Nanotechnology Power Opportunities and Engineering Approaches

A brief review and discussion of a few recent technical papers and product announcements

Note that the items presented are illustrative examples only. This is a dynamic field with many projects, of which only a few will succeed in the long term.

Example Applications

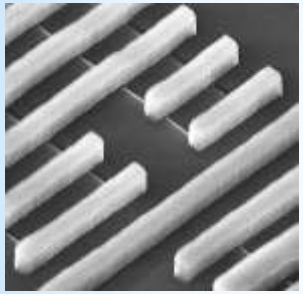
- Electronics Components
  - Semiconductor Devices
  - Supercapacitors
  - Nanomagnetic Inductors & Transformers
  - Sensors & Transducers
- Interconnect Wiring
  - Graphene Printed Circuits
  - Conductive Textile Material
- Energy Production and Storage
  - Photovoltaics
  - Hydrocarbon Photosynthesis
  - Energy Harvesting
  - High-performance Batteries
  - Fuel Cells
- Novel Materials
  - Nanotechnology Composites
  - Adhesives
  - Special Coatings
    - ESD protection
    - Anti-corrosion
    - Anti-adhesion

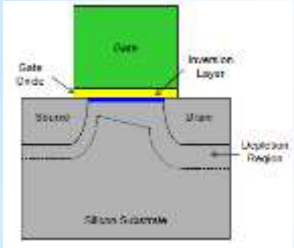
Electronics Components

Semiconductor Devices
Supercapacitors
Nanomagnetic Inductors & Transformers
Sensors & Transducers

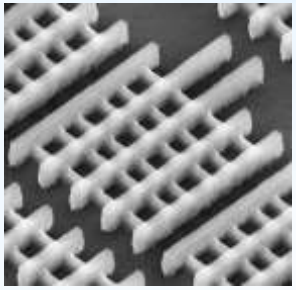
Silicon – Intel's Latest Technology

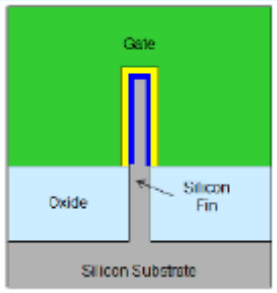
32nm planar
(Sandy Bridge)

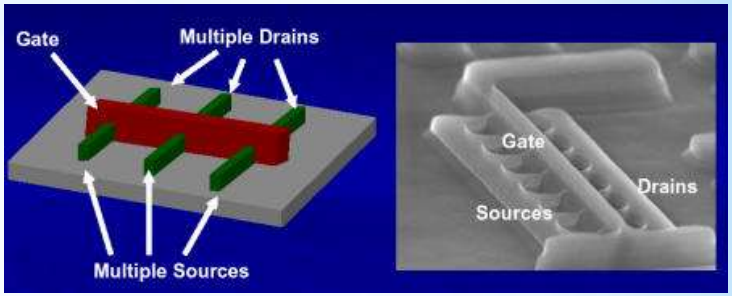




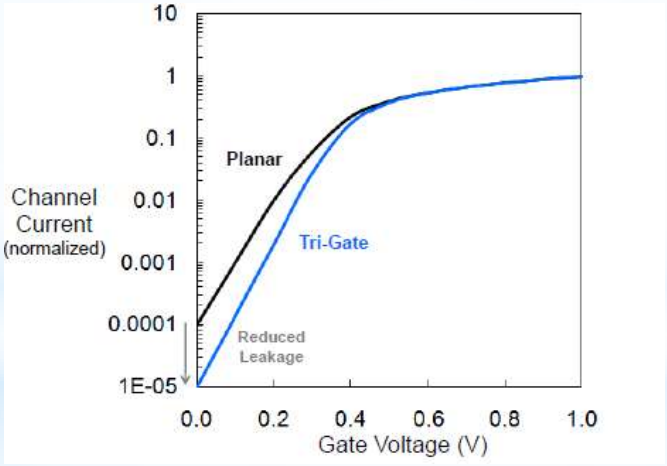
22nm tri-gate or 3-D (Ivy Bridge)

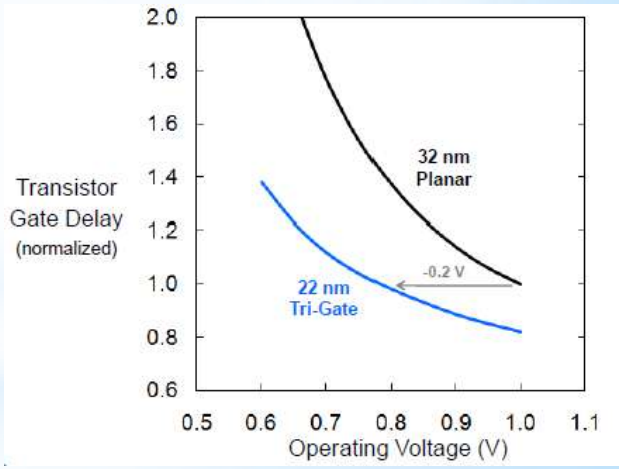






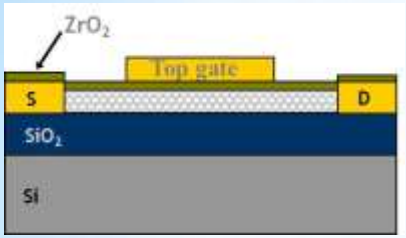
Gate electrode controls fin from 3 sides. Inversion layer area (blue) increased for higher drive current.



