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Power Sources: Fuel Cells, Solar Cells and Batteries

Executive Summary

More efficient power generation paves the way for lower costs and increased capacity. The top research prospects are hydrogen and light. Research efforts also include gaining usable energy from heat, vibrations, fusion and zero-point energy.

Pure hydrogen is a potentially clean energy source for use in both combustion engines, which burn hydrogen, and fuel cells, which release the energy stored in chemical bonds. Researchers are looking for less expensive and less polluting ways to extract hydrogen, and more efficient ways to store it. They are also working on more efficient fuel cell designs, including some so small they fit on a chip.

Today's solar cells are relatively costly because they are made from semiconductor materials that require stringent manufacturing conditions. Researchers are working to bring down prices by increasing silicon solar cells' overall efficiency beyond 15 percent, and by using alternative, cheaper materials. One alternative design has the potential to cut solar cell cost by an order of magnitude.

Researchers are also working to eke out more energy from a pair of 19th-century technologies: thermoelectrics and piezoelectrics. Thermoelectrics convert heat to electricity. Piezoelectrics turn vibrations into electricity, and have considerable potential to power microdevices.

Fusion promises almost unlimited power, but comes with the tremendous challenge of compressing and igniting atoms. Researchers are working on the difficult problem of confining and controlling fusion, and making the process generate more energy than it consumes.

Space is filled with zero point energy created by subatomic particles that appear and disappear. Researchers are looking to this weird quantum effect to gain energy to drive microscopic machines.

What to Look For

Hydrogen:

- Efficient hydrogen extraction from water
- Materials that hold over 6.5% of their weight in hydrogen
- On-the-fly hydrogen extraction for combustion

Fuel Cells:

- Portable devices powered by fuel cells
- Efficient biomass fuel cells
- Practical automobile fuel cells

Solar Cells:

- Solar cells that cost less than 10 cents per kilowatt-hour
- Plastic solar cells with more than 10 percent efficiency
- Practical paint-on solar panels

Other Sources:

- Electricity generated from powerplant waste heat
- Devices powered by car engine waste heat
- Portable devices powered by vibrations
- Controlled, sustained fusion reaction

Power for the people

Most of the technologies that underpin our society would be useless without a source of power. In the same vein, more efficient power generation and storage has the potential to improve current technologies and enable new ones.

Energy use falls into three categories:

- Powering the electric grid
- Powering vehicles
- Powering portable and off-grid devices

Much of today's power source research is aimed finding more efficient ways to generate and store power.

Generating alternatives

Finding more efficient ways to generate power paves the way for lower costs and increased capacity. And renewable, non-polluting power sources make it practical to use more power without depleting resources and taxing the environment.

The top prospects are hydrogen and light. Energy is stored in hydrogen in the chemical bond between a pair of hydrogen atoms. This energy can be released by burning hydrogen as fuel in a combustion engine or chemically breaking the bonds in a fuel cell. Solar energy production transfers energy contained in photons to electrons in order to make the electrons flow.

There are also research efforts aimed at drawing power from heat, vibrations and zero-point energy. And there is a big research effort behind fusion, a long-term prospect.

Wind power is another viable power source, but it is not a subject of widespread technological research. Wind turbine technology is relatively mature, and making it more efficient is largely the realm of engineers rather than researchers.

One line of power research is aimed at finding sources appropriate for the ever-smaller devices enabled by today's microelectronics and nanotechnology. Microdevices can be small enough to be invisible, and nano devices are orders of magnitude smaller.

Power source research includes several types of projects:

- Making hydrogen practical as a combustion fuel
- Making fuel cells more efficient and cleaner
- Making solar power devices cheaper and more efficient
- Converting waste heat to electricity
- Converting vibrations to electricity
- Controlling fusion
- Tapping the tiny amounts of zero-point energy that exists everywhere

Bottled lightning

Storing power more efficiently makes all types of power use more efficient and flexible. Batteries that store more energy per ounce will make more power available when and where it is needed, opening up new possibilities for portable devices.

Research into batteries has several aims:

- More efficient materials that enable more power to be stored in smaller spaces
- Less toxic materials for use in batteries
- Power storage devices that can be integrated into electronics

How It Works

Batteries, fuel cells and solar cells each mimic one of the functions plants perform to gain energy from the sun. Plants capture photons and use their energy to break water molecule bonds to release the energy tied up in them.

Plants liberate electrons to drive chemical reactions that turn carbon dioxide into various carbohydrates.

Batteries, fuel cells and solar cells use free electrons to generate a flow of electricity.

Solar cells transfer the energy contained in photons directly to electrons to cause a flow of electricity.

Fuel cells break chemical bonds to gain electrons.

