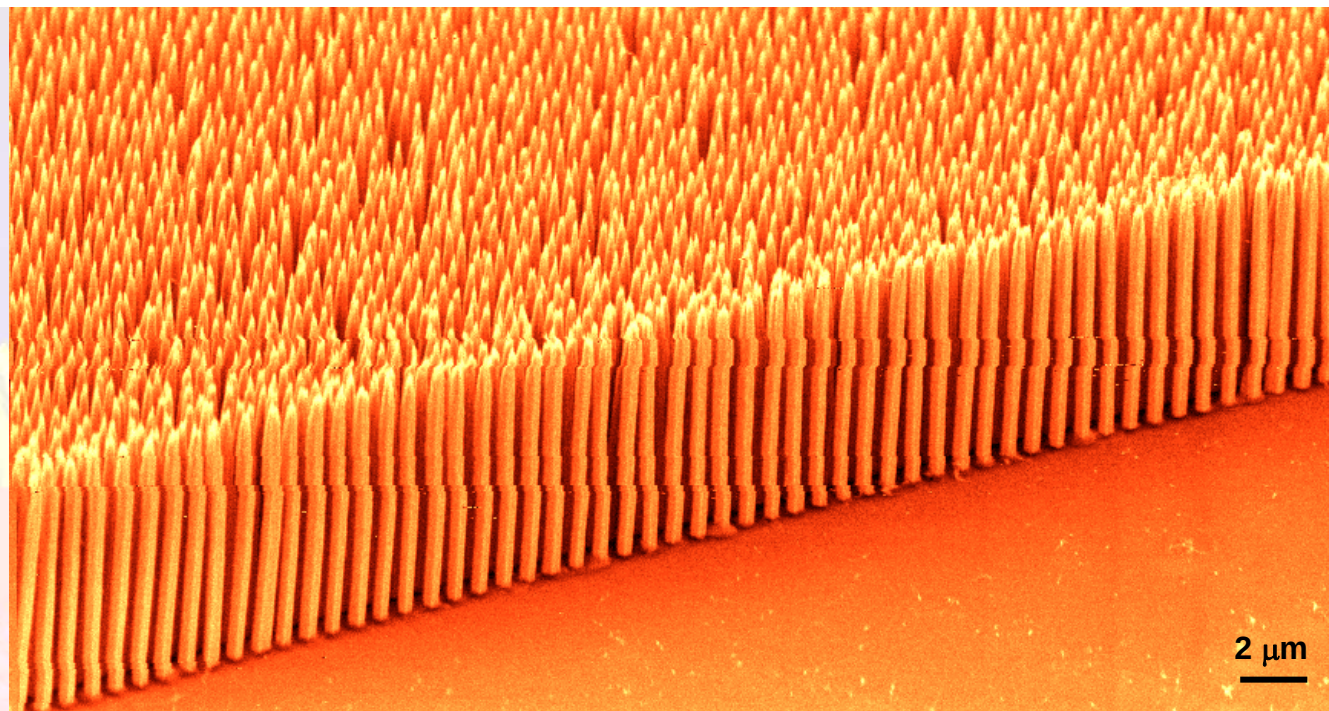


Controlled growth of ZnO nanowires

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

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

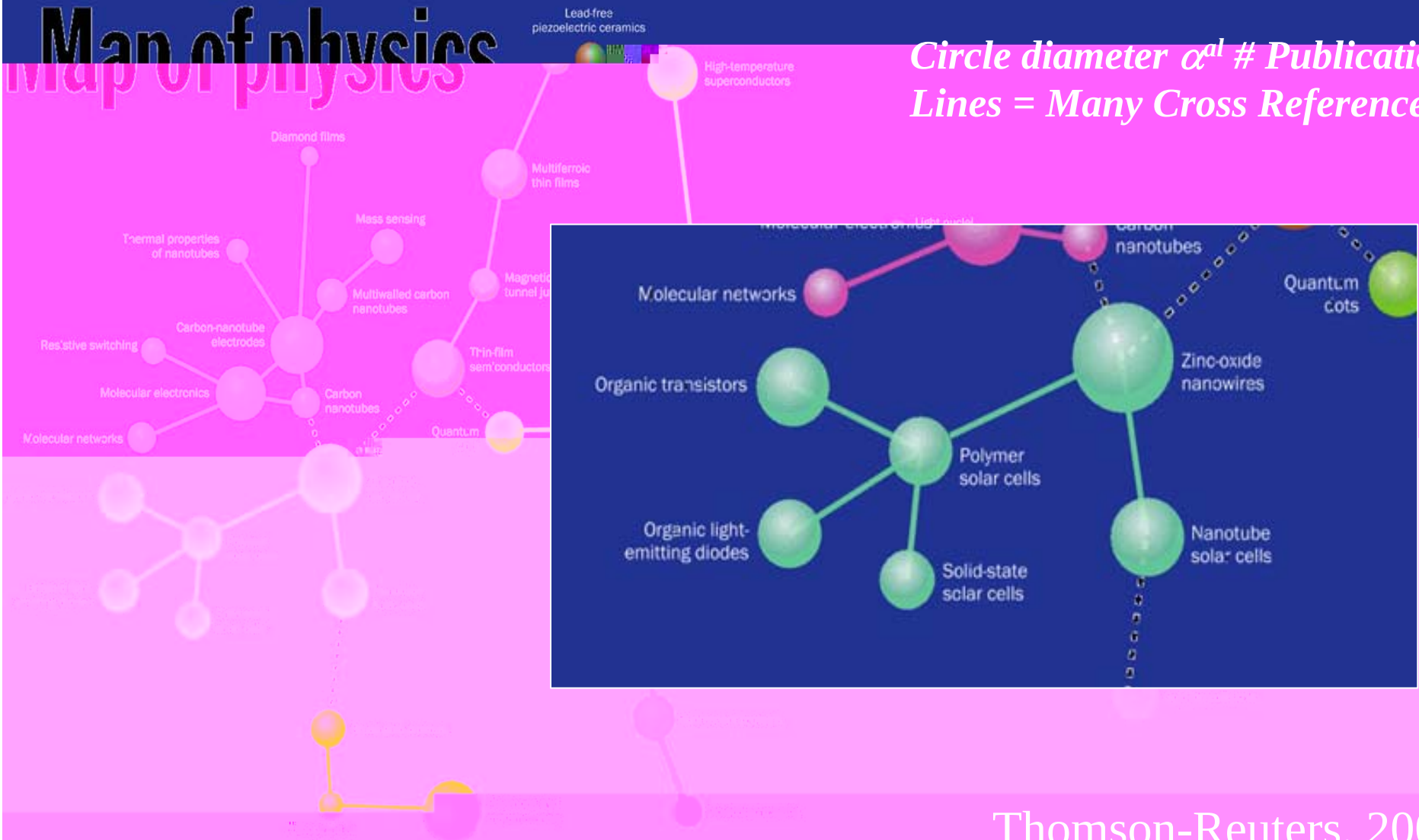
$\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and (HMTA)





Man of physics

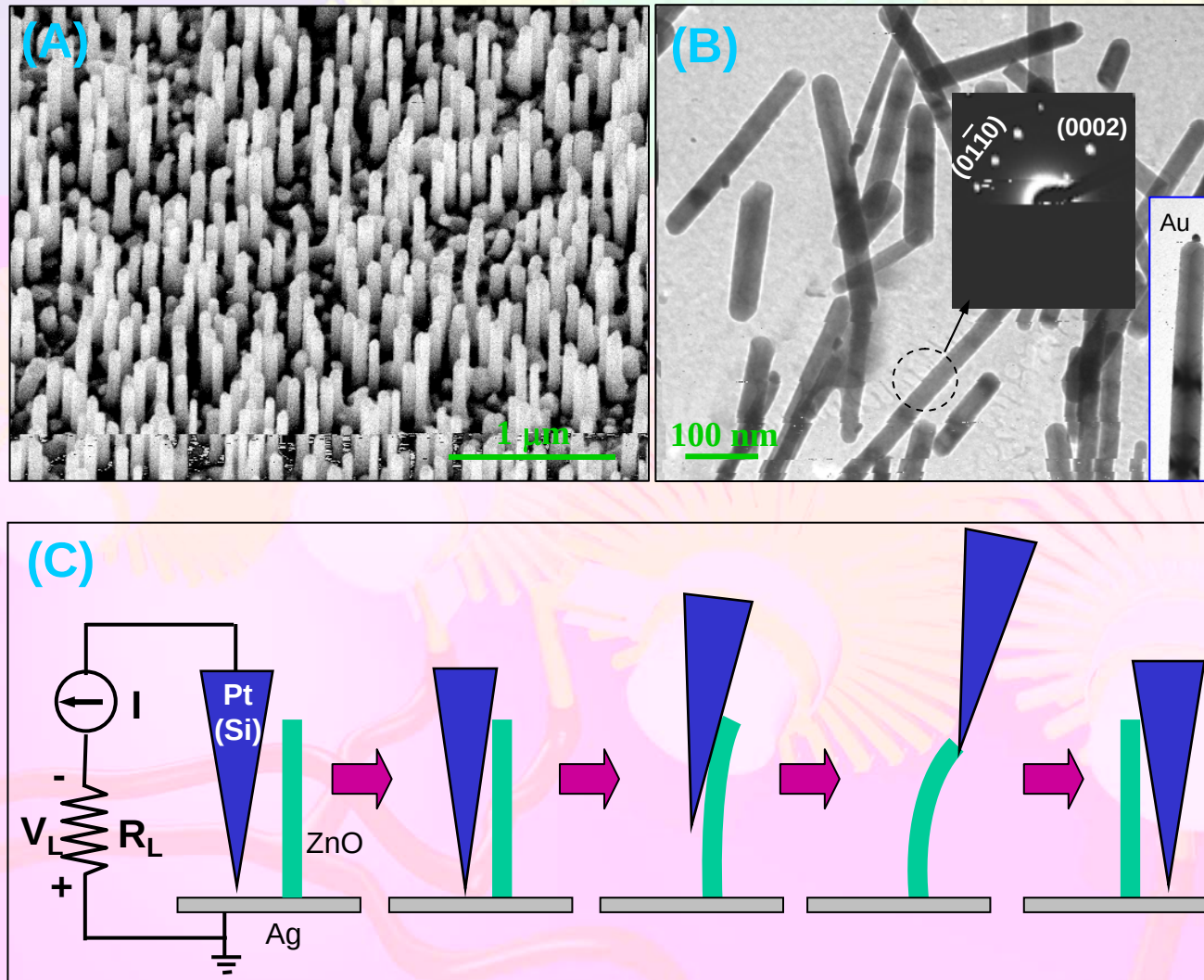
Circle diameter $\propto$ # Publications
Lines = Many Cross References

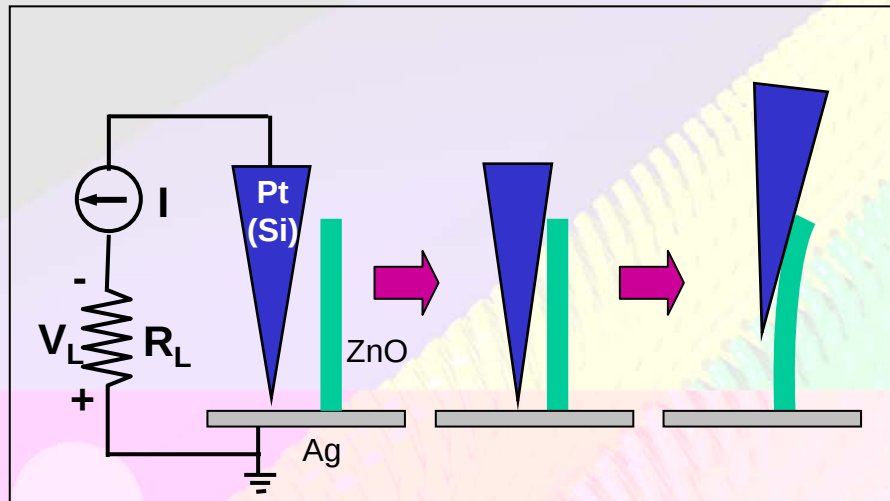


Thomson-Reuters, 2008

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.

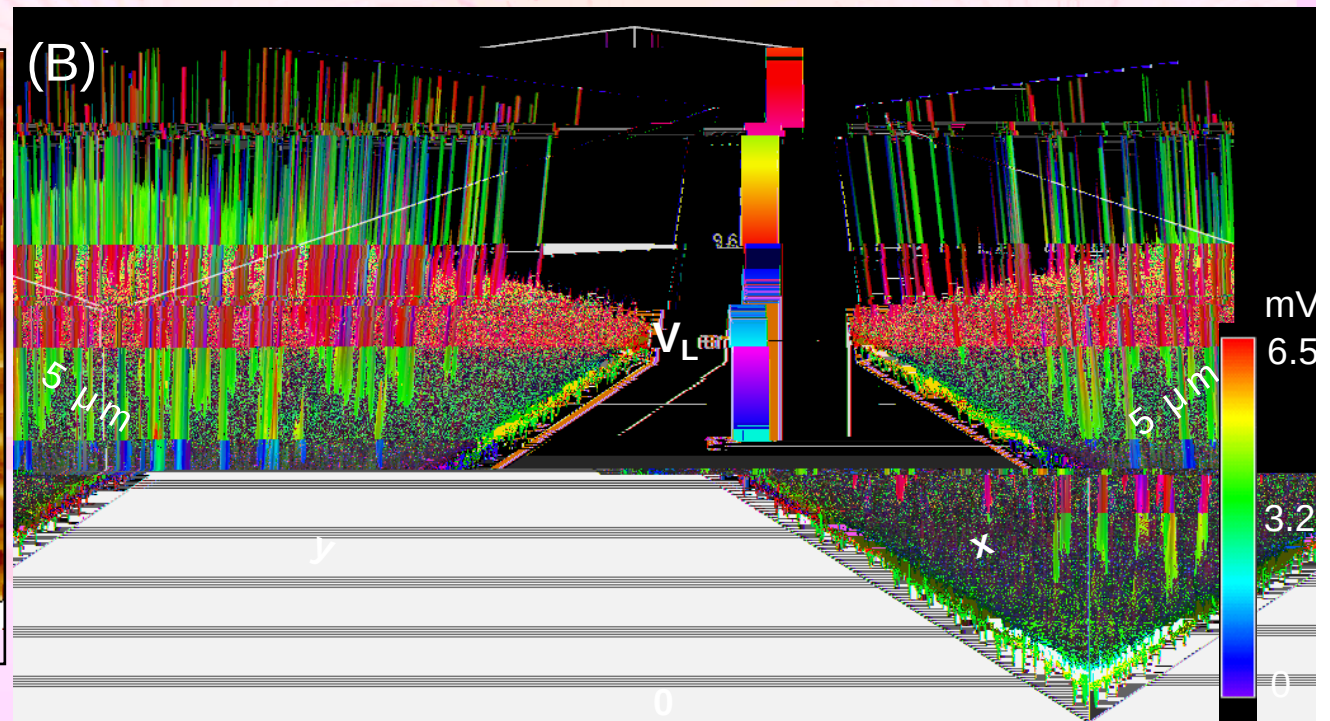
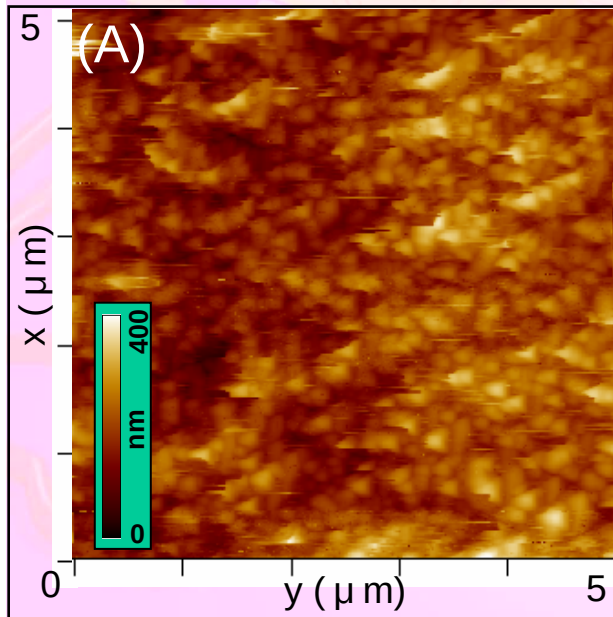
Converting mechanical energy into electricity energy by piezoelectric ZnO nanowires



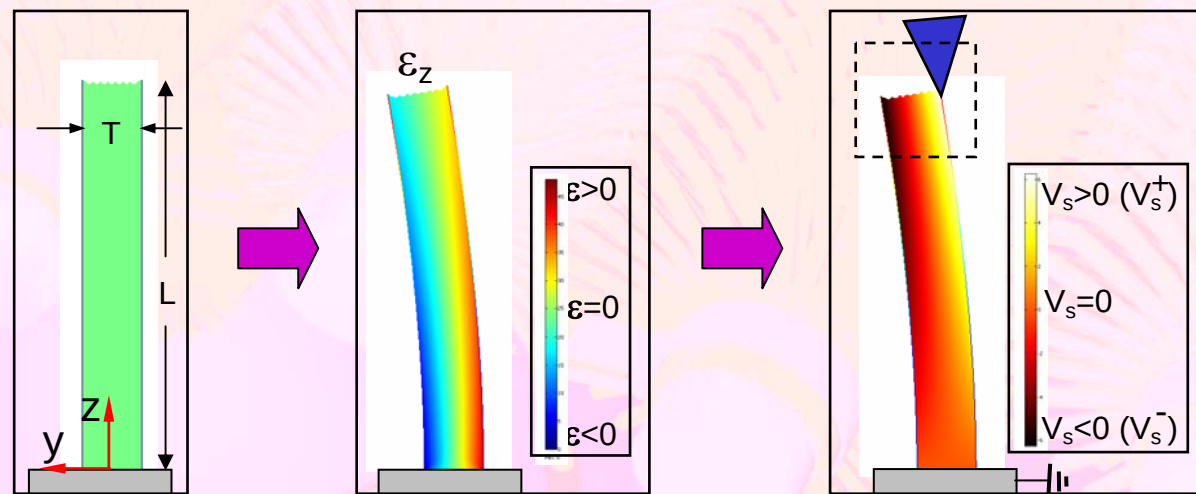


Piezo-electric nano-generator using ZnO nanowires

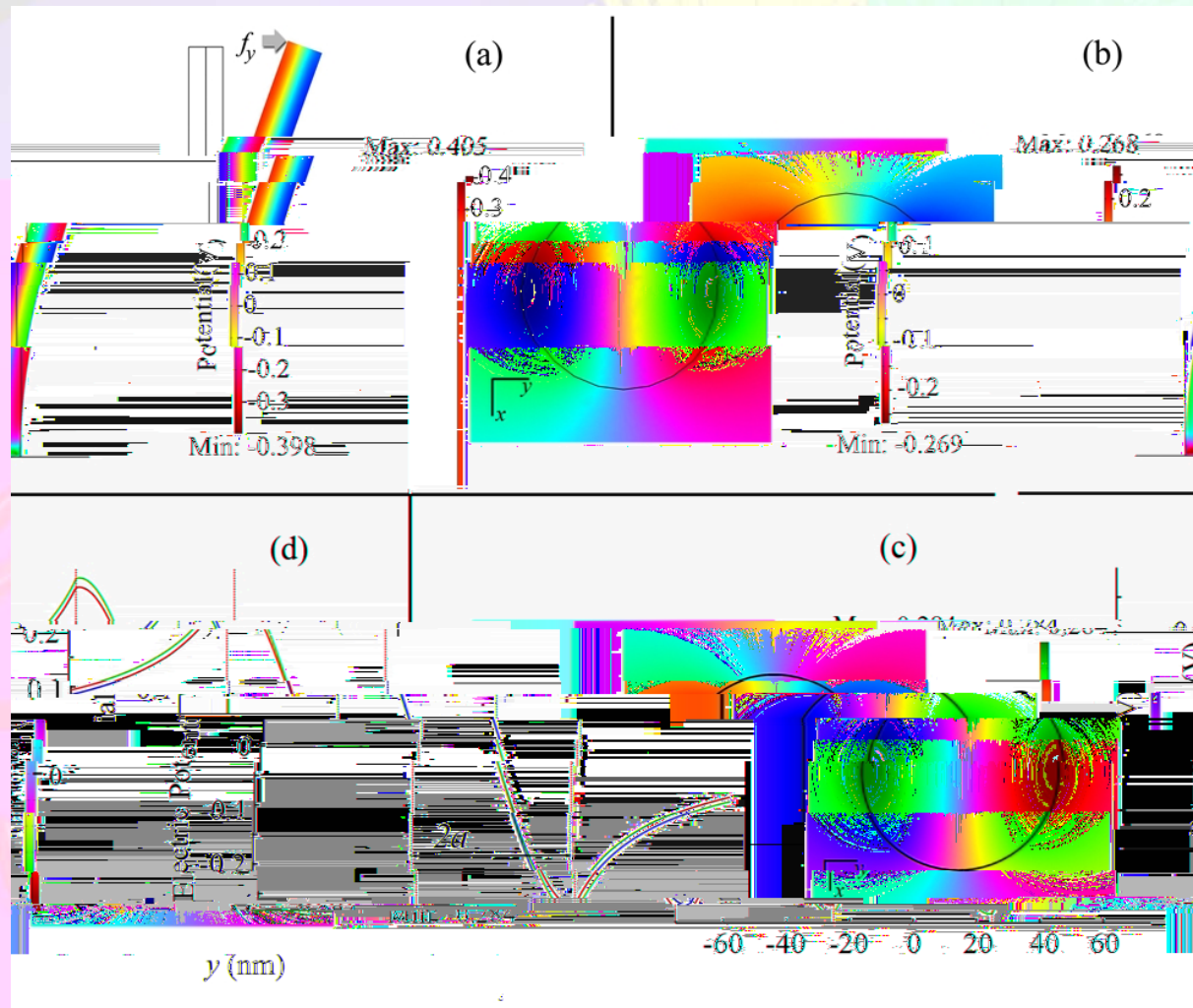
Wang and Song, Science 312 (2006) 242.



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



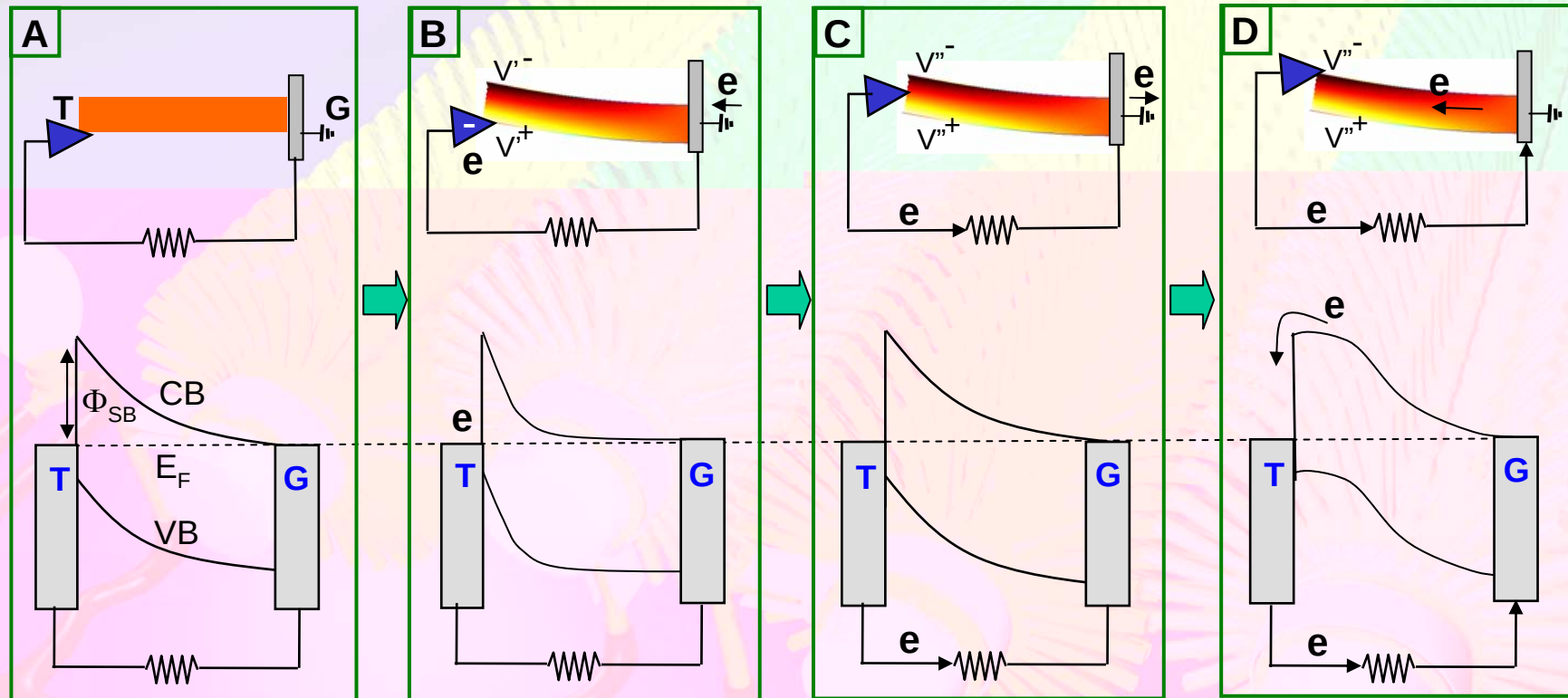
Piezoelectric Potential, $a = 25\text{nm}$