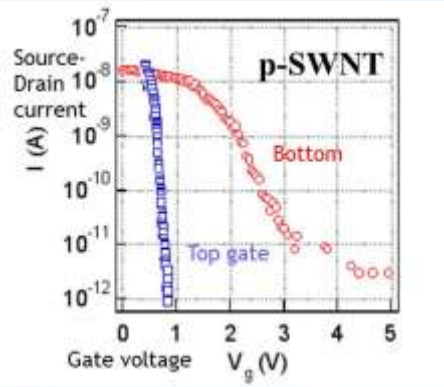


http://www.intel.com/content/dam/www/public/us/en/documents/backgrounders/standards-22nm-3d-tri-gate-transistors-presentation.pdf

Nanotube Transistors



Electrically switched



Advanced Single-Wall Nanotube device
Hongjie Dai group at Stanford, Javey et al. 2002

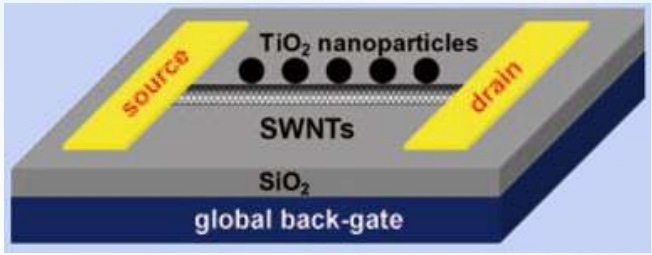


Fig. by Wiely -VCH

Optically switched carbon nanotube

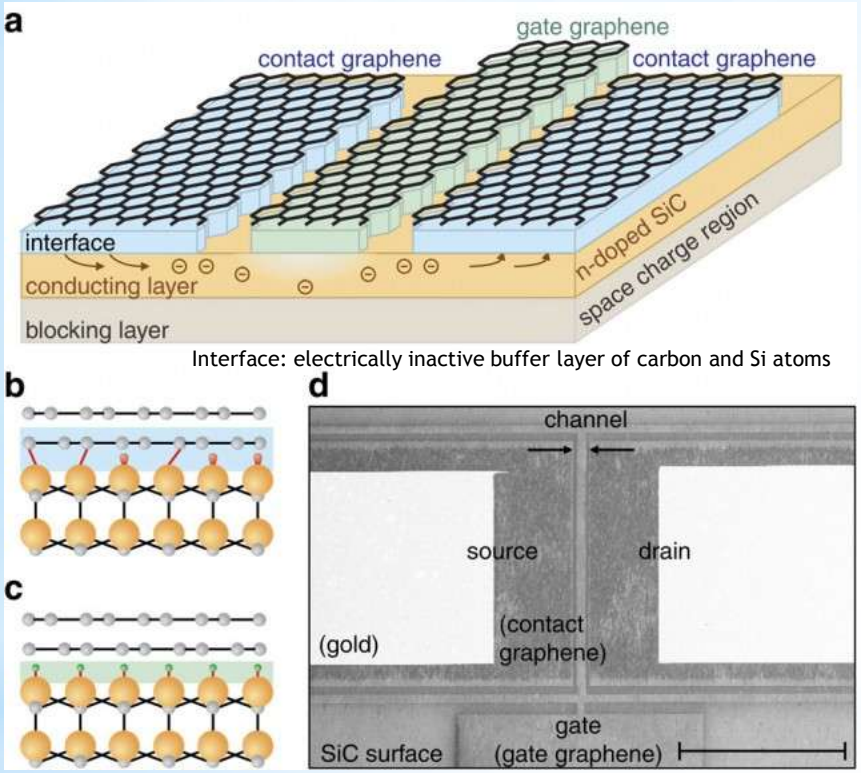
Researchers from Peking University and Columbia have combined titanium dioxide nanoparticles with carbon nanotubes to make light-sensitive transistors that can be made to switch on or off in response to UV light.

The transistors are made by mounting long single walled carbon nanotubes (SWNTs) between chromium and gold electrodes on a silicon wafer backing. They are then dipped in a solution containing the TiO2 nanoparticles, which have oleic acid groups on their surfaces to anchor them to the nanotubes.

Free electrons gather on the nanoparticles in response to light, changing the conductivity of the nanotubes.

http://www.rsc.org/chemistryworld/News/2009/May/28050901.asp

Graphene Transistors



Interface: electrically inactive buffer layer of carbon and Si atoms

Gate insulator: quasi-freestanding bilayer graphene/Schottky contact

Scale bar 100nm

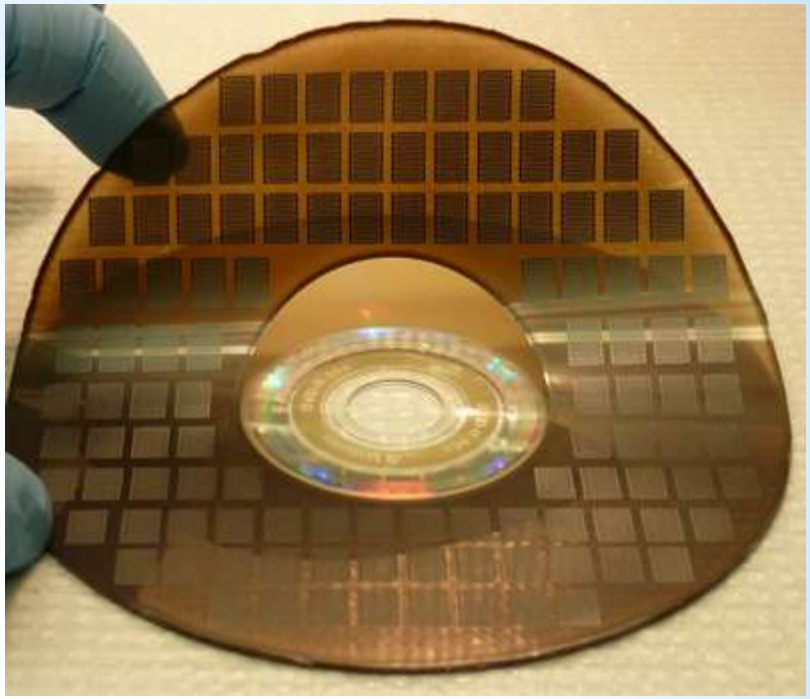
- "Tailoring the graphene/silicon carbide interface for monolithic wafer-scale electronics" S. Hertel et al.
- Graphene (carbon atom monolayer lattice) has very high conductivity and carrier mobility but no electron bandgap.
- This paper reports device fabrication with epitaxial graphene on silicon carbide.
- Proof-of-concept demonstrated high on/off ratio and suitability for complex circuits with high speed and power.

