OBRTNO-PODJETNIŠKA ZBORNICA SLOVENIJE

Jožef Stefan Institute

Novi materiali v energetiki in novi viri električne energije

New Materials in Energy and New Energy Sources

Marija Kosec[1], Danjela Kuščer[1], Janez Holc[1], Janez Škrlec[2]

[1]Institut "Jožef Stefan", Jamova cesta 39, 1000 Ljubljana

[2]Obrtno-podjetniška zbornica Slovenije, Celovška cesta 71, 1000 Ljubljana

marija.kosec@ijs.si

University of Maribor

University of Ljubljana

Energy agency of Podravje

Chamber of Craft and Small Business of Slovenia

19TH International Expert Meeting

KOMUNALNA ENERGETIKA

POWER ENGINEERING

May 11TH to 13TH 2010

Maribor, Slovenia

Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17 (entrance from Koroška cesta 50), Maribor, Slovenia

CONTENT

Introduction: renewable (alternative) energy sources

Solar energy: principles, materials

From maxi to mini devices

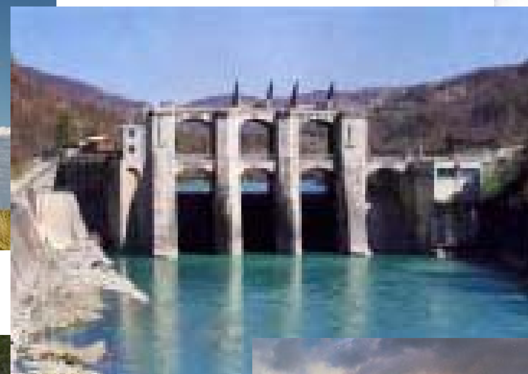
Energy Harvesting

Summary

Alternative Energy Sources of the Future

Wind power

Water power



Geothermal power

Biomass

Solar Power

Integration in nature: three energy sources

WE ARE INTERESTING IN MATERIALS THAT TRANSFORM NATURAL ENERGY SOURCE INTO ELECTRICAL ENERGY

SOLAR ENERGY

Industry exhibits 30 % annual growth
The most extensive material research

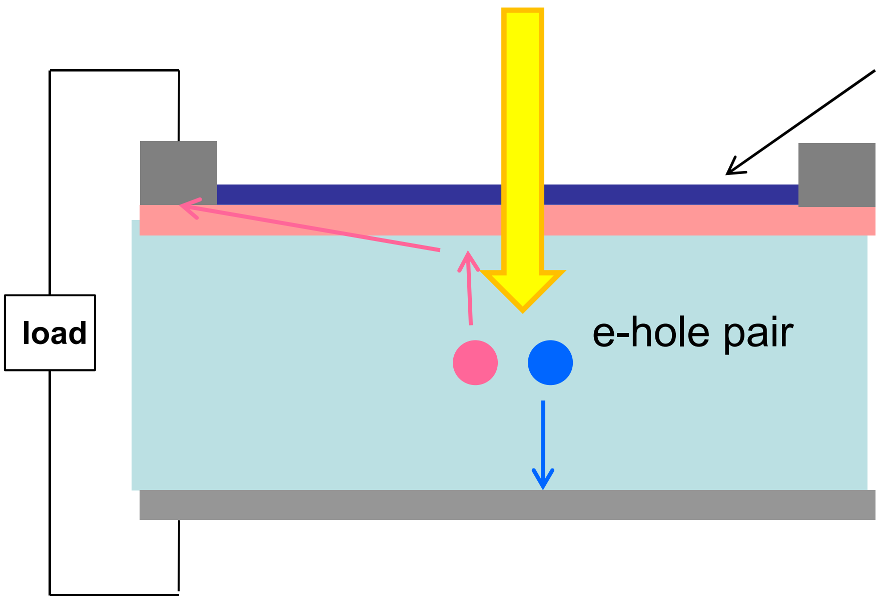
Photons → Electricity

$E=h\gamma \xrightarrow{\text{material}} e^-$

Industrial and research area: Photovoltaic
Devices: solar cells (SC), photovoltaic cell (PC)

Solar Cells/Photovoltaic

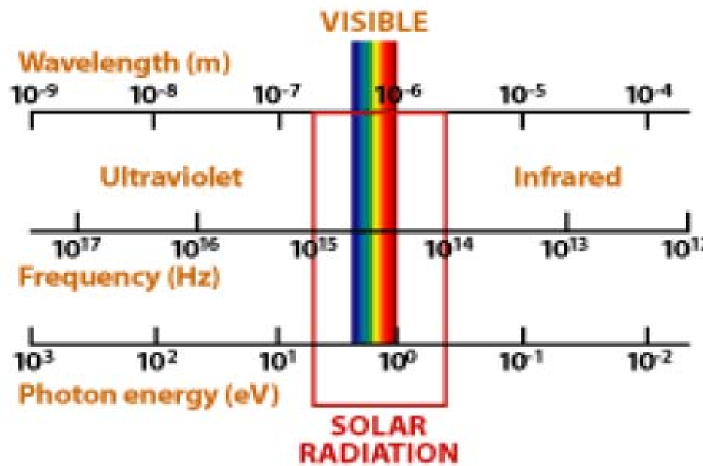
How Solar Cells Work?



Hetero-junction

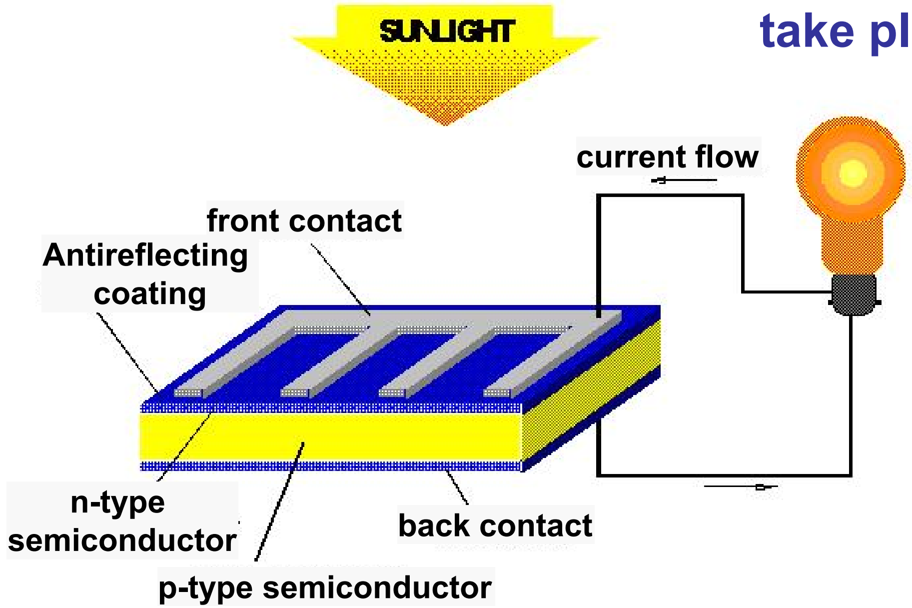
Solar cells are devices that convert light energy directly to electricity:

- Photon excites valence electron
- Electron-hole pair created
- Electron and holes separate
- Band-gap determines what is adsorbed

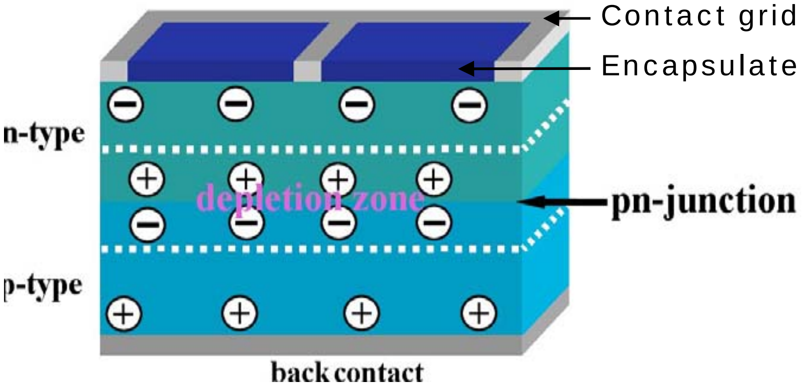


Entire spectrum of sunlight (0.5-2.9 eV)

Semiconducting p-n based solar cells



Absorption of light and transport of electron take place in the same media



The p-n junction allows electrons and holes to move in one direction.
If we provide an external conductive path, electrons will flow through this path to their original (p-type) side to recombine with holes.

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Dye-Sensitised Solar Cells (Photoelectrochemical, Graetzel, DSSC)

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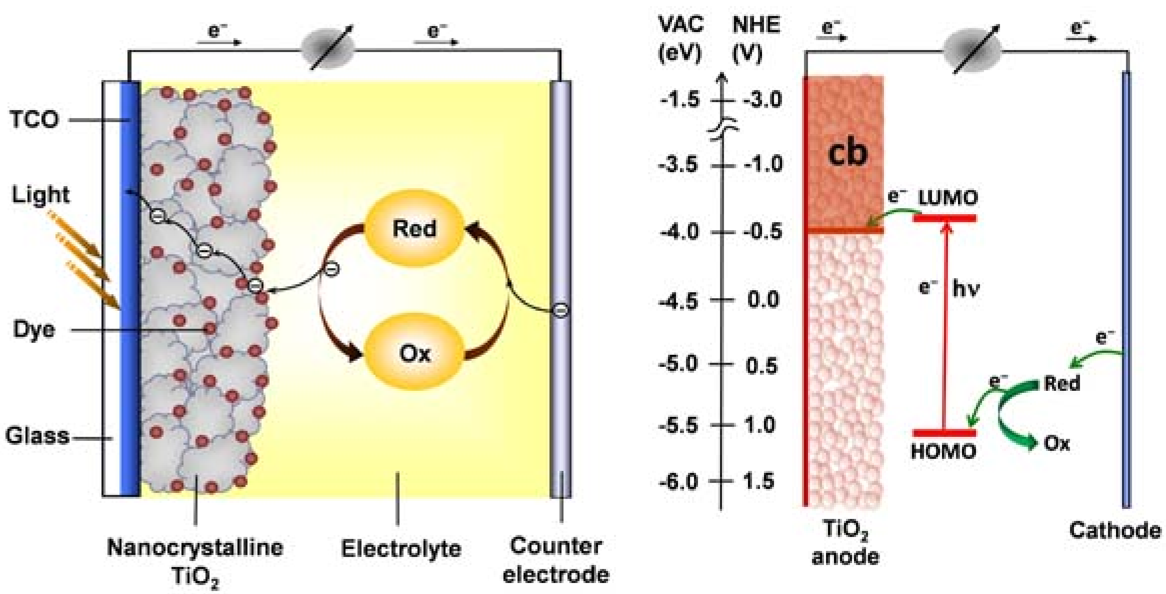
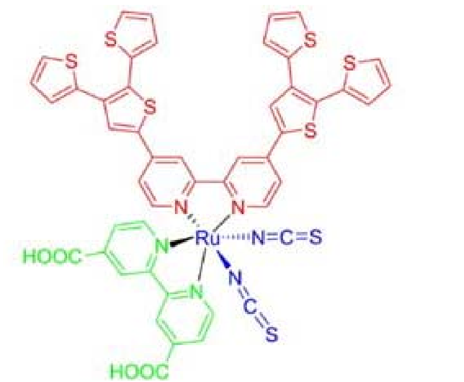
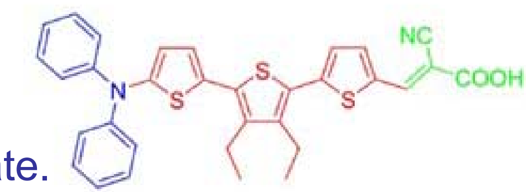
Absorption of light and transport of electron take place in different media



Fundamental processes and energy level diagram of a dye-sensitized solar cell



Thiophene-based Ru^{II}-complex



Metal-free organic dye

- The adsorbed dye molecule adsorb a photon forming an excited state.
- The excited dye transferes an electron to the TiO_2.
- This separate the electron-hole pair leaving the hole on the dye.
- The hole is filled by the electron from the iodine ion.

http://www.uni-ulm.de/en/nawi/institute-of-organic-chemistry-ii-and-advanced-materials/research/research-groups-rg/dyes-for-organic-solar-cells.html

SEMICONDUCTING p-n

Bulk

Bulk
Si, GaAs, AlGaAs

Thin Films

Thin Film
Ionorganic
•a-Si, microcrystalline Si, polycrystalline Si
• CdTe/CdS
• CsT/CuInGaSe_2 (CIGS)

•Polymers
•Conjugated co-polymer

Nano

•Hybride
•Polymer+C60, TiO_2 nano particles
CdS nano particles

•Polymer-nanorods CdT
•Polymer-aligned nano nanorods CdT
•Si nano-tubes
•Quantum dots
•Nanowire

DYE-SENSITISED

TiO_2 mesoporous thick films, dye, iodine electrolyte

Dye

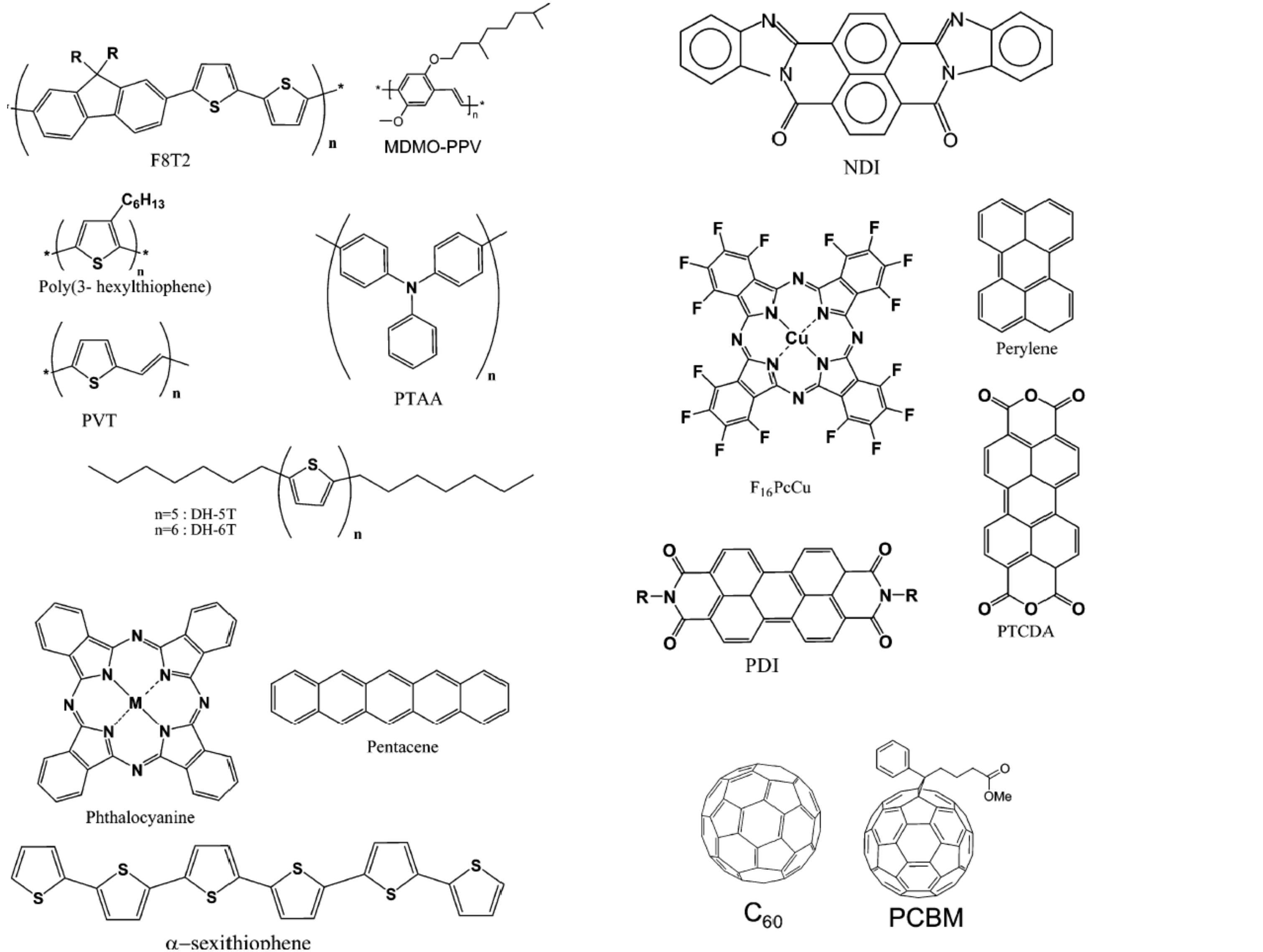
Quantum dots

p-type semiconductors

Advanced trends in PCmaterials: examples

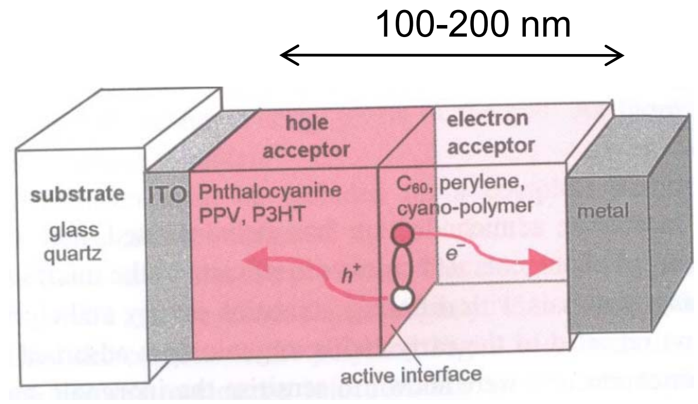
- Organic and hybrid cells
- Nano-crystalline TiO_2 Film (DSSC)
- Quantum dot solar cells
- Nanowire solar cells

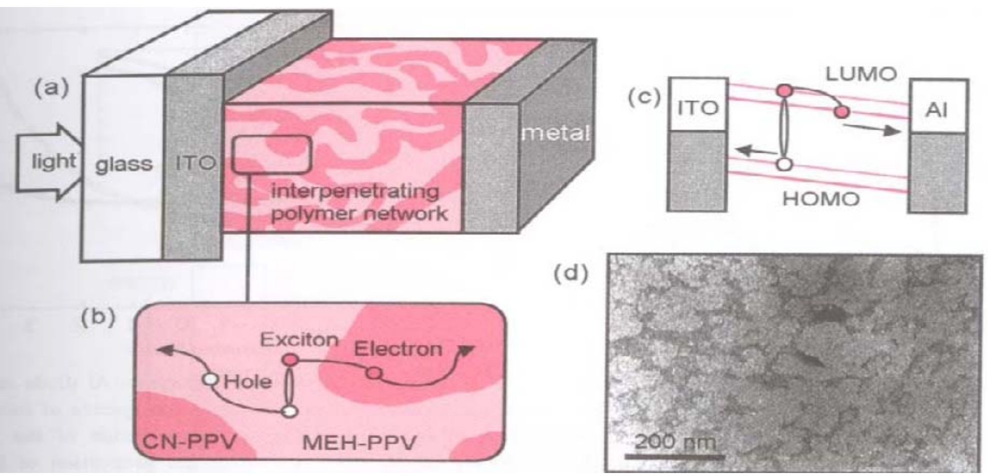
Organic semiconductors used in organic solar cells



Organic Hetero-Junction solar cells

- First organic cells built in the 50‘ had very low efficiency (0.01 %)
- Due to very short diffusion length for excitions (about 10 nm), only the charges very close to the junction could be efficiently separated and collected by the electrodes.