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

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

Working principle of piezoelectric nanogenerator

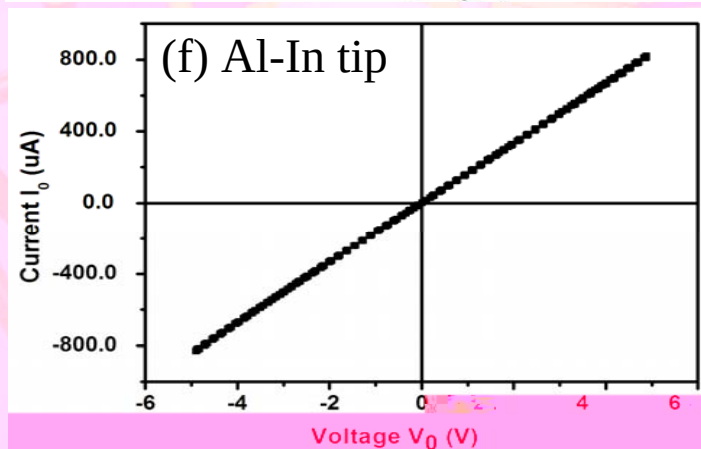
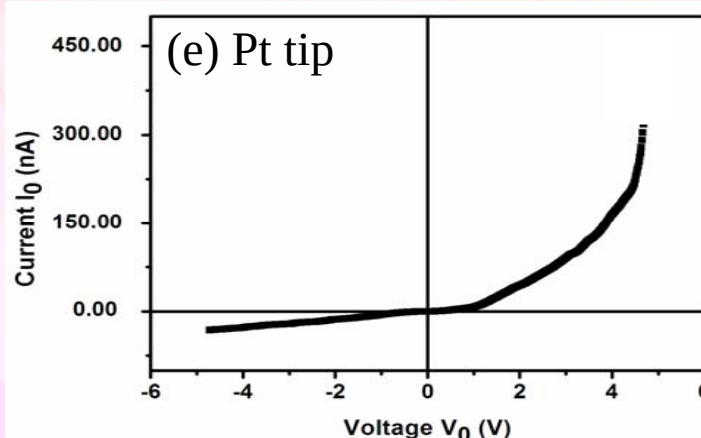
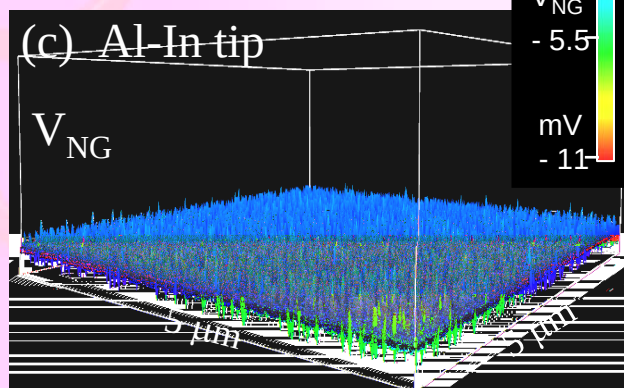
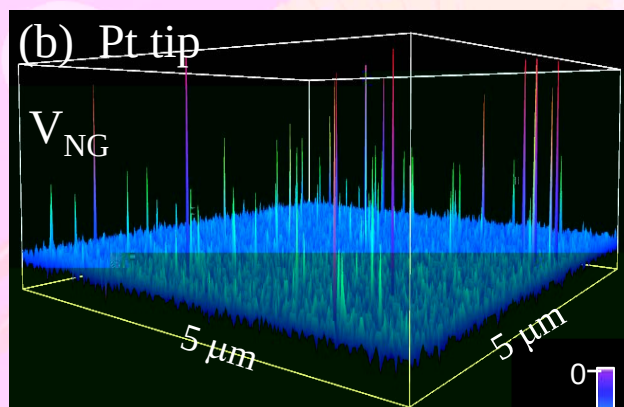
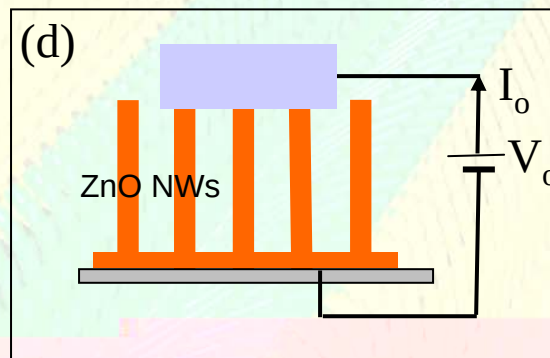
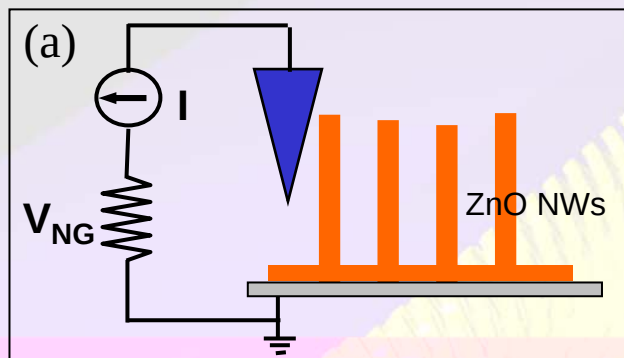


- Piezoelectric charges are ionic charges from the polarization of atoms;
- Piezoelectric charges cannot be quickly depleted by free electrons, although screening is possible;
- Piezoelectric potential preserves to tens of seconds if strain is maintained;
- Piezoelectric potential quickly disappears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

Current generation processes:

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

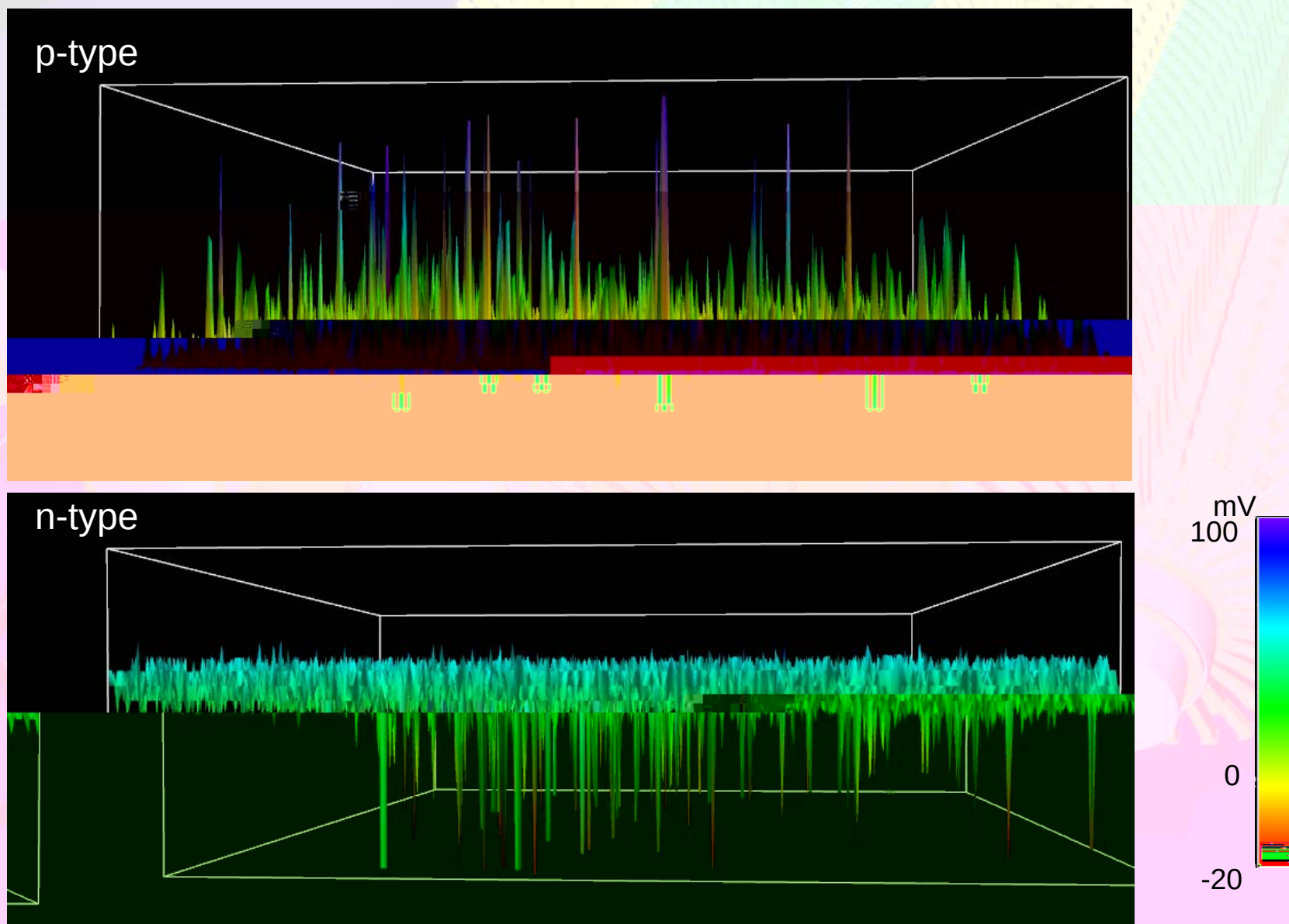
The key role played by Schottky barrier in nanogenerator



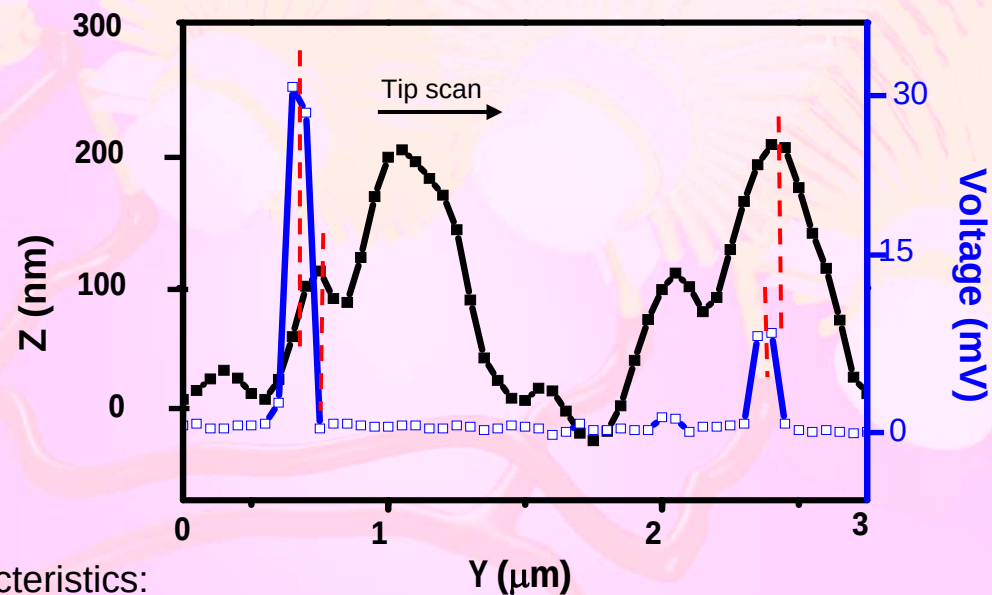
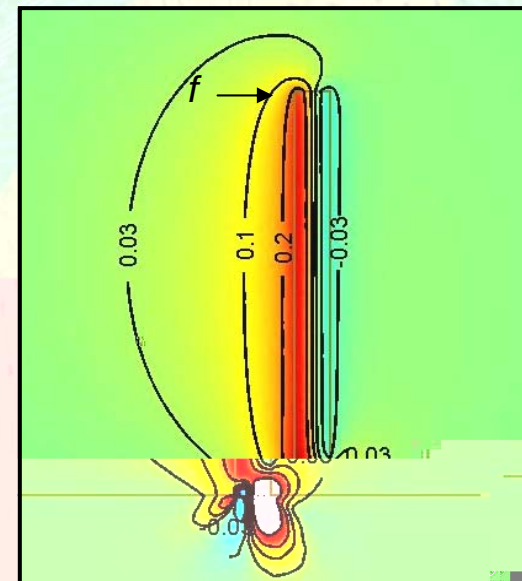
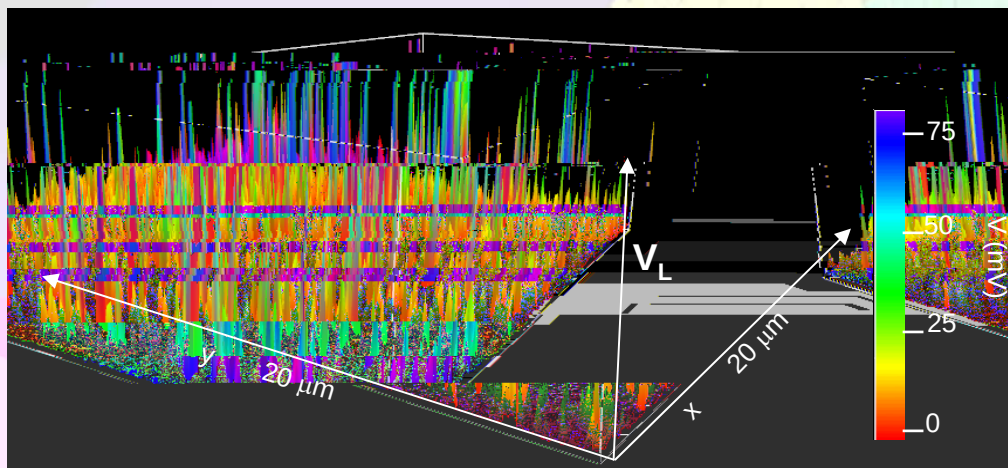
- Schottky barrier is the key for NG:

charge accumulation
charge releasing

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

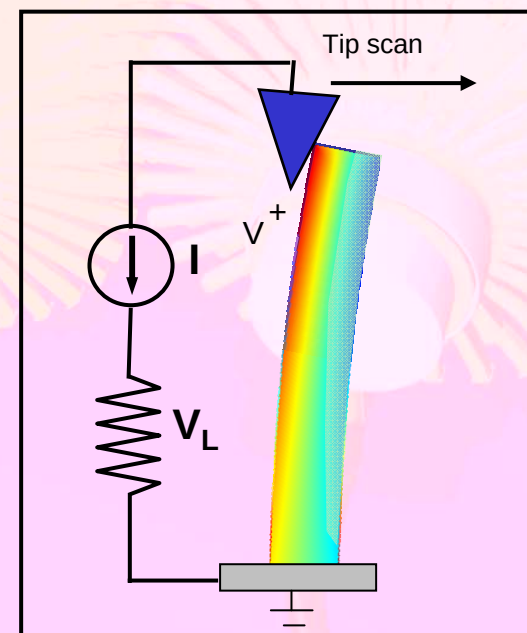


Piezoelectric power generation using the p-type ZnO NW arrays

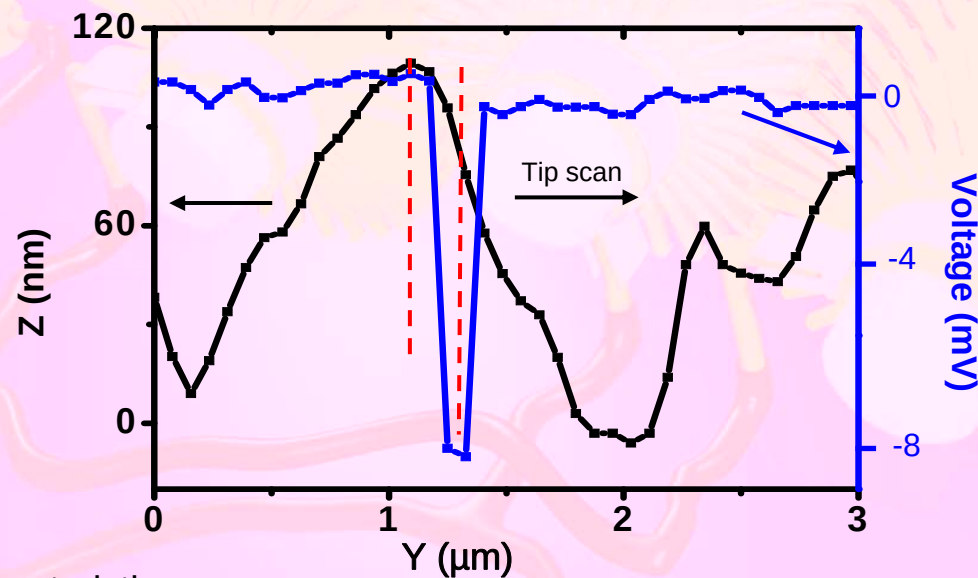
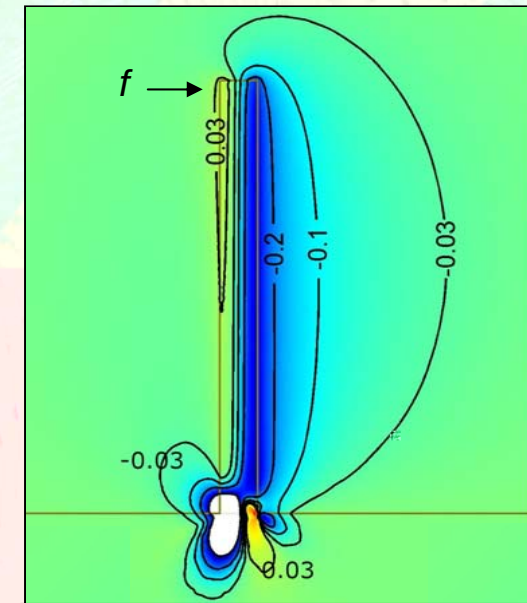
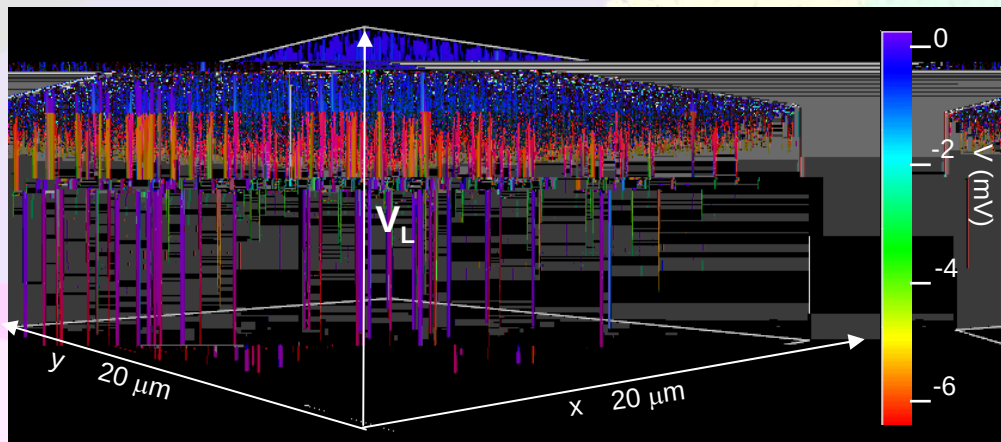


Characteristics:

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

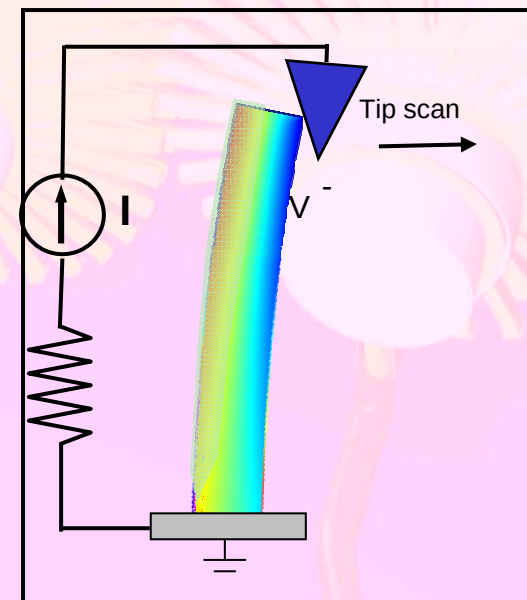


Piezoelectric power generation using the n-type ZnO NW arrays



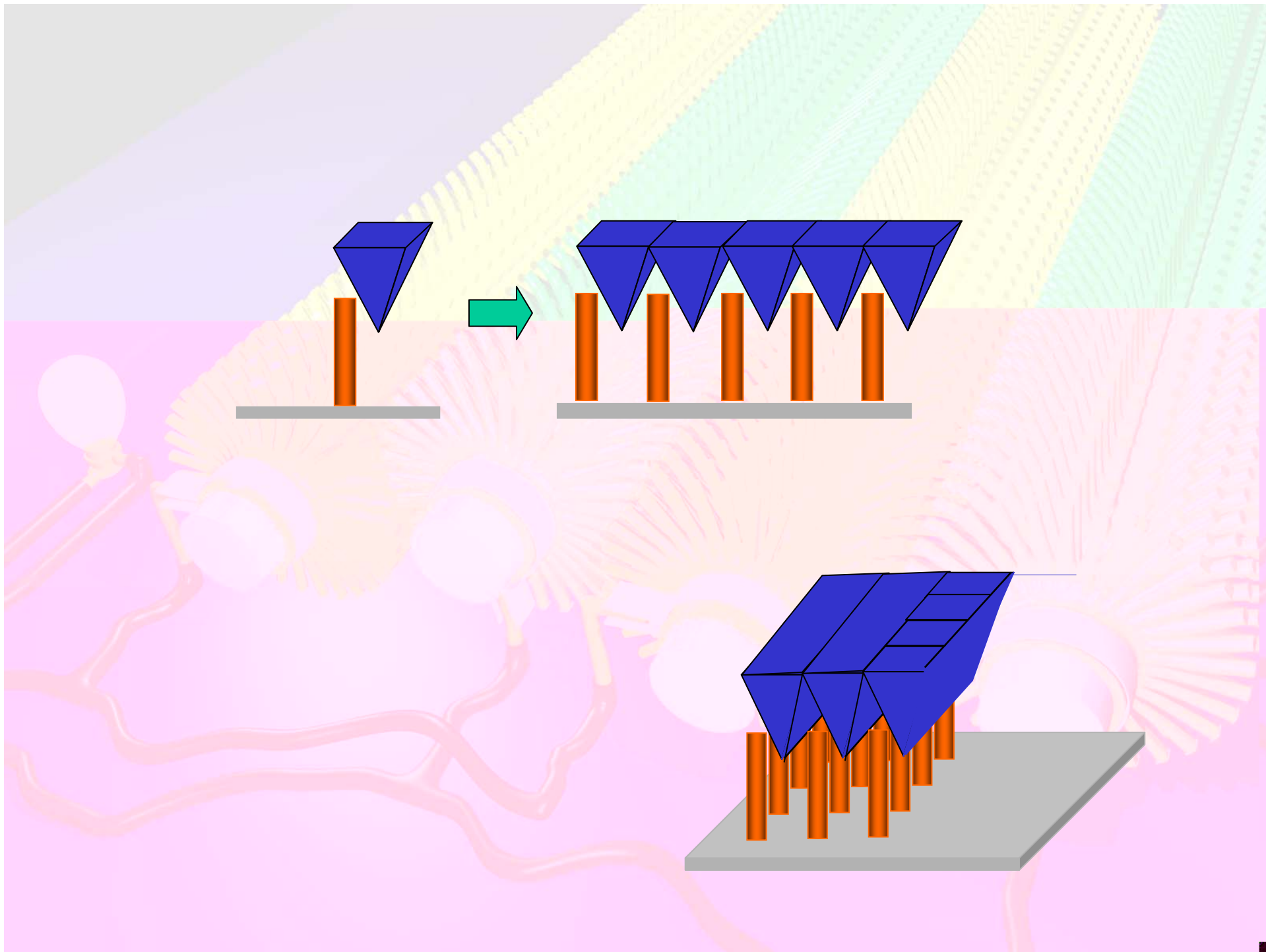
Characteristics:

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



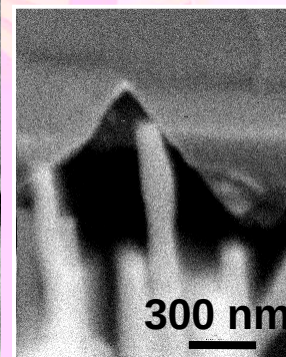
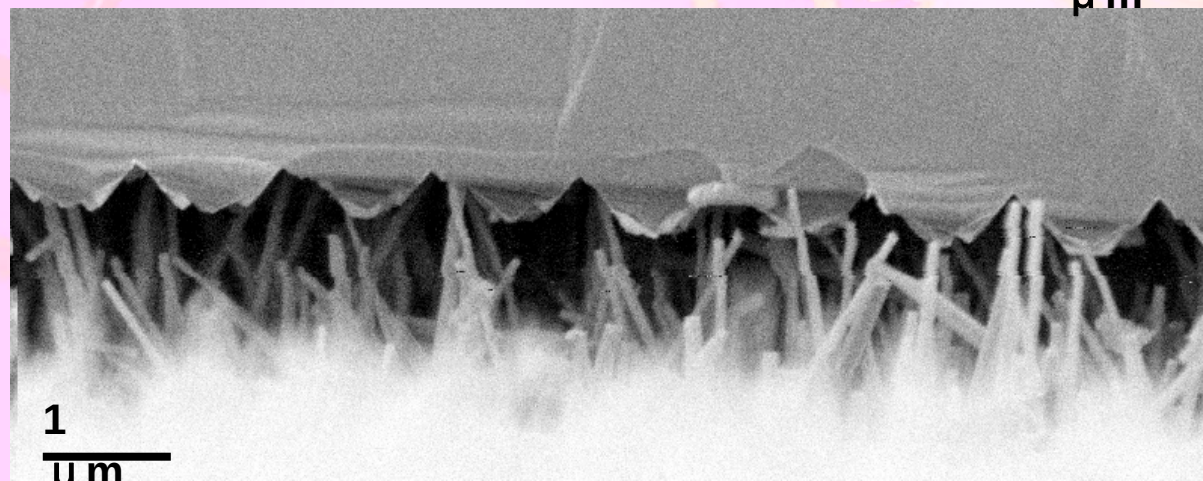
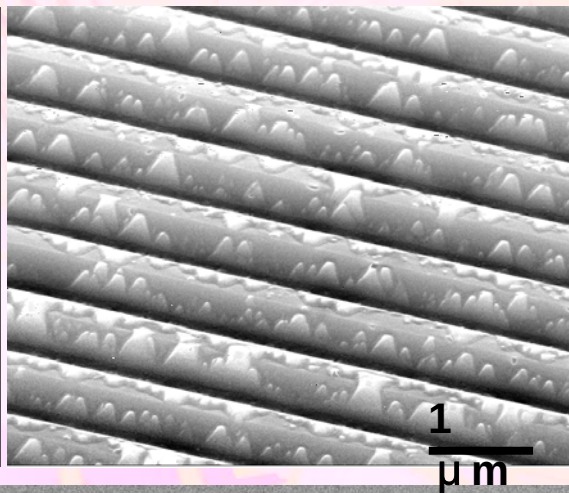
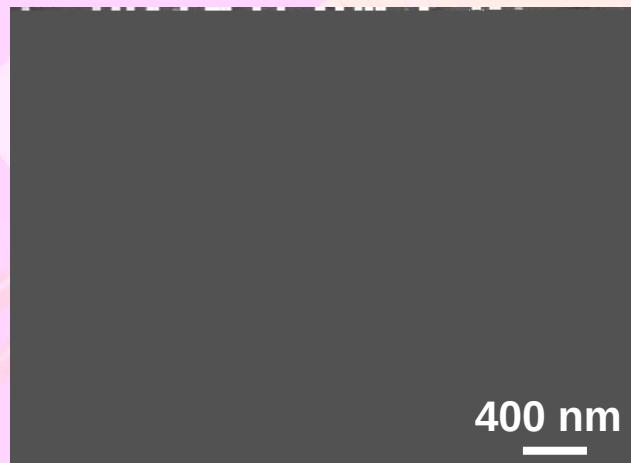
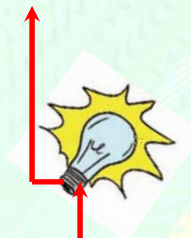
For applications in wireless nanorobotics, remote sensing,
implantable biomedical devices and MEMS
what do we need?