Nature Communications: doi:10.1038/ncomms1955

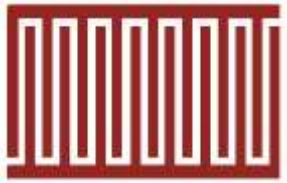
(July 2012)

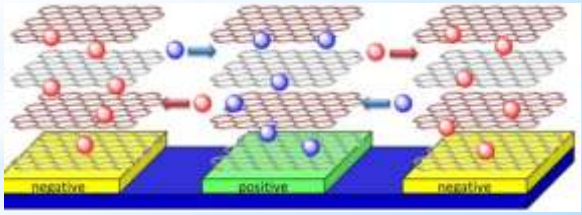
Supercapacitors

- Richard Kaner and Maher El-Kady, California NanoSystems Institute at UCLA, have developed a technique that uses a DVD burner to fabricate micro-scale graphene-based supercapacitors
- They glued a layer of PET onto the surface of a DVD, coated it with graphite oxide* and used a commercial optical drive to laser-scribe an interdigitated planar pattern of electrodes, used with gel electrolyte (PVA-H_2SO_4)
- The large effective area of graphene and its high conductivity provide high power density and low loss



Kaner and El-Kady's micro-supercapacitors. Image: UCLA





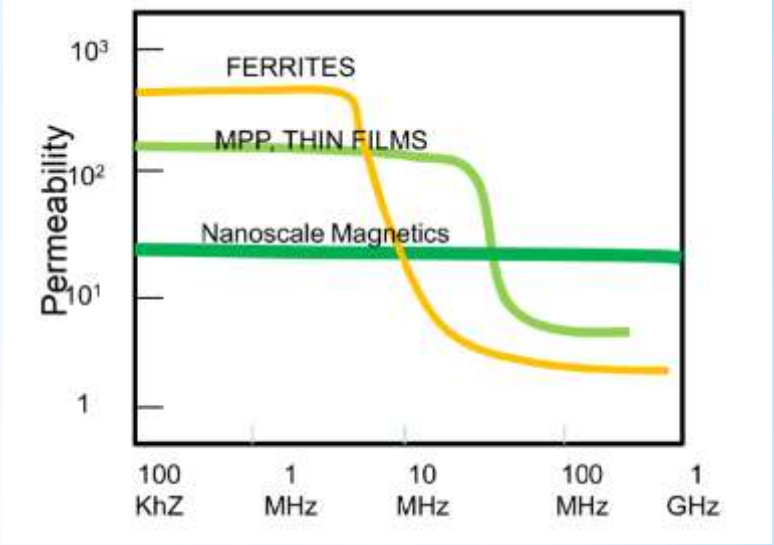
http://newsroom.ucla.edu/portal/ucla/ucla-researchers-develop-new-technique-243553.aspx

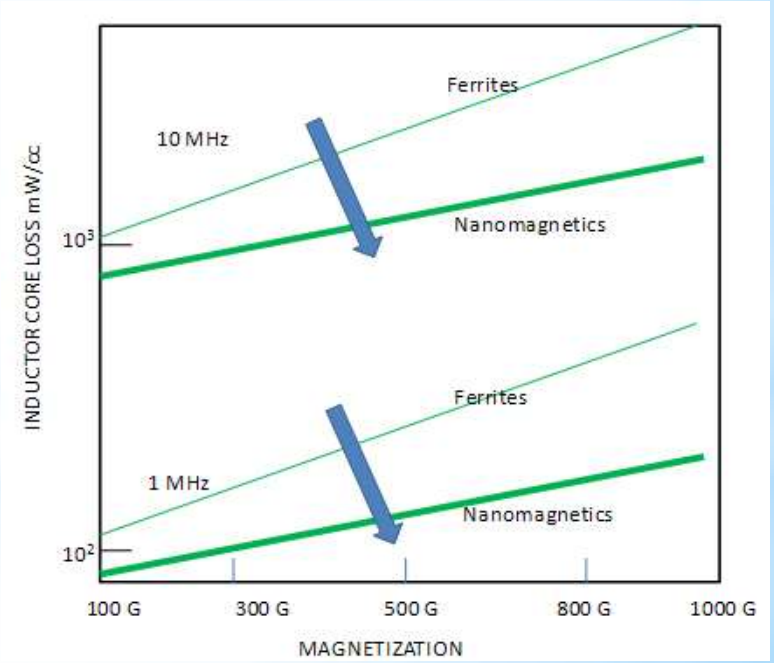
(Feb. 2013)

*"graphite oxide" contains OH and CO groups and epoxy bridges

Nanomagnetics

- Georgia Institute of Technology passive components research
  - Nanomagnetic materials - inductance to 1000nH/mm^2 Q of 20-50, 0.1-1GHz, 90% efficiency
  - Stable properties for wide range of frequencies (1GHz) and low domain wall and eddy current losses
  - Oriented magnetic domains to lower losses at high field strengths
  - Metal nanocomposites for printable silicon-compatible cores





http://www.prc.gatech.edu/events/IIT2011/7.%20Thinflim%20Passives%20Overview.pdf (May 2011)

http://www.prc.gatech.edu/partnership/PDF_flyers/TPI_Flyer.pdf

Nanoscale Transformer

- University of Manchester, UK, team used individual one-atom-thick crystals to construct a multilayer cake that works as a nanoscale electric transformer.
- Graphene was used as a one-atom-thick conductive plane and four atomic layers of boron nitride served as an electrical insulator.
- Electrons moving in one metallic layer pull electrons in the second metallic layer by their local electric fields (Coulomb drag). The metallic layers are insulated electrically from each other but separated by only a few interatomic distances.

http://www.manchester.ac.uk/aboutus/news/display/?id=8856

Strong Coulomb drag and broken symmetry in double-layer graphene, by R.V. Gorbachev, A.K. Geim et al, Nature Physics 8, 896-901 (2012) (June 2012)

Sensors & Transducers

- NIST research has opened a path to using quantum dots as components in better photodetectors, chemical sensors and nanoscale lasers.
- The team achieved understanding and control of nanoparticles whose interactions are key to such devices.
- Quantum dots and gold nanoparticles were placed on small rectangular constructs of DNA.
- The dot fluorescence in response to green laser light varies with the size and distance of gold particles.
- The variation can be used to reveal, for example, the presence of a particular chemical that is selectively attached to the DNA.