A composite of two organic semiconductors sandwithed between two electrodes results in increasing efficiency of solar cell.

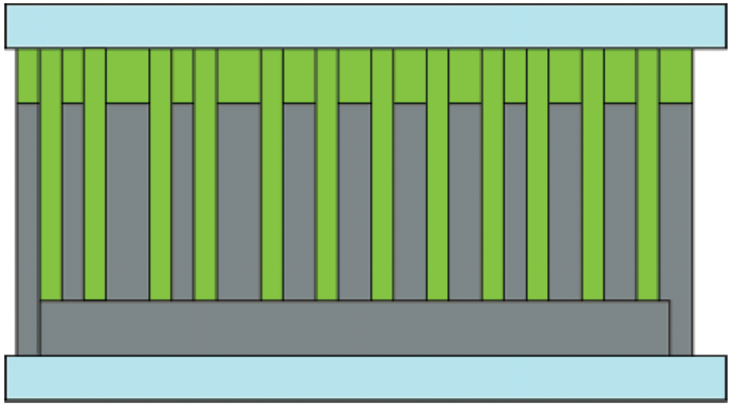
- Nano-scale p-n junction.
- Density of p-n junctions higher
- Larger interfacial area

Hybrid solar cells

•A composite of organic and inorganic semiconductors
(P3OT:CdTe, CuPC:Si, P3HT:TiO_2, P3HT:CIS)

• Inorganic semiconductors have much higher carrier mobility than the organic ones.

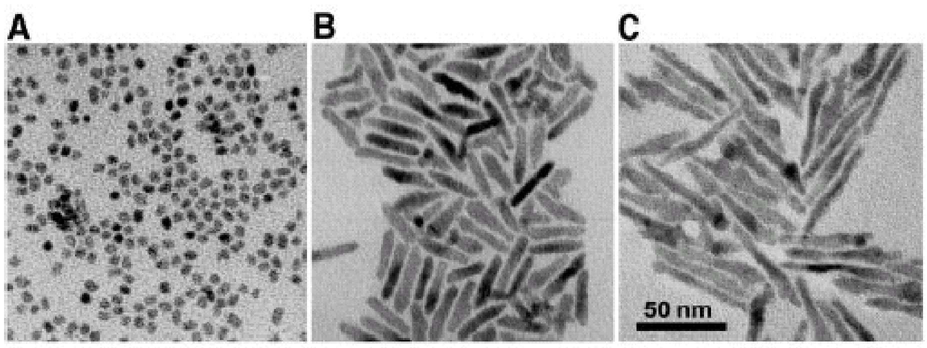
•They can be produced in the form of nanocrystal in order to control the ordering of the microstructure.



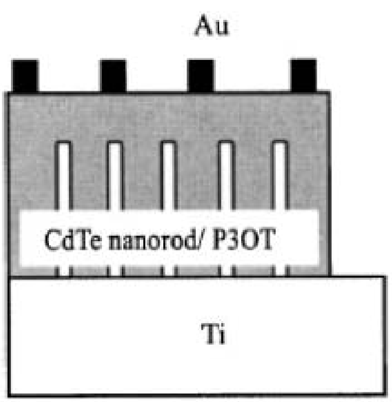
The two phases have to be integrated in percolated highways to ensure high mobility charge carrier transport with reduced recombination. Interspace: 10-20 nm.

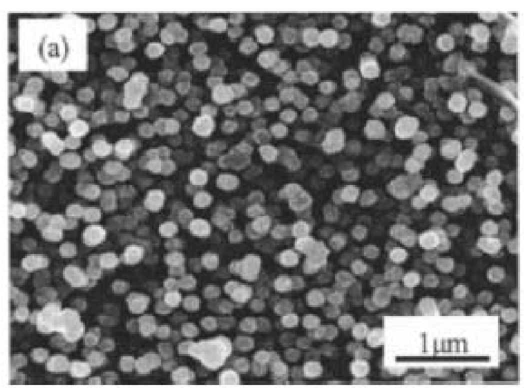
Hybrid solar cells

Hybrid solar cell with vertically aligned CdTe nanorods and a conjugated polymere.

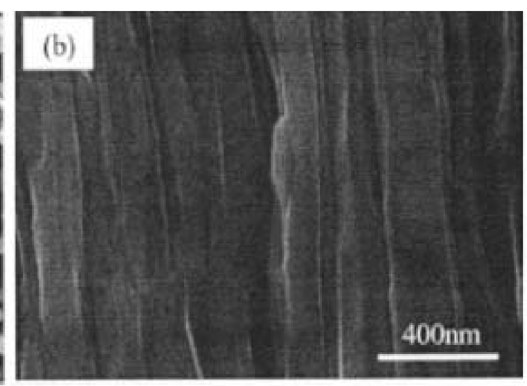


CdTe nanocrystals with dimensions
A) 7 nm by 7 nm
B) 7 nm by 30 nm
C) 7 nm by 60 nm





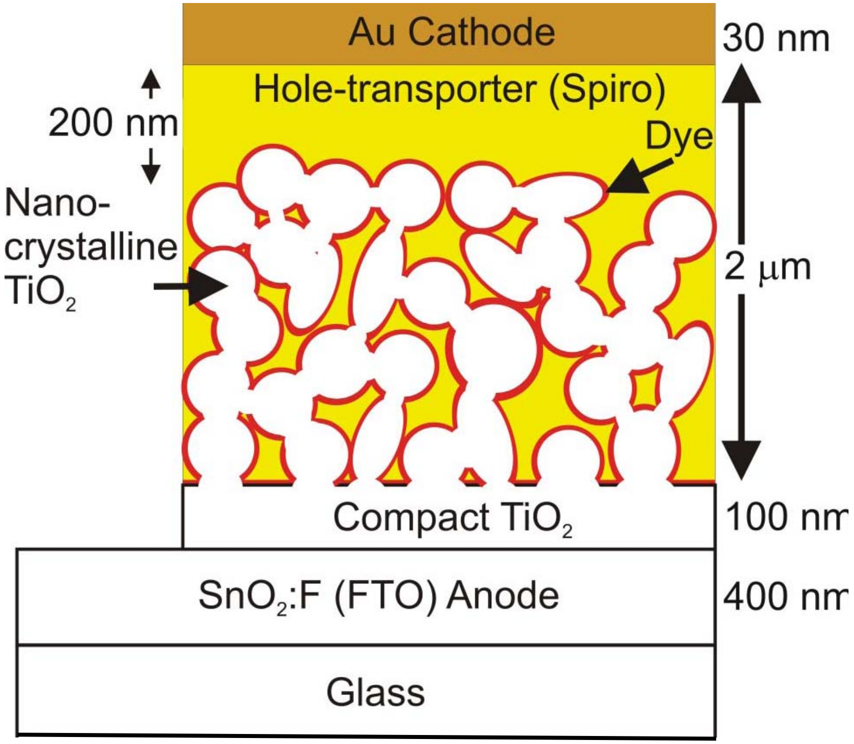
Top view of the vertically aligned CdTe nanorods

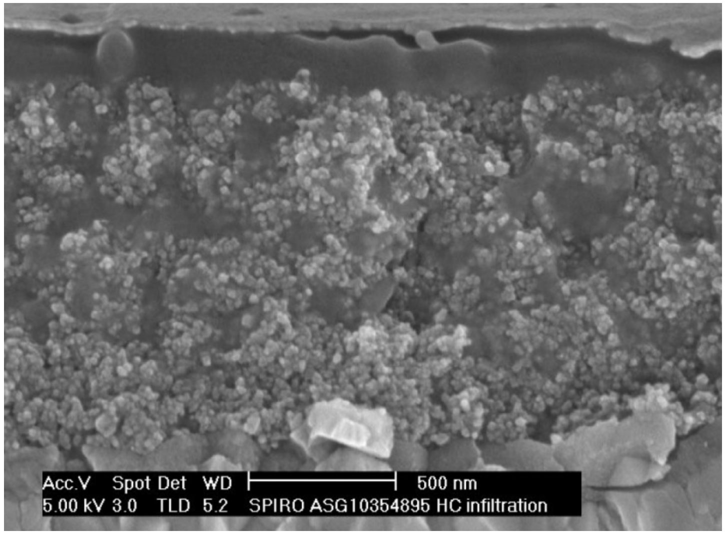


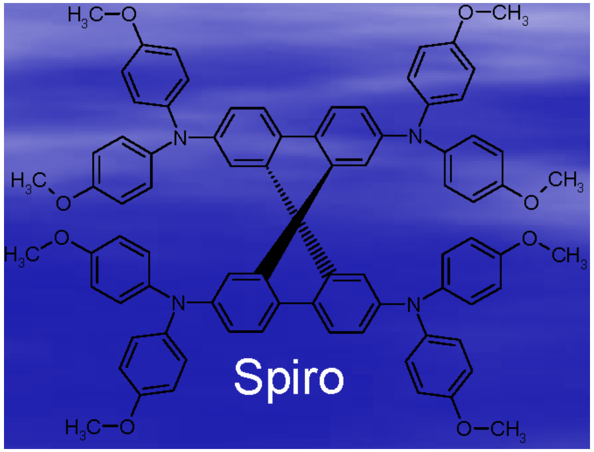
Cross section of the composite layer.

Kang et al, Appl. Phys. Lett. 86 (2005), 113101.

Solid-State DSSC solar cells



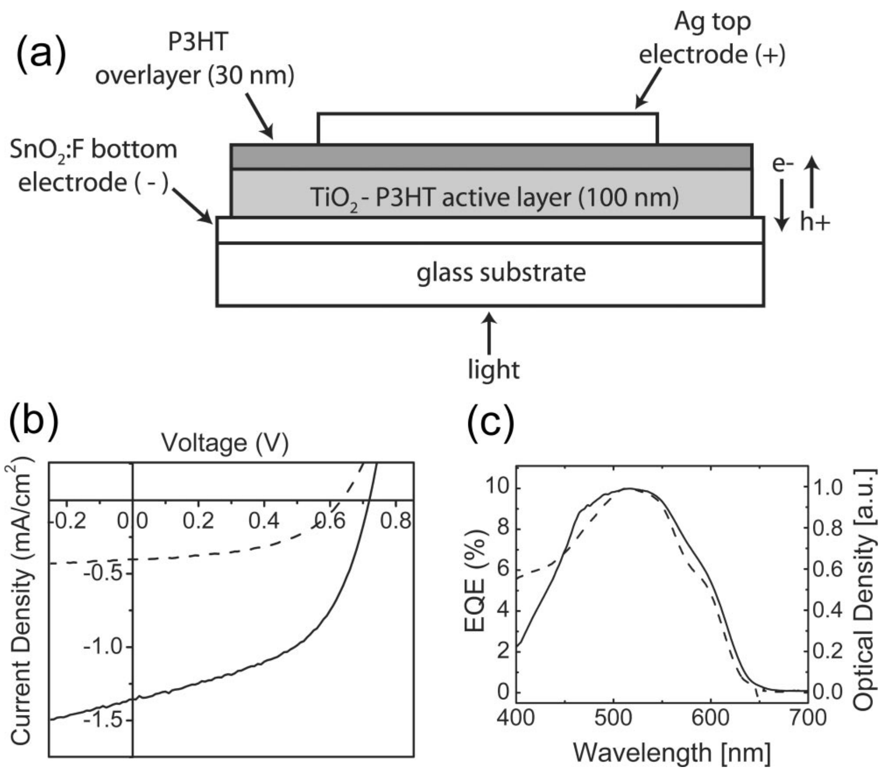


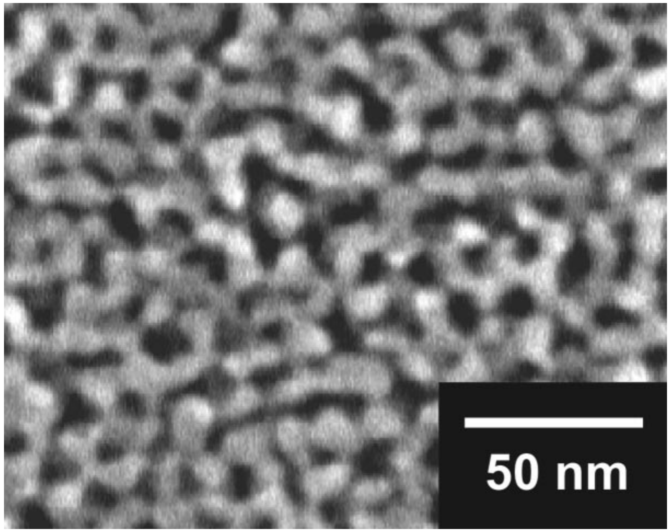


Ligh adsorption in dye, electron transfer to TiO_2, hole transfer to Spiro-MeODAT.

Bach et al, Nature 395 (1998), 583-85.

Nano-crystalline TiO_2 DSSC solar cells

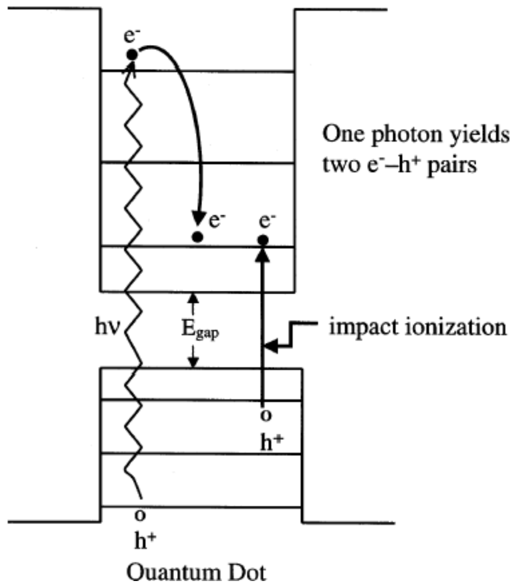


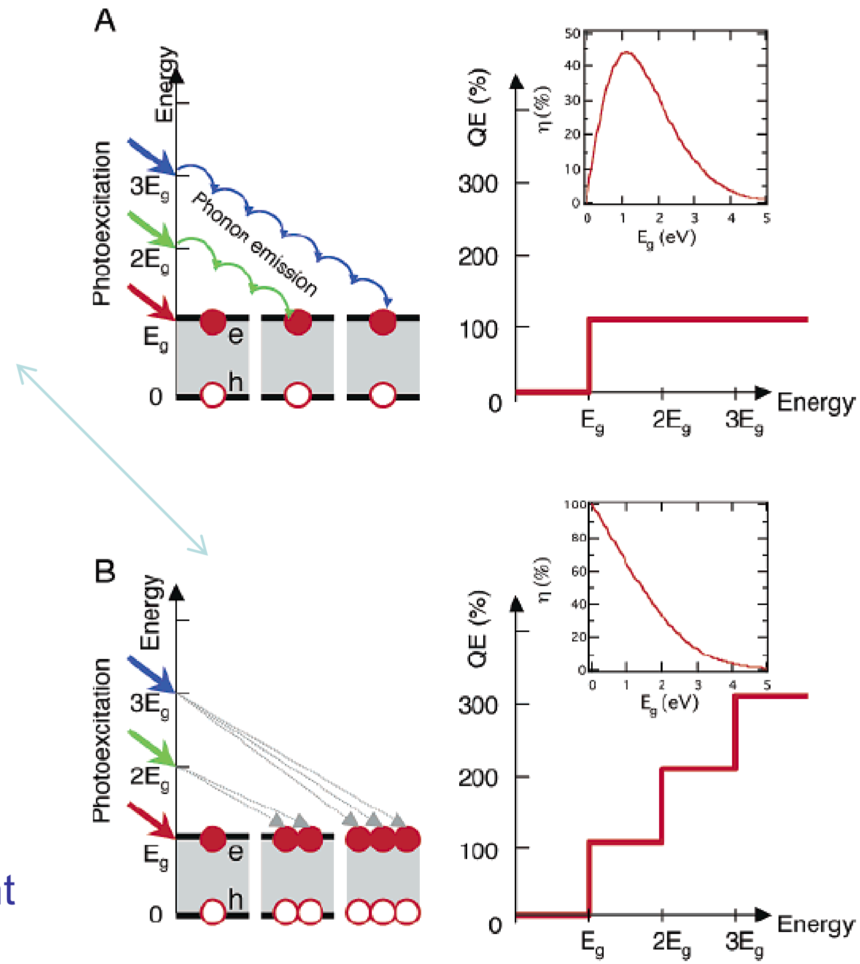


SEM top view image of a mesoporous TiO_2 film following calcination at 400 °C. The pore diameter in the plane of the film is 10 nm.