Batteries are similar, but cyclic — to charge they draw energy to form chemical bonds that store energy, then break those bonds to release the stored energy when it is needed.

Breaking chemical bonds

Batteries generate electricity when two solutions of ions chemically react to transfer electrons from one to the other. Ions are atoms that carry a charge because they have more or fewer negatively-charged electrons than positively-charged protons. Instead of a direct transfer, however, the electrons leave the batteries via one electrode — the cathode — and return through another — the anode. This provides a current of electrons to a device connected to the battery. The anode is generally made from a more conductive material than the cathode.

Fuel cells are similar, but their fuel is replenishable and they cannot be recharged. In fuel cells, the cathode and anode are separated by a membrane. The electrodes are catalysts; the cathode strips electrons from hydrogen, leaving hydrogen ions in the membrane. The anode combines oxygen and electrons with the hydrogen ions to produce water. The electrons flow in a circuit from the cathode to the anode.

Electricity from light

Different types of atoms contain different numbers of electrons arranged in layers around a nucleus of protons and neutrons. One way to picture electrons is in orbit around the atomic nucleus, similar to planets orbiting the sun. Electrons jump to a higher orbit, however, when they gain energy.

Different materials also contain different bandgaps; a material's bandgap is the energy needed to push an electron from the first orbit, or valence band, to a conduction band where electrons can flow from one atom to the next.

Solar cells consist of two layers of a semiconductor; one carries positive charges and the other negative charge. Sunlight is absorbed by the

Elemental energy

The holy grail of fuel is hydrogen, which shows promise as a clean energy source for combustion engines and fuel cells. When pure hydrogen is burned it yields only energy and water. And fuel cells can extract hydrogen from clean sources like ethanol and water.

Hydrogen energy could span the range of energy needs. Automobiles powered by fuel cells are already available, and fuel-cell-driven portable computers are likely to come onto the market in the next year or two. Home-scale fuel cells have the potential to augment and eventually even replace the electric grid.

Using hydrogen is a fuel, however, requires a hydrogen source and a way to make the hydrogen available to be burned or expended chemically. These are formidable challenges. Today's solutions are not always clean, largely because it takes energy to extract hydrogen.

Today's methods usually involve extracting hydrogen from hydrocarbons, most often natural gas, which in turn must be extracted from the earth. It takes a lot of energy to produce hydrogen this way, and little of that energy is green.

Prying hydrogen loose

Researchers are working to find less expensive and less polluting ways to extract hydrogen.

The possibilities involve several candidate sources in addition to fossil fuels: methanol, which is often derived from natural gas, but can also be extracted from plants; ethanol, which is derived from plant matter; and water. Methanol is poisonous to humans, but ethanol and water are nontoxic.

Hydrogen can be extracted from water using electricity, but using electricity to process a fuel decreases its overall efficiency. Researchers are working to make hydrogen fuel more practical by finding more efficient ways to extract it.

Researchers from the National Institute of Advanced Industrial Science and Technology in Japan are following the lead of plants, which use light to break down water molecules in order to gain electrons for chemical reactions. The researchers have found a stable photocatalyst that uses energy from visible light to break water molecule bonds and release hydrogen gas. (See Sunlight Turns Water to Fuel, page 10.)

Stashing hydrogen away

Another area of energy research involves finding more efficient ways to store hydrogen. To date, it's been more efficient to store the hydrogen used as combustion engine fuel rather than generate it on-the-fly.

The key is finding a material that will not only store hydrogen, but give it up when fuel is needed. The challenge is being able to retrieve hydrogen rapidly enough at reasonable temperatures and pressures.

For motor vehicle use it is important that a storage material hold enough hydrogen per pound to be worth the energy it takes to positive layer, and the photons' energy is imparted to the semiconductor's atoms. Electrons in the energized atoms jump from the valence band to the conduction band. From there the electrons are drawn to the negative semiconductor layer and passed to an electrical circuit.

Electricity from heat and vibrations

In theory, it is possible to extract energy from any environment where two areas consistently hold different amounts of energy.

Thermovoltaics extract energy from environments where there are large temperature differences, and piezoelectric materials do the same where there are differences in mechanical energy.

Thermovoltaic methods use the temperature differences between a heat source like a car engine or even a warm body and the outside air.

Given the right materials, electrons will flow from an area of high temperature to an area of low-temperature or vice versa. Thermoelectric generators consist of a pair metals or semiconductors, one negative and one positive, that produce flows in opposite directions. Connecting the cold ends of the pair to a circuit generates electricity because electrons in the negative material flow to the cold end and onto the circuit, where they are are drawn to the cold end of the positive material.