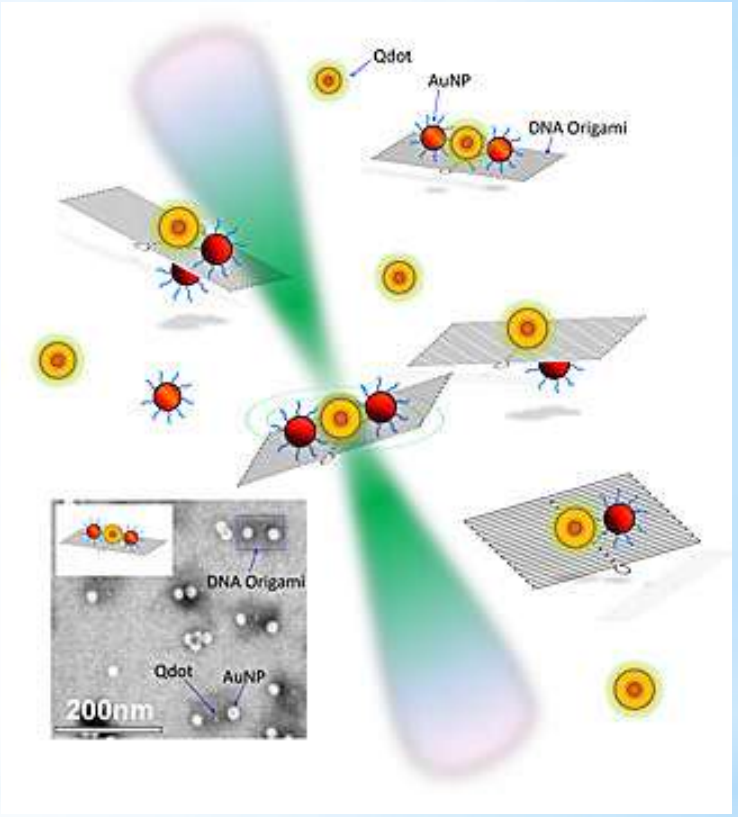


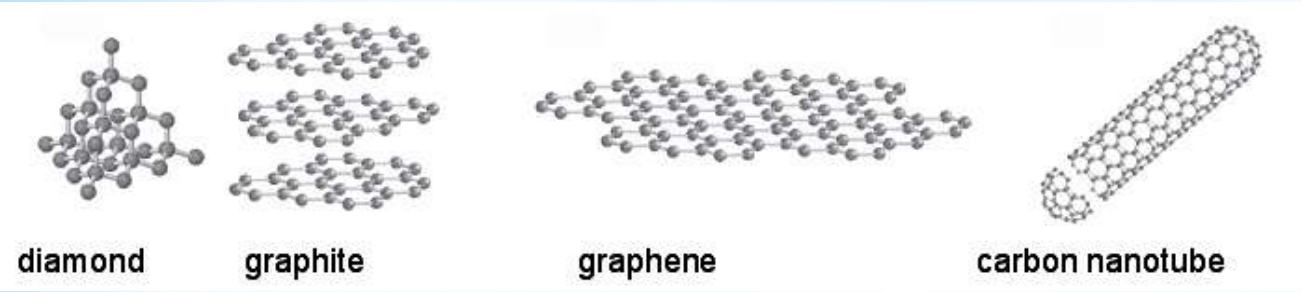
Image: NIST

http://www.laboratoryequipment.com/news/2013/01/discovery-opens-door-quantum-dots-photodetectors-sensors-lasers

Interconnect Wiring

Graphene Printed Circuits
Conductive Textile Material

Graphene-based Conductive Ink



- Graphene is a semi-metal or zero-gap semiconductor with high electron mobility and conductivity.
- NSF grantee Vorbeck Materials of Jessup, MD, is producing graphene-based products, including Vor-ink™ a conductive ink.
- It can be used to draw or print circuits in high volumes on a variety of substrate materials including paper, paperboard, and polymer films, more economically than traditional methods.
- Vorbeck recently expanded capacity to over 40 tons per year.
- Resistivity @ 7μ 14-21Ω/sq.

http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=126923 (Feb. 2013)

Conductive Textiles from Hong Kong Poly U

- Researchers from the Institute of Textiles and Clothing at Poly U have engineered a new fabric that can conduct electricity.
- The fabric is made of flexible polymers and conductive nano-carbon materials laced onto the polymer in a thin layer.
- When stretched or pressed, the thickness of the conductive layer changes, which changes the resistance.
- The effect can be used to measure strain and pressure over a wide range.
- Many applications are envisaged and the technology has been licensed to a start-up called AdvanPro Limited.

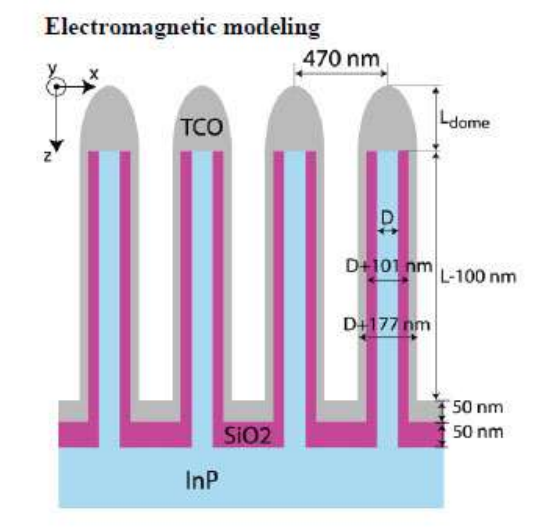
http://www.polyu.edu.hk/ife/corp/en/publications/tech_front.php?tfid=3141 (Feb. 2013)

Energy Production & Storage

Photovoltaics
Hydrocarbon Photosynthesis
Energy Harvesting
High-performance Batteries
Fuel Cells