App. Phys. Lett., 83(2003) 3380-83.

Quantum Dot solar cells

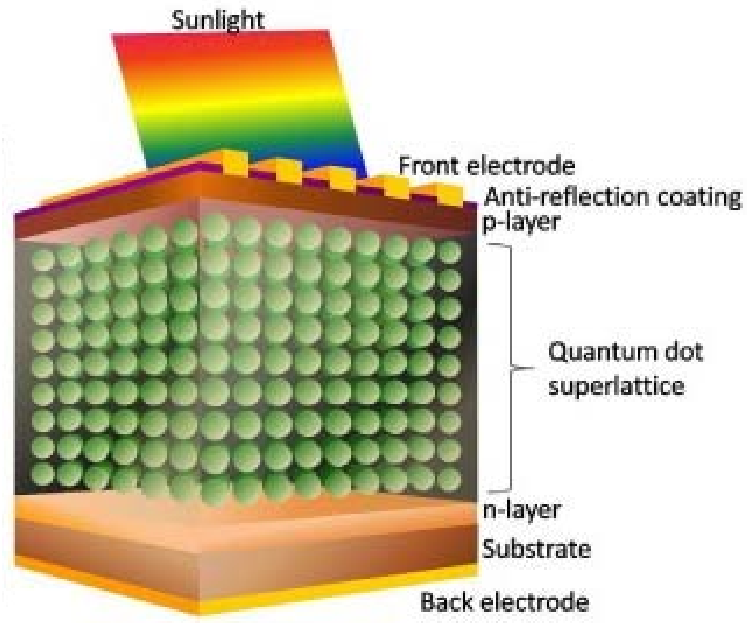




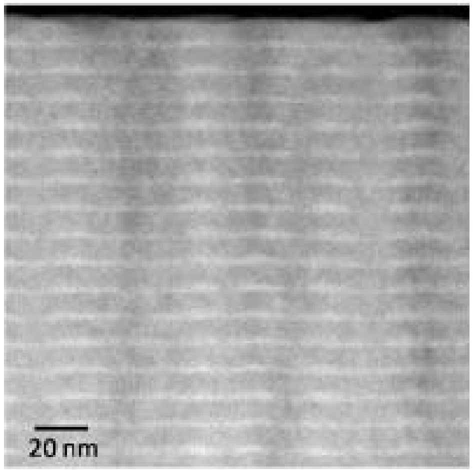
One photon of solar energy excites one electron in conventional PV cells, but possibly more than one "exciton" in quantum dots. By varying their size, quantum dots can be "tuned" to different wavelengths, dramatically increasing their efficiency in capturing solar energy.

Nozik et al, Physica E 14 (2002), 115.
Schaler et al, Nano Letters 6 (2006), 424.

Quantum Dot solar cells



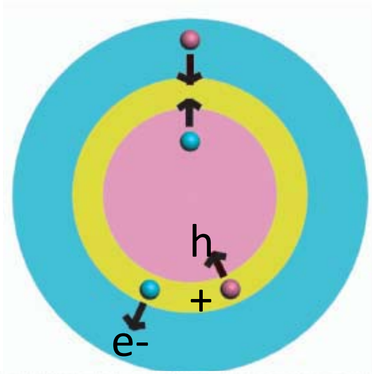
Schematic structure of quantum dot intermediate band solar cell



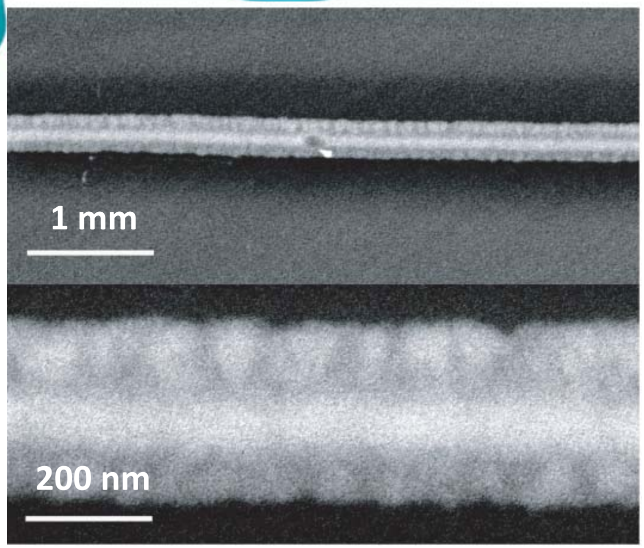
TEM image of self-organized quantum dot superlatice

http://www.ee.t.u-tokyo.ac.jp/gcoe/webmart_en/2009/09/research-on-future-generation.shtml

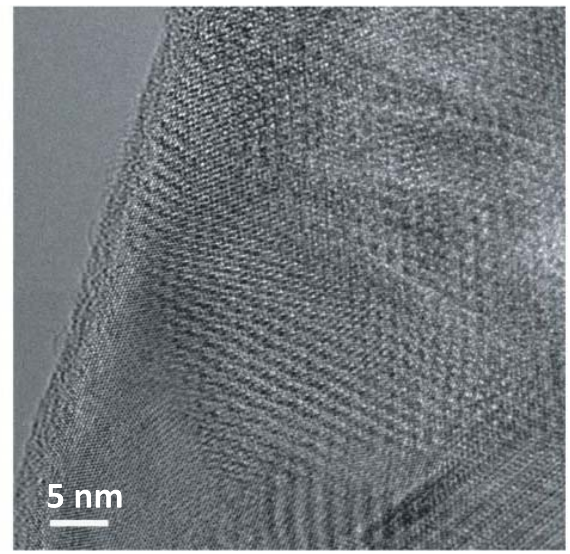
Coaxial-Silicon-Nanowires solar cells



Illustrations of the core/shell silicon nanowire structure; its cross-sectional diagram shows that the photogenerated electrons (e-) and holes (h+) are swept into the n-shell and p-core, respectively, by the built-in electric field.



SEM images of the p-i-n coaxial silicon nanowire. The p-i-n silicon nanowire was grown with 100-nm-diameter gold catalyst, and with i and n-shell growth times of 60 min and 30 min, respectively.

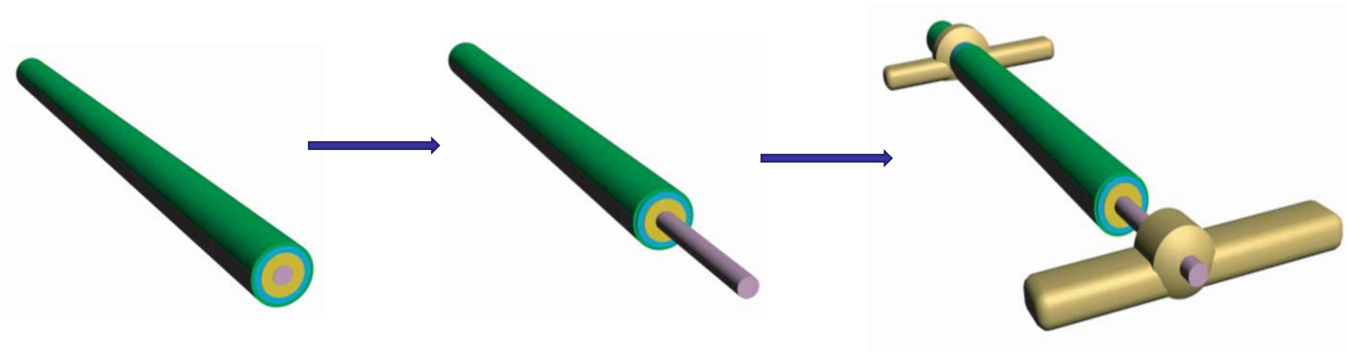


High-resolution TEM image of the p-i-n coaxial silicon nanowire.

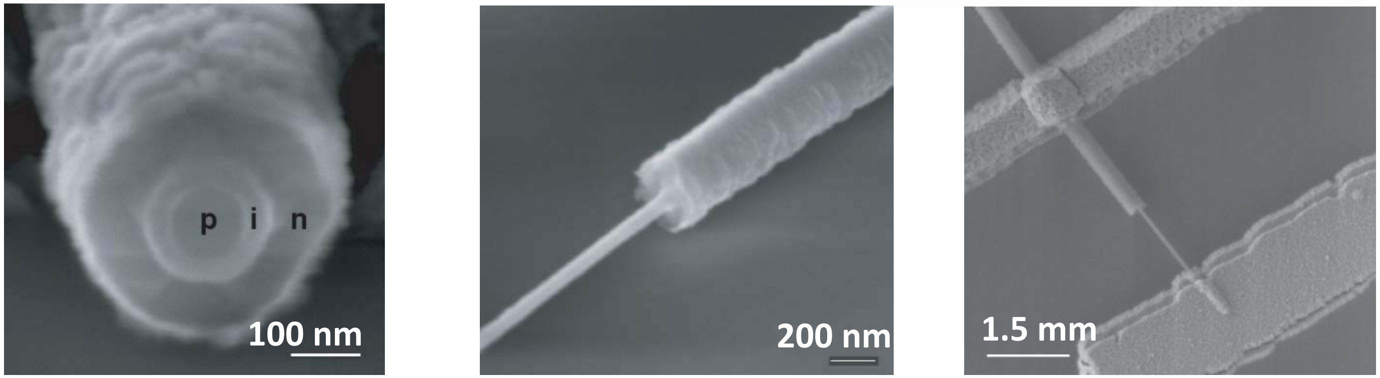
Lieber et al, Nature 449 (2007), 885.

Coaxial silicon nanowires solar cells

a)



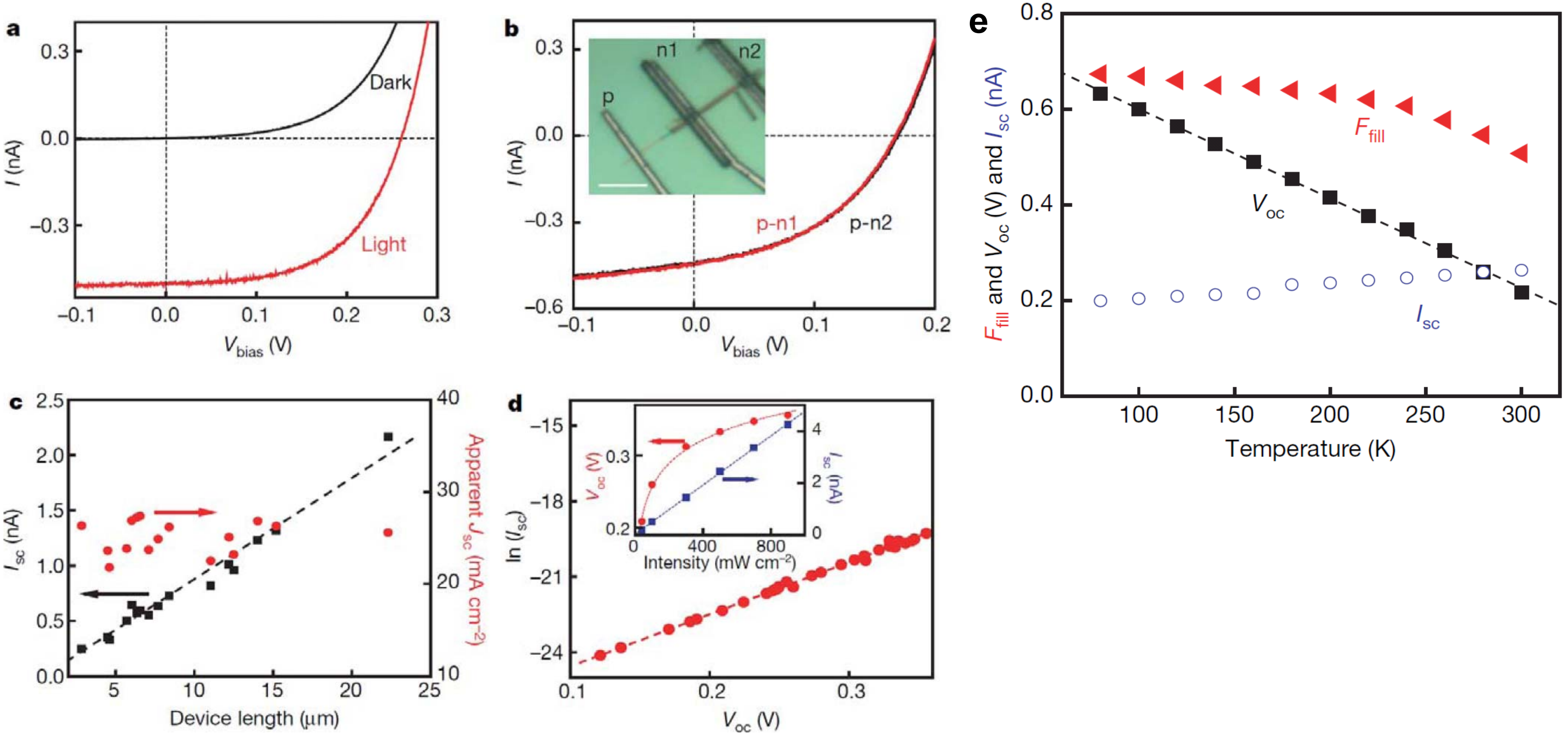
b)



a) Schematics of device fabrication. Left, pink, yellow, cyan and green layers correspond to the p-core, i-shell, n-shell and PECVD-coated SiO_2, respectively. Middle, selective etching to expose the p-core. Right, metal contacts deposited on the p-core and n-shell. b) SEM images corresponding to schematics in a.

Lieber et al, Nature 449 (2007), 885.

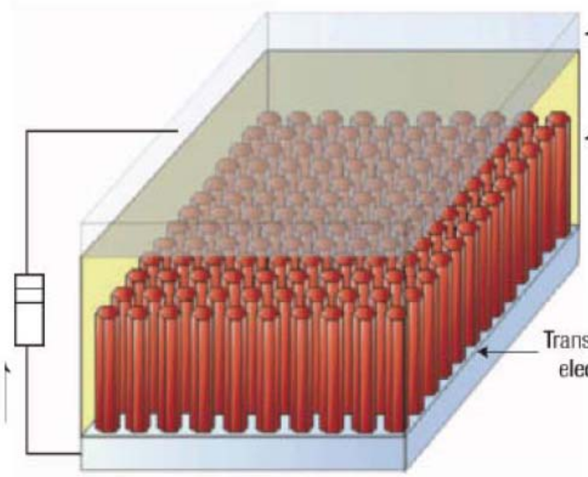
Characterisation of **coaxial silicon nanowires solar cells**

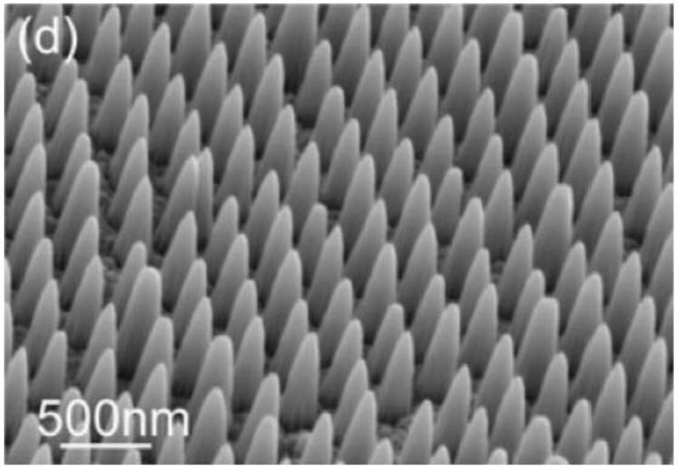


The **overall apparent efficiency** of the p-i-n coaxial silicon nanowire photovoltaic elements – **3.4 %** (upper bound) and **2.3 %** (lower bound)- exceeds reported nanorod/polymer and nanorod/dye systems, and could be increased substantially with improvements (surface pasivation).

Lieber et al, Nature 449 (2007), 885.

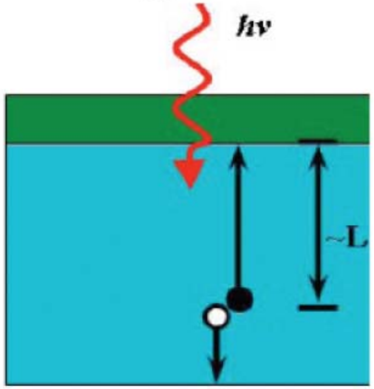
Nanowire application for solar cell

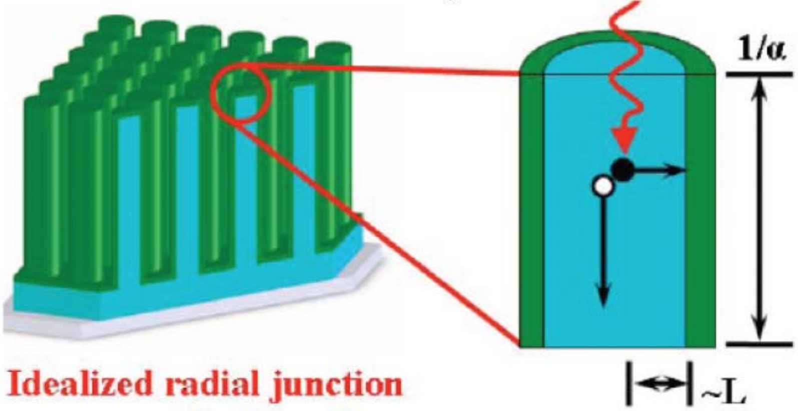




P. Yang, Nature Materials

Y. Cui, Stanford





Idealized radial junction nanorod solar cell

Nanowires decouple light absorption and carrier extraction into different directions !