Piezoelectric crystals generate electric charges on their surfaces when they are subjected to mechanical stress. These charges can produce a small electric current when connected to a circuit.

Some watches are powered by the motion of the person wearing a watch. And some downhill skis contain light-emitting diodes powered by the vibration of the skis.

Energy from Atoms — Fusion

Nuclear fusion is the reaction that powers the sun and hydrogen bombs. The challenge to using fusion as an energy force is controlling it.

It takes a great deal of energy to force a pair of atoms together, but once they come close enough, they fuse to form a new type of atom; the reaction gives off a tremendous amount of energy.

A controlled fusion reaction involves fuel that is compressed to become very dense, a great deal of ignition energy, and a lot of tricky timing. The reaction must also be contained, which is difficult because it takes place at 100,000,000 degrees Celsius, which is hot enough to burn through any material.

Scientists are working on controlling fusion reactions fueled by hydrogen isotopes. Hydrogen is the simplest atom, and normally consists of one proton and one electron. Hydrogen isotopes are denser than plain hydrogen because they also contain one or more neutrons.

haul it around. The U.S. Department of Energy has set a goal of 6.5 percent of a storage material's weight for automobile fuel.

Most of today's hydrogen storage materials are powdered metal hydrides, which can hold 2 to 4 percent of their weight in hydrogen. One research team has discovered a promising new class of materials — metal-organic frameworks, which are relatively inexpensive to manufacture, and have the potential to reach the 6.5 percent goal. (See Hydrogen Storage Eased, page 12.)

National University of Singapore researchers are working with another possibility, lithium nitride, which can store up to 11.5 percent of its weight as hydrogen, but currently only works at higher-than-practical temperatures. (See Metal Stores More Hydrogen, page 13.)

These technologies are two to 10 years from practical use.

Chemical power

The alternative to burning hydrogen is releasing its energy chemically in a fuel cell. This is generally more efficient than burning it. Combustion engines use 15 percent of hydrogen's potential energy, whereas fuel cells use 40 to 60 percent. Fuel cells also sidestep combustion's storage problem because hydrogen extraction typically occurs as part of the fuel cell's chemical processes. (See How It Works, page 2)

Researchers are improving fuel cells by making them more efficient, smaller, cheaper and nontoxic. Researchers are also working on producing fuel cells that don't require highly purified fuels.

There are several types of existing fuel cells:

- Alkaline
- Molten carbonate
- Phosphoric acid
- Polymer electrolyte
- Solid oxide

Phosphoric acid and alkaline fuel cells are older, more expensive technologies. The two most actively under development are solid oxide and polymer electrolyte.

Solid oxide is today's most efficient type of fuel cell. It reclaims waste heat to process fuel, and runs on widely available petrochemicals like gasoline and diesel. It has high manufacturing costs, however, and takes time to start up. Its high operating temperatures and high output make this type of fuel cell suited to powering buildings and large vehicles.

Polymer electrolyte fuel cells have high energy densities; they operate at low temperatures, which allows them to start quickly; and they can be small and light — all key advantages for use in automobiles. They require pure ethanol or methanol as fuel, and are suited for lower-and medium-power applications.

An emerging variant of the polymer electrolyte fuel cell is the direct methanol fuel cell, which draws hydrogen directly from methanol, eliminating the fuel processing step. So far, however, they are not very efficient.

The reaction is similar to the internal combustion engines used in cars, where fuel is compressed and a spark ignites the fuel. When successfully sparked, the fuel explodes, releasing energy.

The compressed fusion fuel, or plasma, is held in place by lasers, and the reaction is sparked by a laser. The laser energizes the plasma because as photons travel through it, they slow down, transferring heat to the plasma.

Who to Watch

Hydrogen Generation/Storage

Mei-Yin Chou
Georgia Institute of Technology
www.physics.gatech.edu/people/faculty/mchou.html

Stefan Czernik
National Renewable Energy Laboratory
www.nrel.gov/chemistry_bioenergy/hydrogen.html

Raphael Idem
University of Regina
www.uregina.ca/engg/faculty_students/idem.htm

Craig Jensen
University of Hawaii at Manoa
www.chem.hawaii.edu/UH_Chem/faculty/jensen.html

Fuel Cells

Lutgard C. De Jonghe
University of California at Berkeley
www.mse.berkeley.edu/faculty/DeJonghe/lut.html

Steven Holdcroft
Simon Fraser University
www.sfu.ca/chemistry/faculty/Holdcroft/

Walter Podolski
Argonne National Laboratory
www.ipd.anl.gov/energy_partners/fuelcell.html

Richard E. Rocheleau
University of Hawaii at Manoa
www.hnei.hawaii.edu/template.asp?userID=38

Scott Samuelsen
University of California, Irvine
www.apep.uci.edu/samuelsen

Robert F. Savinell
Case Western Reserve University
www.cwru.edu/cse/eche/people/faculty/savinell/

Kenneth Stroh
Los Alamos National Laboratory
www.lanl.gov/mst/fuelcells/

Levi Thompson
University of Michigan
www.engin.umich.edu/dept/che/research/thompson/

Regenerative fuel cells, which use water as fuel and reclaim the water produced when they generate electricity, are a long-term possibility. Research initiatives are focused on using solar energy to extract hydrogen from water.