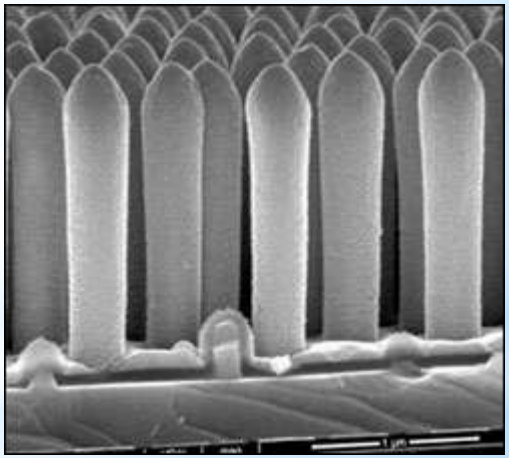
Nanowire Photovoltaic Cells

- InP Nanowire Array Solar Cells Achieving 13.8% Efficiency by exceeding the ray optics limit, Wallentin et al, Lund U. Sweden
- The nanowires are made of indium phosphide and work like antennae that absorb sunlight and generate power. They are assembled on surfaces of one square millimetre that each house four million nanowires. A nanowire solar cell can produce an effect per active surface unit several times greater than today's silicon cells.
- The right size is essential for the nanowires to absorb as many photons as possible, according to an author. "If they are just a few tenths of a nanometer too small, their function is significantly impaired."



TCO: transparent conductive oxide

(top contact - TCO; bottom - substrate)



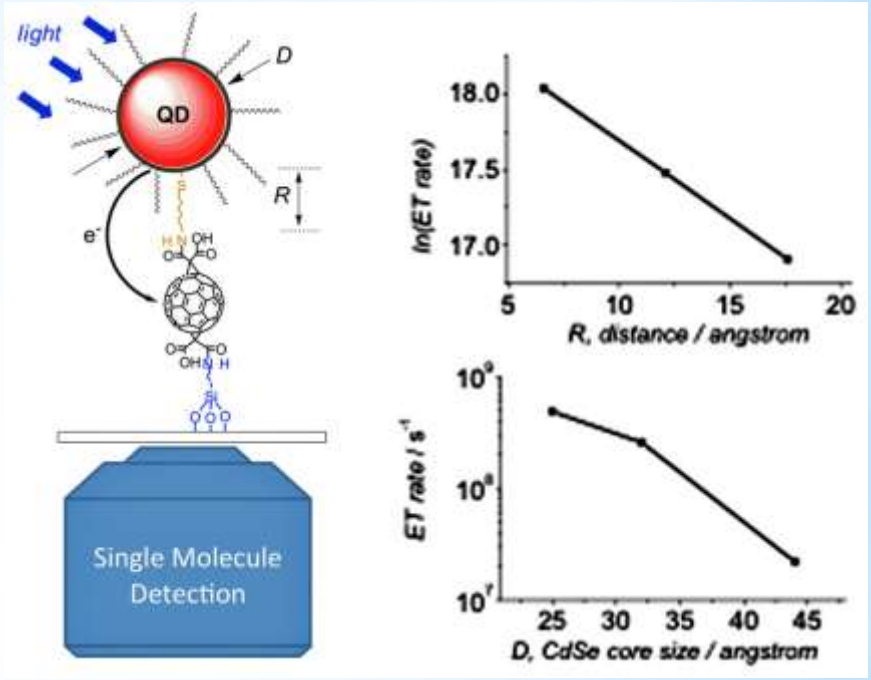
SEM image – Lund U.

http://www.photonics.com/Article.aspx?AID=52871

http://www.sciencemag.org/content/suppl/2013/01/16/science.1230969.DC1/Wallentin.SM.pdf

Quantum Dot/Fullerene Photovoltaics

- Scientists at the DOE Brookhaven National Laboratory have assembled nanoscale pairings of light-absorbing, colloidal quantum dots and carbon-allotrope fullerene nanoparticles, which can convert light to electricity.
- Previously, quantum dots have been combined with dyes, fullerenes, and titanium oxide to produce dye-sensitized and hybrid solar cells, but so far the power conversion rates have remained quite low.
- By varying the length of the linker molecules and the size of the quantum dots, the DOE scientists can control the light-induced electron transfer. "This control makes these dimers promising power-generating units for molecular electronics or more efficient photovoltaic solar cells," said Mircea Cotlet, who conducted this research with materials scientist Zhihua Xu



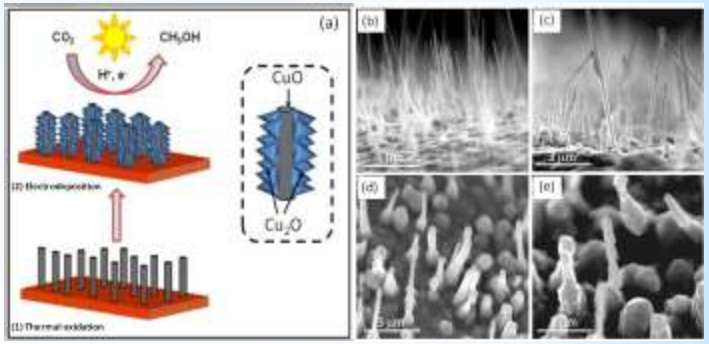
L: Photoinduced electron transfer in quantum dot-bridge-fullerene heterodimers.

R: Control of electron transfer rate by varying interparticle distance and quantum dot size

http://www.bnl.gov/newsroom/news.php?a=11260 (May 2011)

Nanowires Produce Methanol

- Researchers from The Univ. of Texas at Arlington have a new method for producing methanol from CO_2 and sunlight using copper oxide nanowires.
- Copper oxide, CuO, nanorods were coated with Cu_2O and submerged in a water-based solution of CO_2. Irradiating the combination with simulated sunlight caused a photoelectrochemical reduction of the CO_2 that produced methanol.
- The experiments generated methanol with 95 percent electrochemical efficiency and avoided the excess energy input, also known as overpotential, of other methods.
- Other methods require a co-catalyst, operate at high pressures and temperatures and may use toxic or rare catalysts.