Atwater, Caltech

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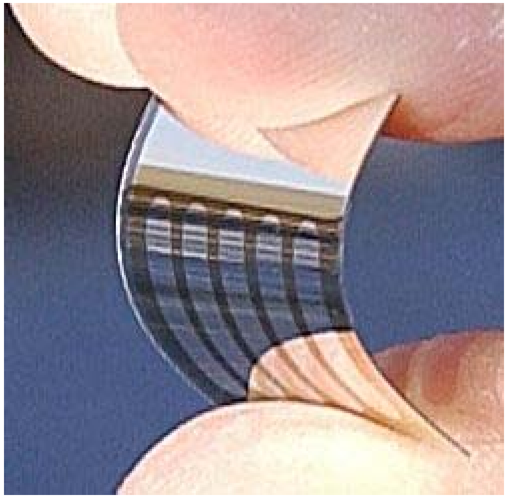
Today Choise of Solar Technologies

- Crystalline silicon
- Amorphous silicone
- Cadmium telluride
- Copper indium galium diselenide (CIGS)
- Dye sensitised solar cells (DSSC)
- Organic-polymere



Organic flexible solar cell

DSSC solar cell

CdSe solar cell

Thin Film technologies on the market

Nanoparticle Si

CIGS/CIS

Cd/Te

DCCS

Organic PV

http://ewh.ieee.org/r6/san_francisco/nntc/events/Nanosolar-IEEE%20SFBA%20Nanotech_JPark_061609.pdf

Type	Benefit	Efficiency	Challenges
a-Si Nano-Si	Thin film; Flexible substrate Roll-to-roll processing	8-10 %	Constant degradation low-efficiency
CdTe	Fairly high efficiency Well proven Lower cost/watt over life	9-11 %	Cd is toxic
Cu-In-Ga diselenide	High efficiency at low cost Long life, transparent, printable; no disposal problems	10-14 %	Price of indium New process stability
DSSC	Transparent/colours,; Printable, no disposal problems	11 %	Price of Ru Liquids handling Lifetime 5 years?
Organic	Potential for low-cost; large area; no disposal problems	2-6 %	Cost; Efficiency; Lifetime 1 year Narrow spectrum

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Organic Solar Cells

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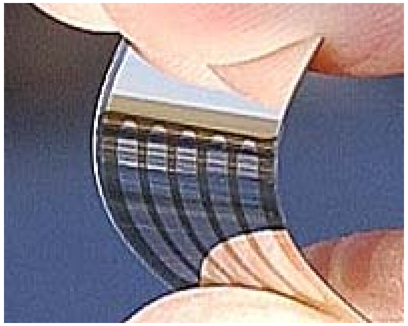
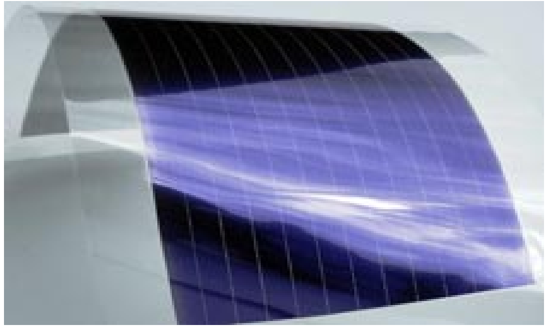
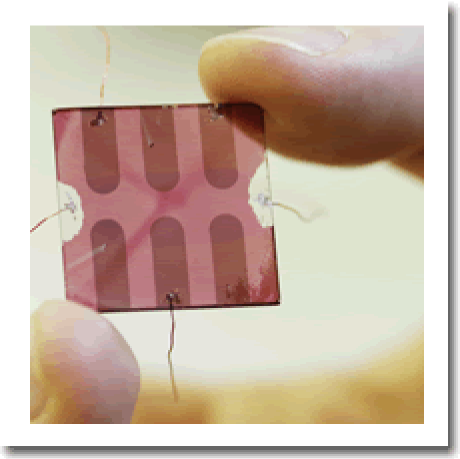
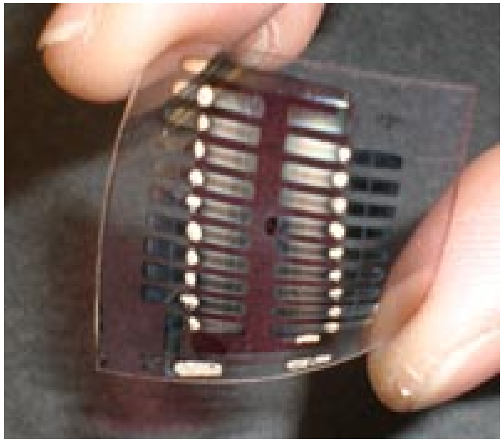
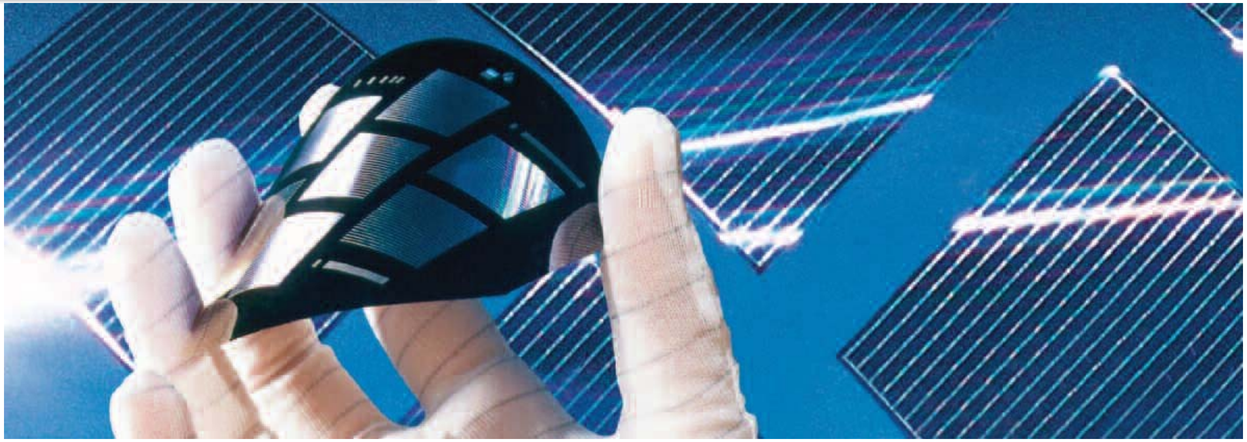
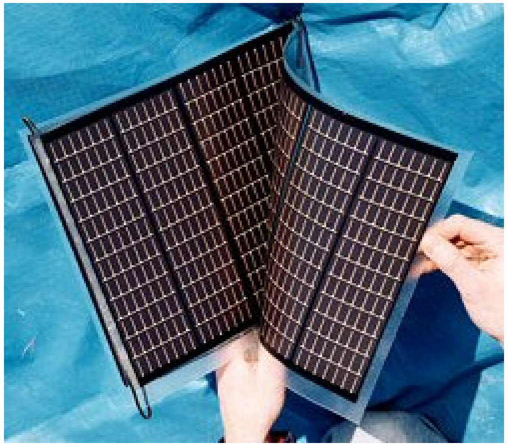




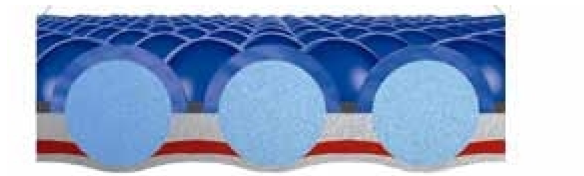


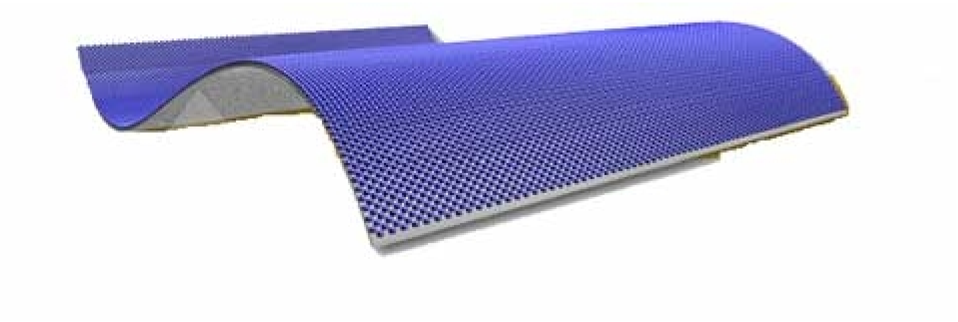


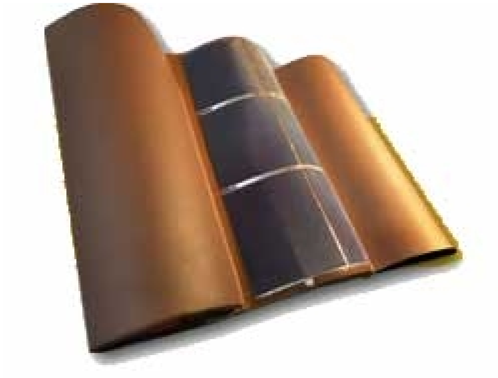




Flexible Cells to expand Solar Energy applications







http://www.gizmag.com/go/1782/picture/2062/

Transparent plastic solar cells fitted into windows

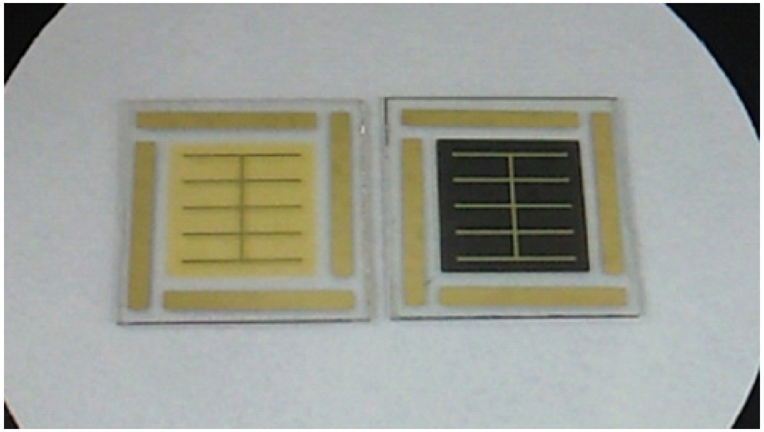
A transparent solar cell Konarka hopes will be fitted into power-generating windows.

http://news.cnet.com/8301-11128_3-10235480-54.html

Flexible Thin Film Solar Cells to be printed like money

Printable plastic solar cells

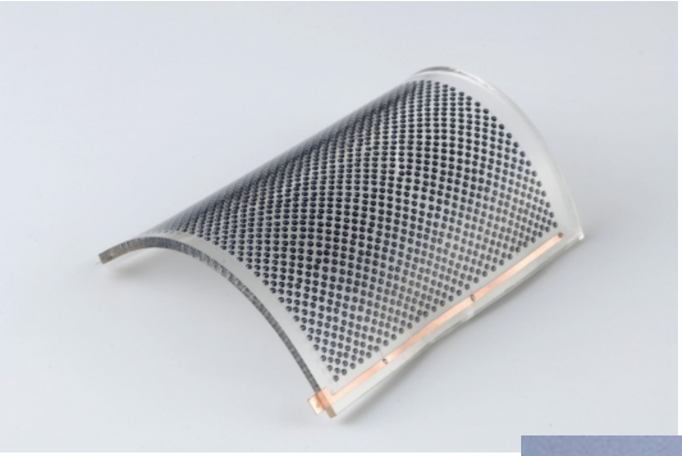
http://www.gizmag.com/printable-thin-film-solar-cells/11062/picture/68581/

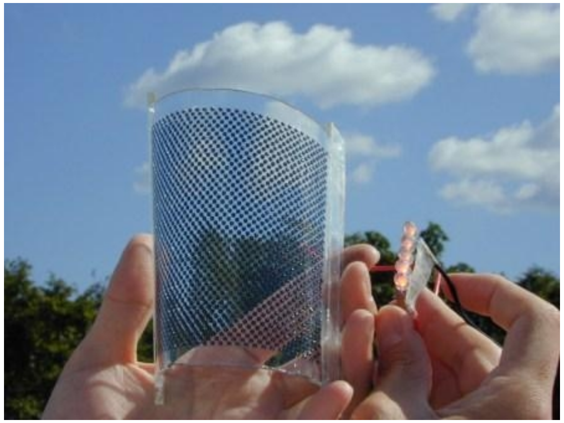


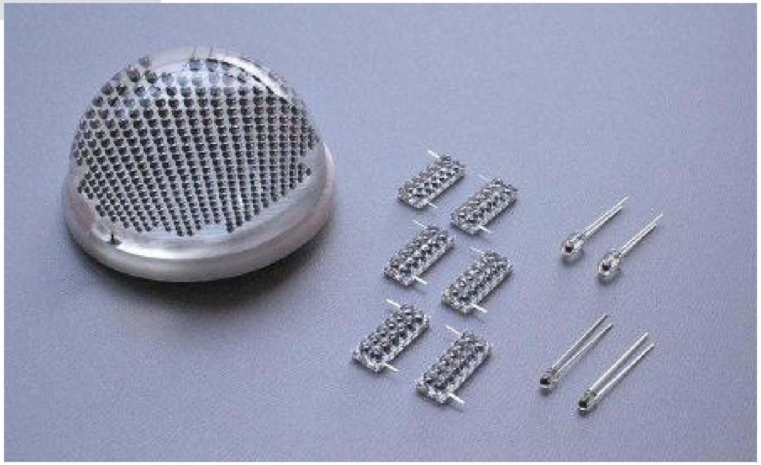
Last month at the meeting of the Japan Society of Applied Physics, a research group from the Kyoto Institute of Technology introduced a new photovoltaic cell that is capable of generating electricity not only from visible light, but from ultraviolet and infrared light as well. The research group, led by associate professor Saki Sonoda, hopes that this will lead to a more efficient PV cell that can be single-junction rather than the more conventional multi-junction.

http://www.gizmag.com/pv-cell-ultraviolet-infrared-light/14708/picture/113419/

Sphelar cells are the new 'power windows'



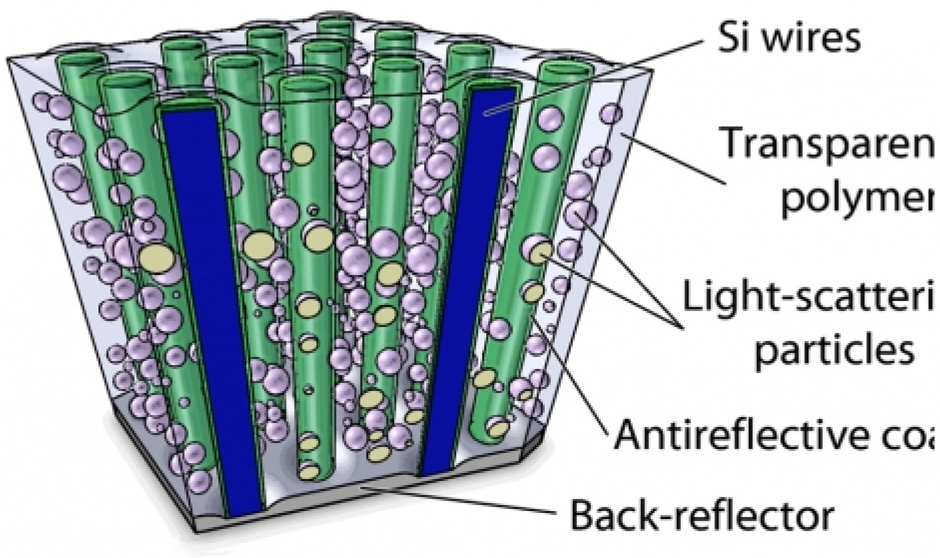


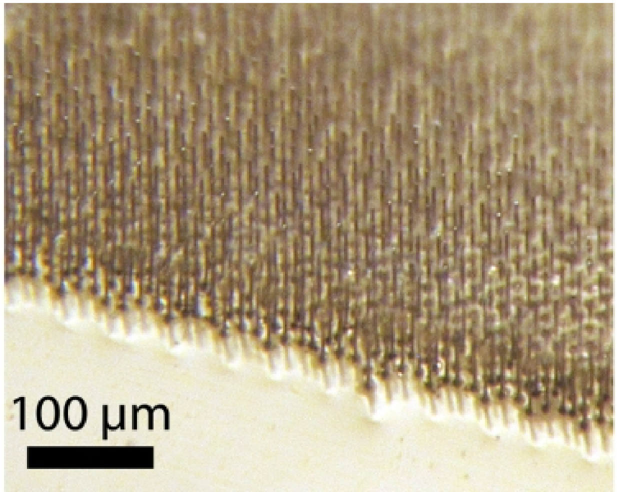


Developed by Kyosemi Corporation, Sphelar solar cells are one of the most intriguing solar solutions that we have seen in a while. On display at the recent PV Expo 2010 in Tokyo, these tiny spherical cells gave us a glimpse of how windows in buildings might be used to collect solar power in the not-so-distant future.
Sphelar cells are solidified silicon drops measuring 1.8 mm in diameter and are highly transparent, which is advantageous for a number of reasons. They can be embedded in glass to create a transparent solar cell window, capable of absorbing light from any direction or angle. Because both sides of the glass can collect light, this should translate into highly efficient energy harvesting.
The cells can also be embedded in flexible surfaces, allowing for them to take on unusual shapes or be bent if necessary. The Sphelar Dome is one such example, designed to absorb more energy in the early morning and late evening unlike a flatter design.