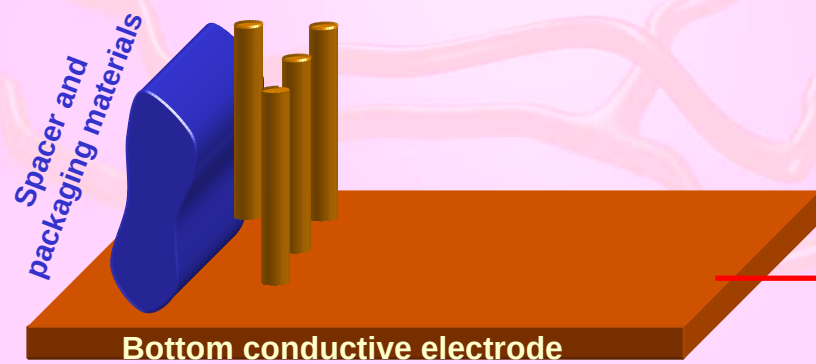
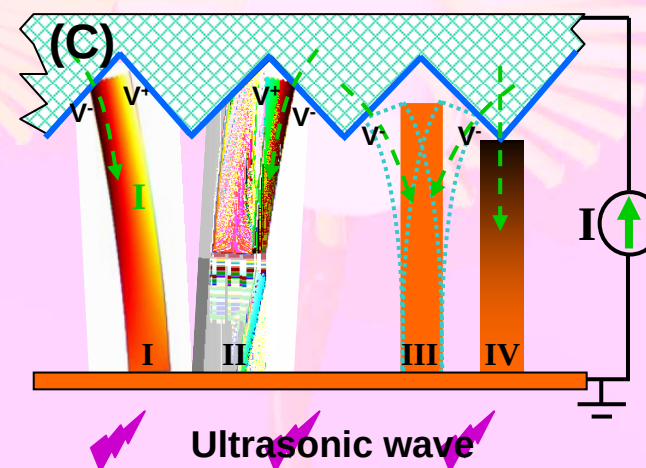
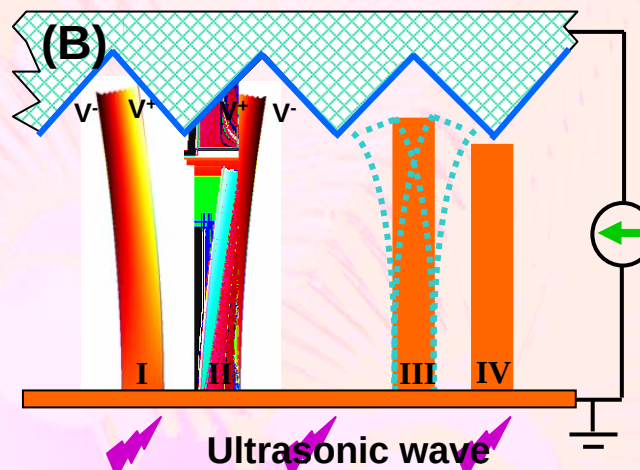
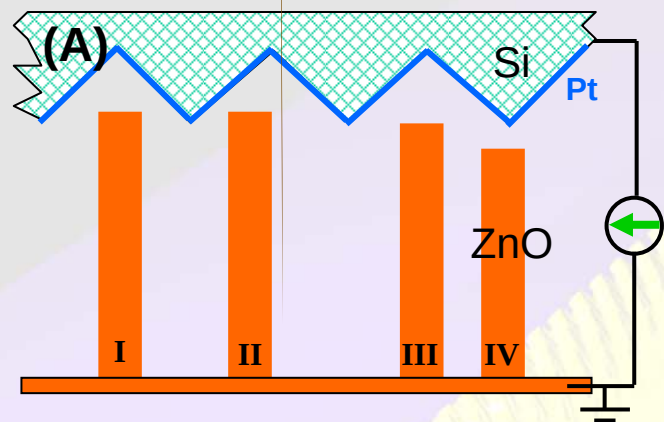
- we must eliminate the use of AFM for making the mechanical deformation of the NWs so that the power generation can be achieved by an adaptable, mobile and cost-effective approach over a larger scale.
- All of the NWs are required to generate electricity simultaneously and continuously, and all the 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.

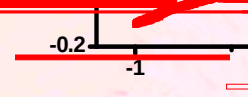
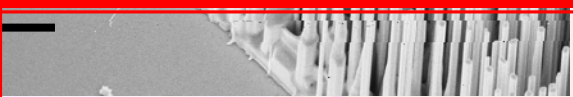
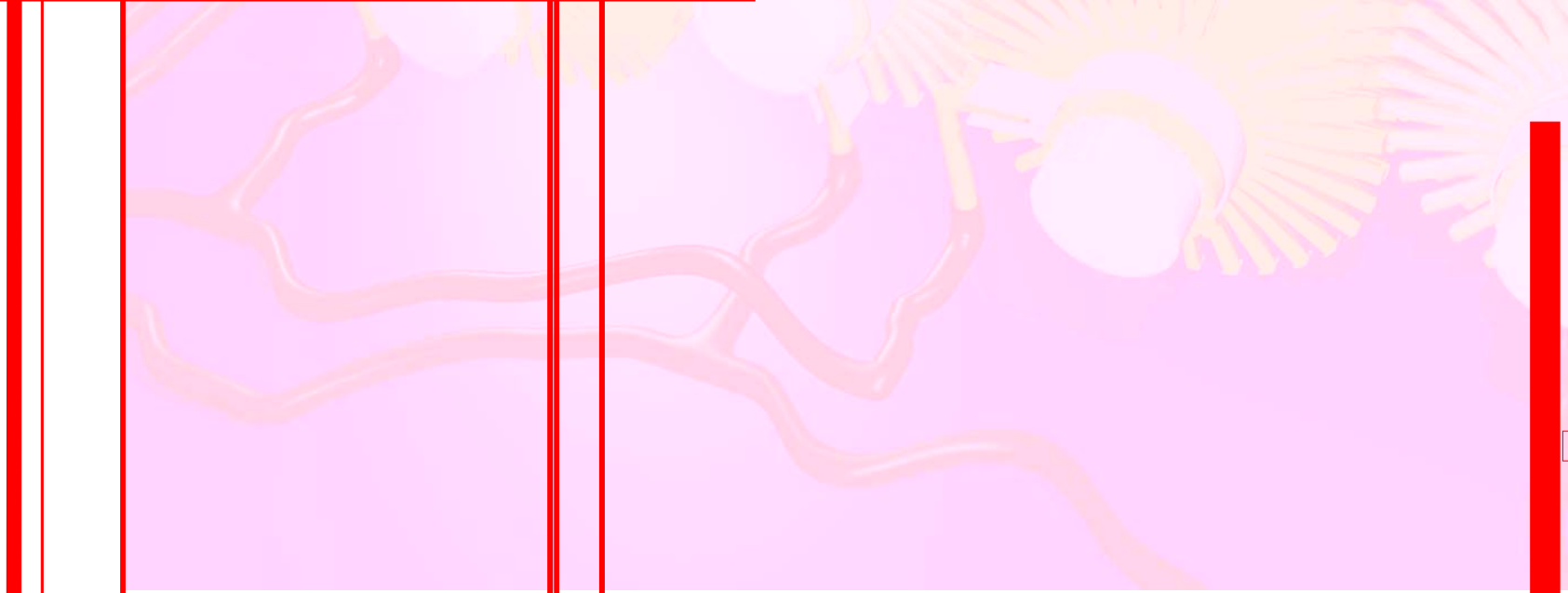
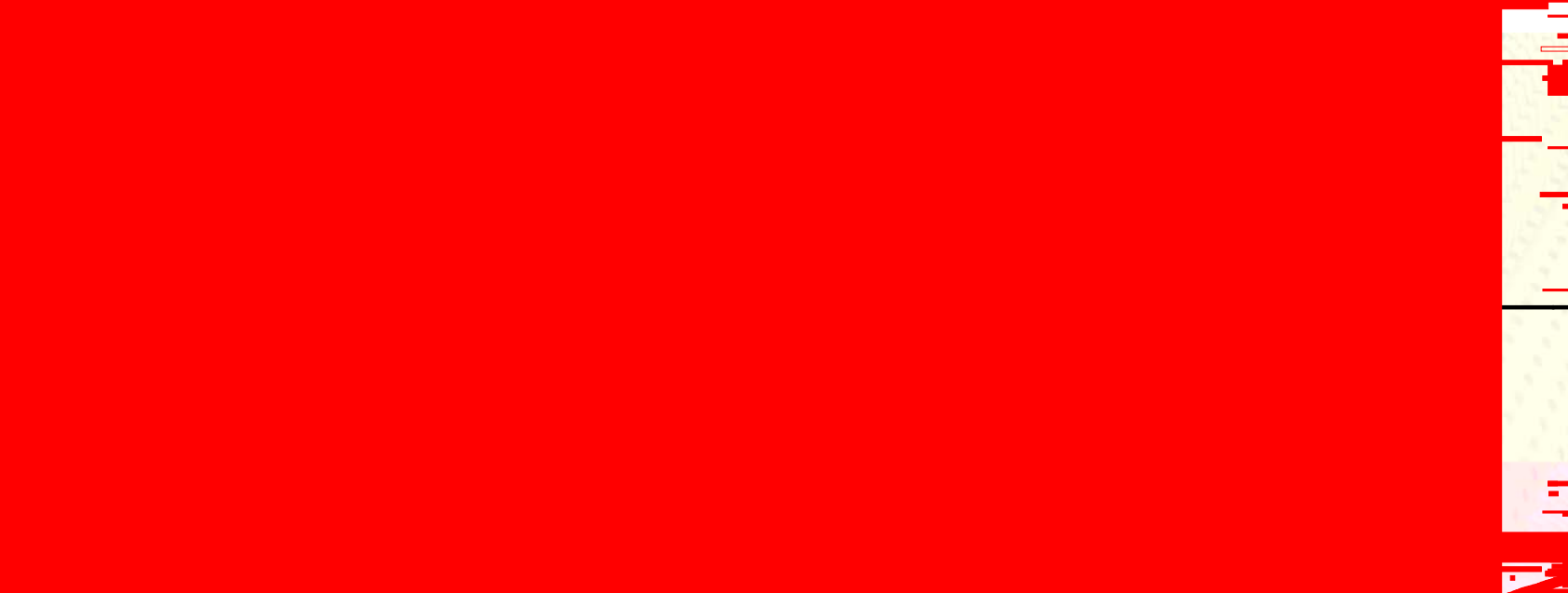


Spacer and
packaging materials

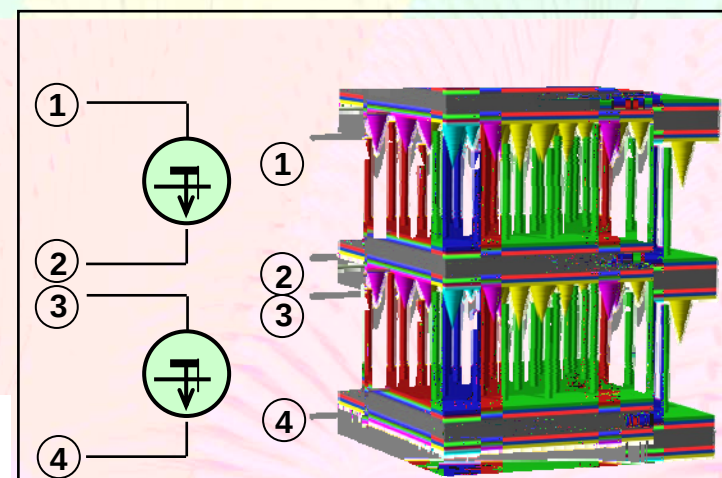
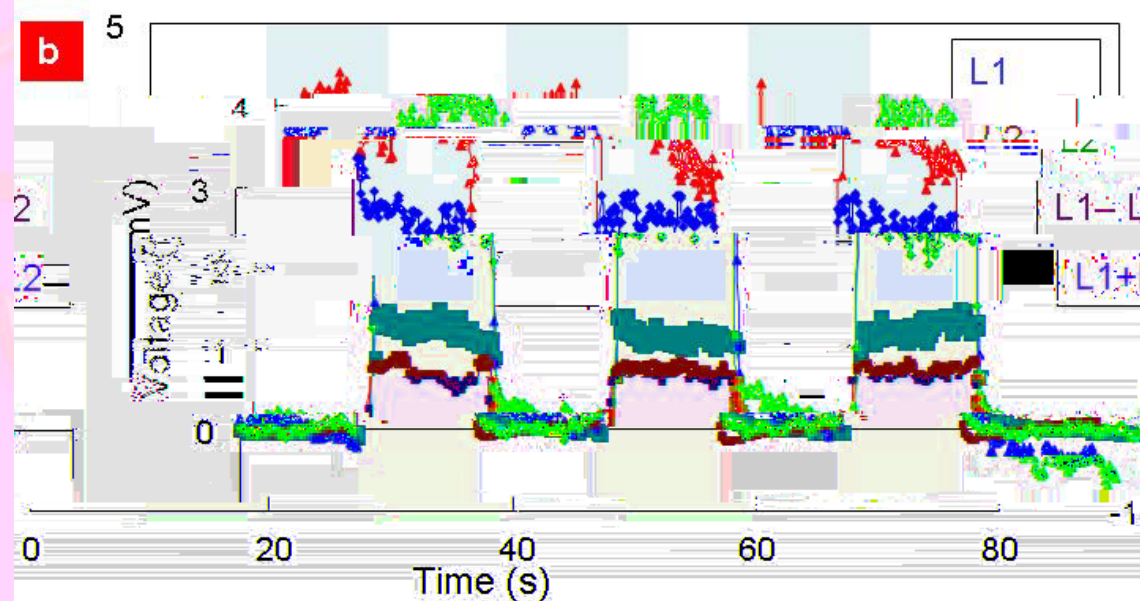
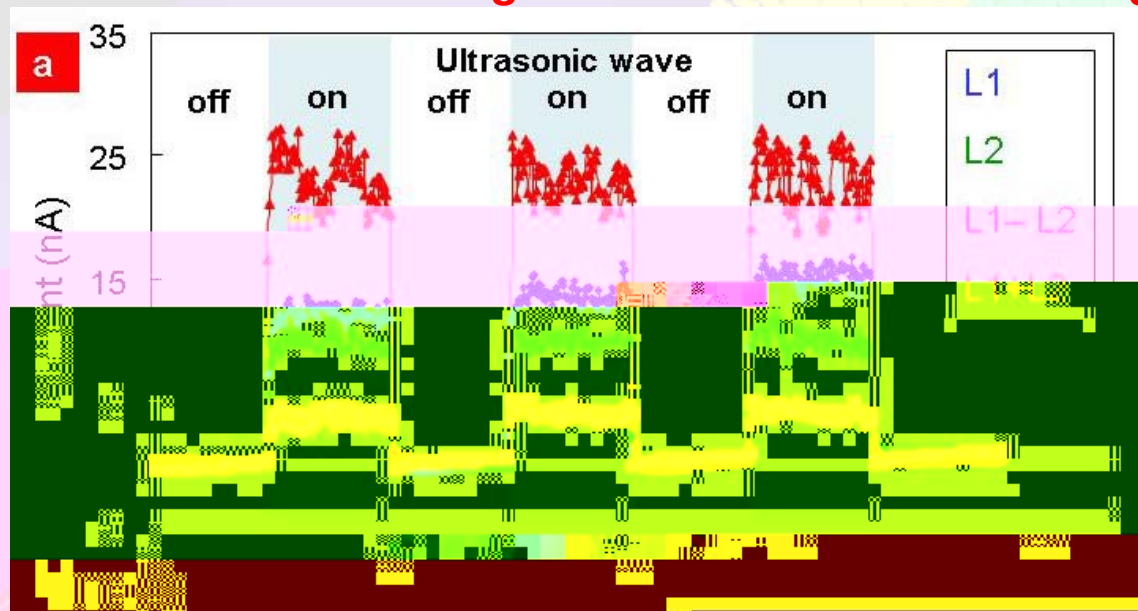
Bottom conductive electrode



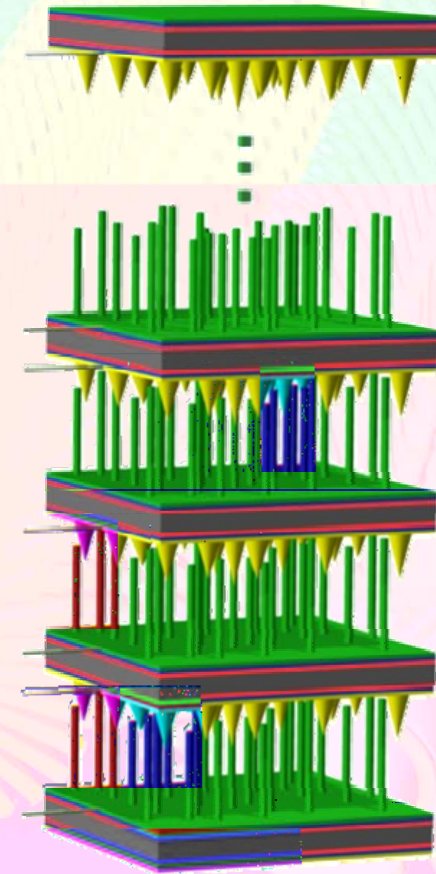
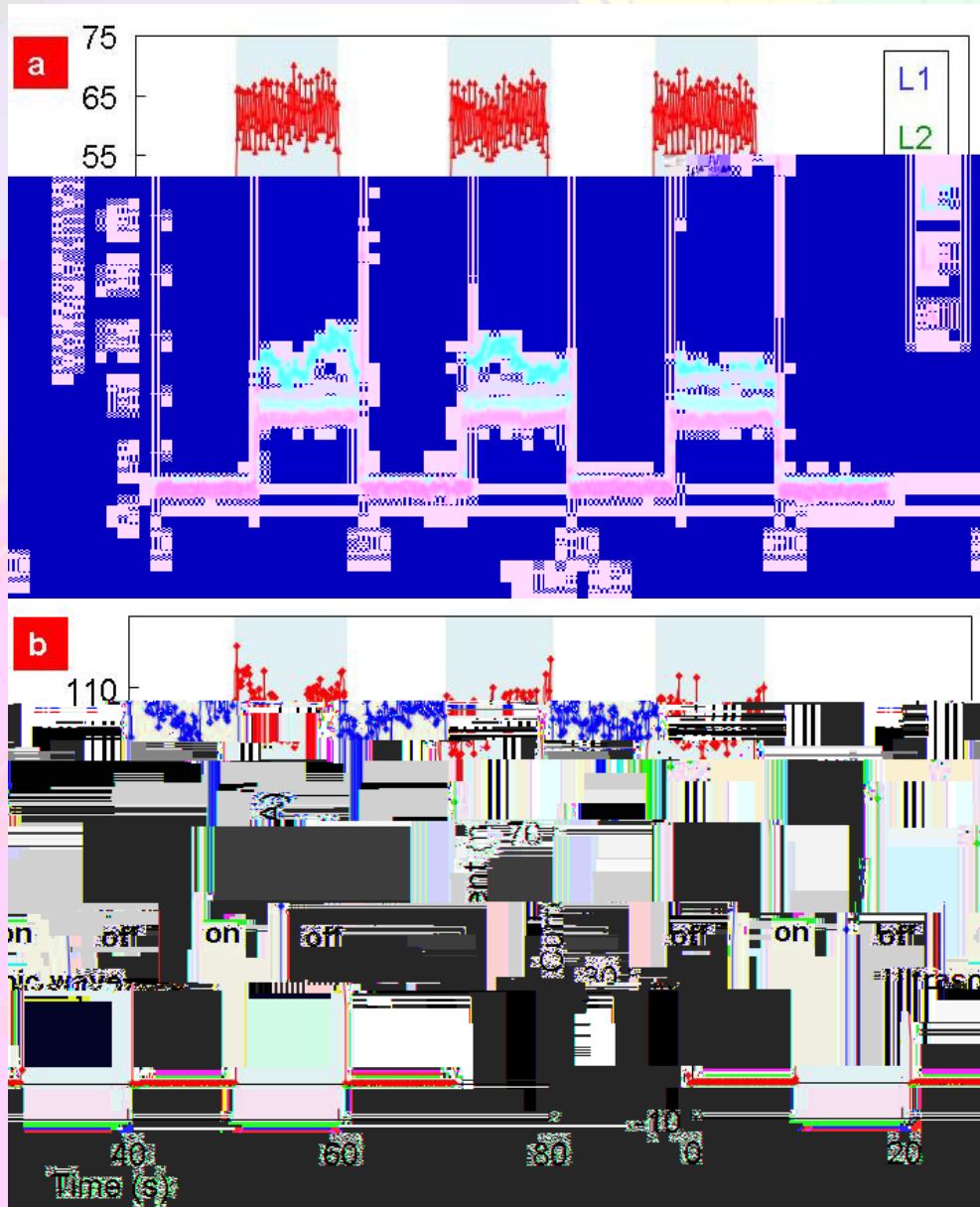




Output current and voltage signals by connecting two single-layered NGs in parallel and anti-parallel, and serial and anti-serial, illustrating the 3D integration of the NGs for raising output power



**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

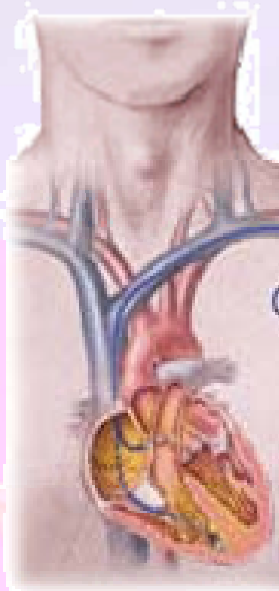
Nano Letters, 8 (2008) 4027

Textile-fiber based nanogenerator; “power shirt”



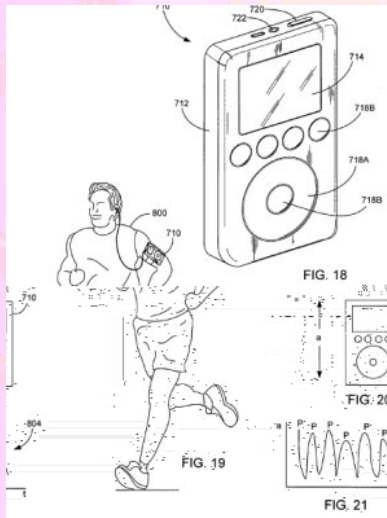
Qin, Wang and Wang, Nature 451 (2008) 809

Low frequency nanogenerator in muscles/fabrics



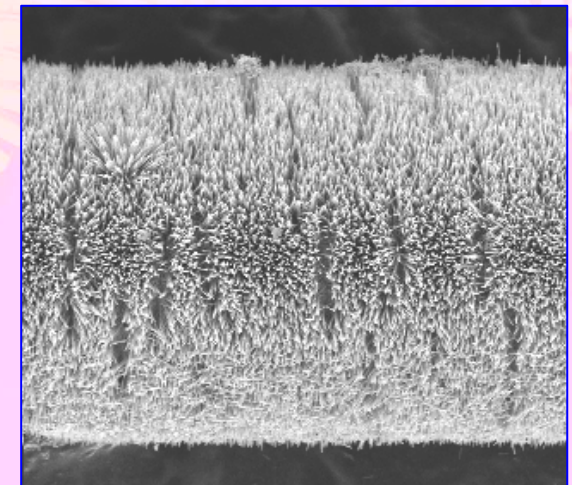
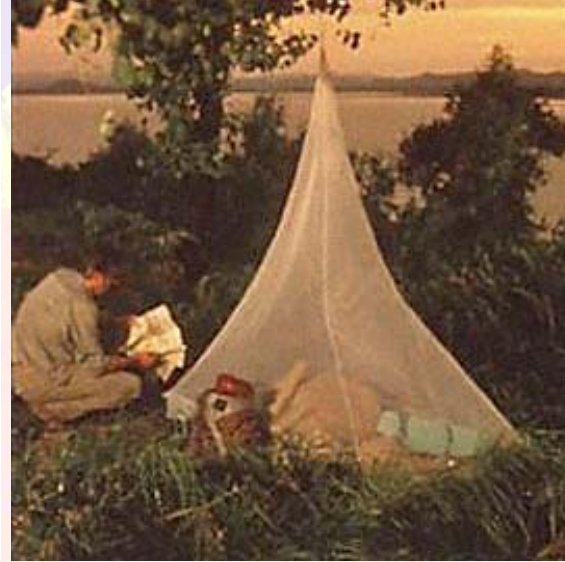
Applications:

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

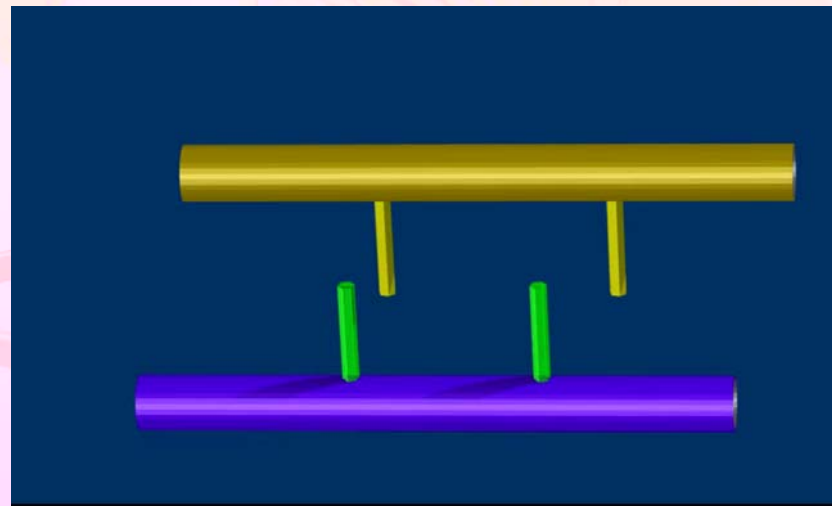
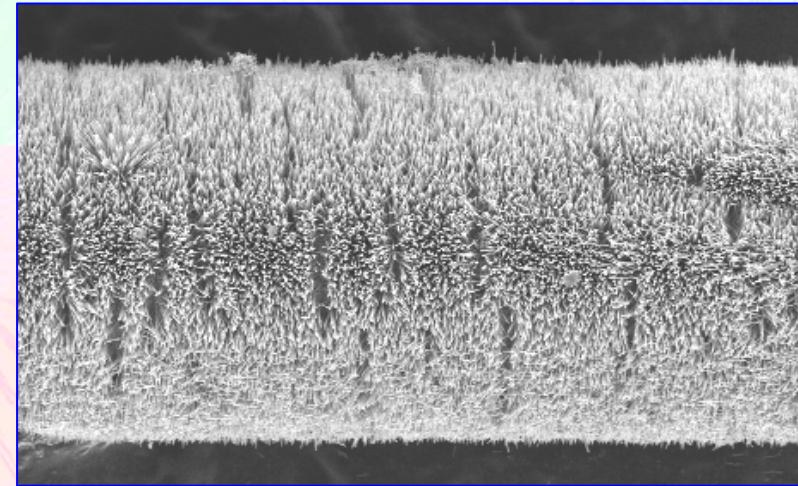
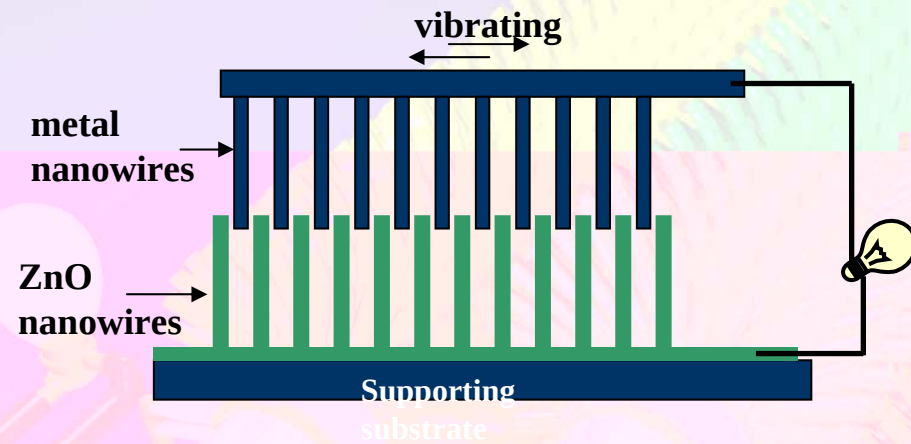