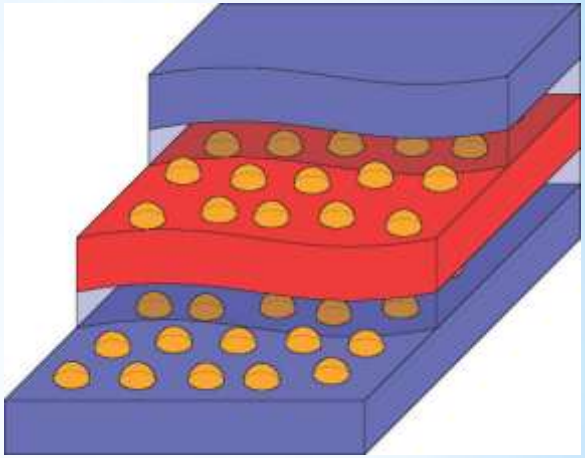
Ghazaleh Ghadimkhani, et al. Efficient solar photoelectrosynthesis of methanol from carbon dioxide using hybrid CuO–Cu_2O semiconductor nanorod arrays. *Chem. Commun.*, 49, 1297-1299 doi: 10.1039/C2CC38068D

http://www.ncbi.nlm.nih.gov/pubmed/23296091

http://www.laboratoryequipment.com/news/2013/02/copper-oxide-sunlight-turn-co2-fuel

Waste Heat into Electricity

- "Powerful and efficient energy harvester with resonant-tunneling quantum dots," Jordan et al, Phys. Rev. B 87, 075312 (2013) *(U. of Rochester)*
- The work proposes a nanoscale heat engine that uses resonant tunneling in quantum dots to convert heat into electrical current in a geometry which separates current and heat flows.
- By putting two quantum dots in series with a hot cavity, electrons that enter one lead must gain a prescribed energy to exit the opposite lead, transporting a single electron charge. This condition yields an ideally efficient heat engine.
- Despite the simplicity of the physical model, the rectified current and power are larger than any other candidate nanoengine. The high power and efficiency of the layered structure persist even if the quantum dots exhibit some randomness.
- The researchers estimate the power at one watt per square inch per degree C temperature difference.



An array of nano energy harvesters in what the researchers call a "swiss cheese sandwich" arrangement

Powerful and efficient energy harvester with resonant-tunneling quantum dots, Jordan et al. Phys. Rev. B 87, 075312 (2013)

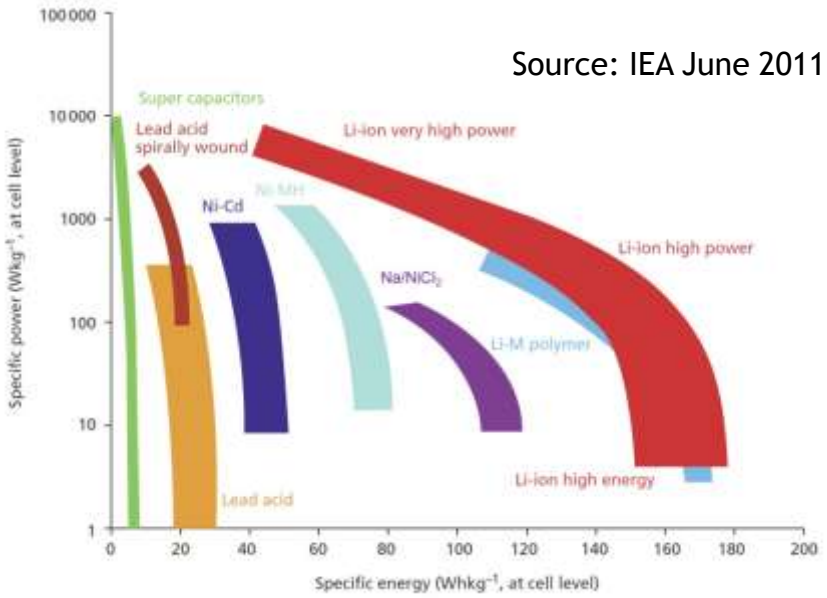
http://link.aps.org/doi/10.1103/PhysRevB.87.075312

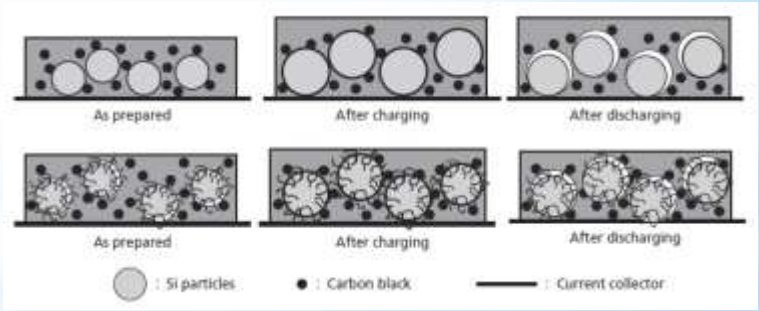
http://www.rochester.edu/news/show.php?id=5562 (Feb. 2013)

Polymer-derived Ceramics (PDCs) for Li-ion Batteries

- "Polymer-derived ceramics as anode material for rechargeable Li-ion batteries: a review" Bhandavat et al. Nanomaterials and Energy,Volume 1, Issue 6,November 2012
- The authors' objective is to improve cyclic performance, particularly for automotive applications. The Li capacity and durability of conventional graphite anodes are limitations.
- PDCs exhibit high chemical and thermodynamic stability under adverse operational conditions.
- Silicon oxycarbide- and Silicon carbonitride-based ceramics are practical and popular choices for researchers.
- Anodes are improved by: reducing active particle size and using stable nanoporous architectures, resilient composite structures and conductive binders that bond with the active material.