http://www.gizmag.com/sphelar-cells-are-the-new-power-windows/14633/picture/112731/

Less is more for highly absorbing, flexible, cheaper solar cells





A schematic diagram of the light-trapping elements used to optimize absorption within a polymer-embedded silicon wire array (Image: Caltech/Michael Kelzenberg)

http://www.gizmag.com/highly-absorbing-flexible-solar-cells/14232/picture/110897/

Energy Harvesting

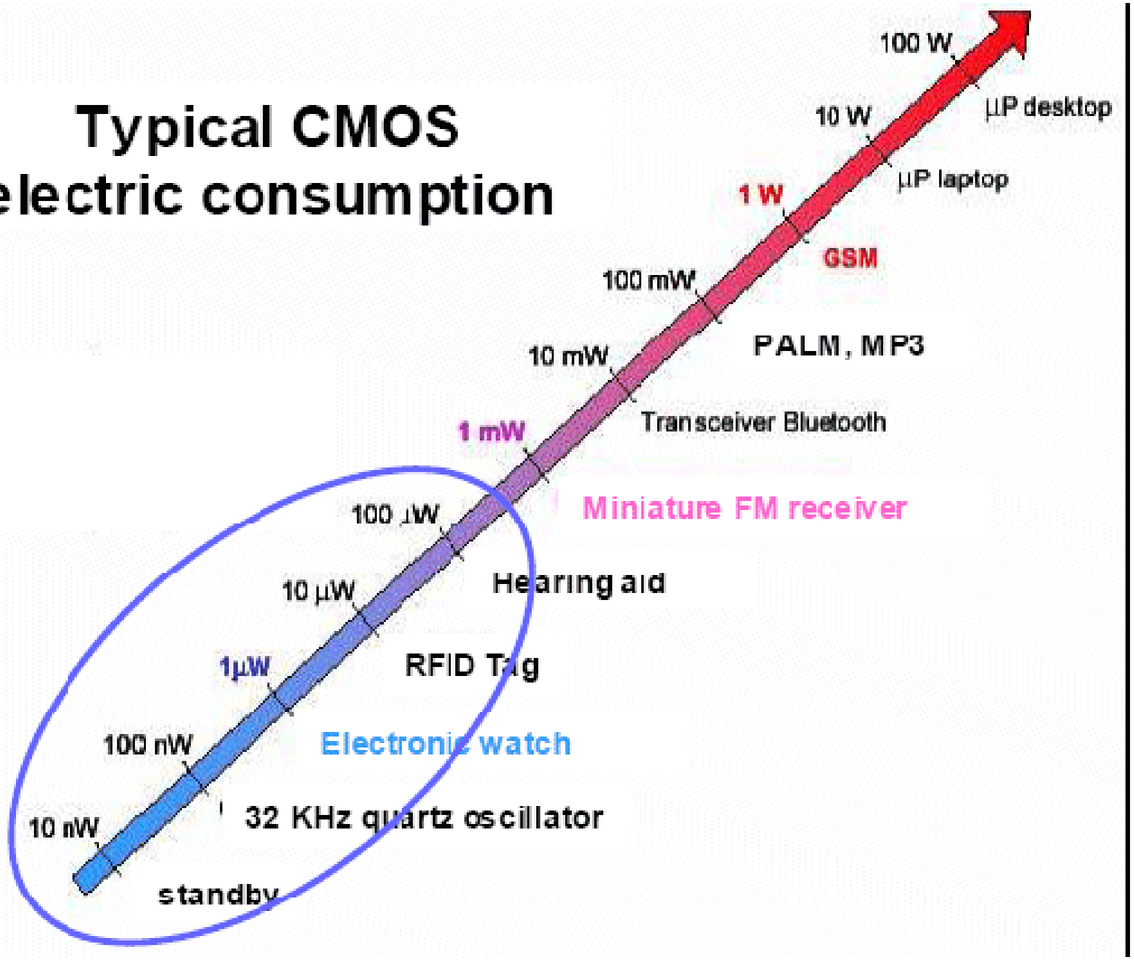
Energy Harvesting is the process of capturing minute amounts of energy from naturally-occurring energy sources, accumulating them and storing them for later use.

Energy-harvesting devices efficiently capture, accumulate, store, condition and manage this energy and supply it in a form that can be used to perform a helpful task.

Energy Harvesting Module is an electronic device that can perform all these functions to power a variety of sensor and control circuitry for intermittent duty applications.

http://www.energyharvesting.net/

Typical CMOS electric consumption



Common Sources of Energy Harvesting:

Thermal Energy – waste energy from furnaces, heaters, and friction sources

Mechanical Energy – from sources such as vibration, mechanical stress and strain

Light Energy – captured from sunlight or room light via photo sensors, photo diodes, or solar panels

Electromagnetic Energy – from inductors, coils and transformers

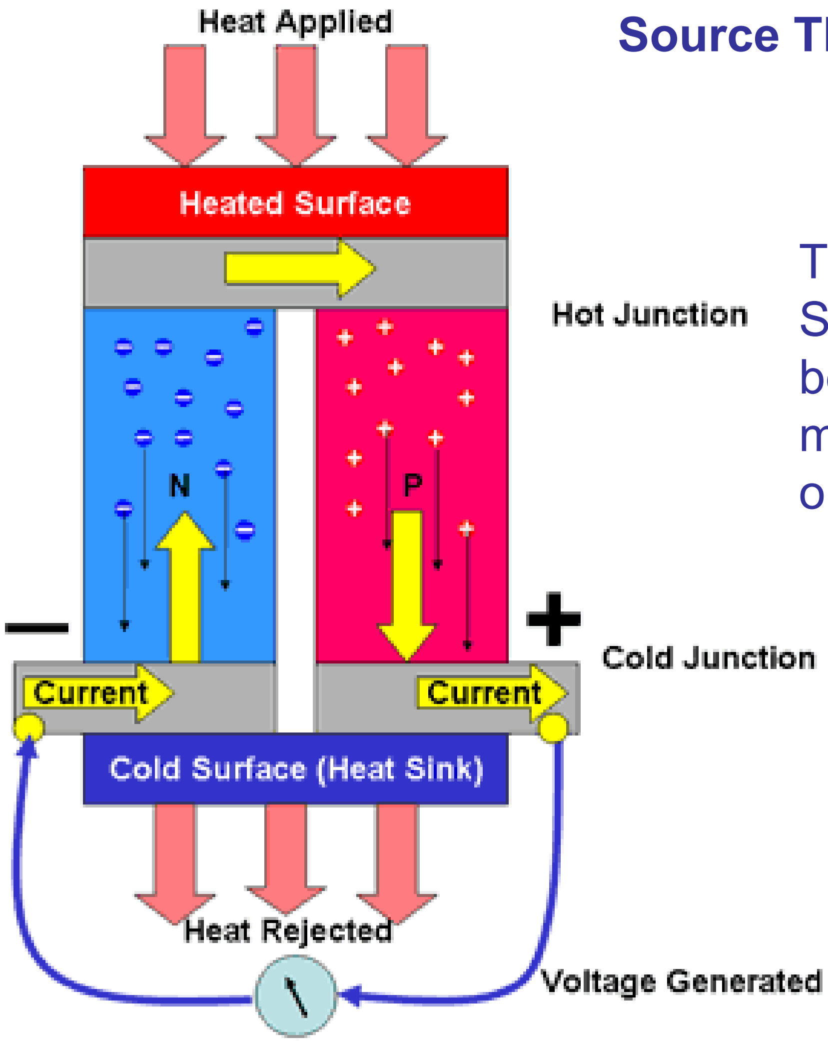
Natural Energy – from the environment such as wind, water flow, ocean currents, and solar

Human Body – a combination of mechanical and thermal energy naturally generated from bio-organisms or through actions such as walking and sitting

Other Energy – from chemical and biological sources

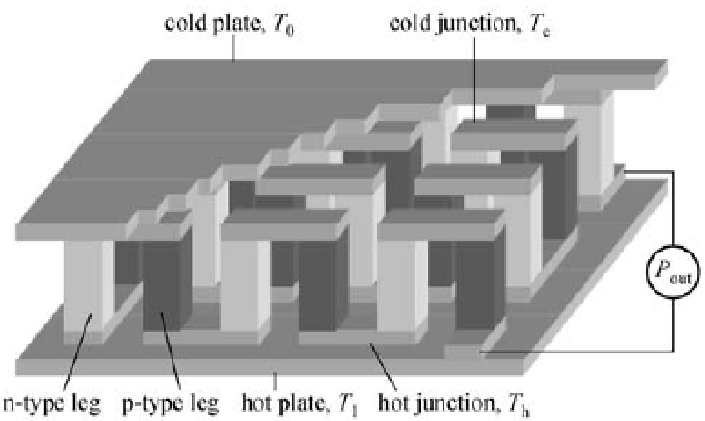
http://www.energyharvesting.net/

Source Thermal Energy



The thermoelectric generators based on Seebeck effect, a temperature difference between the joint of two dissimilar materials (semiconductor or metal) leads to a voltage over it

Cold side

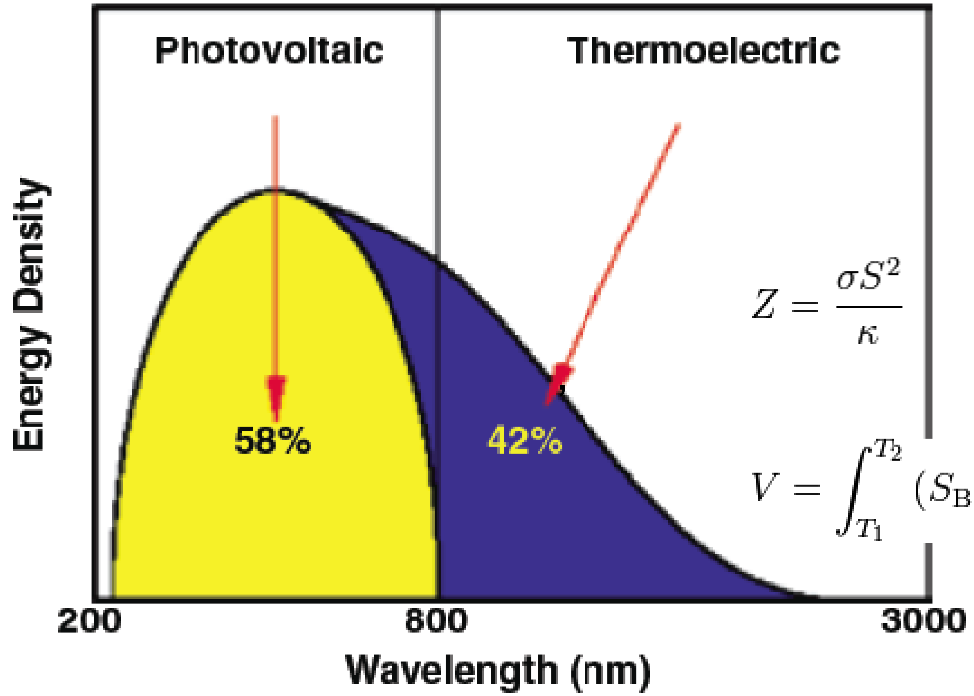


Hot side

Thermoelectric generator

D. Jia, J. Liu,Front. Energy Power Eng. China 2009, 3(1): 27–46

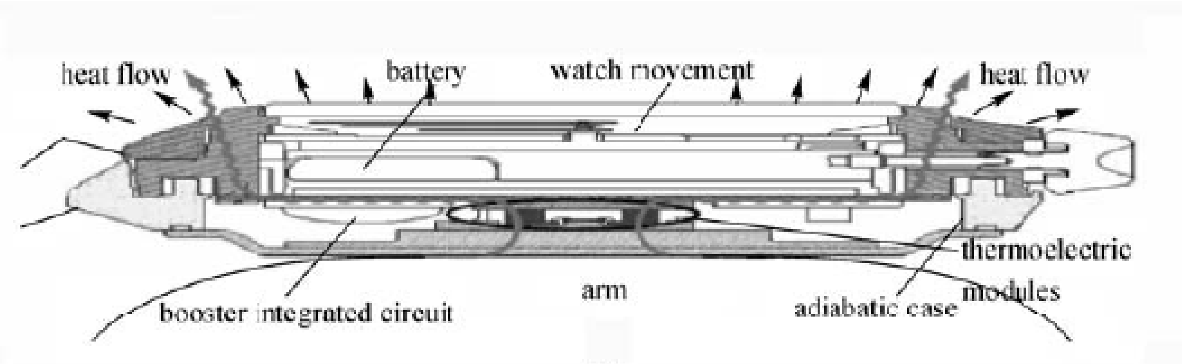
	Wavelenth	Spectrum	%
Photovoltaic	~200–800nm	UV & visible light	58
Thermoelectric	~800–3000nm	IR	42



$$Z = \frac{\sigma S^2}{\kappa}$$

$$V = \int_{T_1}^{T_2} \left(S_{\mathrm{B}}(T) - S_{\mathrm{A}}(T)\right) dT .$$

Figure 2. Sun radiates energy as a 6000 K blackbody radiator with part of the energy in the ultraviolet (UV) spectrum and part in the infrared (IR) spectrum.



Thermoelectric driven Seiko wristwatch driven by human skin heat dissipation. With only a 1.5K temperature drop across the thermoelectric modules, the open circuit voltage is 300 mV, and thermal to electric efficiency is about 0.1%.

D. Jia, J. Liu,Front. Energy Power Eng. China 2009, 3(1): 27–46

Source Thermal Energy

Example of materials: p-type Bi_2Te_3/Sb_2Te_3 and n-type $Bi_2Te_3/Bi_2Te_{2.7}Se_{0.3}$

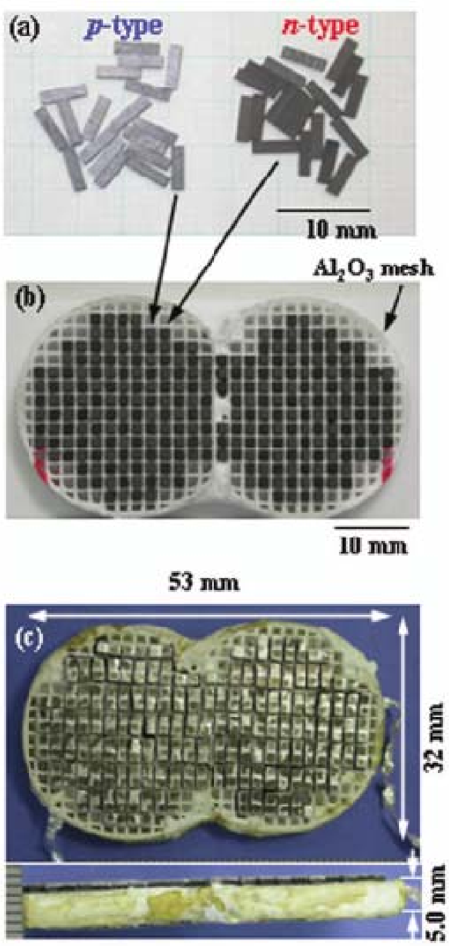
However, it is difficult (expensive) to produce these bismuth telluride V–VI-semiconductors, single crystals and are not compatible with the current standard silicon chip fabrication process.

D. Jia, J. Liu,Front. Energy Power Eng. China 2009, 3(1): 27–46

Source Thermal Energy

p-type: $Ca_{2,7}Bi_{0.3}Co_4O_9$
n-type: $La_{0.9}Bi_{0.1}NiO_3$

Solution: from single crystal to ceramics



Photographs shown are of oxide *p*- and *n*-type legs a, Al_2O_3 meshes inserted with the oxide legs b, and a perfected module after heating c.