- **Low frequency:**
muscle movement/contraction, heart beating, blood flow, air flow, foot steps
- **Flexible/foldable soft materials as substrates of any shape/curvature**
- **Vibration driven in medium/air**
- **Materials growth at low temperature**

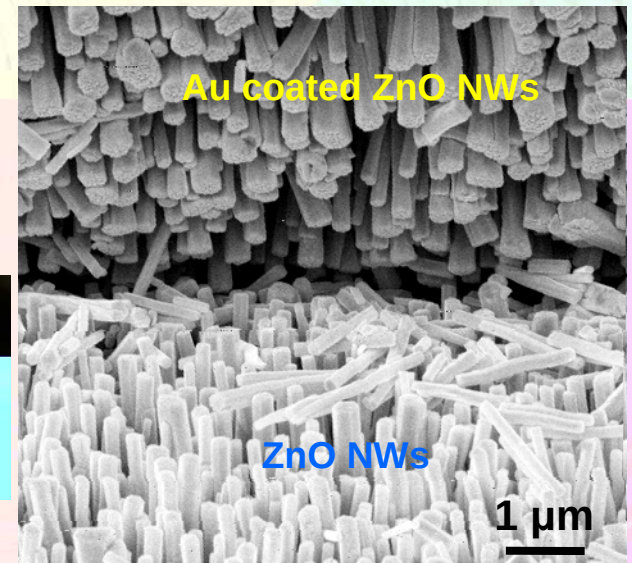
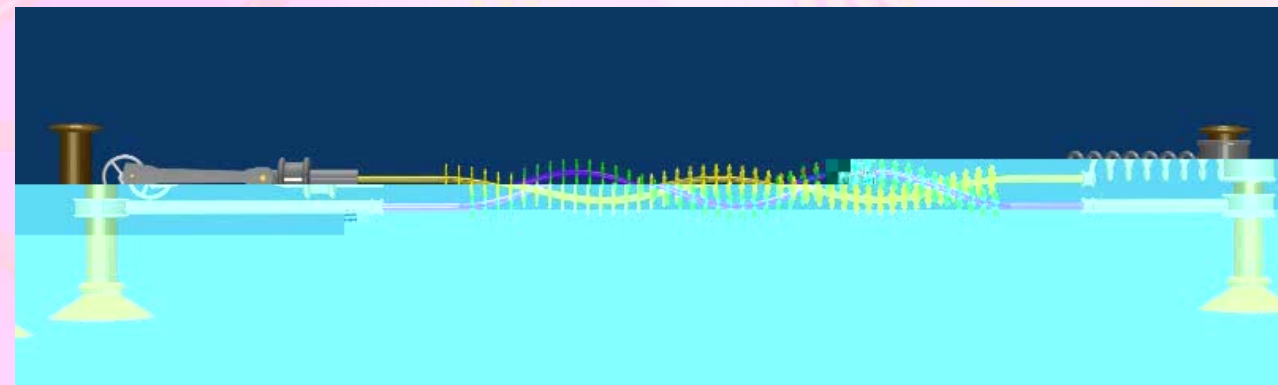
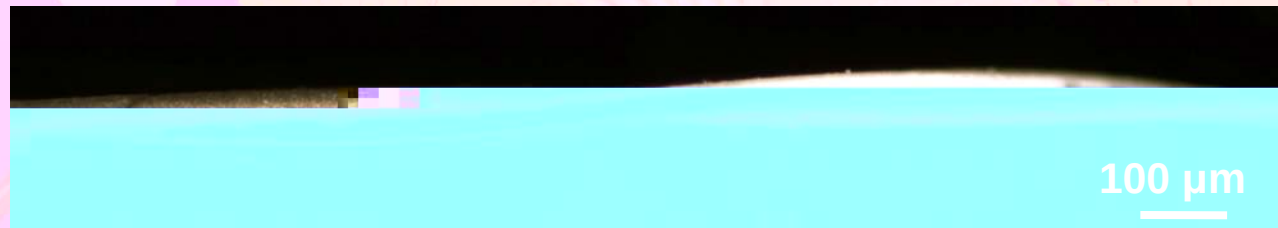
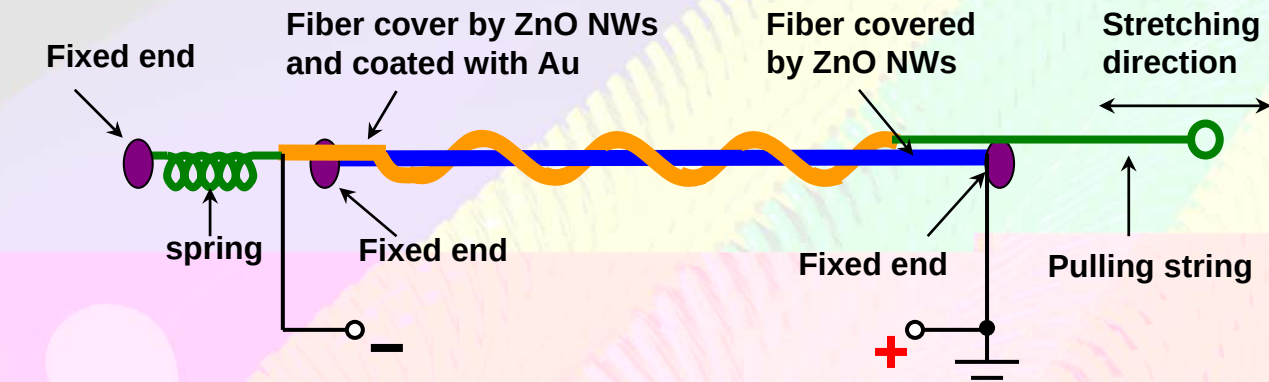
Textile fiber based nanogenerators

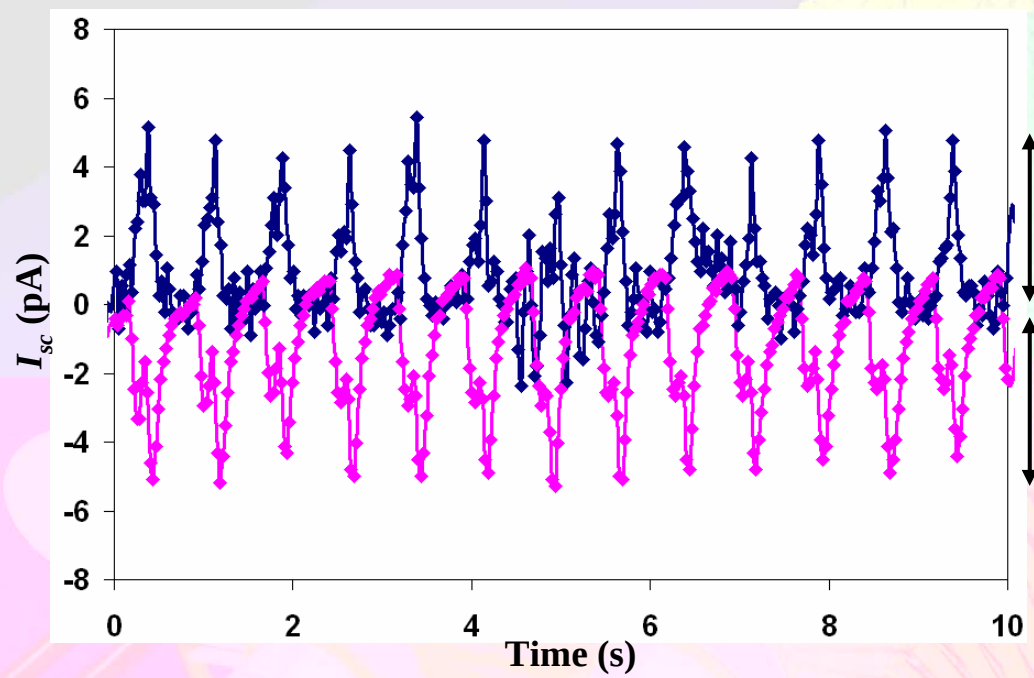


Textile fiber based nanogenerators

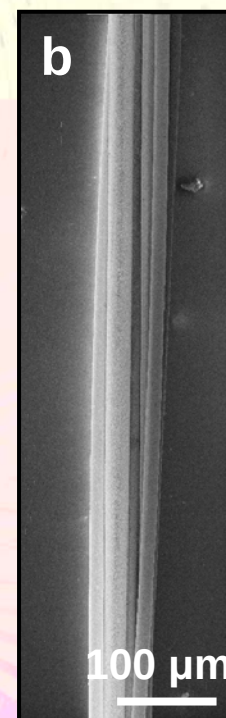
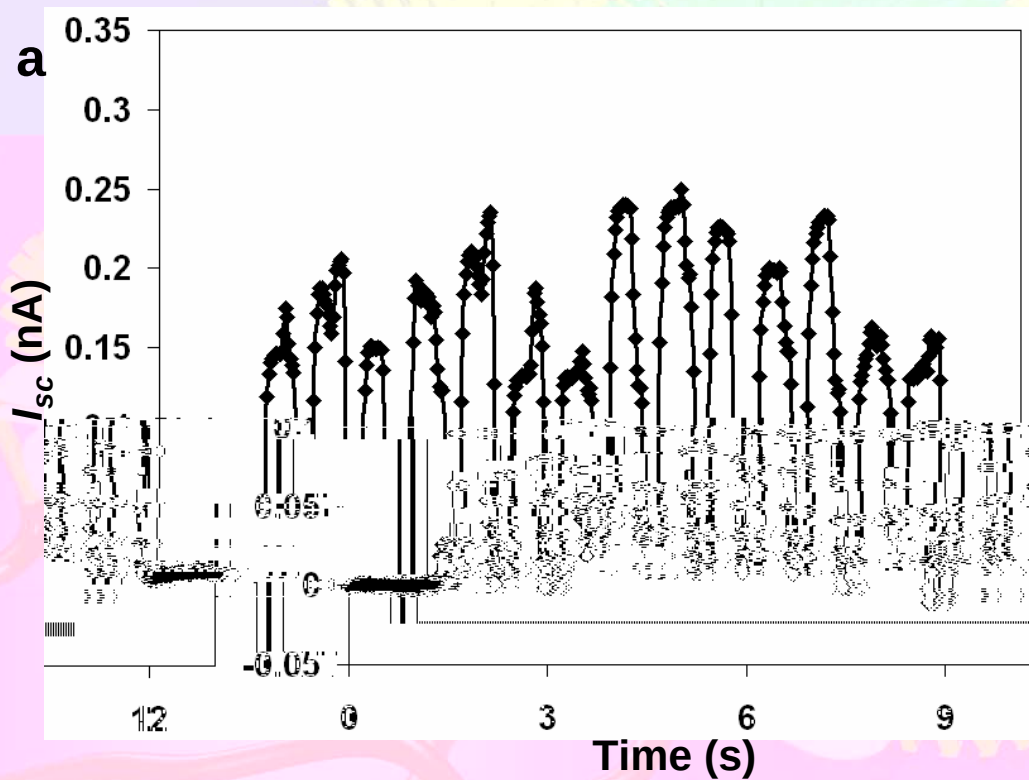


Textile fiber based nanogenerator





Raising the output power by multiple fibers



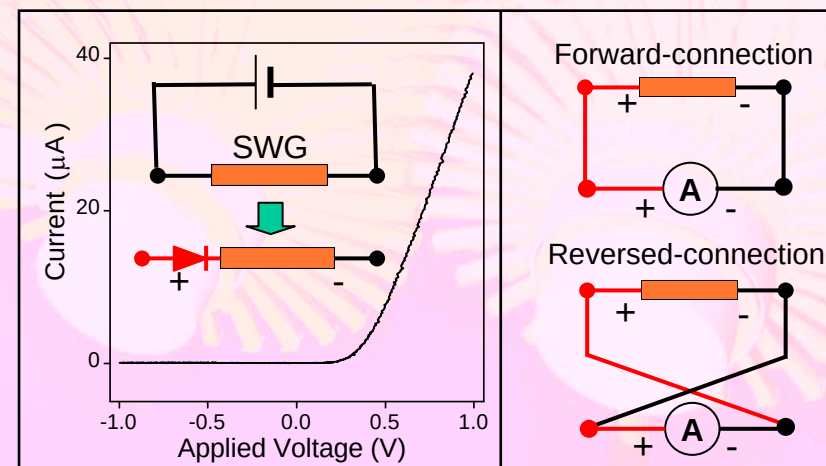
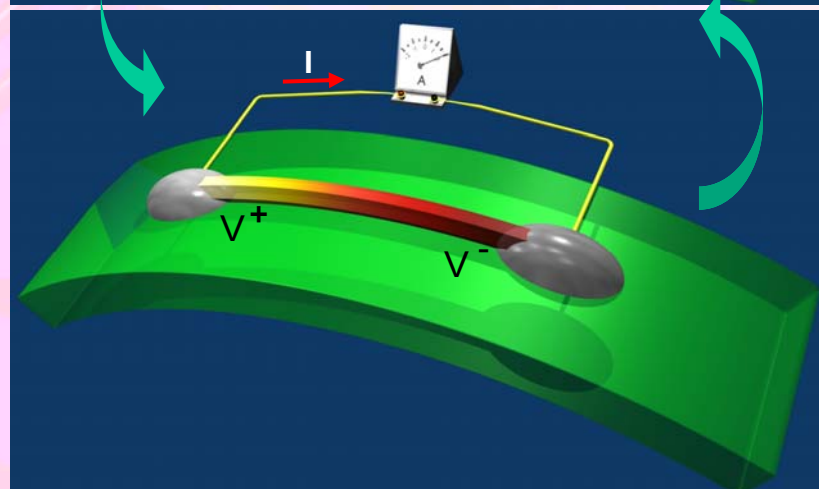
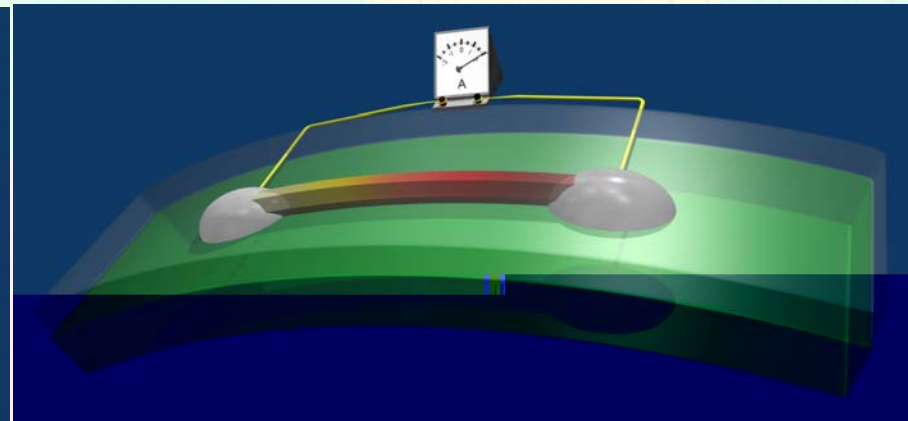
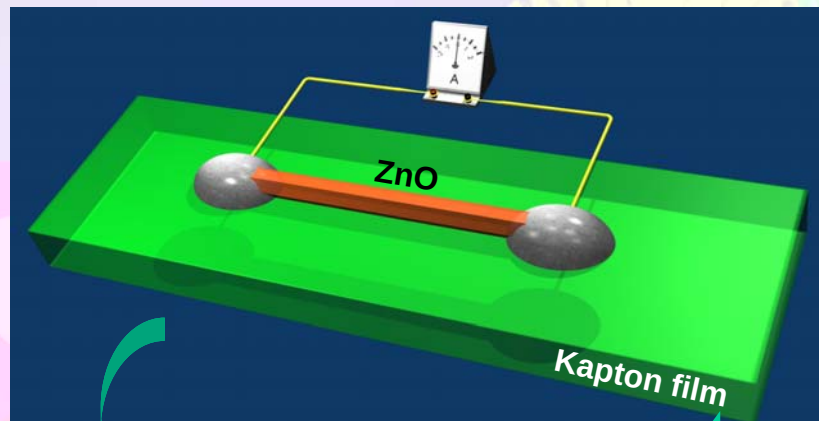
Qin, Wang and Wang, Nature 451 (2008) 809

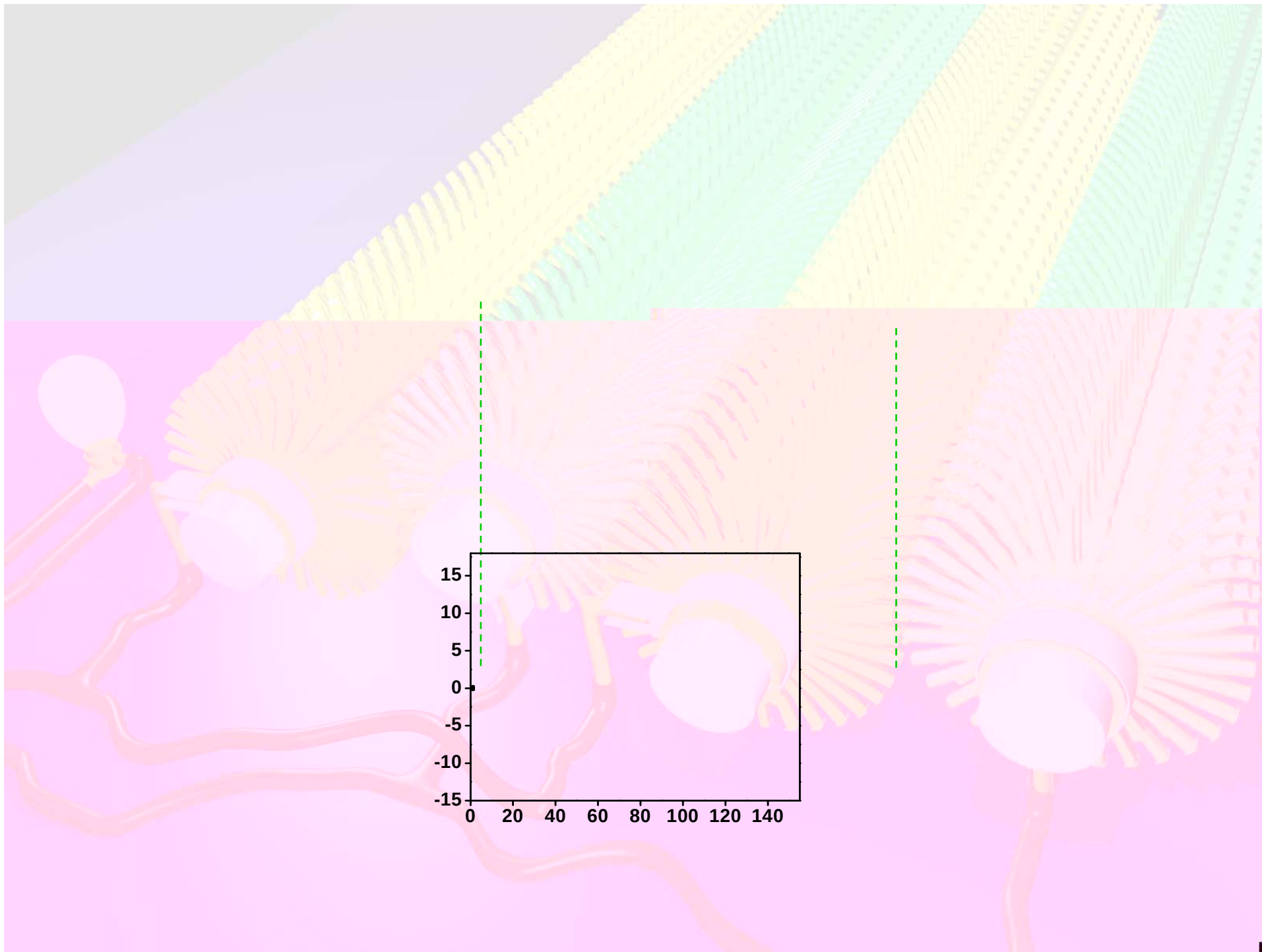
The background of the slide is a microscopic image of a flexible nanogenerator. It features a series of parallel, wavy, yellowish-gold lines (fine-wires) that are densely packed and appear to be bonded to a substrate. These wires are connected to a network of red, wavy lines (likely conductive traces or packaging). The overall structure is flexible and curved, demonstrating its mechanical properties. The text is overlaid on this image.

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

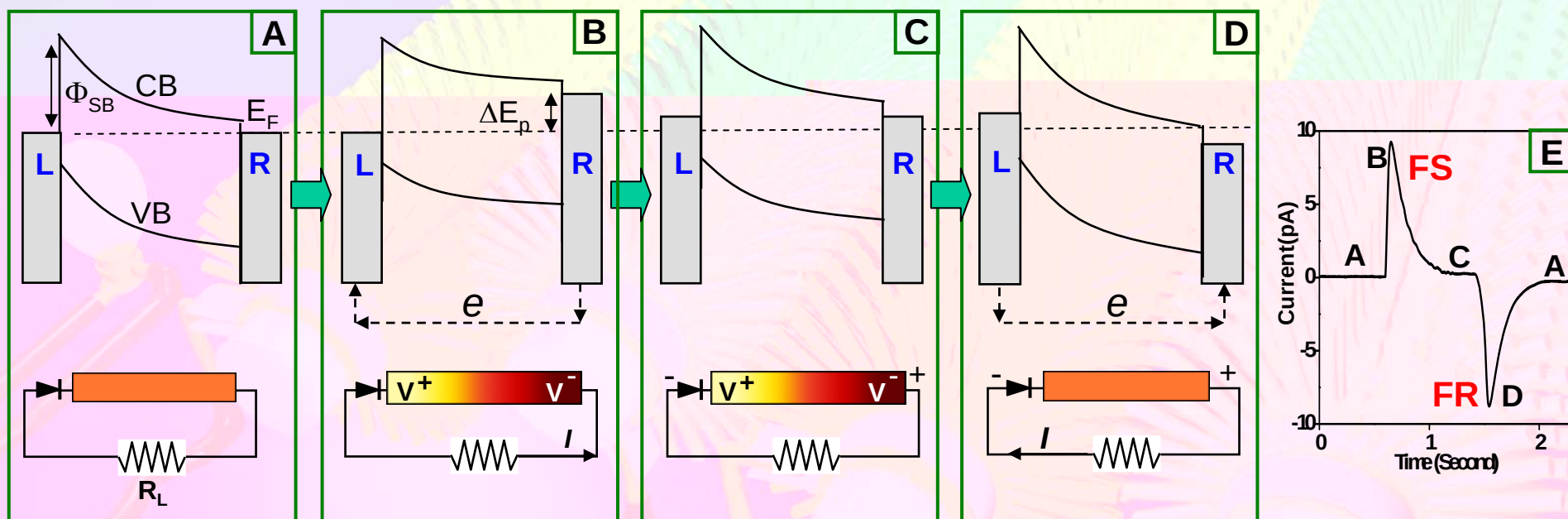
Yang, Qin, Dai & Wang, Nature Nanotechnology, 4 (2009) 34-39

Experimental set up and the polarity test

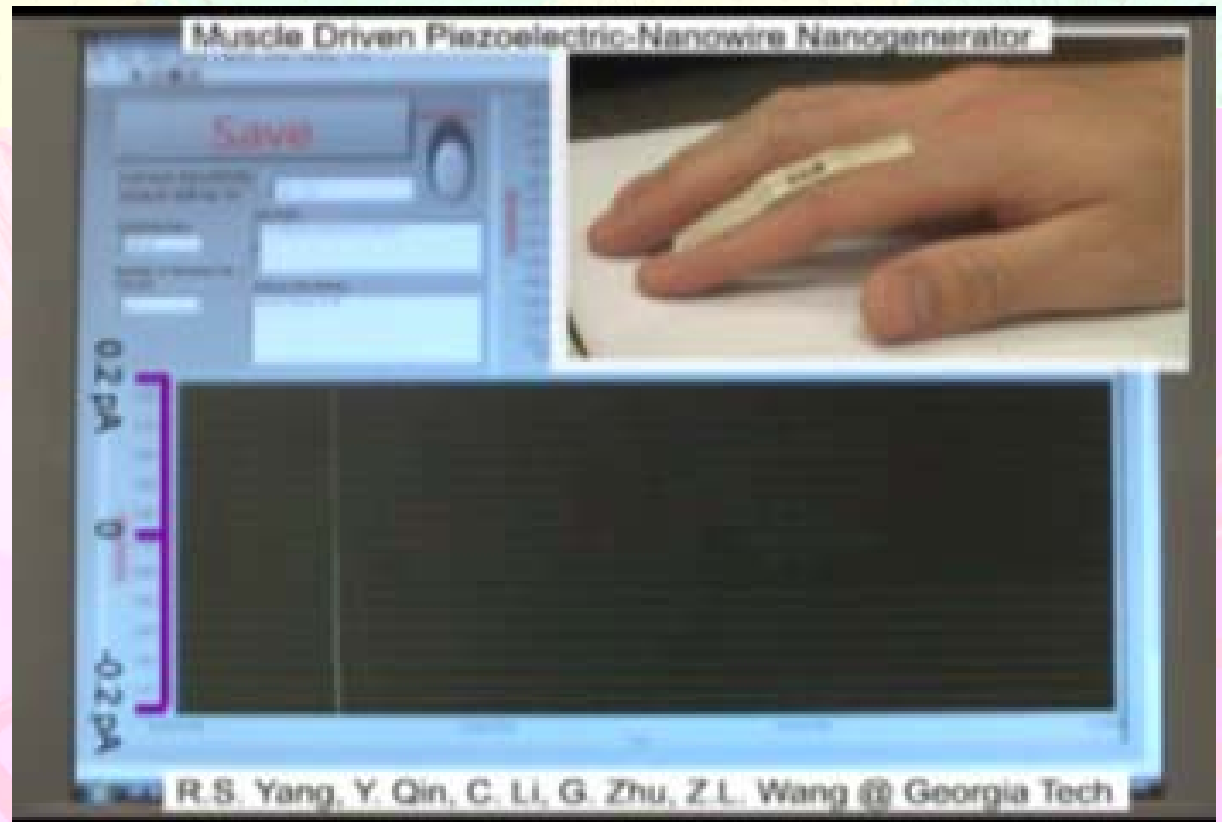
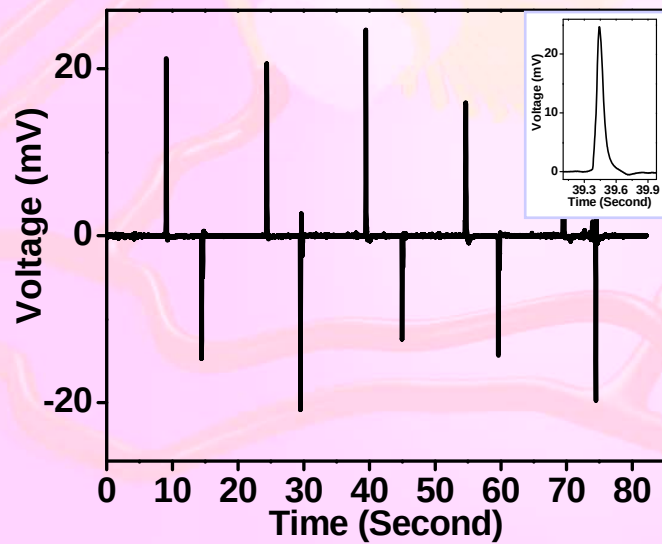
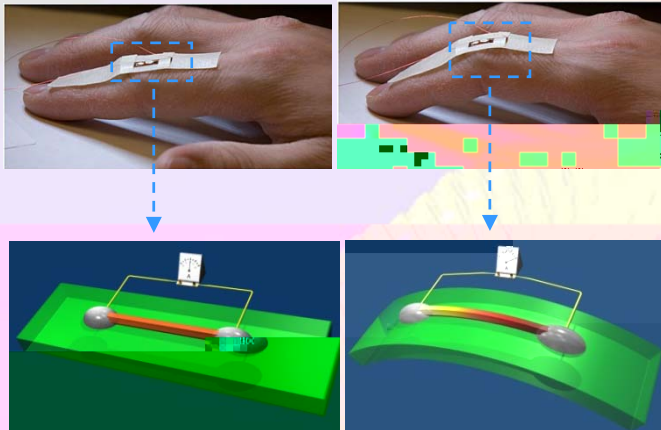