Source: IEA June 2011



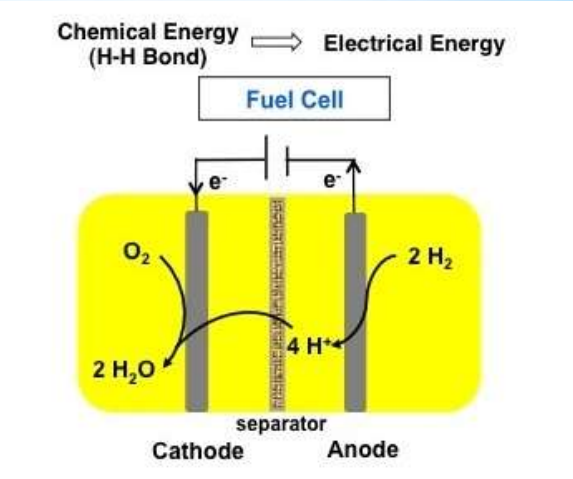


CNTs or Graphene improve conductivity & strength

http://www.icevirtuallibrary.com/content/article/10.1680/nme.12.00030

Fuel Cell Technology

- Researchers at DOE Pacific Northwest National Lab. have demonstrated an iron-based catalyst whose efficiency approaches that of commercial platinum catalysts*.
- This work reports an iron-compound molecule that splits H_2 at room temperature at a rate of 0.66-2/sec. an operating potential of about 0.8V and low overpotential (efficiency) of 160–220 mV.
- The iron complex, $Cp^{C_6F_5}Fe(P^{tBu}_2N^{Bn}_2)(H)$, has pendant amines in the diphosphine ligand that function as proton relays.



*Tianbiao Liu, Daniel L. DuBois and R. Morris Bullock. An iron complex with pendent amines as a molecular electrocatalyst for oxidation of hydrogen, *Nature Chemistry*, February 17, 2013, http://www.nature.com/nchem/journal/v5/n3/full/nchem.1571.html

Novel Materials

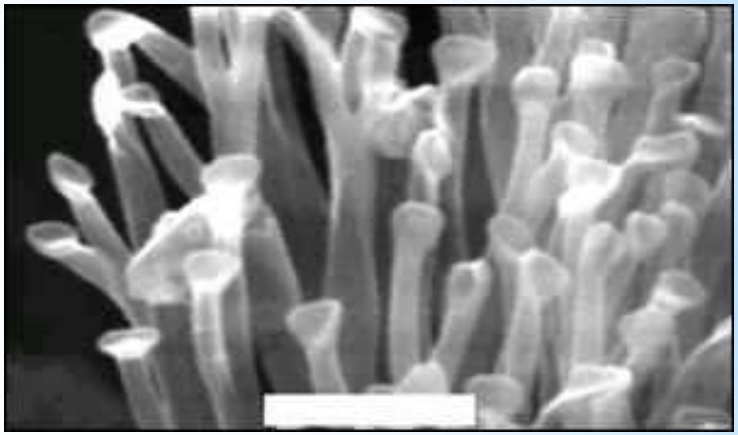
Nanotechnology Composites
Adhesives
Special Coatings
- ESD protection
- Anti-corrosion
- Anti-adhesion

Nanotechnology Composites

- Nanoclay/polymers are used in autos (large quantities), cables and other applications because of good although unspectacular characteristics and low cost.
- The strength and light weight of composites made with carbon fiber are well known, and carbon nanotubes (CNTs) have 100x greater tensile strength, but their full potential has not yet been realized because of many practical difficulties.
- Lockheed Martin announced in May 2011 that the F35 will use carbon nanotube reinforced polymer for wingtip fairings, which are non-load-bearing. Lockheed says they will be stronger, lighter and lower cost than a carbon fiber alternative. Airbus is also experimenting with the technology.
- CNTs have been used commercially in tennis rackets, golf clubs, baseball bats, arrows and bicycles by Yonex, Easton and others. Generally, the nanomaterials are incorporated into the resin systems; conventional fibers bear most of the loads and improvements are small.
- Another interesting material is 3Ms prepreg resin containing nanospheres of silica. Used in conventional carbon fiber composites it greatly increases compression strength and durability, reduces moisture absorption and improves processing properties. It is used in fishing rods and masts.

Gecko-inspired Adhesive

- Geckos have millions of hairs (setae) on their feet that allow them to stick to nearly every surface (and release cleanly). Each seta branches into 100–1,000 200nm tips that adhere through van der Waals forces.
- A team of polymer scientists and a biologist at the University of Massachusetts Amherst have invented "Geckskin," a device about 16 sq. in. that can hold 700 pounds on a smooth wall.
- The key innovation was an adhesive soft pad woven into a stiff fabric, which allows the pad to "drape" over a surface to maximize contact, woven into a synthetic "tendon," that maintains stiffness and rotational freedom.
- Geckskin uses simple everyday materials such as polydimethylsiloxane (PDMS), which holds promise for developing an inexpensive, strong and durable dry adhesive.

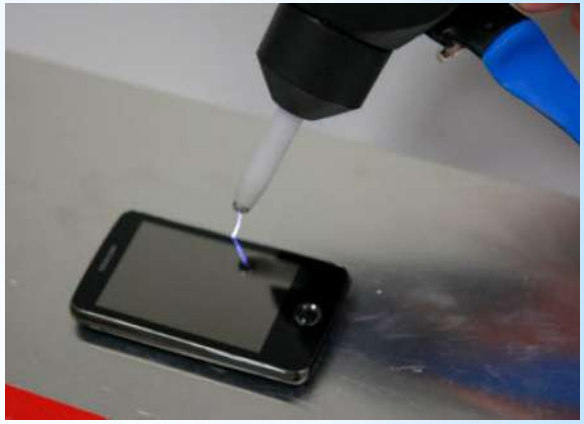


Michael D. Bartlett, Andrew B. Croll, Daniel R. King, Beth M. Paret, Duncan J. Irschick, Alfred J. Crosby. **Biomimetics: Looking Beyond Fibrillar Features to Scale Gecko-Like Adhesion (Adv. Mater. 8/2012)**. *Advanced Materials*, 2012; 24 (8): 994 DOI: 10.1002/adma.201290037