Funahashi R, Mikami M, Mihara T, Urata S and Ando N 2006,*J. Appl. Phys.* **99** 066117

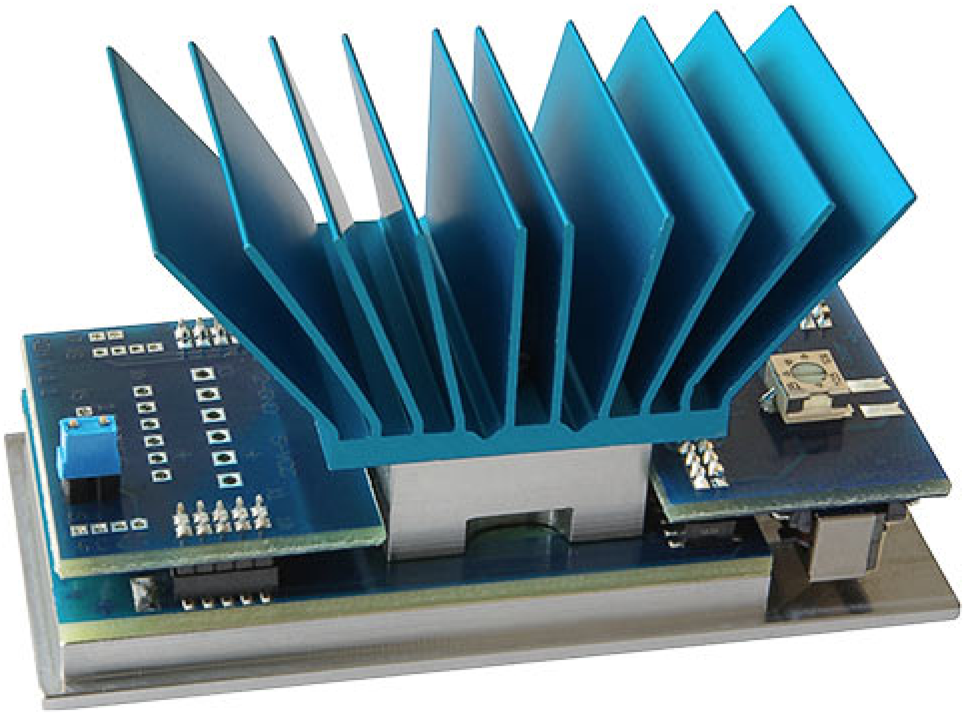
Table 8. Open circuit output voltage, power, power density and power per unit area values for novel thermoelectric devices.

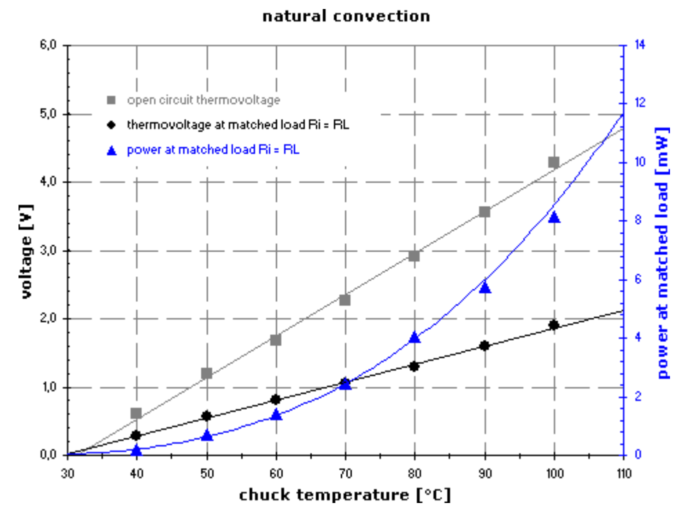
Composition	ΔT	Dimensions	Open circuit (V_{OC})	Power	Power/area or power density
BiTe thermopile, 158 thermocouples per stage	—	Thermopile size: 0.67 cm × 0.84 cm × 0.18 cm	1.6 V	250 μW	2.47 mW cm^{-3}
Coiled generator fabricated using screen print technique	5	1 cm^2 2cm^2	0.8 V 1.6 V	0.8 μW 1.6 μW	0.8 μW cm^{-2}
Polymer-based wafer level fabrication (51 thermocouples)	20	Area = 0.26 cm^2 Height = 150 + 10 μm	—	—	12.0 nW cm^{-2}
PbTe-based, cross-plane quantum-dot superlattice (QDSL) unicouple devices fabricated from nanostructured thick films	220	Length = 95 μm Cross sectional area = 4 mm^2	—	89 mW	2.2 W cm^{-2}
Thermoelectric generator coupled with catalytic butane combustor 34 thermocouples	—	Each element = 0.95 mm × 0.95 mm × 2.0 mm Total volume = 0.955 cm^3	2.31 V	184 mW	192.67 mW cm^{-3}
Generator fabricated using polysilicon surface micromachining	5	Area = 1 cm^2 Thickness = 400 nm	5 V	1 μW	1.0 μW cm^{-2}
Micro Sb–Bi thermocouple strips embedded within a 50 μm thick flexible epoxy film (100 pairs of thermocouples)	30	16 mm × 20 mm × 0.05 mm	0.25	—	—

K. A. Cook-Chennault, N. Thambi, A. M. Sastry, Smart Mater. Struct. 17 (2008) 043001

Conceptual design of thermoelectric generator producing electricity from waste heat in the engine exhaust. ~1 kW of thermoelectric generator will extract waste heat from the exhaust that will deliver electrical power to recharge the battery.

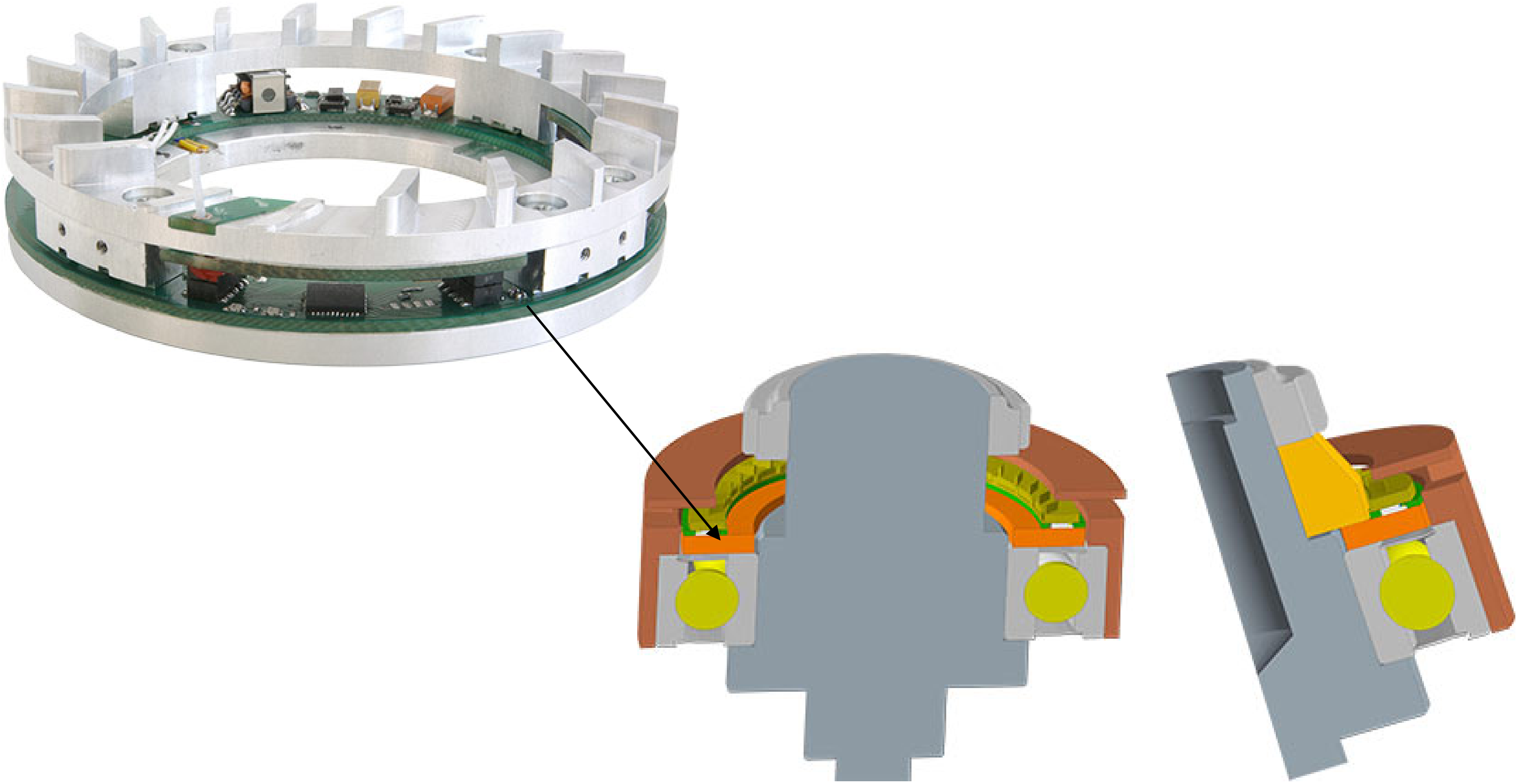
http://www.electrochem.org/dl/interface/fal/fal08/fal08_p54-56.pdf





Energy harvesting evaluation kits from Micropelt GmbH.

http://www.micropelt.com/applications/te_power_plus.php



Micropelt wireless shaft based bearing condition monitoring driven by thermoelectric generator.

http://www.micropelt.com/applications/te_power_ring.php

U.S. Department of Energy

Categorical Exclusion Determination Form

Program or Field Office: Advanced Research Projects Agency - Energy (ARPA-E)

Project Title: 25A1001 - Advanced Semiconductor Materials for High Efficiency Thermoelectric Devices

Location: *- Multiple States - California, North Carolina, Oklahoma

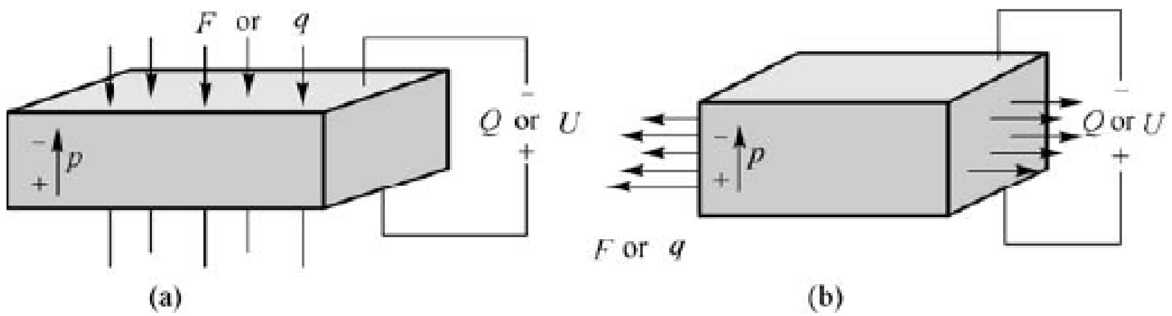
Proposed Action or Project Description: American Recovery and Reinvestment Act: ☒

Phononic Devices is commercializing advanced thermoelectric semiconductor materials and devices designed to convert waste heat from industrial and commercial processes into usable electric power and cooling. Despite the national security risks and pollution concerns associated with fossil fuel consumption, the Department of Energy estimates that 50-60% of all the energy consumed in the US per year is wasted as heat. Thermoelectric designs that efficiently capture and utilize this waste heat are an intense area of research and investment interest. Developed in partnership with the University of Oklahoma, Phononic Devices' unique and proprietary approach combines enhanced Seebeck thermopower with thermally insulating semiconductor materials and is projected to dramatically enhance thermal to electric energy conversion efficiency. Leveraging superior efficiency with low cost thin film manufacturing processes is projected to result in high performance and cost competitive "green" thermoelectric products. As a highly efficient energy harvesting power source from waste heat and effective source of active solid state cooling, Phononic Devices' approach makes possible a more than $125B market opportunity.

……..As a highly efficient energy harvesting power source from waste heat and effective source of active solid state cooling, Phononic Devices' approach makes possible a more than **$125B market opportunity**. (Dec 2009)

Source: Mechanical Energy:

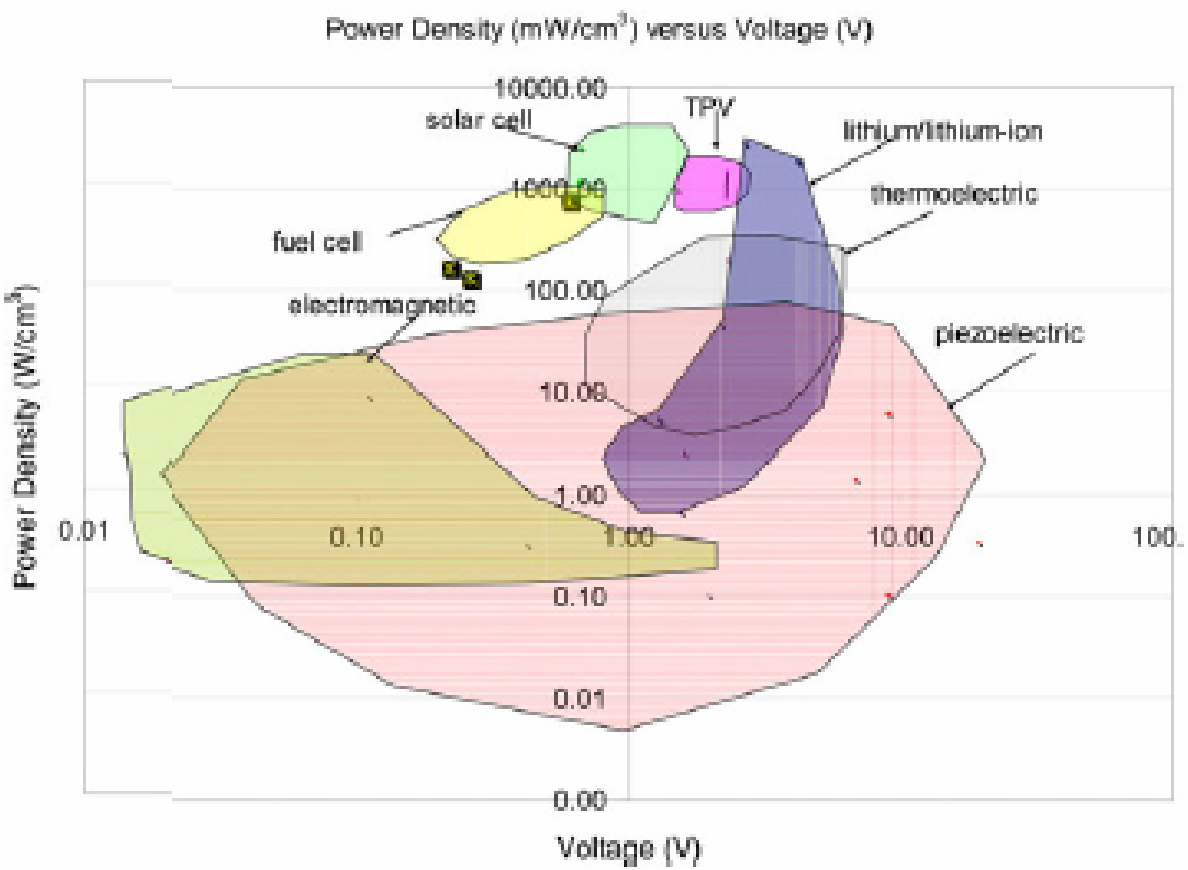
Piezoelectric harvesters



$$Q = d\sigma + \varepsilon^{\sigma} E$$

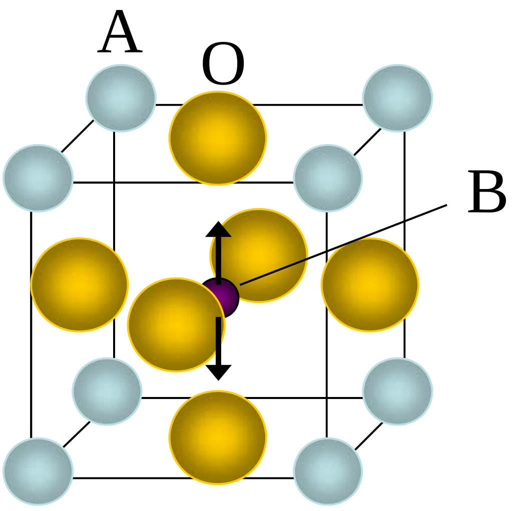
Schematic illustration of the piezoelectric direction of forces applied and charges or voltage harvested in two operation modes:

(a) compression mode caused by pressure
(b) transverse mode by bending



Plot of power density versus voltage for common regenerative and lithium/lithium-ion power supply strategies [Cook2008]

Piezoelectric ceramics: Composition



$BaTiO_3$,

$PbTiO_3$ (PT)

Piezoelectric materials based on Pb(Zr,Ti)O3 solid solution (PZT):
Excellent piezoelectric response, possibility to tailor the properties by changing the stoichiometry and/or doping for a wide range of applications.

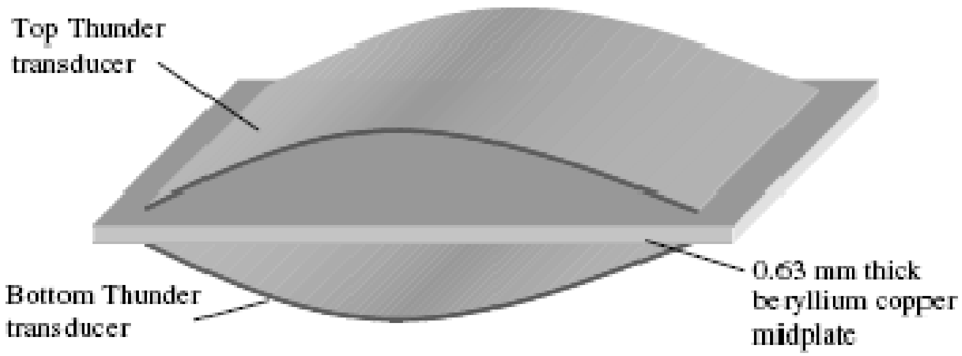
Further compositions

$Pb(Mg_{1/3}Nb_{2/3})O_3$ (PMN)
$Pb(Mg_{1/3}Nb_{2/3})O_3 – PbTiO_3$ (PMN-PT)

$Pb(Zn_{1/3}Nb_{2/3})O_3 – PbTiO_3$ (PZN-PT), (PMN-PZN-PT)

high lead content (~60w%) → ecological problems

Since last ten years: searching for lead free materials Example:(K,Na)NbO3 s.s. (KNN).