Mechanism of the AC generator

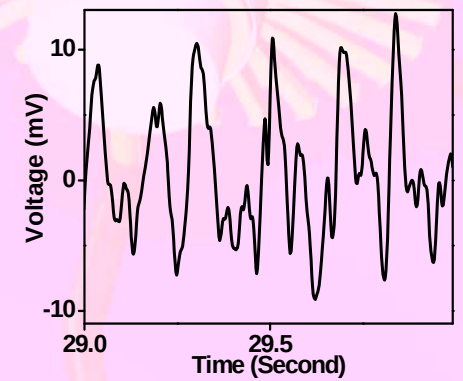
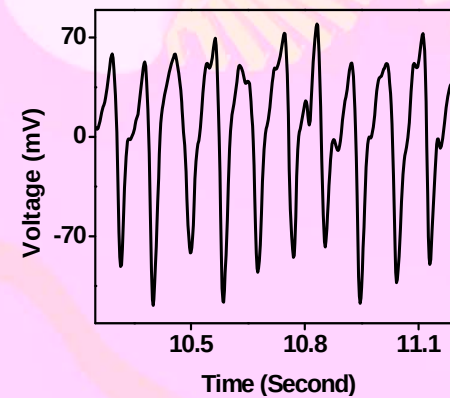


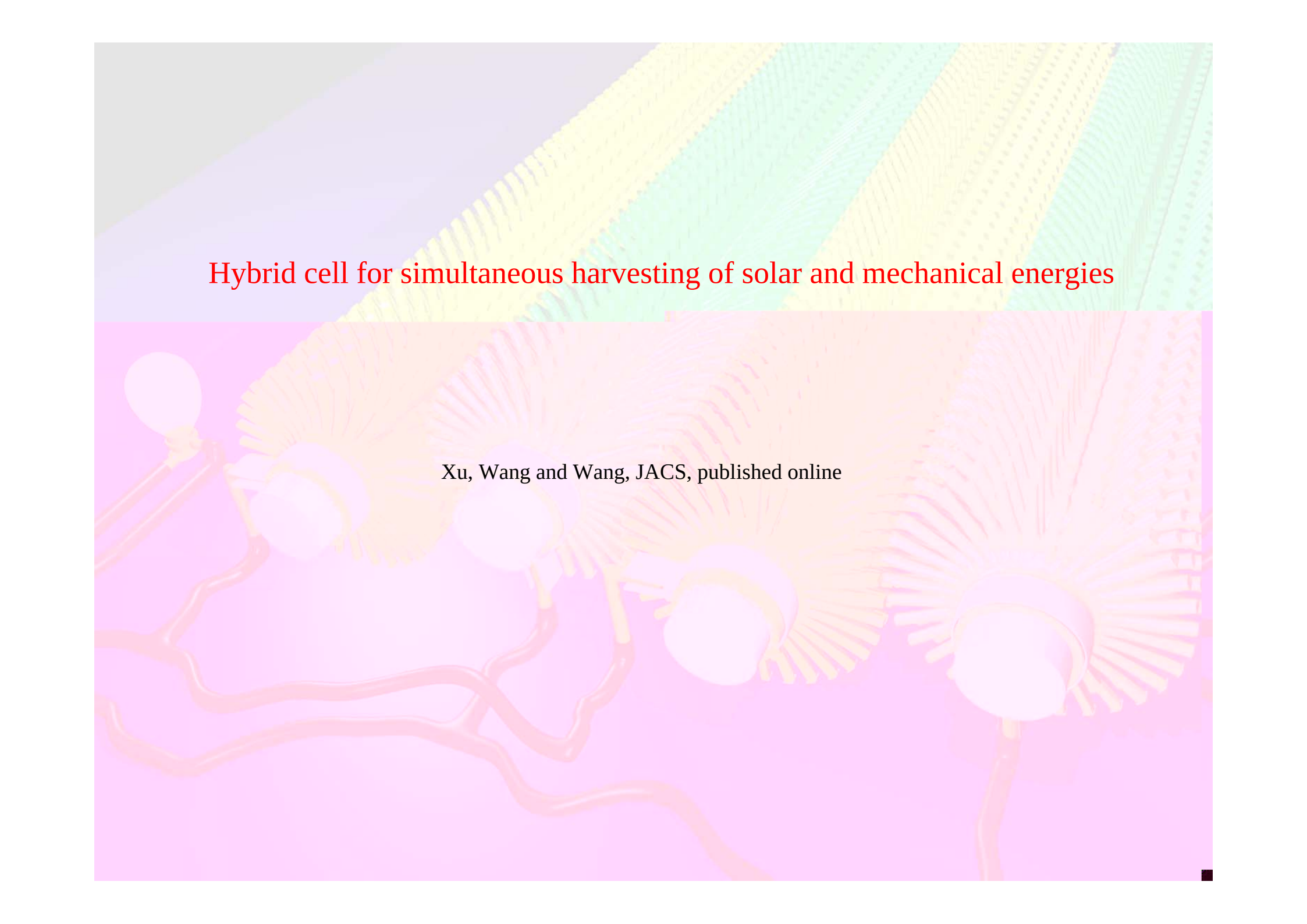
Electricity generation by finger movement



Nano Letters, 9 (2009) 1201

Electricity generation by a running hamster





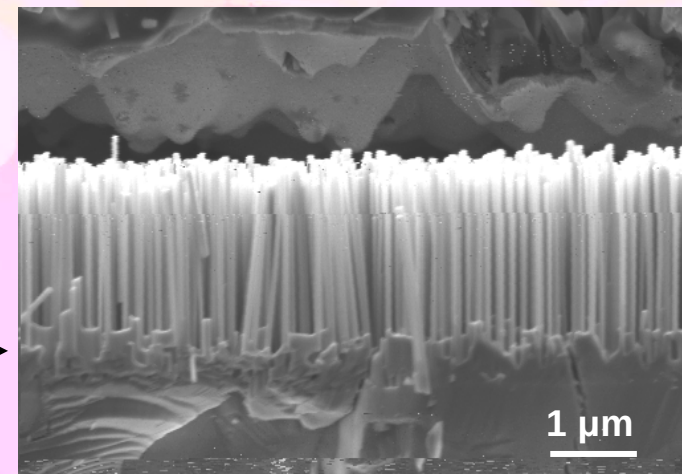
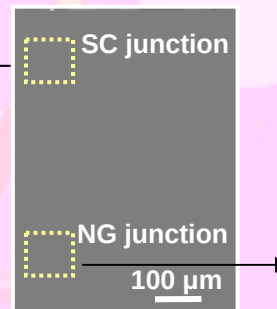
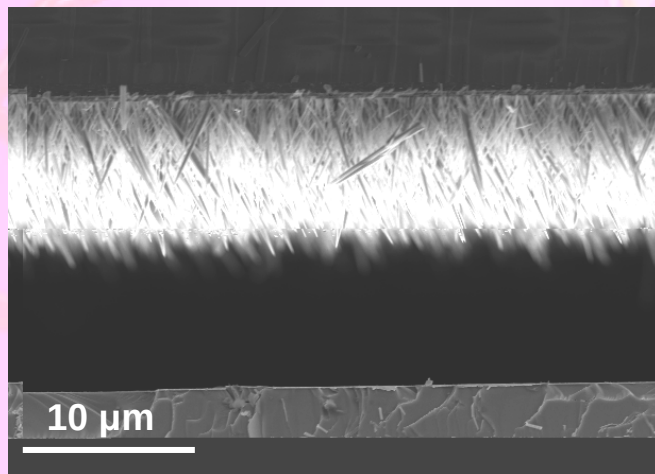
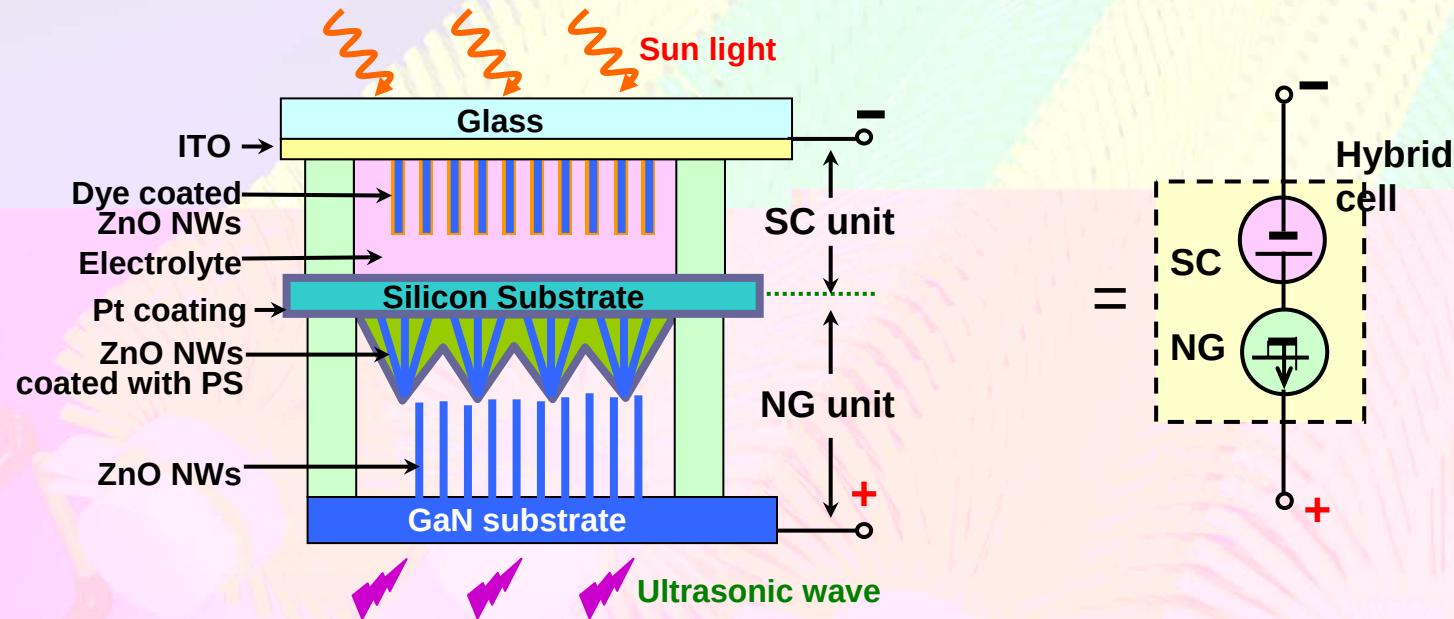
Hybrid cell for simultaneous harvesting of solar and mechanical energies

Xu, Wang and Wang, JACS, published online

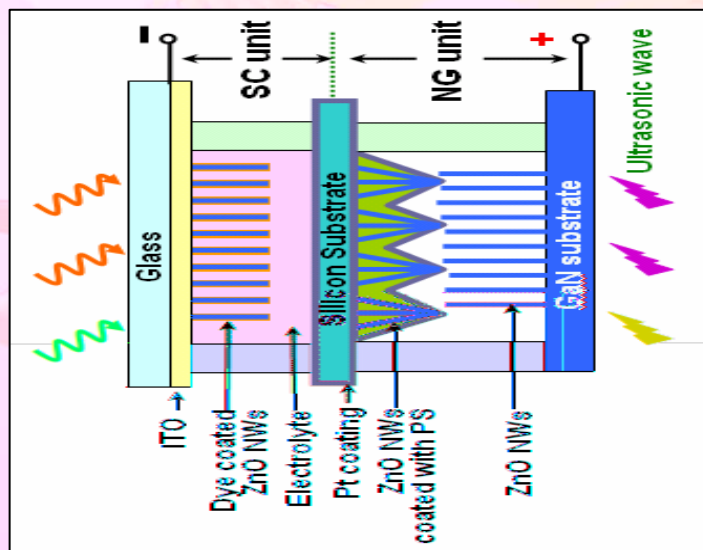
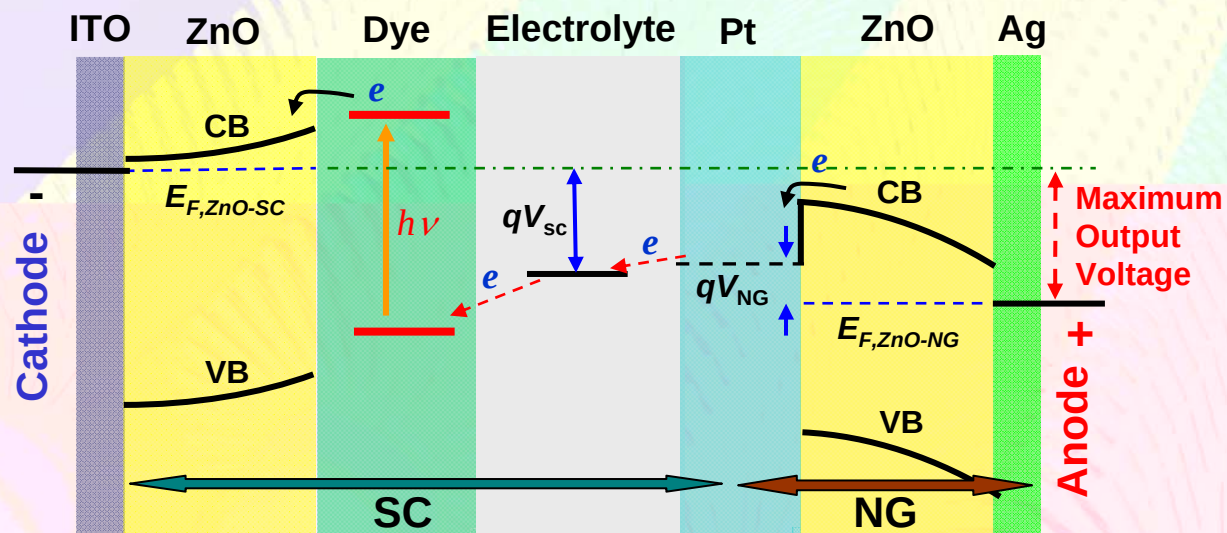
The concept of hybrid cell



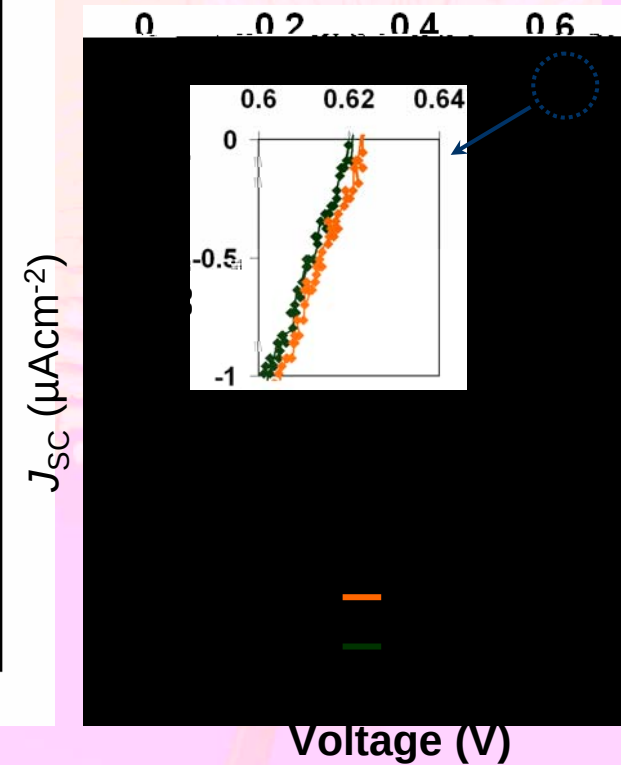
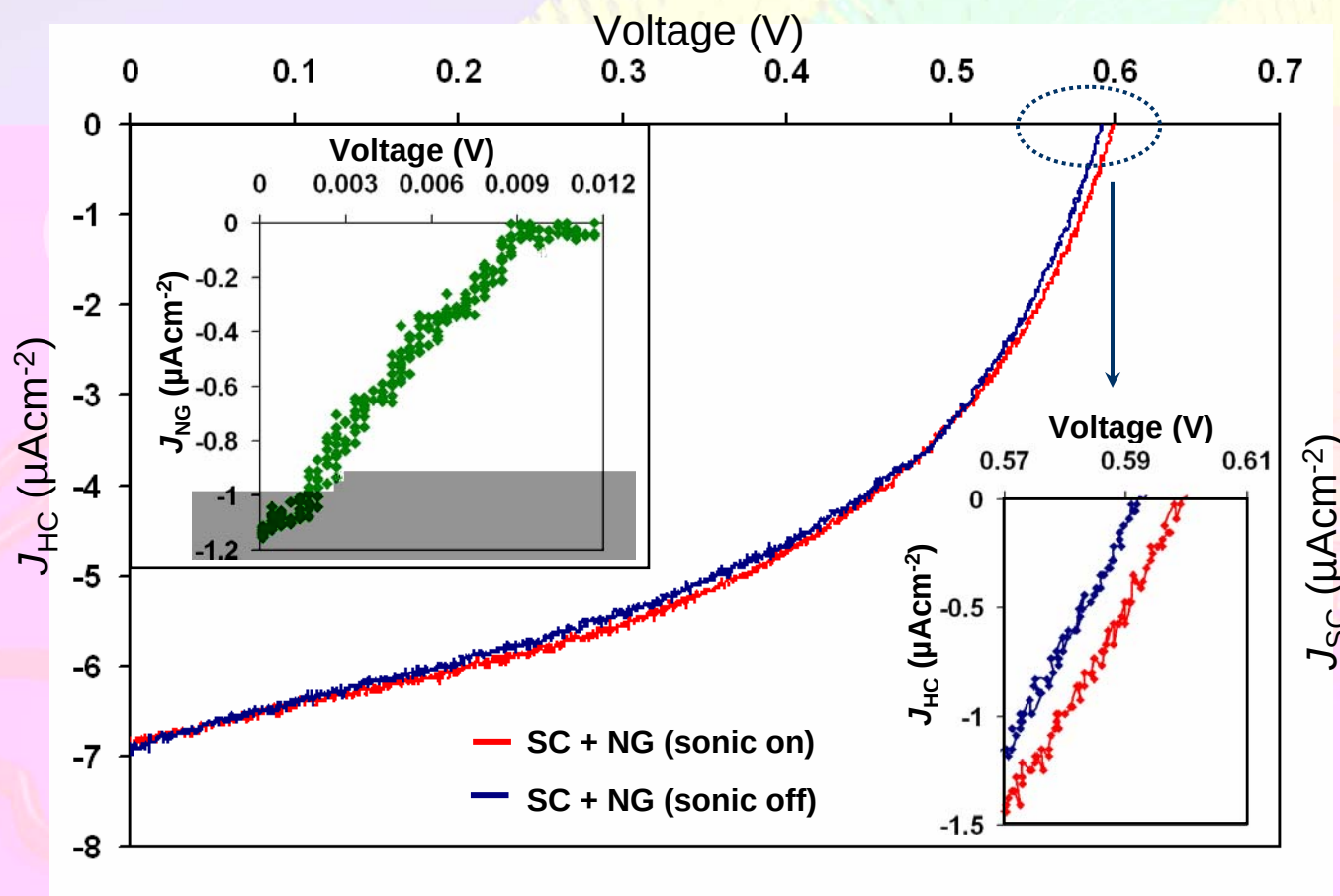
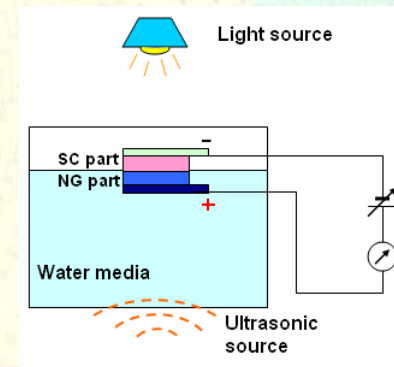
Design and fabrication of a hybrid cell composed of serially integrated SC and NG



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

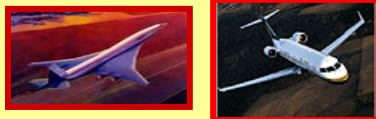


Performance of the hybrid cell composed of serially integrated SC and NG



Harvesting multi-type energies

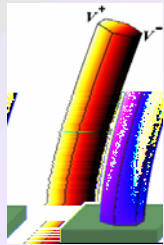
Vehicle Concepts



Virtual System Integration and Evaluation Environment

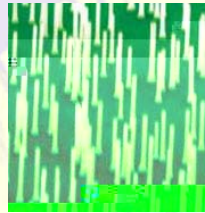


Perspectives of Piezoelectric Nanogenerator

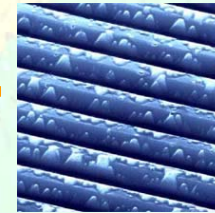


Bending piezoelectric ZnO nanowire (NW) generates electrical potential along side surfaces

To deflect many NWs simultaneously for continuous output

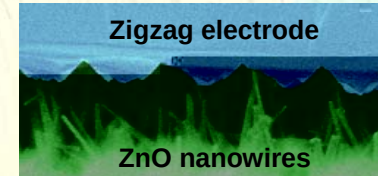


Vertical aligned ZnO NW arrays

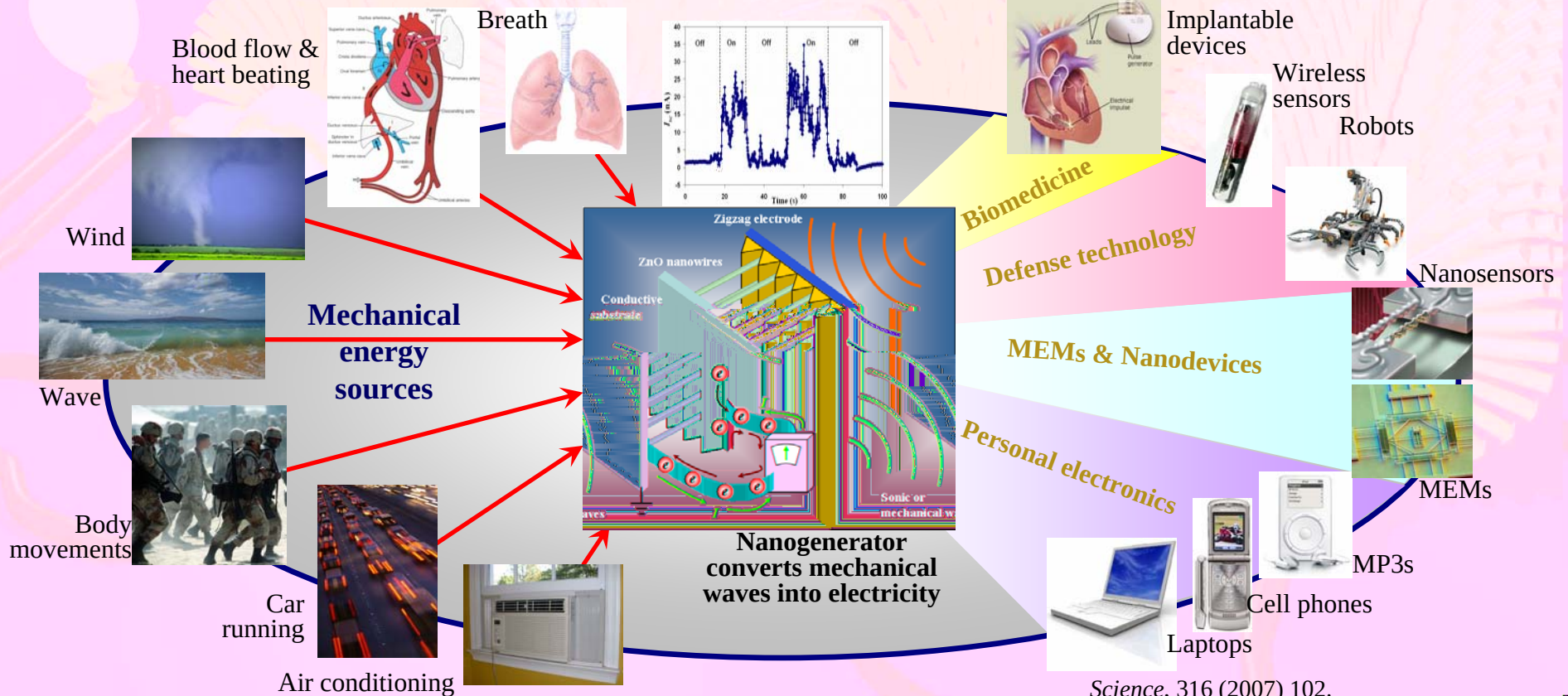


Zigzag silicon trench coated with platinum

Integrate with spacing control



- Mechanical vibration triggers the bending of NWs;
- Piezoelectric potential collects by the trenches.



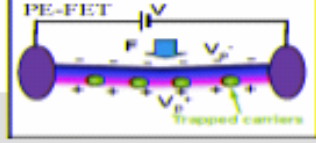
Nano-Piezotronics, what is it about? What can it be used for?