http://www.sciencedaily.com/releases/2012/02/120216165500.htm

Anti-Shock Nanotech Coating

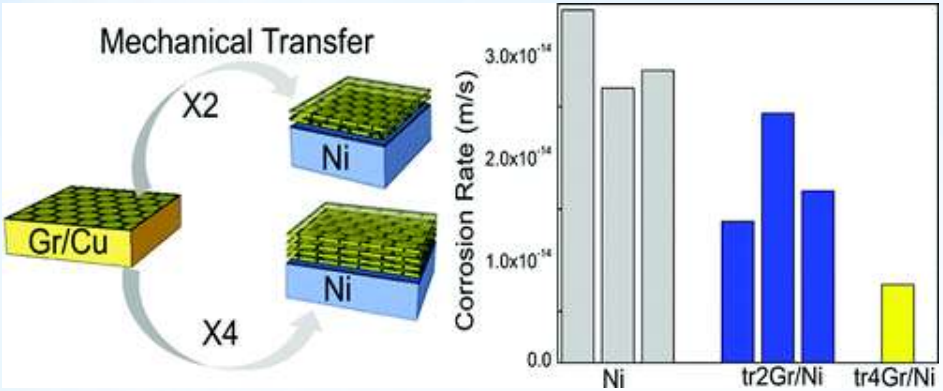
- Shocking Technologies develops Voltage Switchable Dielectric™ materials that protect electronic components from harmful electrostatic discharge (ESD).
- A Voltage Switchable Dielectric™ (VSD™) material is a polymer nano-composite that functions as an insulator (dielectric) during normal circuit operation and becomes conductive when the voltage increases beyond a predefined characteristic voltage.
- The VSD material becomes an insulator again after the voltage drops back below the characteristic voltage to normal operating levels.

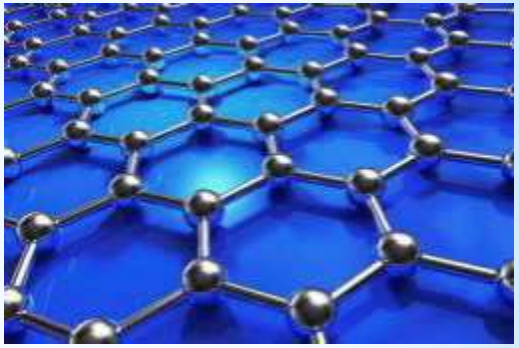


http://venturebeat.com/2010/12/07/shocking-technologies-uses-nanotech-material-to-protect-devices-from-static-electricity-discharges/

http://www.shockingtechnologies.com/

Graphene Protects Metals from Corrosion



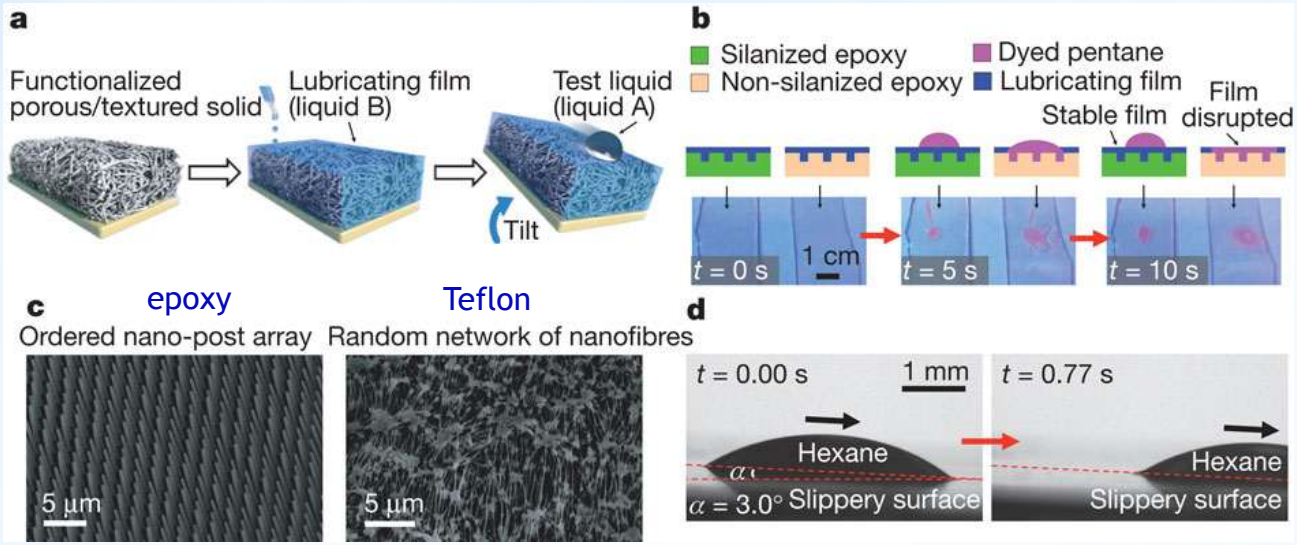


- Copper films coated with monolayer graphene grown *via* chemical vapor deposition are corroded 7 times slower in an aerated Na_2SO_4 solution compared with the corrosion rate of bare copper.
- Nickel with a multilayer graphene film grown on it corrodes 20 times slower while nickel surfaces coated with four layers of mechanically transferred graphene corrode 4 times slower than bare nickel.
- Electrochemical impedance spectroscopy measurements suggest that while graphene itself is not damaged, the metal under it is corroded at cracks in the graphene film

"Graphene: Corrosion-inhibiting Coating," Prasai et al. *ACS Nano*, **2012**, *6* (2), February 2, 2012

http://www.laboratoryequipment.com/news/2012/02/miracle-material-graphene-protects-metals-corrosion

Anti-adhesion Self-repairing Coating



- Natural nonwetting structures, particularly the leaves of the lotus, have led to liquid-repellent microtextured surfaces, but problems restrict application
- Slippery Liquid-Infused Porous Surfaces (SLIPS) is conceptually different because it uses nano/microstructured substrates to lock in place a perflourinated lubricating fluid (e.g. Krytox) which forms a stable, defect-free and inert 'slippery' interface
- It is robust, repels water, hydrocarbons, crude oil, blood, ice, ants, bacteria etc. and it is applicable to various materials such as porous Teflon membranes
- It is expected to be useful in electronics, solar panels, fluid handling, optical sensing, medicine, and as self-cleaning and anti-fouling material operating in extreme environments

Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity, Wong et al. NatureVolume: 477,Pages:443–447 Date published:(22 September 2011)

http://www.nature.com/nature/journal/v477/n7365/full/nature10447.html