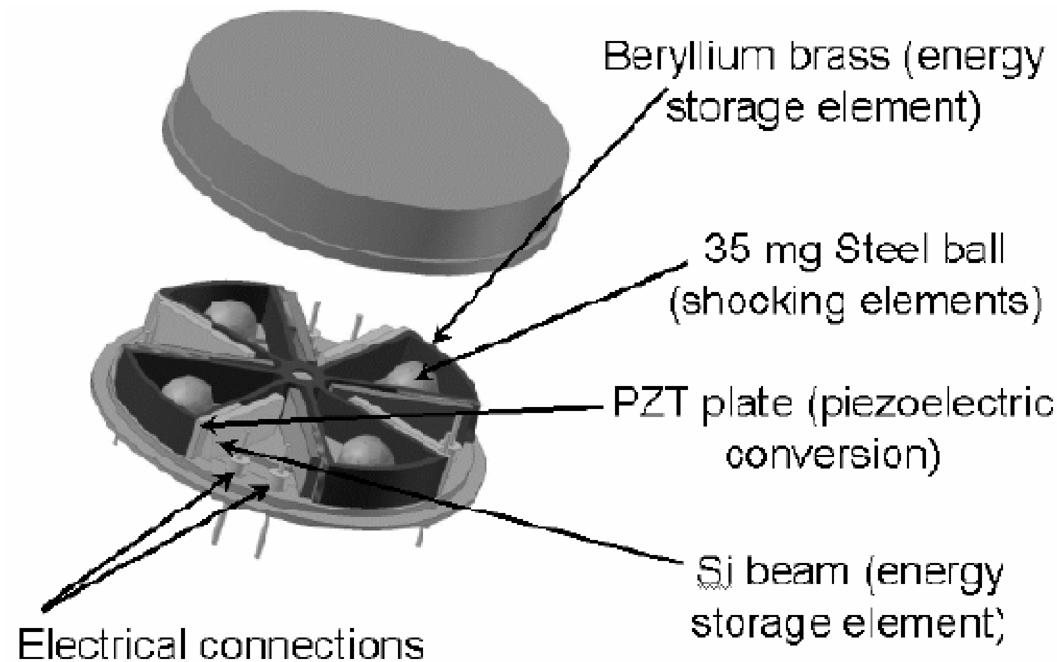
Human power shoe insert PZT bimorph
Power : **8.4 mW** at 0.9 Hz at 500 kOhm.

Shenck N S and Paradiso J A 2001 Energy scavenging with shoe-mounted piezoelectrics *IEEE Micro.* **21** 30–42

Shoe Power Generator, Embedded in the Sole of a Shoe, Harvest Energy

ScienceDaily (Apr. 27, 2010) — Dr. Ville Kaajakari, assistant professor of electrical engineering at Louisiana Tech University has developed a technology that harvests power from a small generator embedded in the sole of a shoe.

http://www.sciencedaily.com/releases/2010/04/100426113137.htm



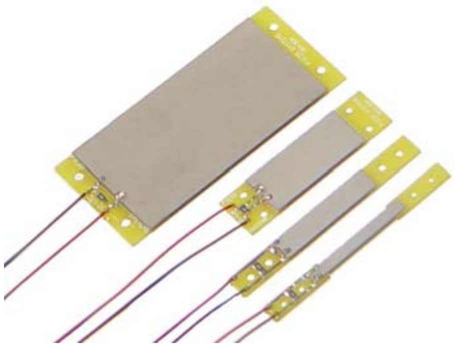
Impact piezoelectric type harvester

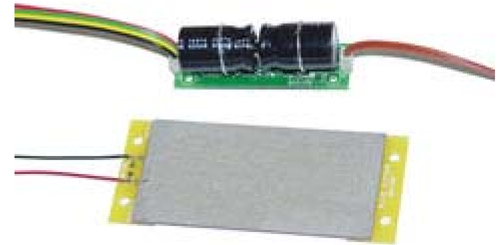
8 bimorphs PZT/Si, 0.266x3x2 mm3

Impacts of a 35 mg mass

Harvested energy : **63 nW**/bimorph at 6Hz at 26kOhm.

B. Cavallier, P. Berthelot, H. Nouira, E. Foltête, L. Hirsinger and S. Ballandras, IEEE Ultrasonics Symposium, 18-21 september 2005, Rotterdam, pp. 943-945

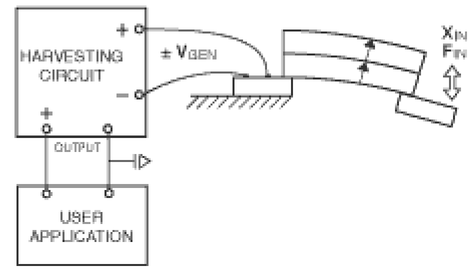




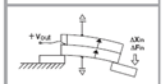
PIEZOELECTRIC ENERGY HARVESTING KIT

250 USD

http://piezo.com/prodproto4EHkit.html



PIEZO BENDING GENERATOR

PART NUMBERS DOUBLE QUICK-MOUNT BENDING GENERATORS  Y-poled for parallel bending operation (3 wire).	PIEZO MATERIAL	WEIGHT (grams)	STIFFNESS (N/m)	CAPACITANCE (nF) (Parallel Operation)	RATED TIP DEFLECTION ① (mm_{peak})	MAX. RATED FREQUENCY (RESONANT FREQUENCY) ① (Hz)	OPEN CIRCUIT VOLTAGE ① At rated deflection (V_{peak})	CLOSED CIRCUIT CURRENT ① At rated deflection / cycle (μA_{peak} / Hz)	RATED OUTPUT POWER ① At rated deflection and frequency (mW_{rms})
EH220-A4-503YB	5A4E	10.4	1.9×10^2	232	± 2.6	52	± 20.9	± 57	7.1

① Cantilever mount. Force applied at the outermost tip of the mount.

MECHANICAL

Overall Dimensions	3.00" Long x 1.25" Wide x 0.9" High
Weight	10.4 grams

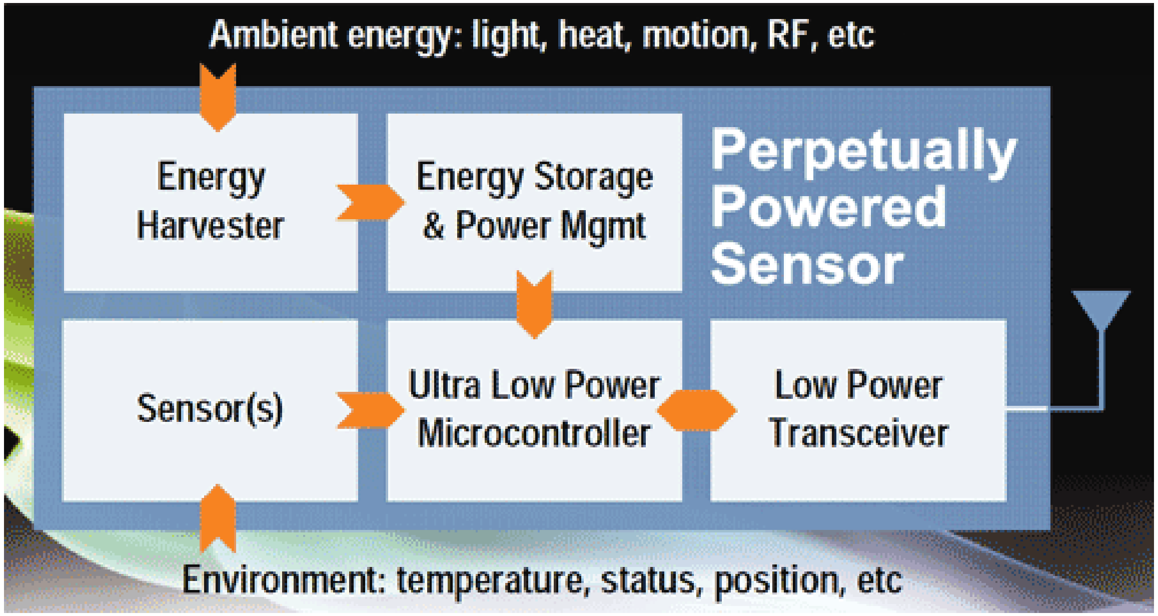
ENVIRONMENTAL

Operating Temperature Range	0 to 90° C
ROHS	Piezo exempt, product compliant

Table 12. Description of novel piezoelectric energy harvesting devices, along with power and energy capabilities.

Material	Application	Dimensions	Power	Energy/power density	Voltage	Load
PZT composite-d33 compressive loading of 39 MPa	Composite	—	—	12 mW cm^{-3}	—	—
PVF2, d33 compressive load	Wind mill rotor design	500 μm × 90 mm × 70 mm	2.4 μW	0.76 μW cm^{-3}	1 V	400 kΩ
PVDF bimorph, d31-mode	Shoe insert	—	1.3 mW	—	18 V	250 kΩ
PZT dimorph, d31-mode	Shoe insert	—	8.4 mW	—	64.8 V	500 kΩ
PVDF bimorph windmill, 12 cantilever bimorphs d31 loading	Windmill	Each bimorph: 60 × 20 × 0.5 mm^3	10.2 mW	1.42 mW cm^{-3}	6.8 V	4.6 kΩ
PZT-5A membrane, d31 loading from blood pressure	Biomedical	Surface area = 1 cm^2 Thickness = 9 μm	2.3 μW	2.6 mW cm^{-3}	—	—
PZT rectangular structure, knee implant, d33 compressive loading	Knee implant	1.0 × 1.0 × 1.8 cm^3	4.8 mW	0.89 mW cm^{-3}	—-	—
PZT thin-film membrane generator coupled with heat engine	Hybrid	Surface area = 3 mm^2 Thickness = 3.4 μm	56 μW	5.5 W cm^{-3}	—	—
PZT cymbal device, d33 loading	Cymbal	Diameter = 29 mm Thickness = 1 mm	29 mW	43.9 mW cm^{-3}	—	—
PZT projectile generator, d33 compressive loading	Pulse generator	Diameter = 1.27 cm Thickness = 0.13 cm	25 kW	151.4 kW cm^{-3}	500 V	10 Ω
PMN-PT composite-d33 compressive loading of 40.4 MPa	Composite	—	—	22.1 mW cm^{-3}	—	—

K. A. Cook-Chennault, N. Thambi, A. M. Sastry, Smart Mater. Struct. 17 (2008) 043001



Energy harvesting for sensor application.

http://www.ti.com/ww/en/apps/energy-harvesting/index.shtml?DCMP=MSP430_Energy&HQS=Other+OT+430energy

RFID

Energy harvesting: Photovoltaic cells

Rucksack that use solar cells to charge personal electonics like MP3 players, cell phones, GPS, radios, and other personal electronics.

Slovenia: Where we are?

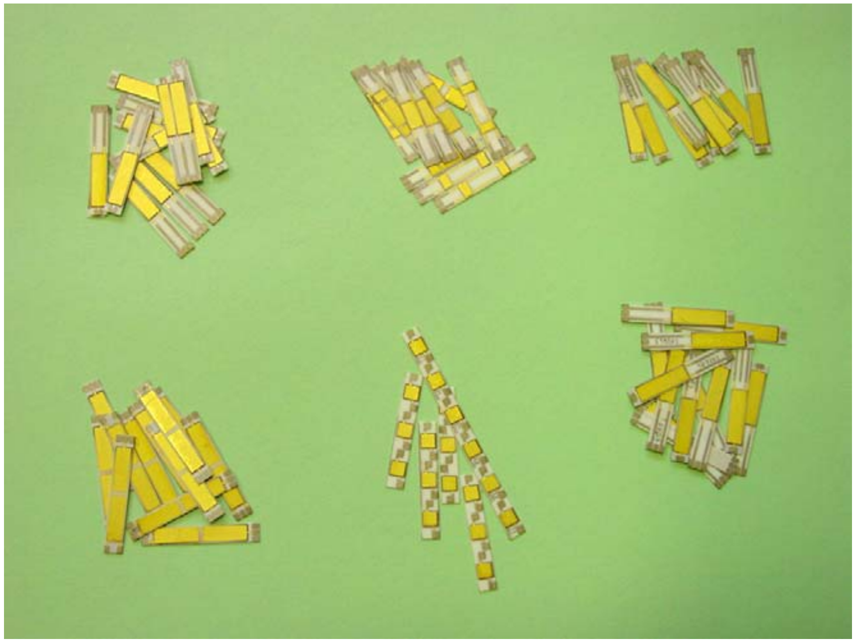
Strong in material research,
however fragmented
weakly connected to other fields

University of Ljubljana, Faculty of Electrical Engineering
Laboratory of Photovoltaics and Optoelectronics: http://lpvo.fe.uni-lj.si/
materials (Si, Graetzel type), devices, modulus,systems

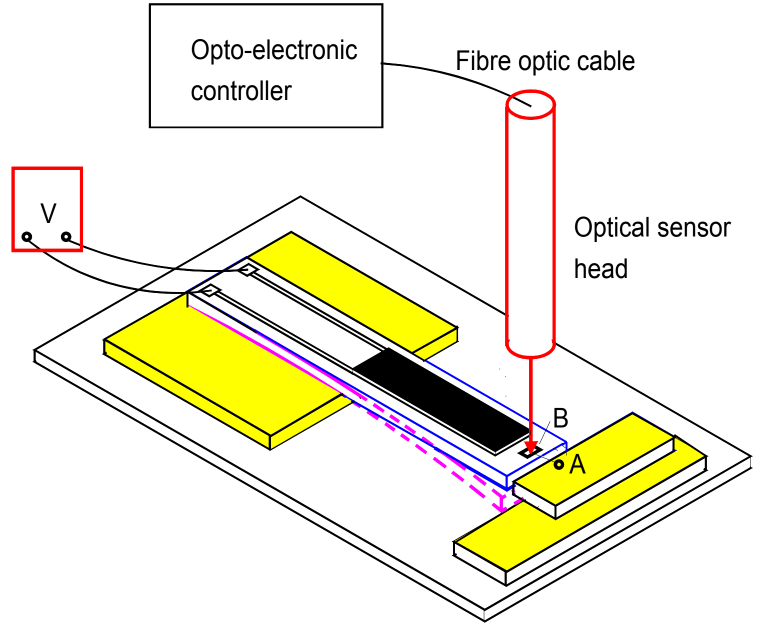
National Institute of Chemistry: http://www.ki.si/en/
L02 Laboratory for The Spectroscopy of Materials
CO: Low Carbon Technologies, CO NOT
Photovoltaic materials: DSSC type

Jožef Stefan Institute
Electronic Ceramics Department: http://www.ijs.si/
Piezoelectrics: Bulk, thick, thin films
Transparent conductive oxides TCO: In2O3:ZnO: Ga2O3
Technologies: screen printing, ink jet printing