**ADVANCED
MATERIALS**

DOI: 10.1002/adma.200602918

Nanopiezotronics**

By Zhong Lin Wang



fundamental principle of nanopiezotronics, piezoelectric and semiconducting properties of nanowires and nanocantilevers, and fabricating electronic devices and components, such as field-effect transistors, diodes, and rectifiers. Nanopiezotronics is based on the principle of piezoelectricity, which converts mechanical energy into electric energy. It is anticipated to have a wide range of applications in electromechanical coupled electronics, energy harvesting in the environment, and self-powered nanosystems.

This article introduces the fundamental principle of nanopiezotronics, which utilizes the coupled piezoelectric and semiconducting properties of nanowires and nanocantilevers for designing and fabricating electronic devices and components, such as field-effect transistors, diodes, and rectifiers. The article also discusses the applications of nanopiezotronics in energy harvesting, self-powered nanosystems, and other areas.

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

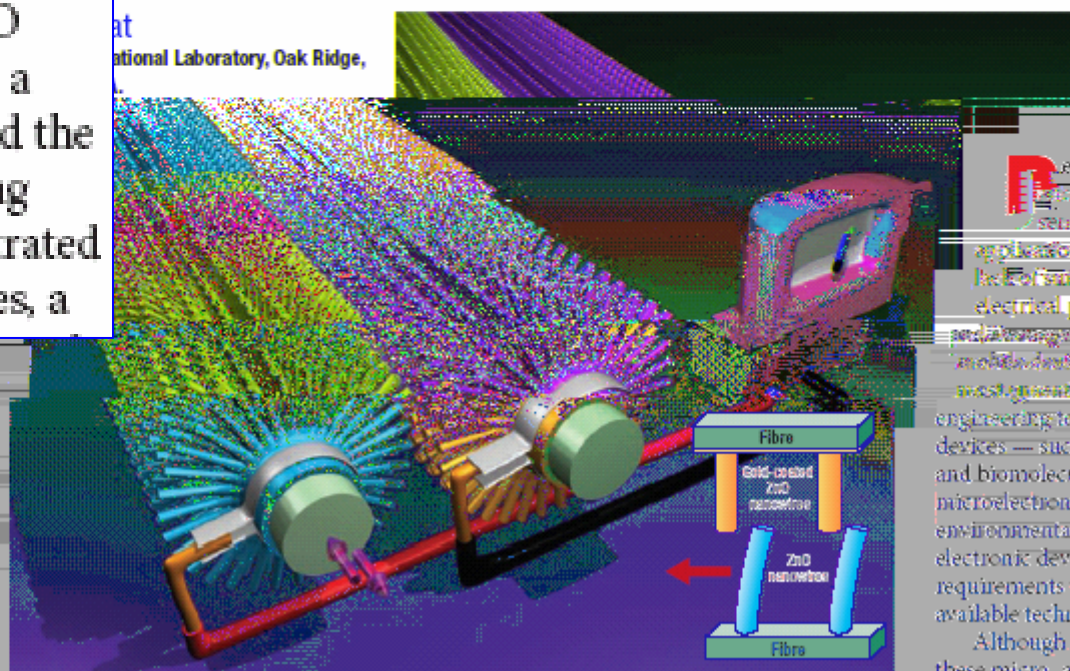
ENERGETIC MATERIALS

Flexible approach pays off

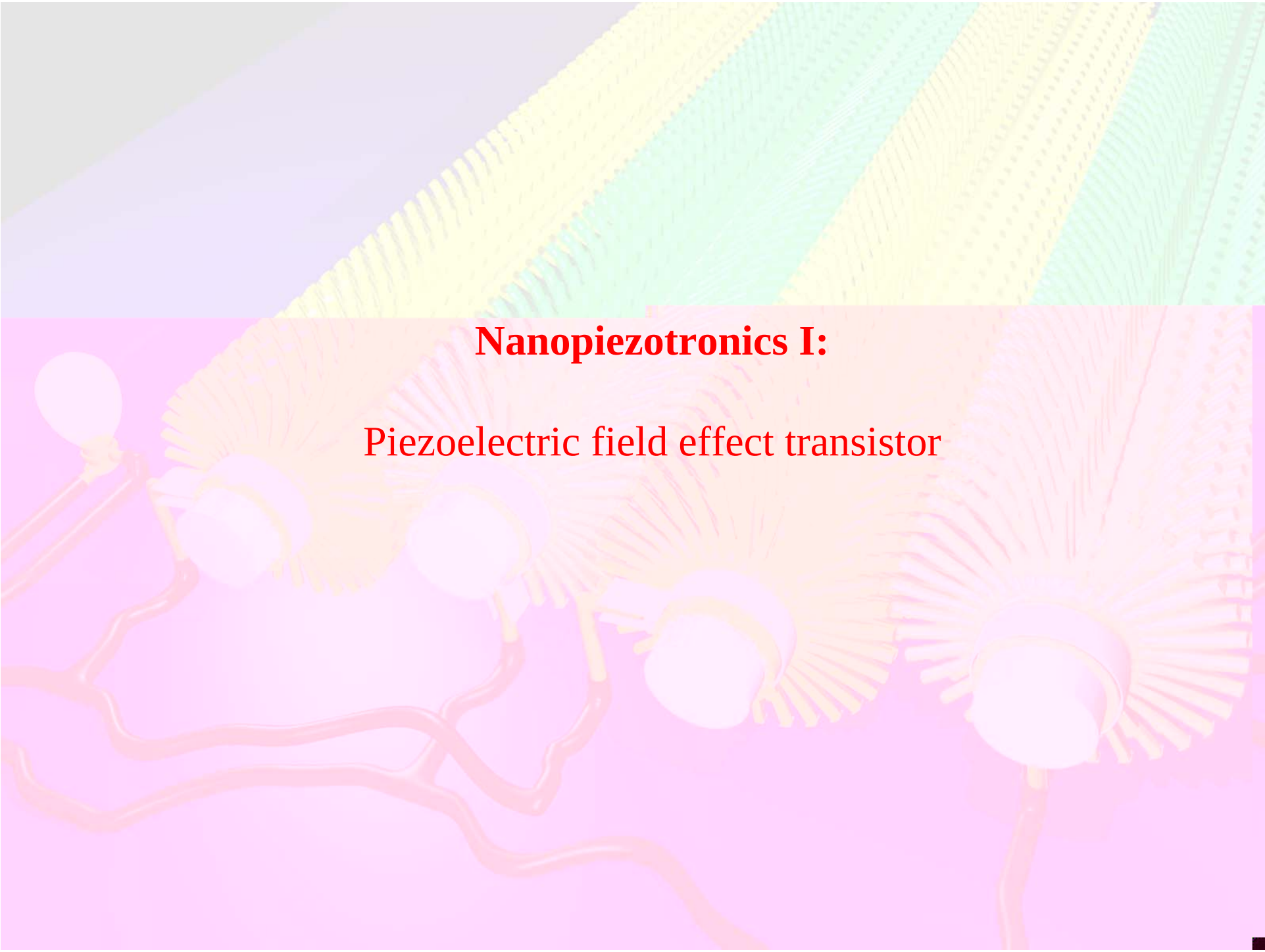
Researchers have managed to extract electrical energy from environmental noise by exploiting the piezoelectric properties of zinc oxide nanowires with a device that could herald a new generation of local power sources.

resulting electrical polarization of ZnO was converted into electricity through a combination of piezotronic effects⁶ and the piezoelectric–semiconducting coupling process⁷. Although this work demonstrated the potential of piezoelectric nanowires, a

and systems of the fully piezotronic and piezo-electronic devices — such as ultrasensitive chemical sensors, nanorobots, mechanical systems (MEMS), sensors and other personal devices — have energy requirements that are not fully met by technologies such as batteries. The energy requirements of micro- and nanoscale devices are



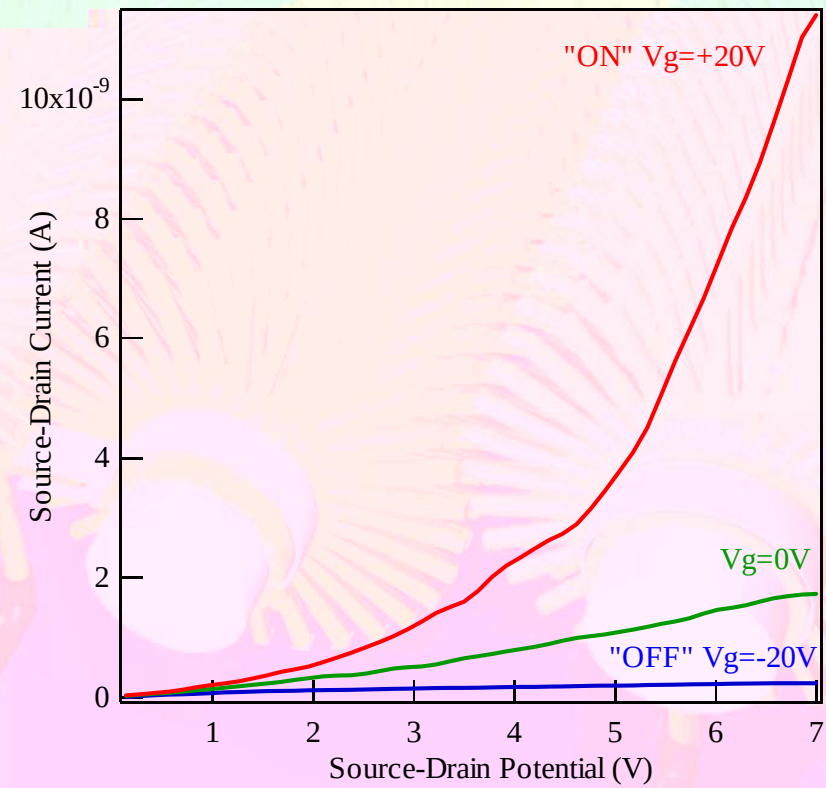
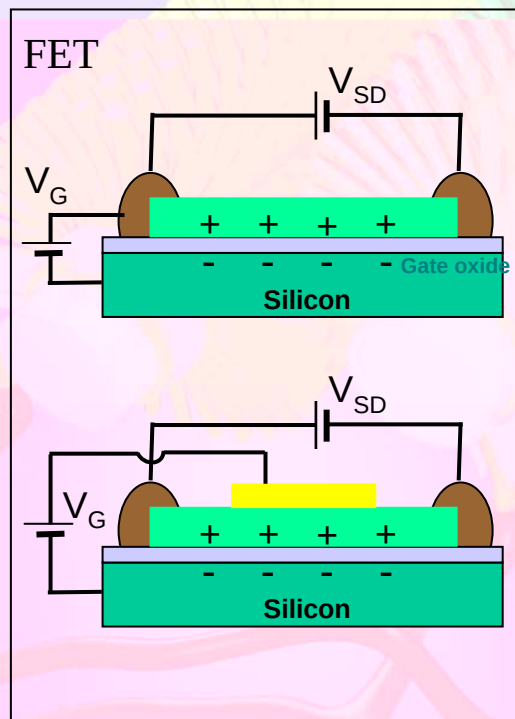
engineering technologies — such as and biomolecular microelectronics — environmental electronic devices requirements that are not fully met by available technologies. Although these micro- and



Nanopiezotronics I:

Piezoelectric field effect transistor

Nanobelt based FET



Piezoelectric potential at the surface of a ZnO nanowire

- No free charge inside the wire:

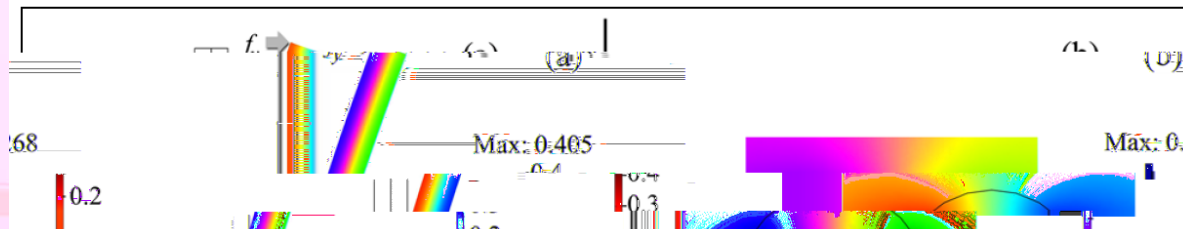
$$\nabla \cdot \vec{D} = 0$$

- No external body force:

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

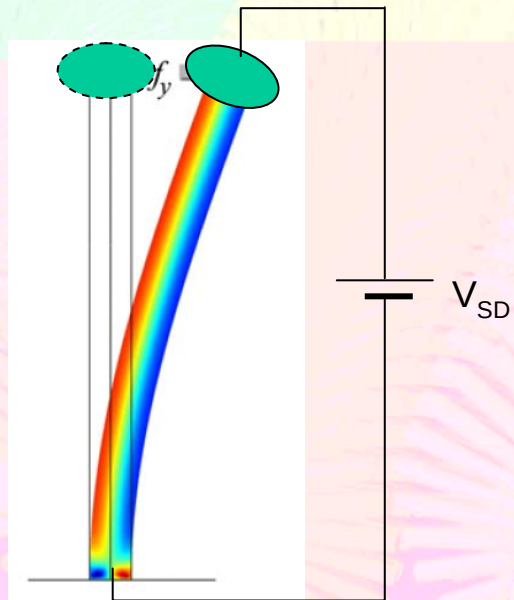
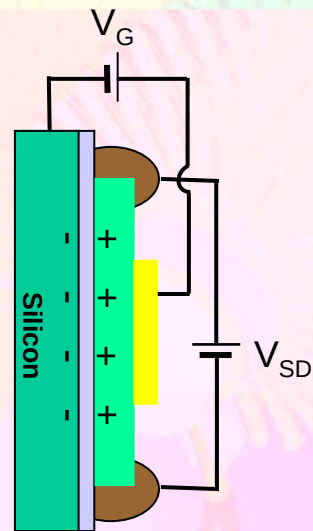
- Maxwell's stress tensor T_{ij} is small and can be neglected

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



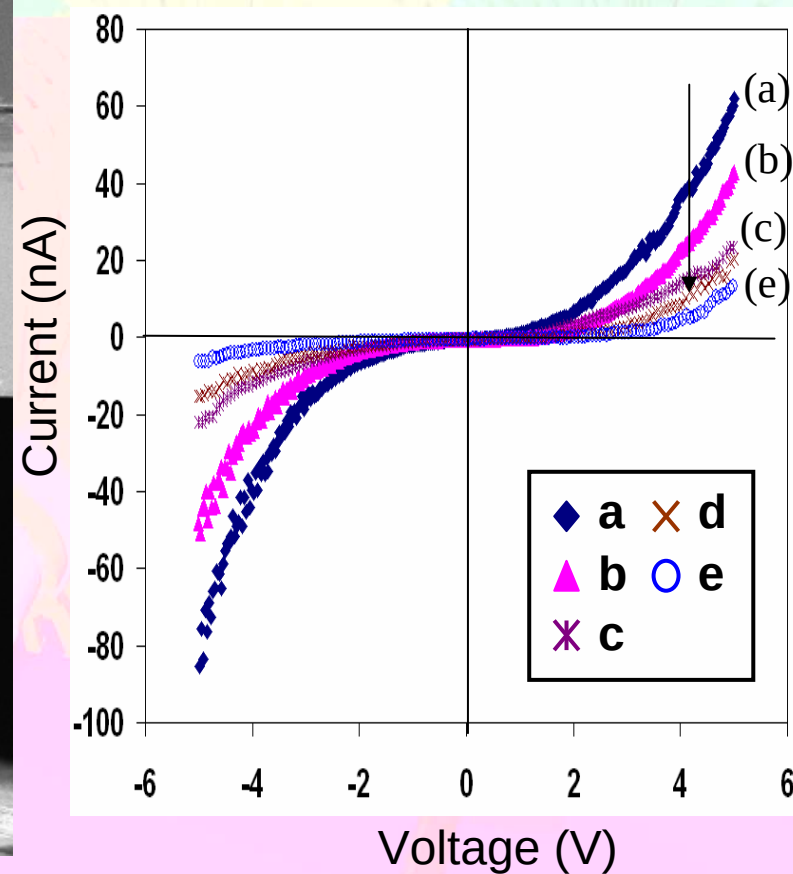
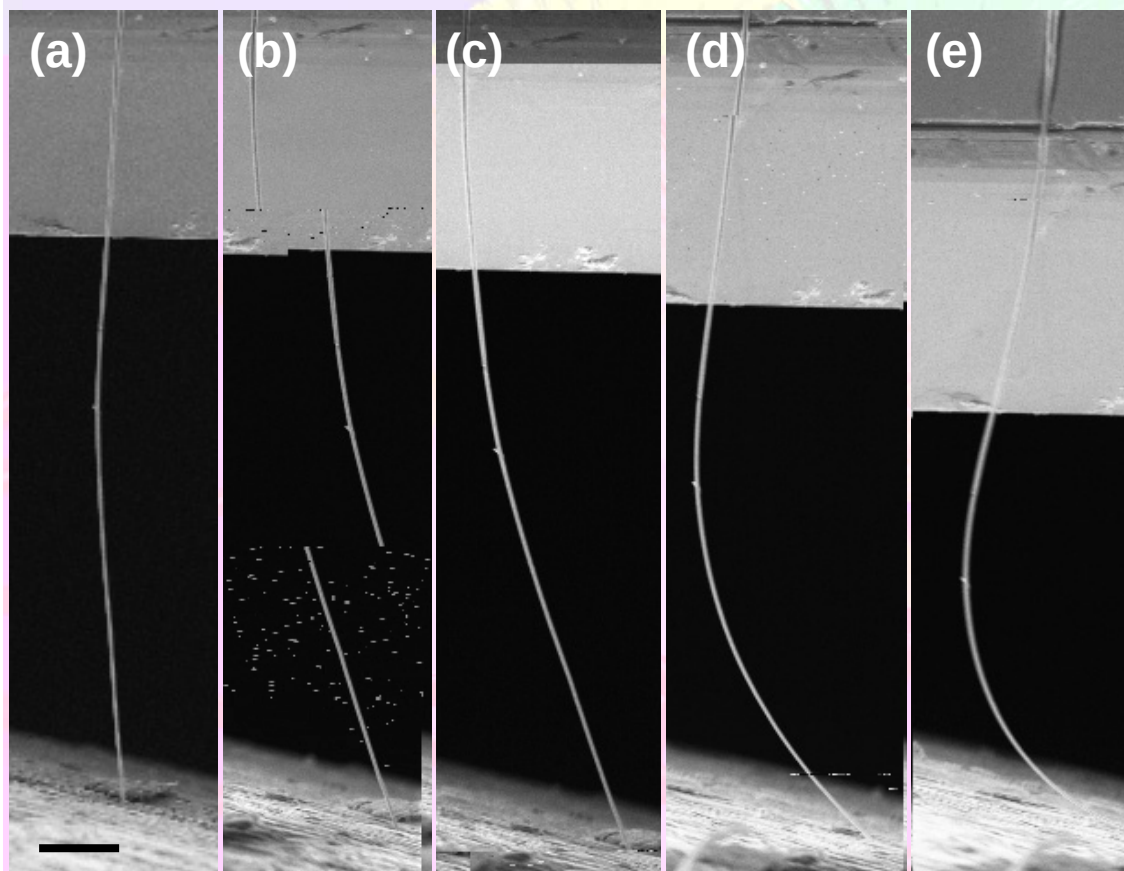
Piezoelectric FET

FET



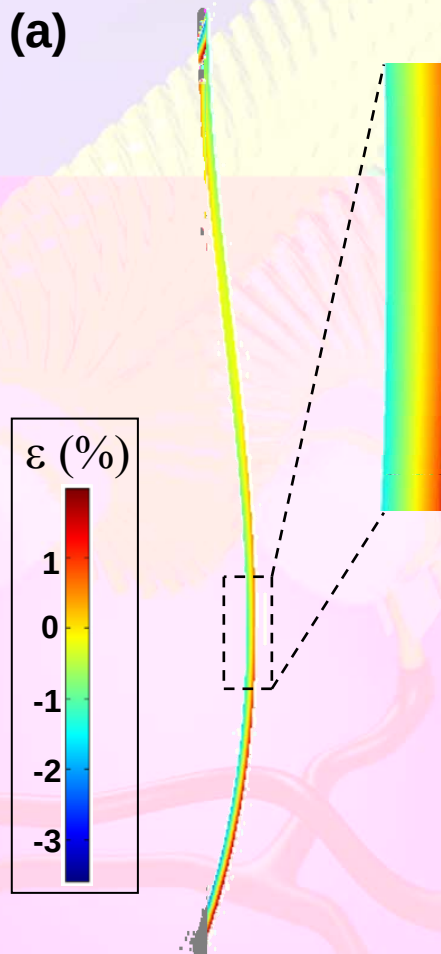
Wang, Adv. Mater., 19 (2007) 889-992

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

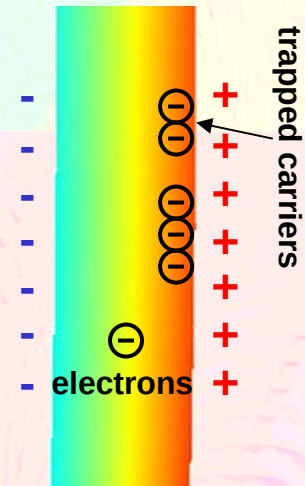


Mechanisms of the P-FET

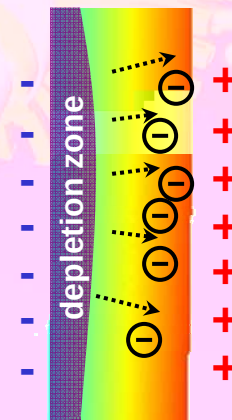
(a)

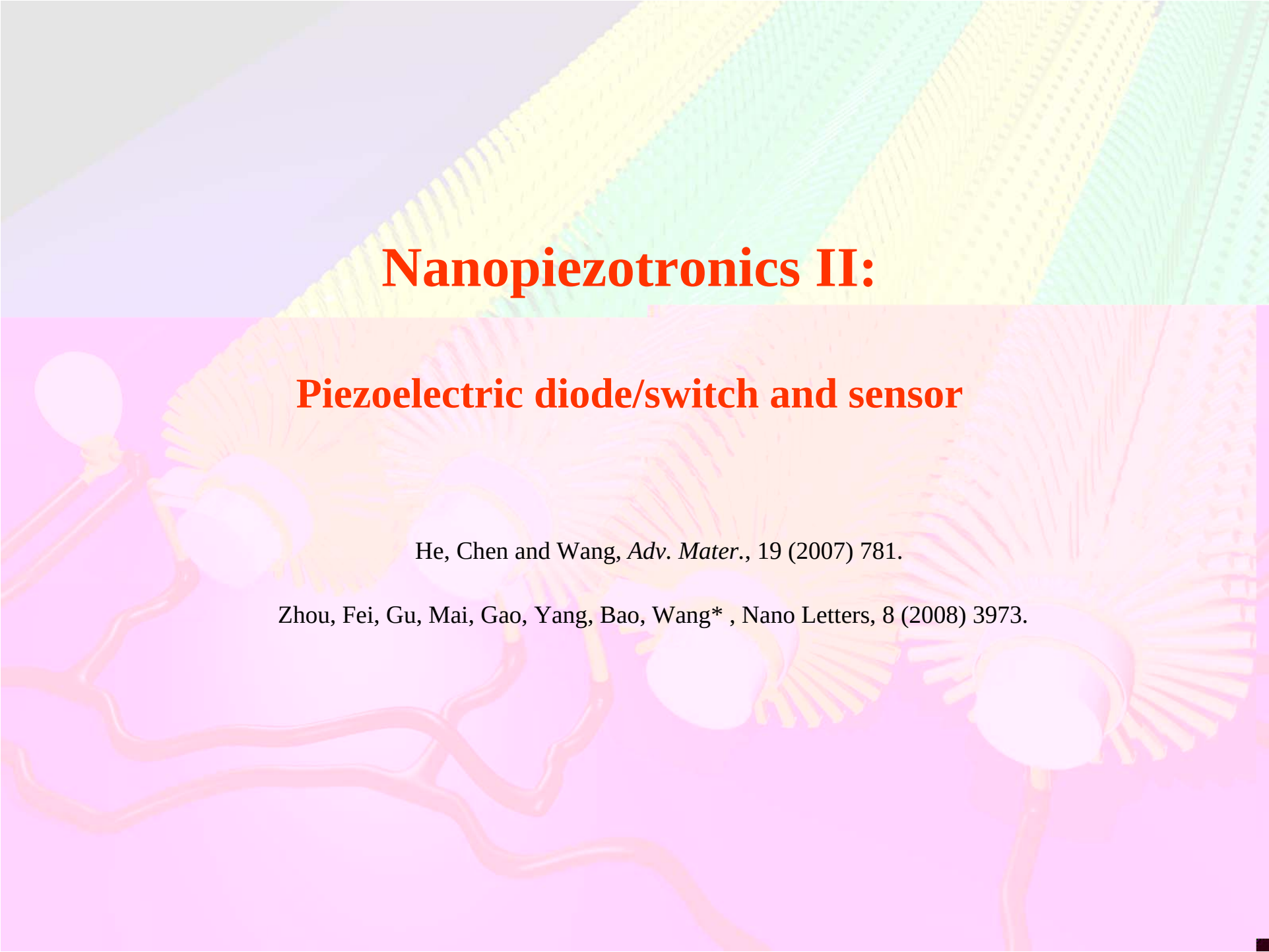


(b) Carrier trapping



(c) Charge depletion zone





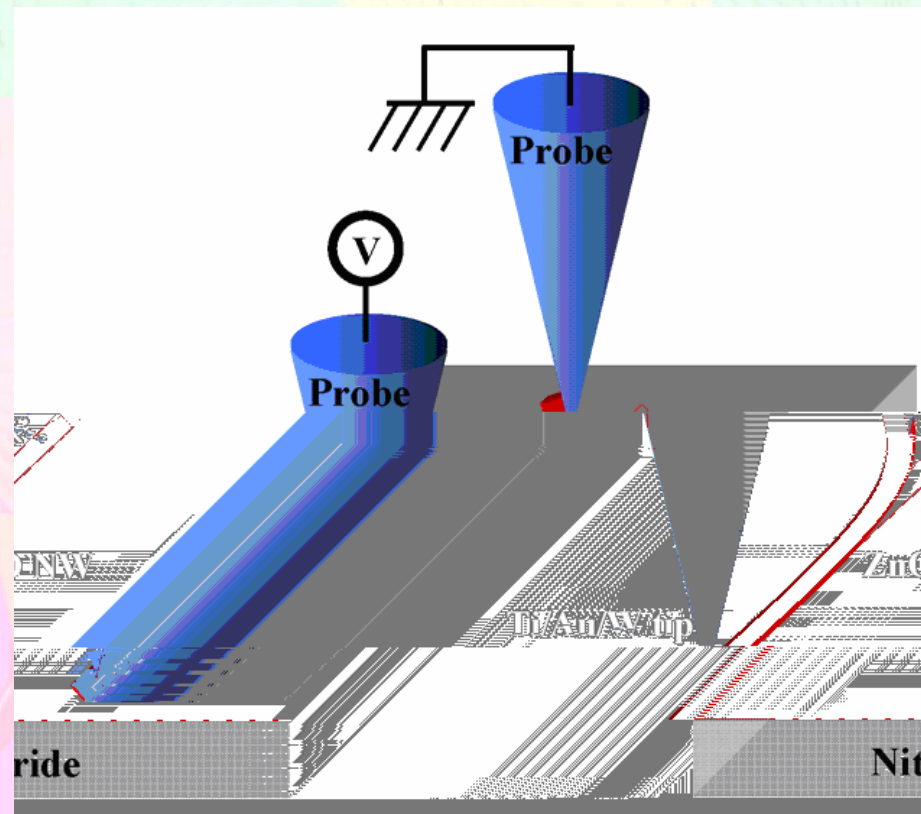
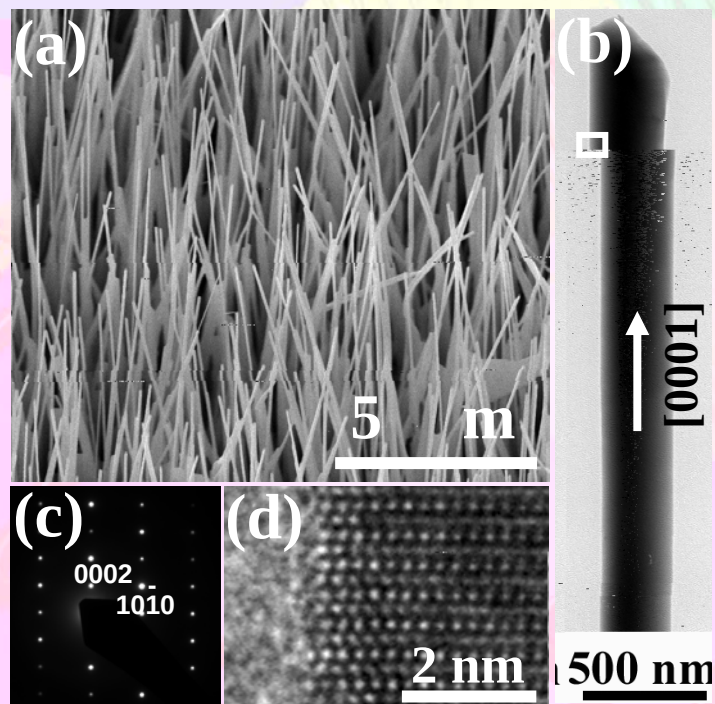
Nanopiezotronics II:

Piezoelectric diode/switch and sensor

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

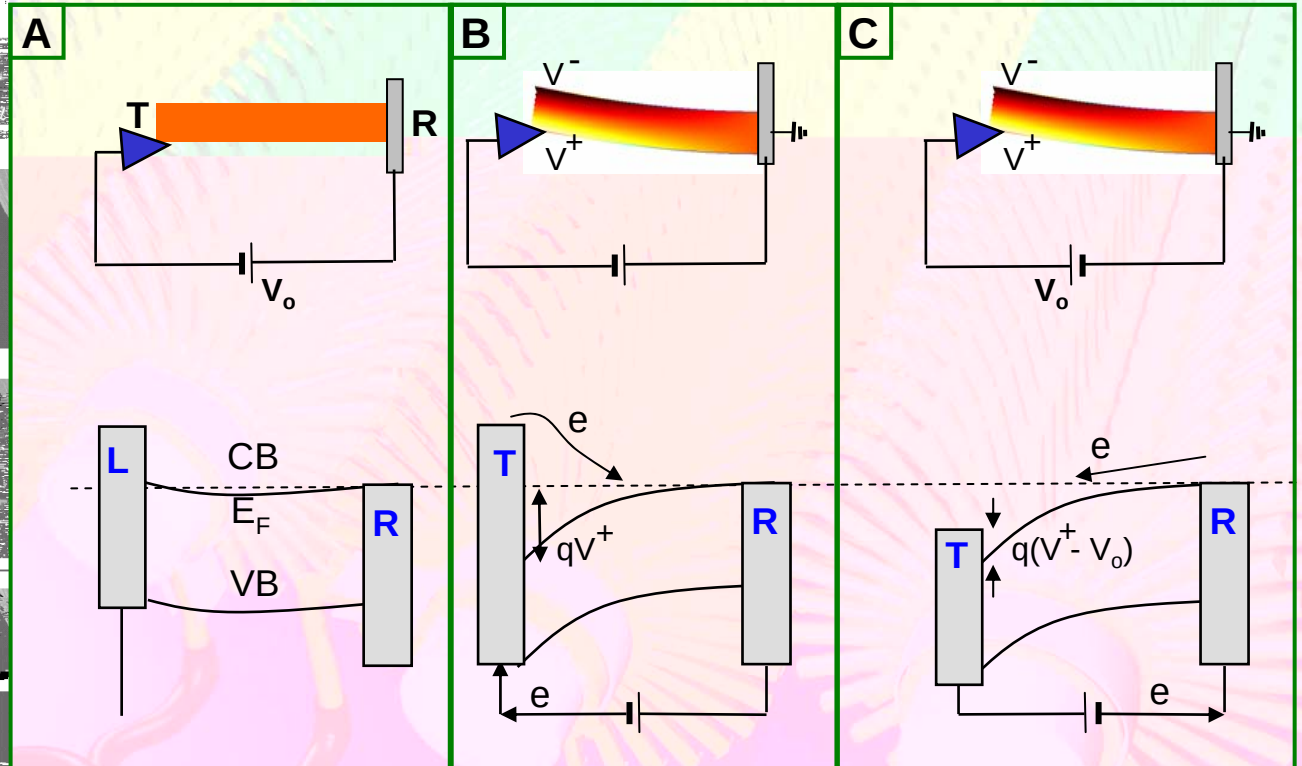
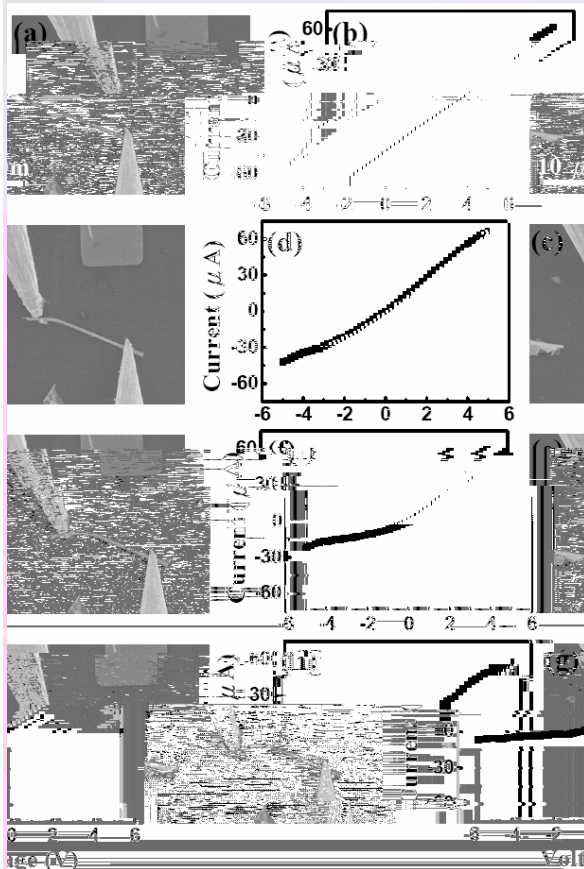
Zhou, Fei, Gu, Mai, Gao, Yang, Bao, Wang* , *Nano Letters*, 8 (2008) 3973.

Piezoelectric diode



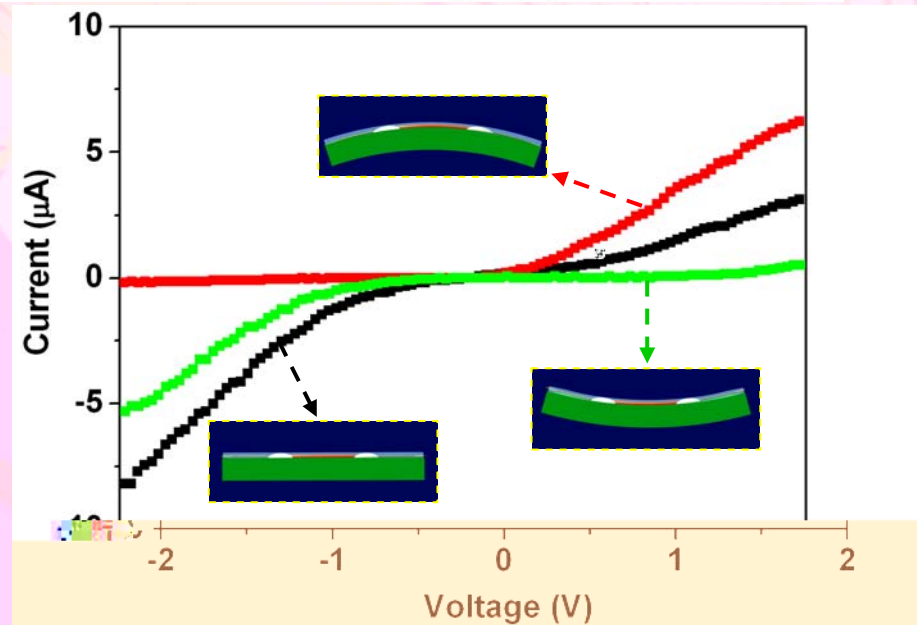
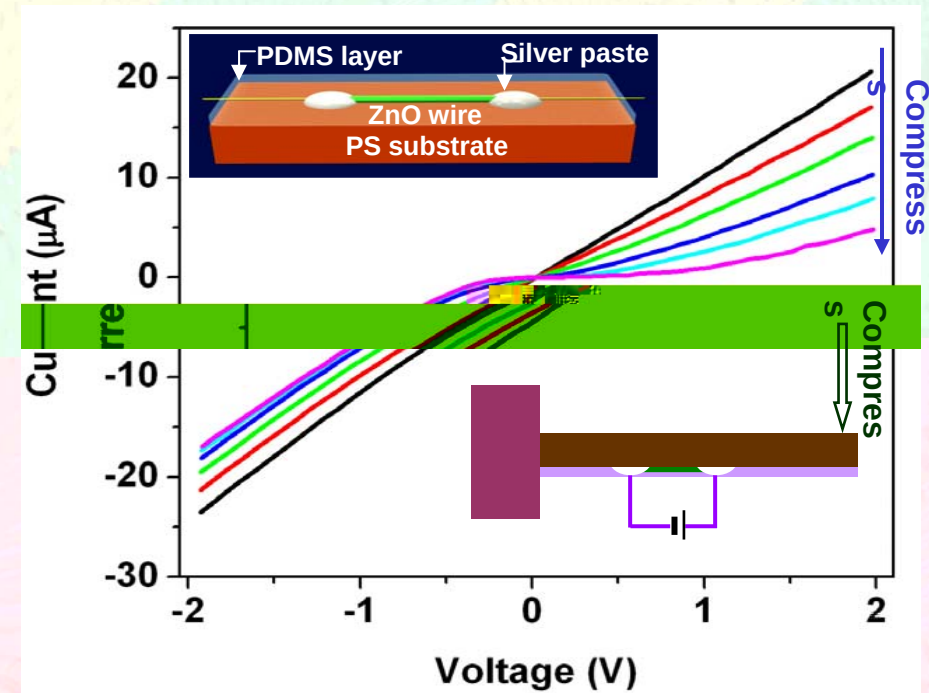
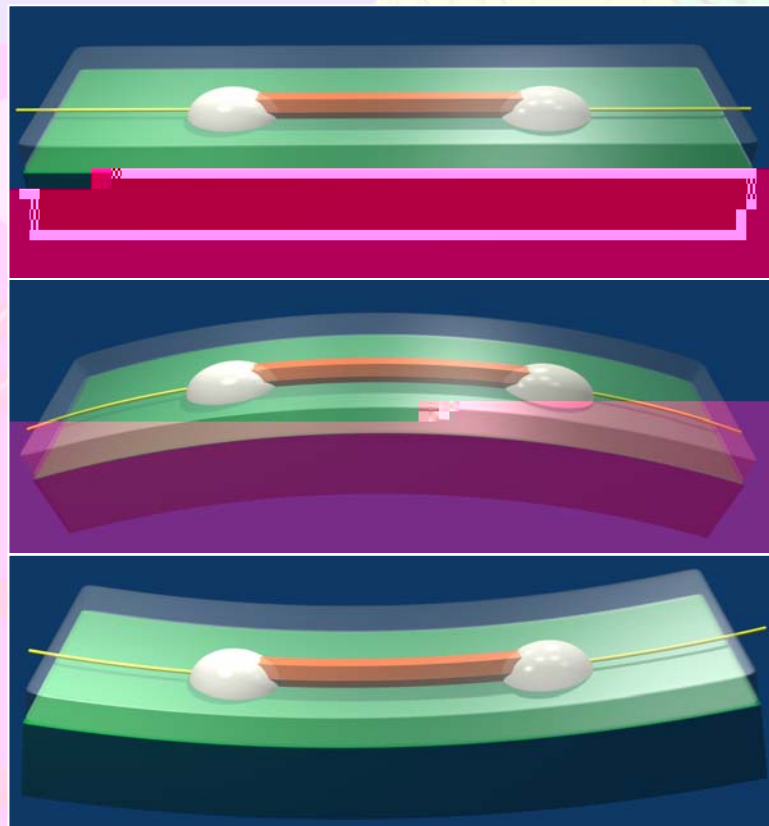
Adv. Mater., 19 (2007) 781.

Piezoelectric diode



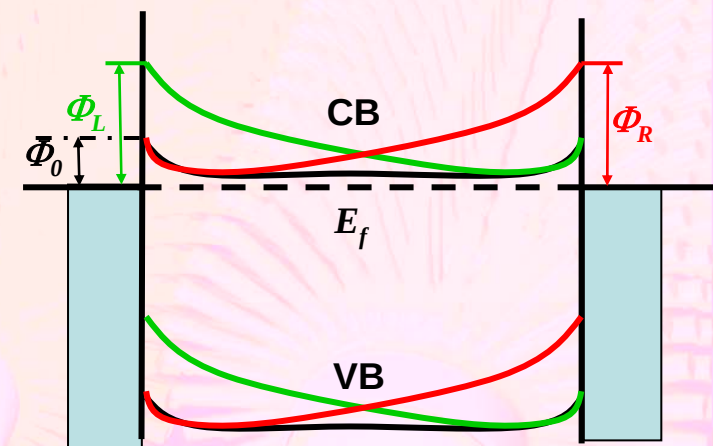
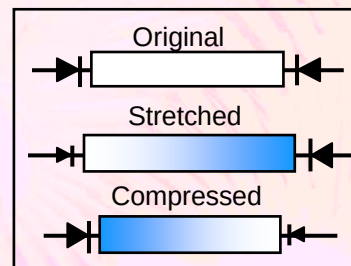
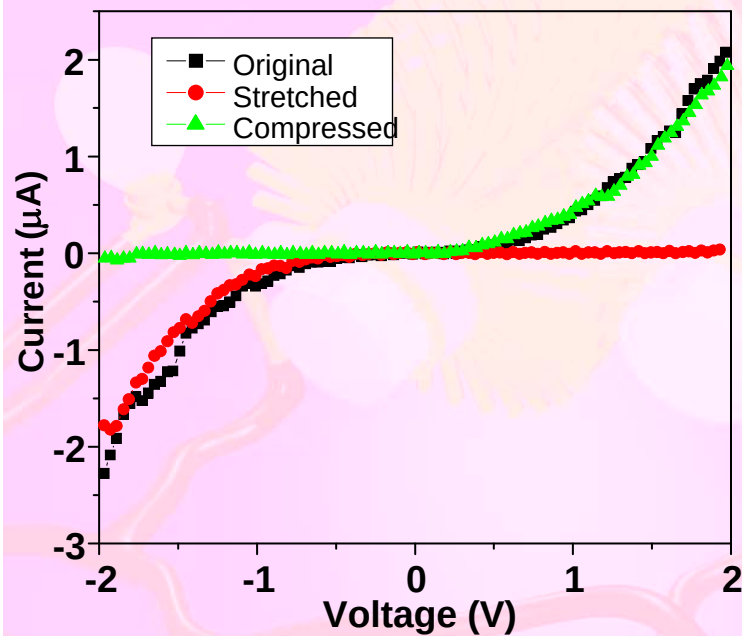
Adv. Mater., 19 (2007) 781.

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



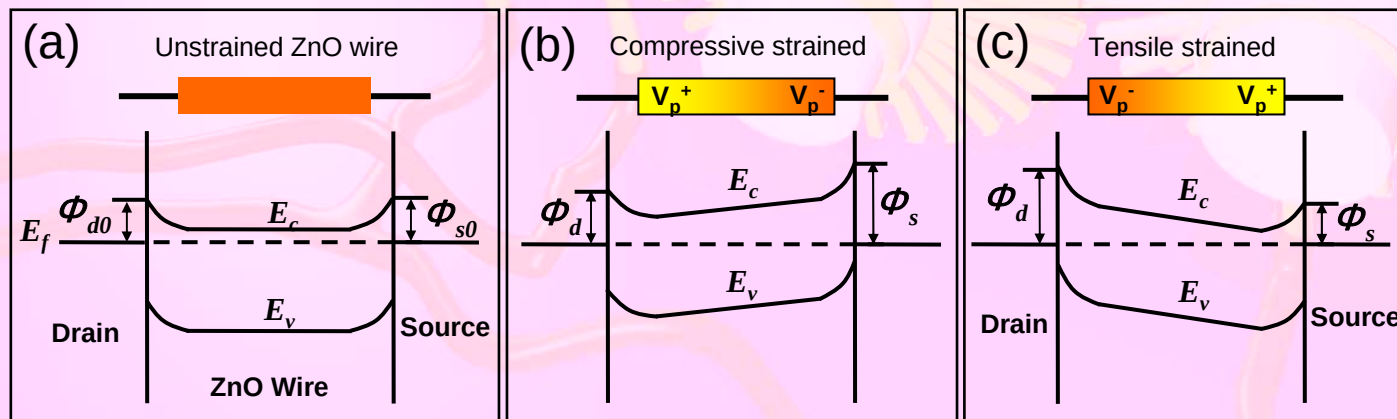
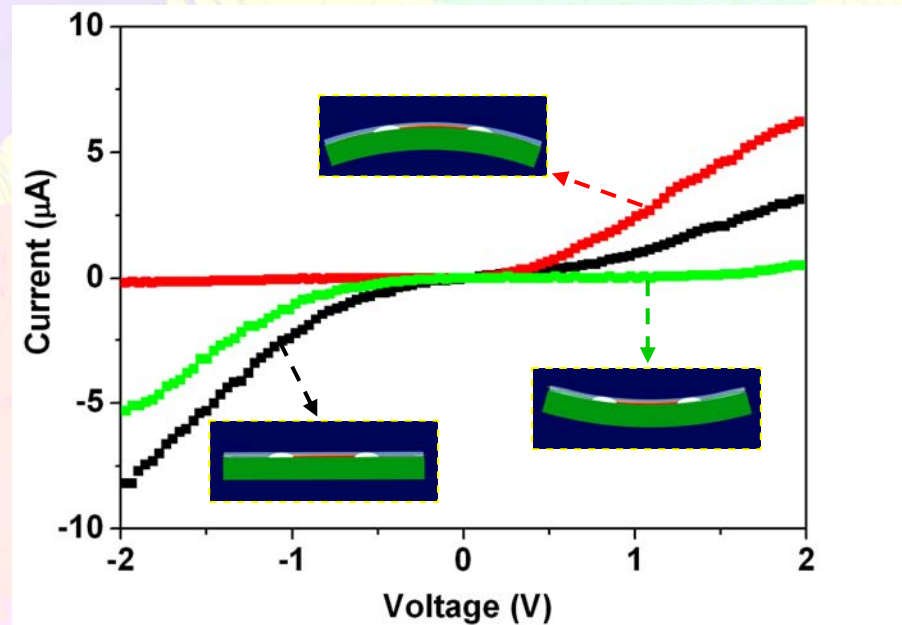
Nano Letters, 8 (2008) 3973.

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





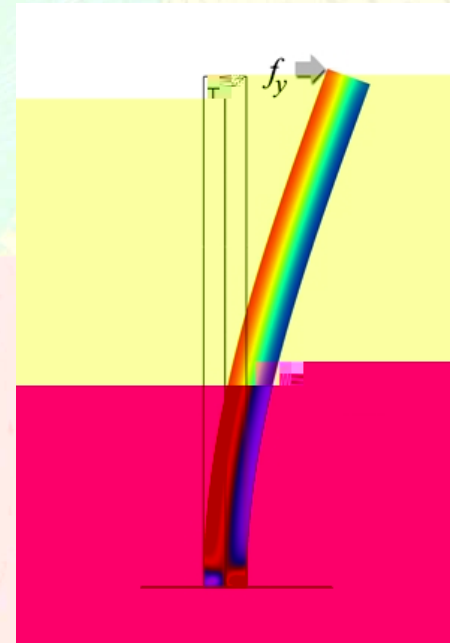
Nanopiezotronics III:

Free-standing FET based piezoelectric force/flow sensor

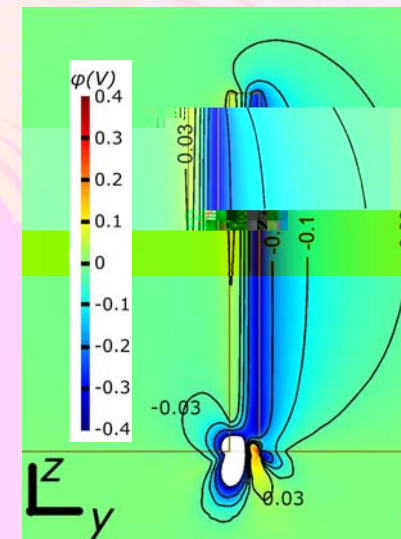
Fei, Huang, Wang* , Nano Letters, submitted

Piezoelectric potential at the root of a free-standing nanowire

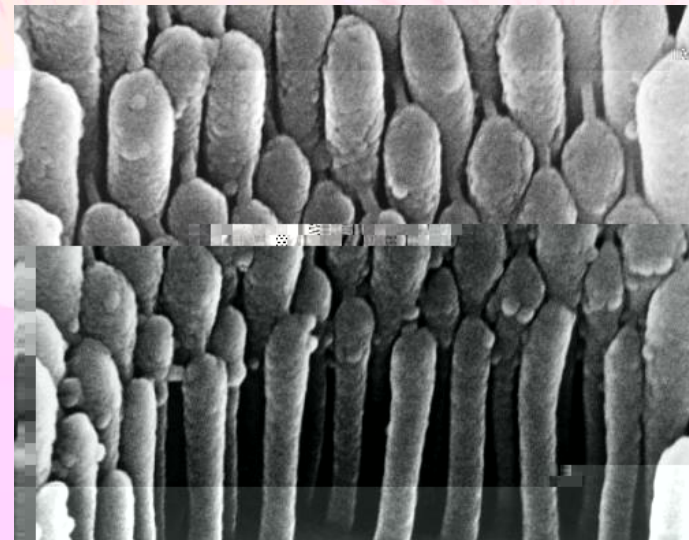
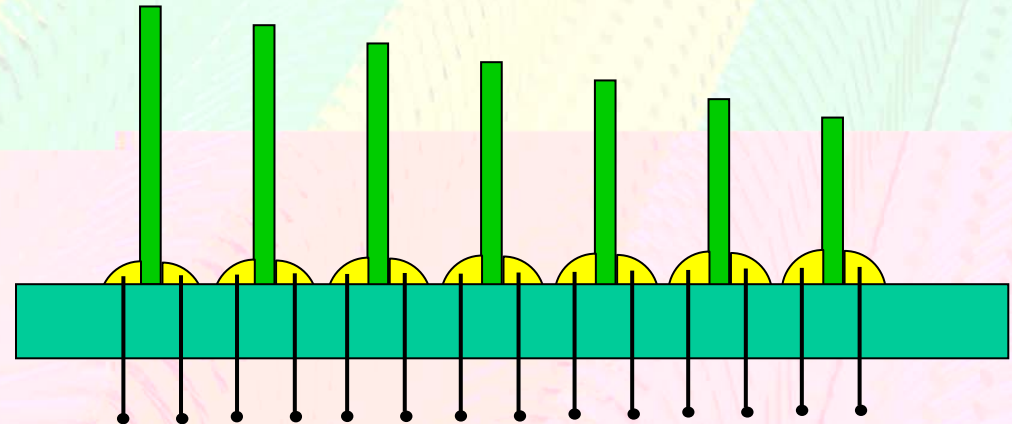
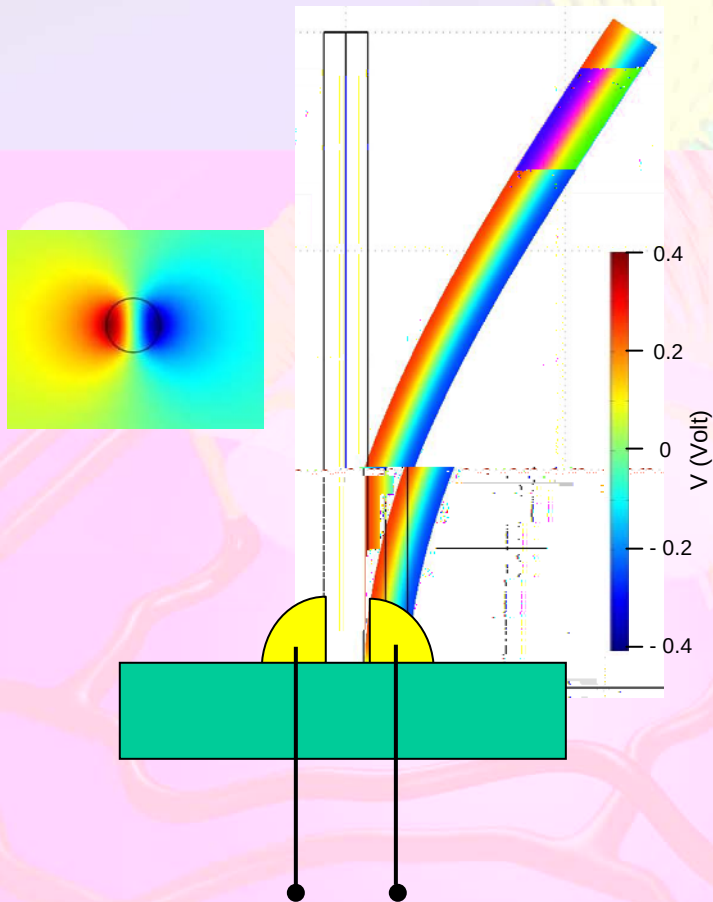
Gao and Wang “Electrostatic Potential in a Bent Piezoelectric Nanowire – The Fundamental Theory of Nanogenerator and Nanopiezotronics”, Nano Letters, 7 (2007) 2499-2505.