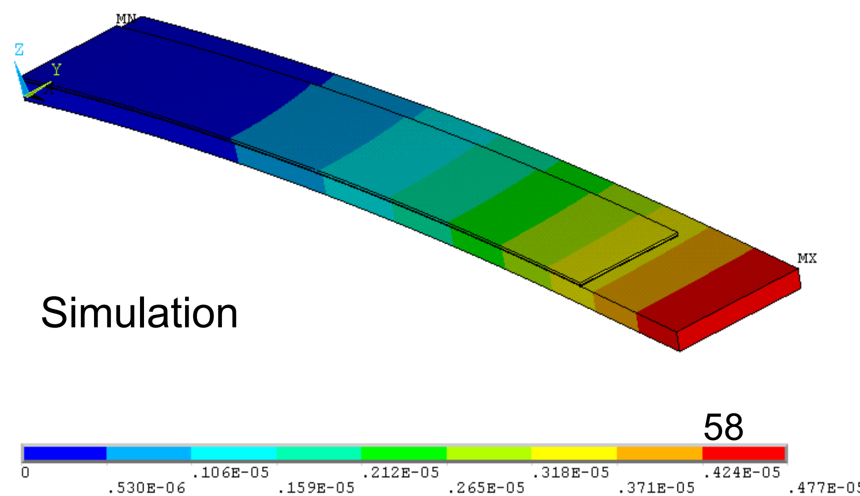
Piezoelectric PZT thick films



Test samples of PZT on alumina prepared by screen printing

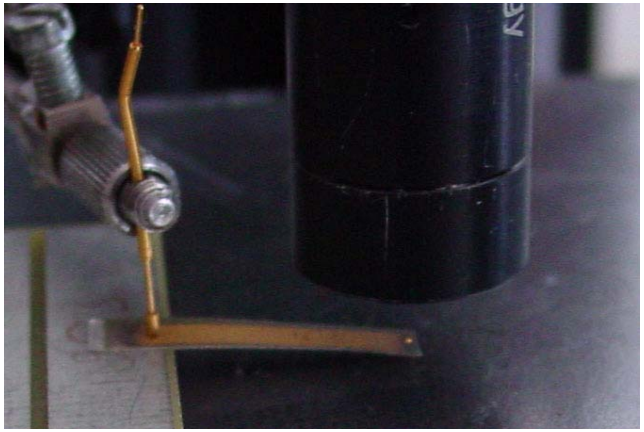


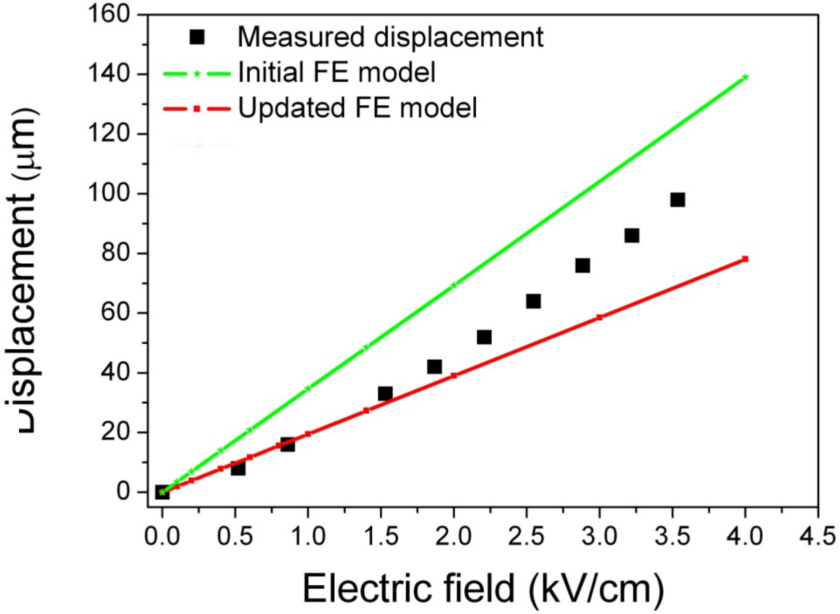
Measuring of piezo coefficient

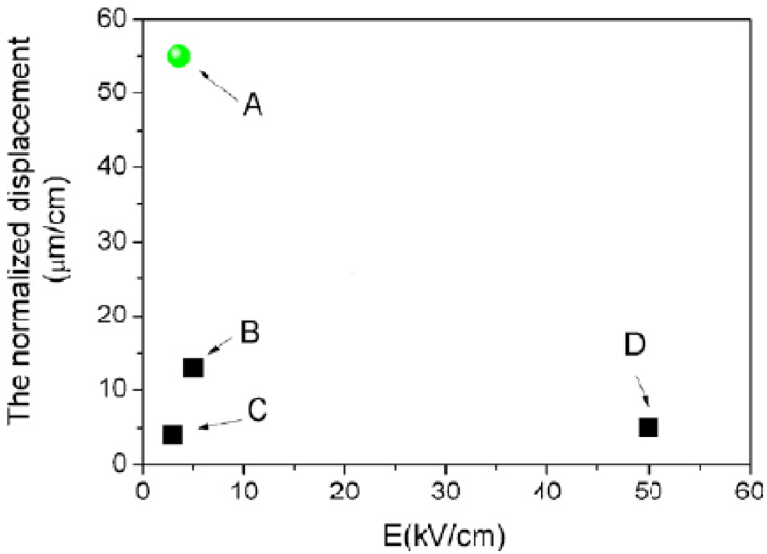


Simulation

Piezoelectric bending actuator







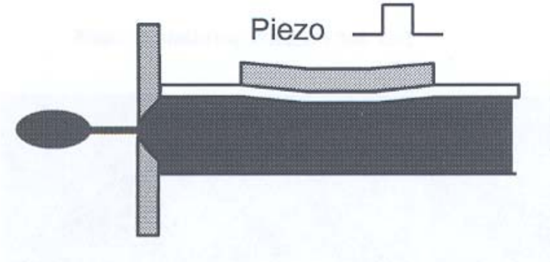
H. Uršič, M. Hrovat, J. Holc, M. Santo Zarnik, S. Drnovšek, S. Maček, M. Kosec: 0.65PMN–0.35PT BIMORPH ACTUATORS WITH A LARGE DISPLACEMENTS Sensors and Actuators, Chemical B, 133(2), 2008, 699-704

Intenzive work on lead free piezoelctrics

Pattering: Ink jet printing

Dimatix ink jet printer

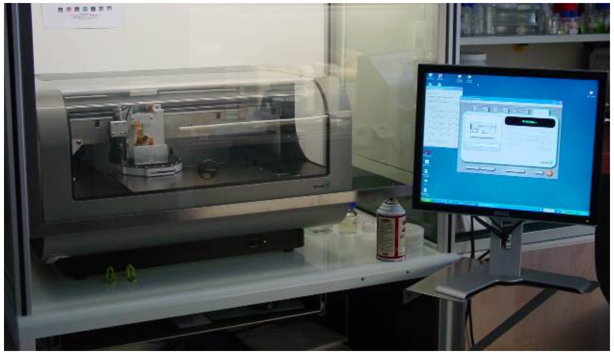
Commercial printing head

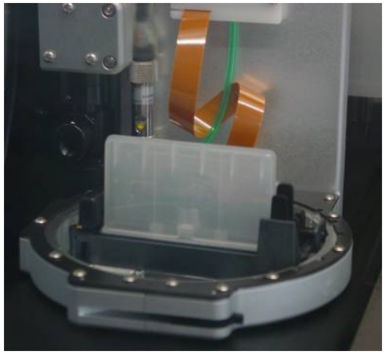


http://www.dimatix.com

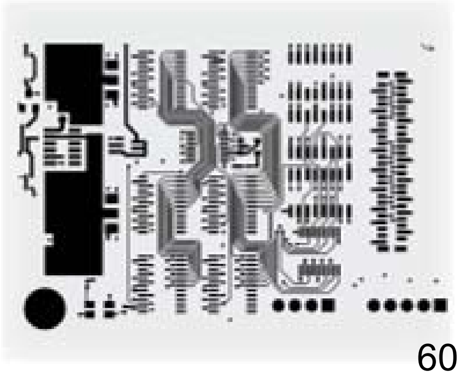
Drop-on-demand Ink-jet printing

Drops generated only when required





Computer controlled shapes



Transparent conductive oxides (In_2O_3:ZnO)

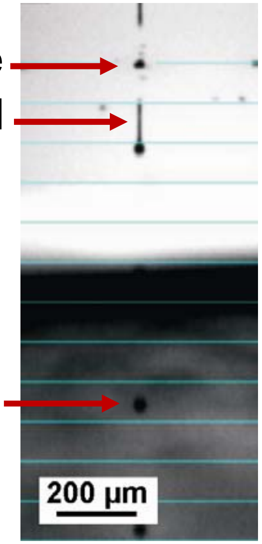
Alkoxide and acetate based solution in 2-methoxyethanol

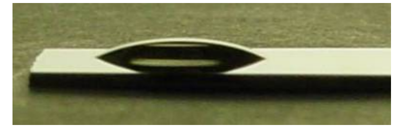
In_2O_3/ZnO 89.3/10.7wt%

For chemical solution deposition

Modified solution

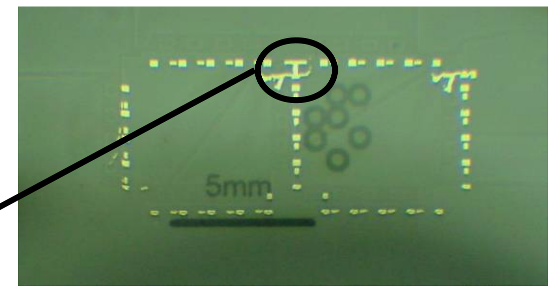
Drop watcher camera

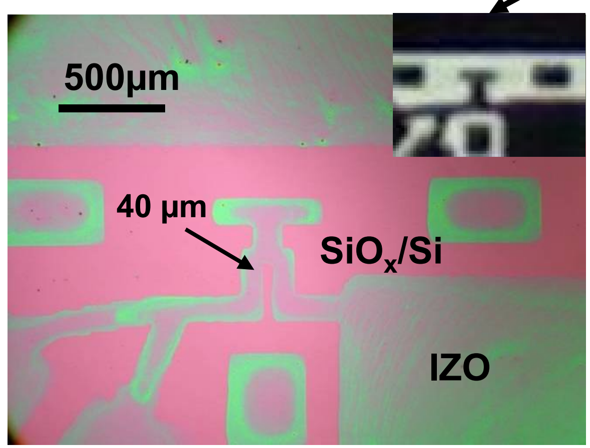


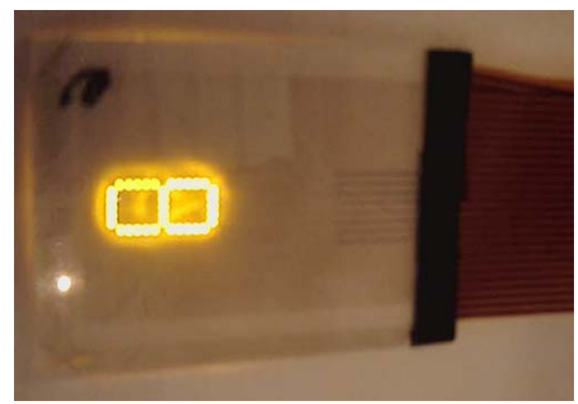


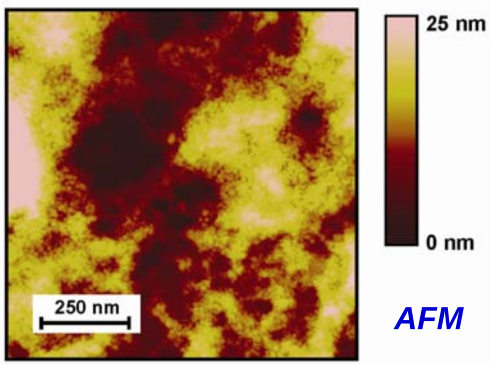
Contact angle measurement

- Good jetting of the modified solution
- Printing possible on different substrates
- Transparent on glass and polymer









AFM

FESEM

Well defined structure

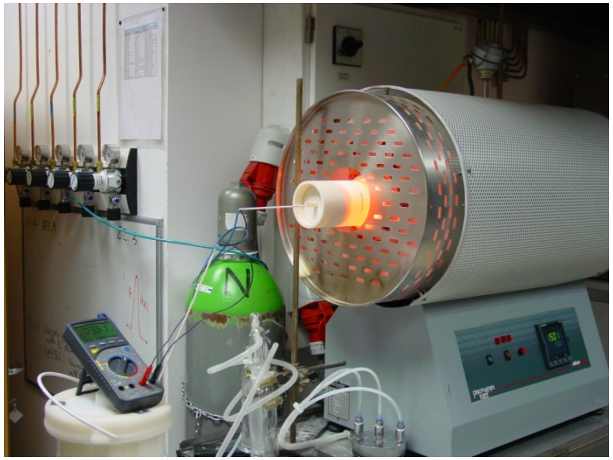
Processing of ceramic targets

→ **Solid state synthesis**
High-quality raw materials, homogenisation of raw materials, prefiring, sintering, optimisation of sintering T, atmosphere, time.

The objective is to minimise the processing steps in order to avoid the contamination.

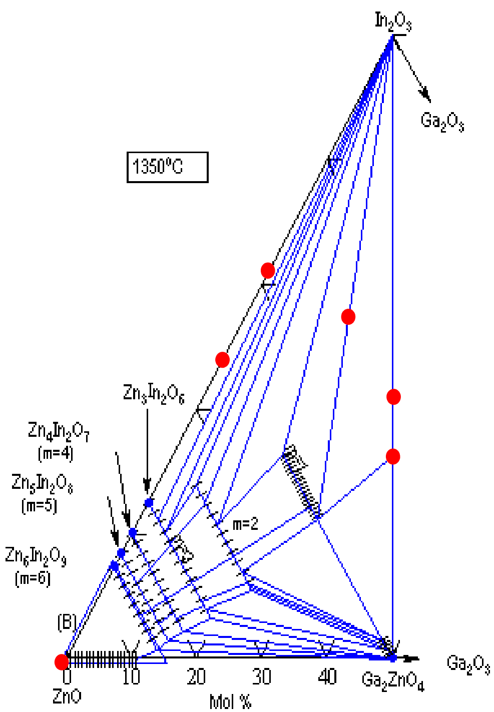
Plastic inventory

High-energy mill

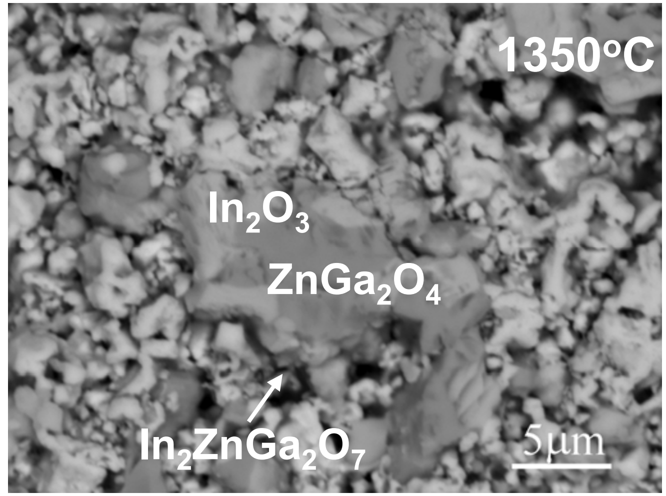


Furnace for sintering

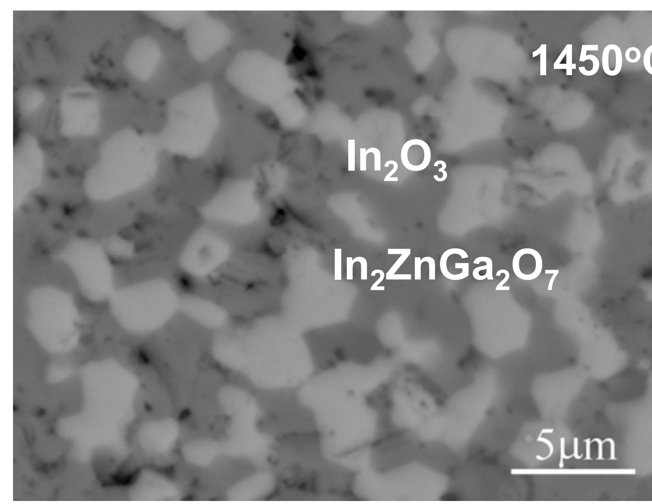
Synthesis of ceramic in In_2O_3: ZnO : Ga_2O_3 system



ZnO-In_2O_3-Ga_2O_3 phase diagram



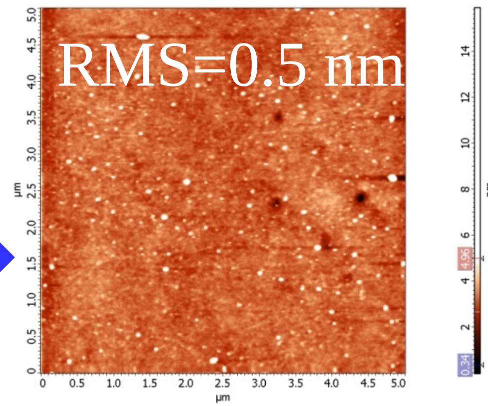
Solid-state synthesis



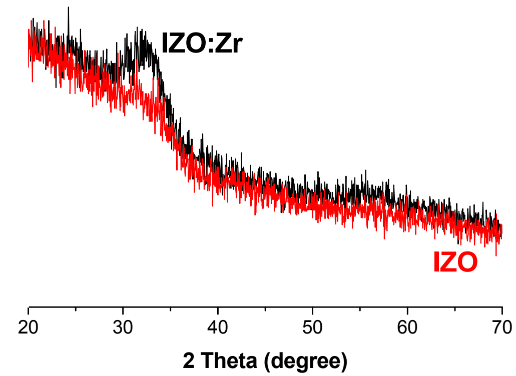
Mechanochemical activation

From ceramic to device

Sputtering



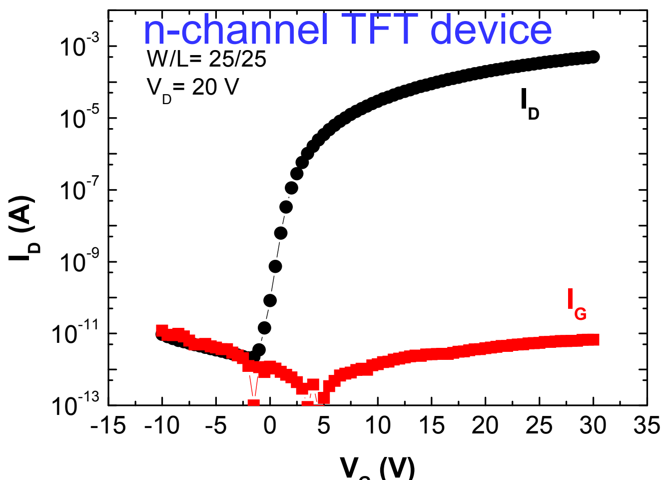
AFM image of the thin-film surface



XRD pattern of the thin-film

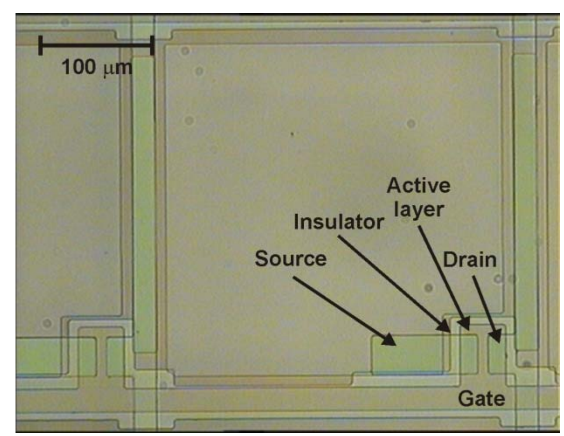
Sputtered thin films prepared from high-quality ceramic targets are smooth and amorphous.

Shaping



Treshold voltage = 4V
Gate voltage swing = 0.5V/dec
On/Off ratio = 10^8
Field effect mobility = 55 cm^2/Vs

Characterisation



Thin-film transistor

Summary:

Brief overview on materials for photovoltaic
Energy harvesting:
- thermoelectric materials
- piezoelectric materials

Slovenia: where we are?

Thank you