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

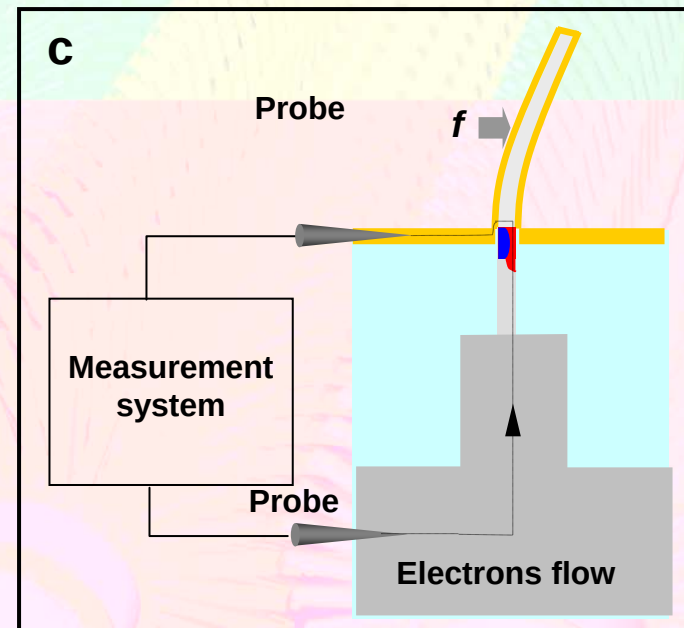
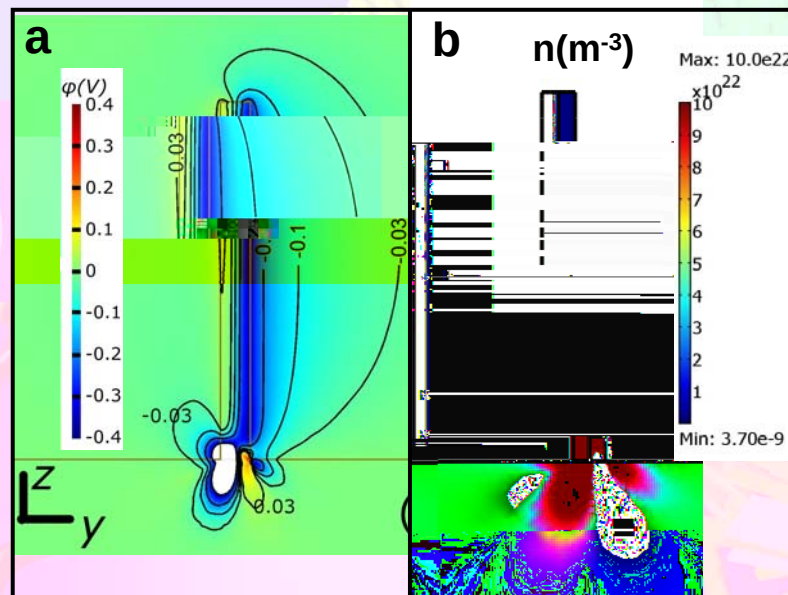


Design idea of hearing aid

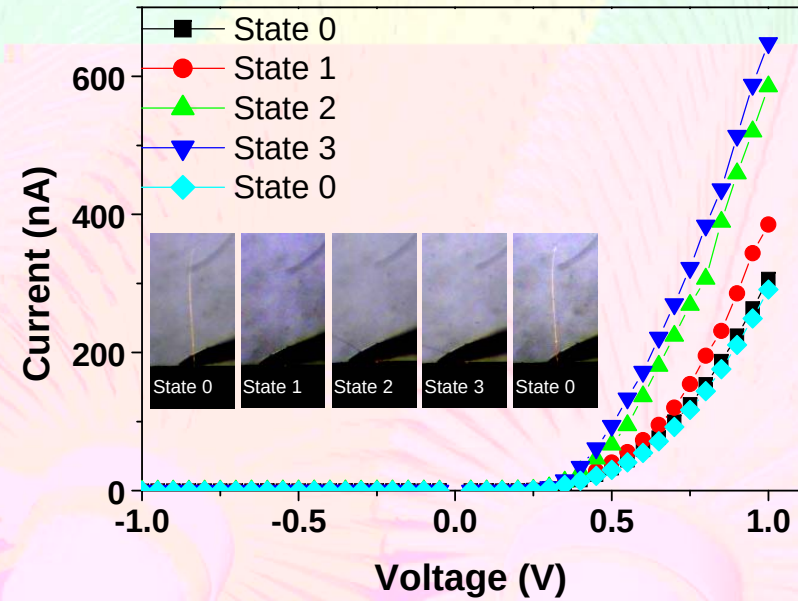
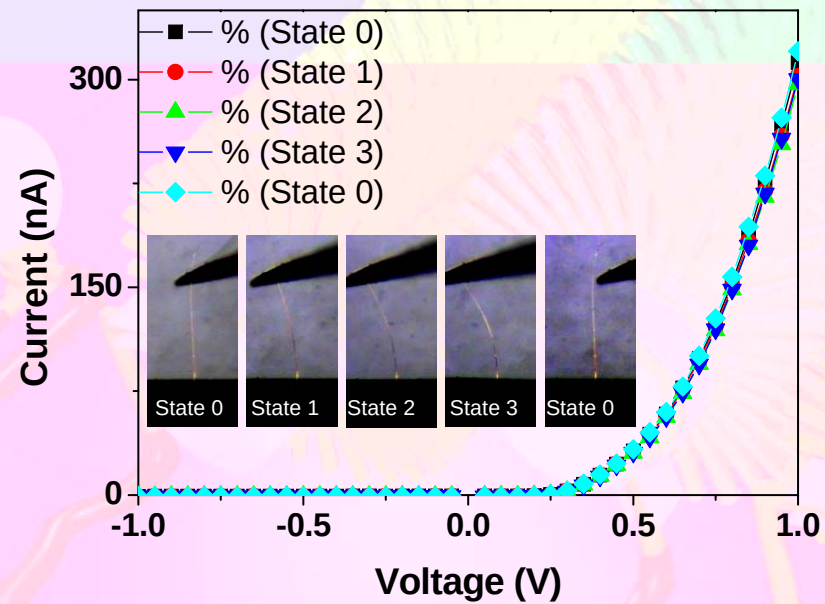


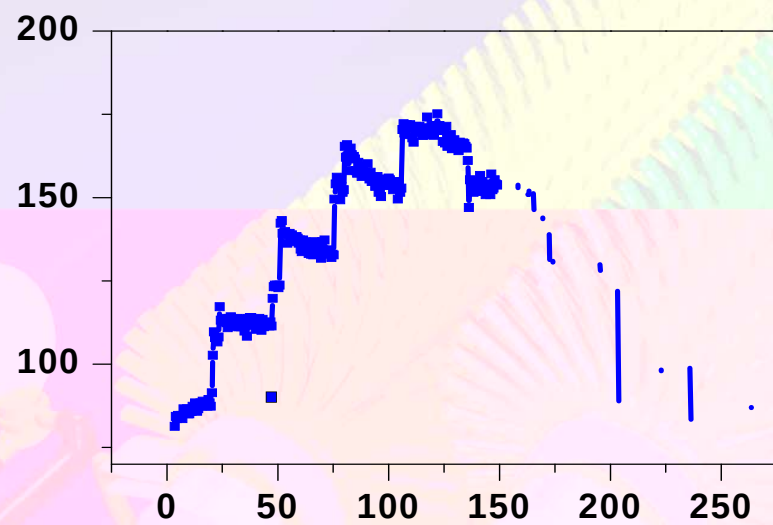
Inner year cell

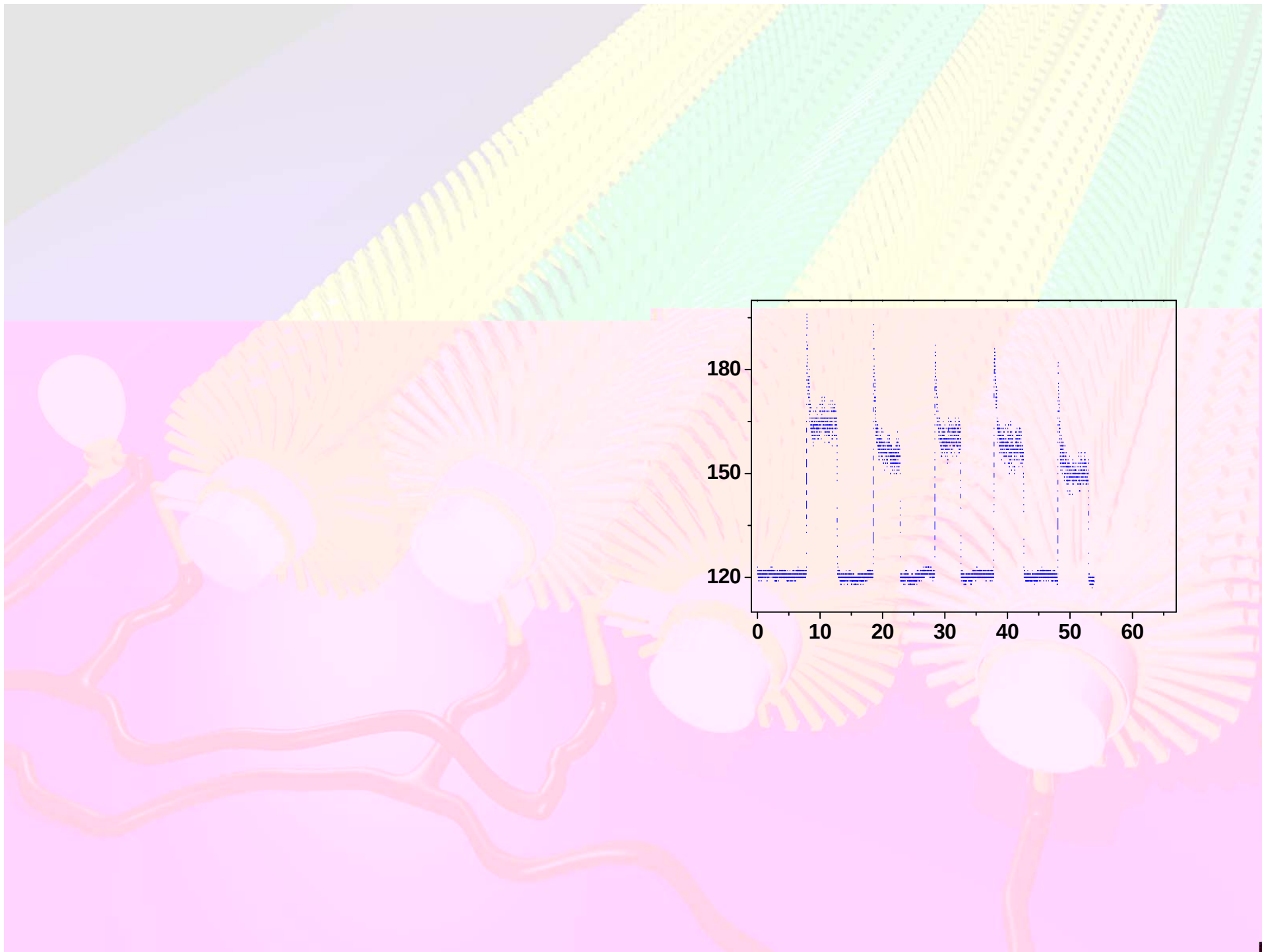
Theoretical basis of free-standing nanowire nanosensors



Experimental testing about the piezopotential at the nanowire root





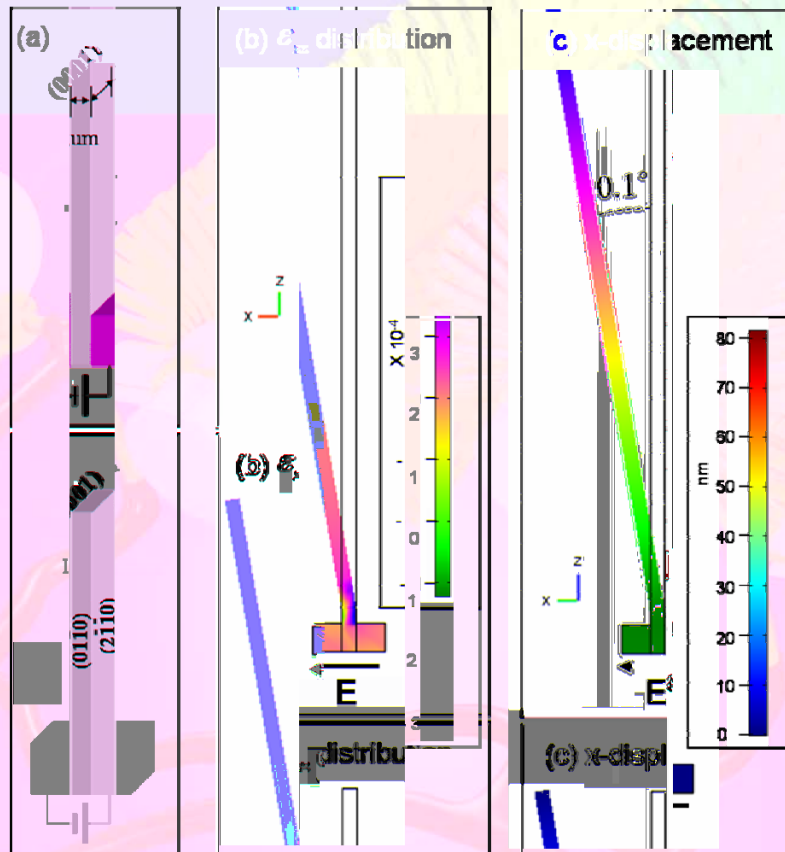




Converse piezoelectric sensor/transducer using free-standing nanowires

Hu, Wang, Nano Letters, in press

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



Piezoelectric equations

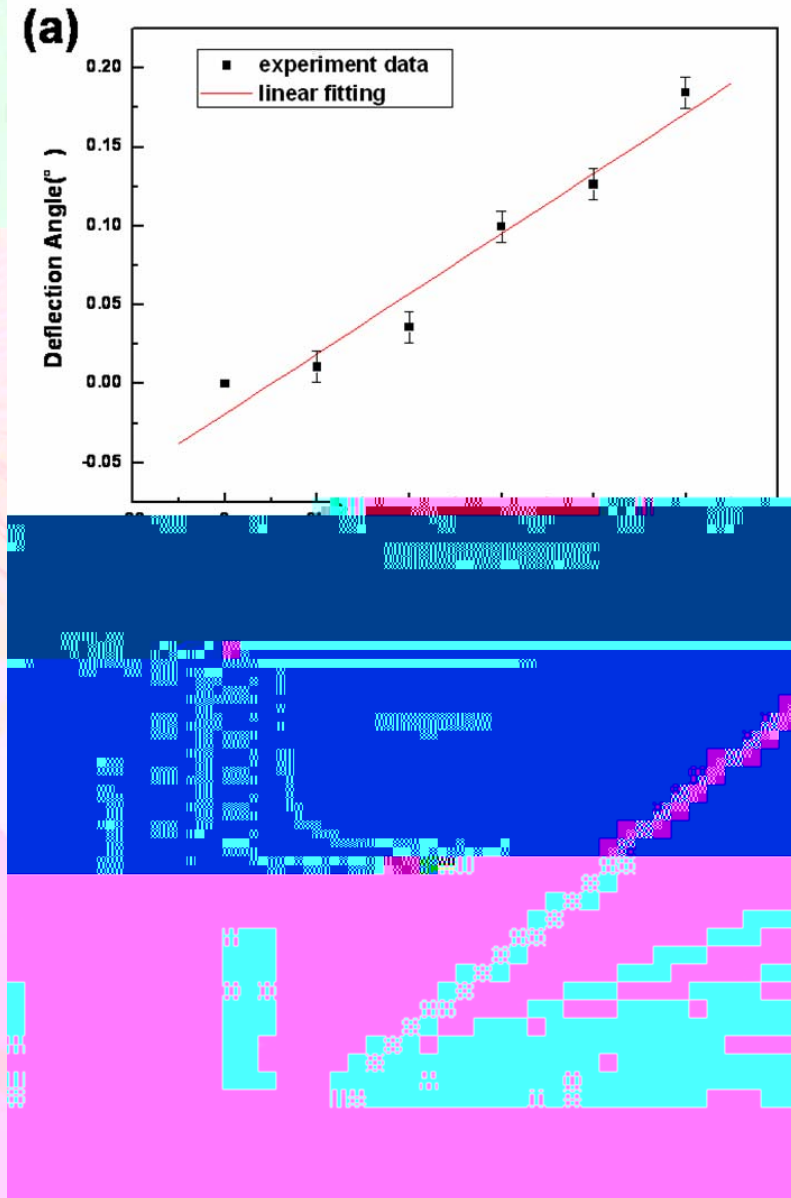
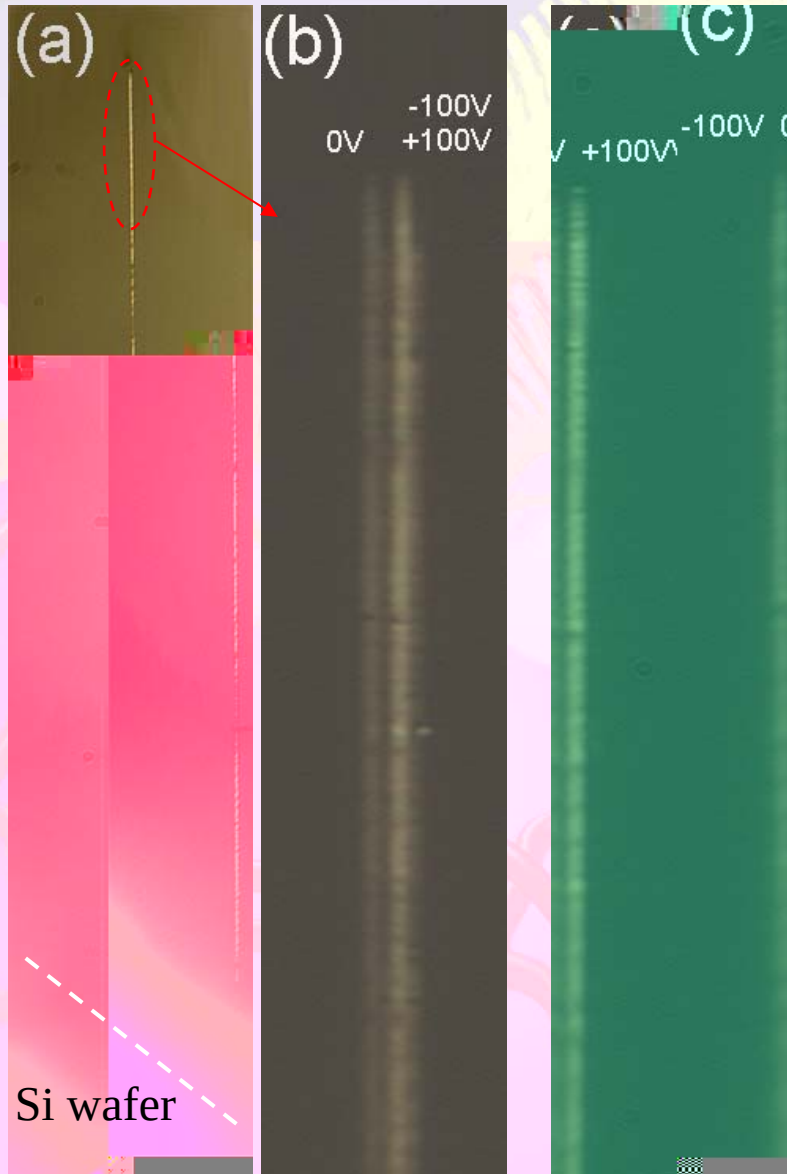
$$\begin{cases} \sigma_p = c_{pq} \varepsilon_q - e_{kp} E_k \\ D_i = e_{iq} \varepsilon_q + \kappa_{ik} E_k \end{cases}$$

Piezoelectric tensor

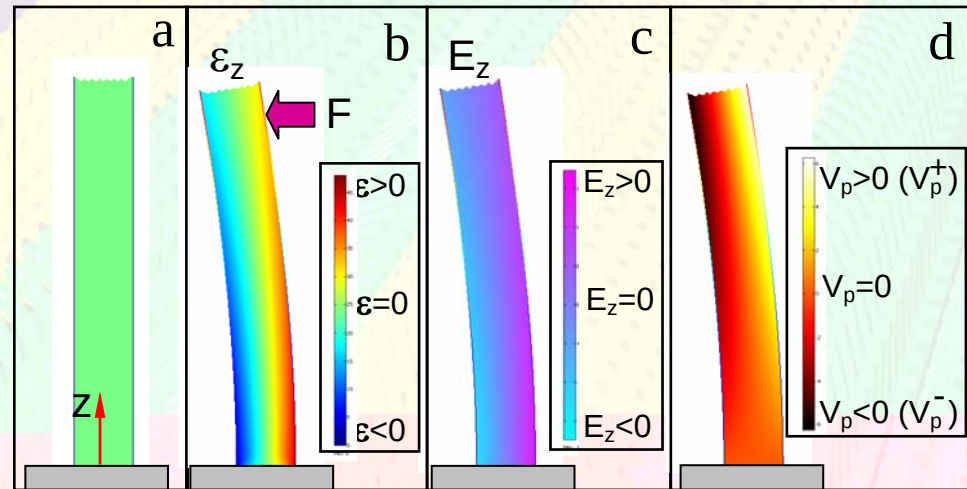
$$e_{iq} = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix}$$

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



DOI: 10.1002/adma.200602918

Nanopiezotronics**

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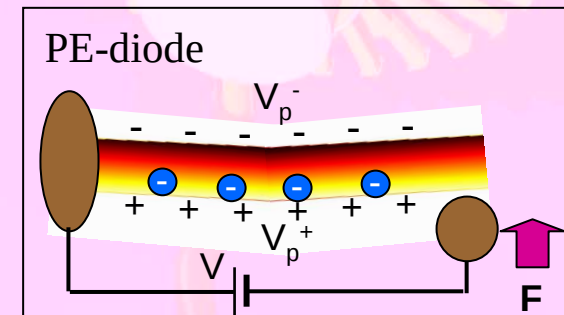
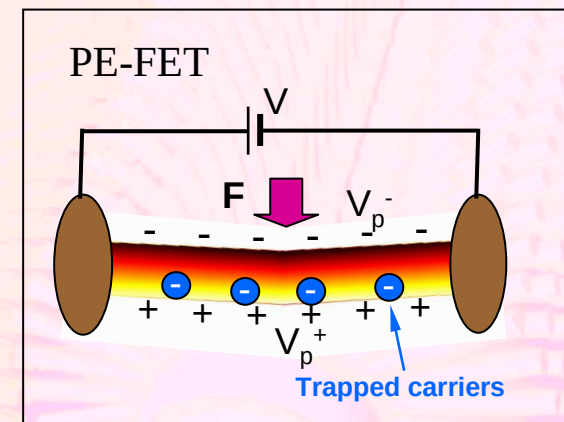
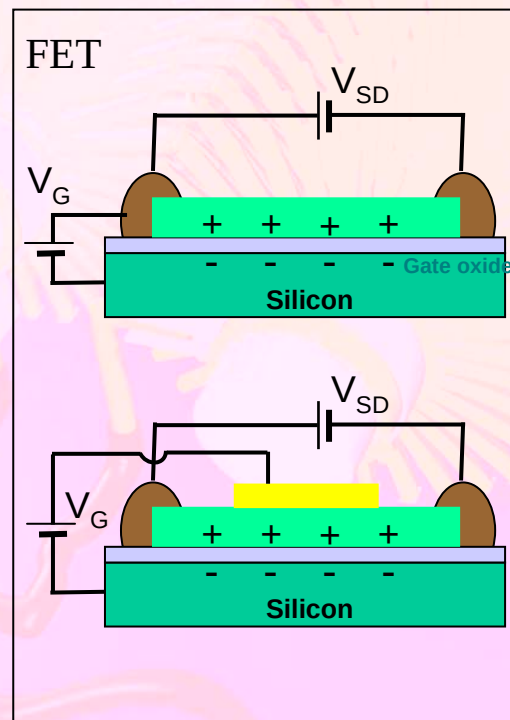
By Zhong Lin Wang

fundamental principle of nanopiezotronics, piezoelectric and semiconducting properties of nanowires and nanocatalytic electronic devices and components, such as field-effect transistors, nanowire-based sensors, and nanowire-based energy harvesters.

This article introduces the fundamental principle of nanopiezotronics, piezoelectric and semiconducting properties of nanowires and nanocatalytic electronic devices and components, such as field-effect transistors, nanowire-based sensors, and nanowire-based energy harvesters.

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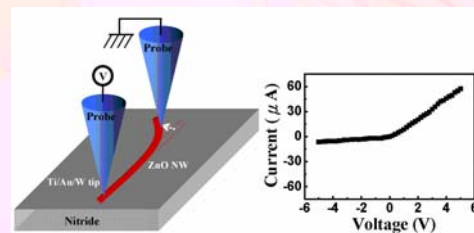
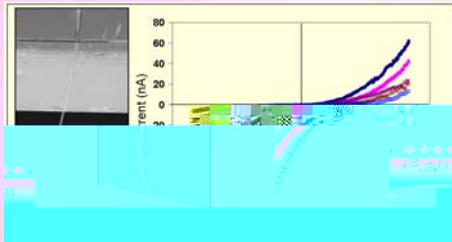
Materials Today, 10 (2007) 20-28;
Adv. Mater., 19 (2007) 889-992



Nano-Piezotronics

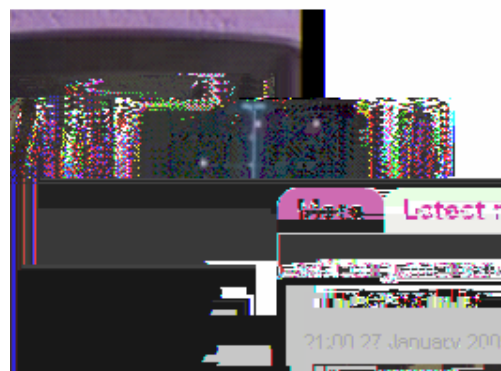
➤ **Piezotronics** is a field of using piezoelectric-semiconducting coupled properties/effects for creating/fabricating novel and unique electronic devices and components (ZLW).

Piezoelectric-field effect transistor



ces that could soon be in your hands

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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](#)

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.

Technology Review: TR10: Nanopiezoelectronics - Microsoft Internet Explorer

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Technology Review: March/April 2009

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March/April 2009

TR10: Nanopiezoelectronics

Zhong Lin Wang thinks piezoelectricity could power implantable medical devices and more.

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

MULTIMEDIA

Zhong Lin Wang describes his work to power the nanoworld.

Nanoscale sensors are exquisitely sensitive with power, and, of course, tiny. They are detecting molecular signs of disease in tiny amounts of poisonous gases in the air, and contaminants in food. But the batteries and circuits necessary to drive these devices make them difficult to fully miniaturize. Zhong Lin Wang, a materials scientist at Georgia Tech, is to bring power to the nanoworld with minuscule generators that take advantage of piezoelectricity. The sur-

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Piezoelectric nanogenerator

- **Fundamental mechanism**
- **DC nanogenerators**
- **Fiber based nanogenerators**
- **Muscle driven nanogenerators**
- **Hybrid cell**

Nano-Piezotronics

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