Taking a cue from nature

Several research teams are taking advantage of natural processes to develop small-scale fuel cells.

Researchers from Ernst Moritz Arndt University in Germany have fashioned a simple, clean fuel cell that captures the hydrogen produced when microorganisms metabolize carbohydrates like sugar. The device generates relatively low amounts of power. (See Munching Microbes Feed Fuel Cell, page 14.)

A method from St. Louis University calls for releasing the energy contained in ethanol's hydrogen bonds in a process that depends on enzymes. (See Alcohol Powers Fuel Cell, page 14.)

Researchers are also working on small fuel cells aimed at portable devices and even microdevices.

Lawrence Livermore National Laboratory scientists have fashioned a methanol fuel cell that weighs eight grams and packs more power than a lithium ion battery. (See Fuel Cell Aimed at Handhelds, page 14.) And Lehigh University researchers have fashioned a chip-sized fuel cell that uses a catalyst to extract hydrogen from a mix of methanol and water. (See Hydrogen Chip to Fuel Handhelds, page 11.)

In general, these fuel cell technologies are five to 10 years away from practical use.

The ultimate power source

The sun is the ultimate clean power — it has fueled the vast majority of earth's life for several billion years.

Solar devices mimic the first step of the biological food web — plants extracting energy from the sun — by capturing photons and converting them to electricity.

Today's solar cells are relatively costly because they are made from semiconductor materials that require stringent manufacturing conditions. Researchers are working to bring prices down by making silicon solar cells more efficient and by using cheap alternative materials.

The most efficient solar cell possible would be made from a material that could capture all the wavelengths radiated by the sun and convert all the energy those photons contain into a flow of electrons. The sun radiates about 48 percent infrared light, or heat, 45 percent visible light, and 7 percent ultraviolet light, though most of the ultraviolet radiation is filtered out by the atmosphere.

Sand and sun

Solar cells are made from one or more semiconductors, typically silicon. (See How It Works, page 2.) The most efficient commercial solar cells are usually made of crystalline silicon, the same relatively expensive material used in computer chips.

Alan West
Columbia University
216.119.76.245/fac_page_west.html

Solar Cells

Robert W. Birkmire
University of Delaware
www.udel.edu/iec/Resumes/Birkmire/RWB-CV.html

Sanford A. Klein
University of Wisconsin
www.engr.wisc.edu/me/faculty/klein_sanford.html

Steven A. Ringel
Ohio State University
www.eleceng.ohio-state.edu/~ringel/

Ajeet Rohatgi
Georgia Institute of Technology
users.ece.gatech.edu:80/~arohatgi/

Tadashi Saitoh
Tokyo University of Agriculture and Technology
www.tuat.ac.jp/~eeeng/

James Sites
Colorado State University
www.physics.colostate.edu/People/faculty/sites

Gerhard Willeke
Fraunhofer Institute
www.ise.fhg.de

Batteries

Dan Doughty
Sandia National Laboratories
www.sandia.gov/pstg/battery.html

Roger Frech
University of Oklahoma
cheminfo.chem.ou.edu/faculty/ref.html

Gary L. Henriksen
Argonne National Laboratory
www.transportation.anl.gov/staff/henriksen.html

John Owen
University of Southampton
www.chem.soton.ac.uk/research/profiles/electrochem/owen/owen.htm

Günther G. Scherer
Paul Scherrer Institut (Switzerland)
ecl.web.psi.ch/contact.html

Pritam Singh
Murdoch University
wwwphys.murdoch.edu.au/mueri/battres.html

Michael Thackeray
Argonne National Laboratory
www.cmt.anl.gov/science-technology/batteries/advancedelectrode.shtml

Xiao-Qing Yang
Brookhaven National Laboratory
www.bnl.gov/msd/

Current commercial silicon solar cells have an overall efficiency of about 15 percent, meaning about 15 percent of the photons that hit the device are eventually captured and converted to electricity. Most of the inefficiency is due to the inability to capture more photons. Today's commercial devices convert about 95 percent of captured photons to electricity.

Capturing more photons comes down to increasing the range of wavelengths the semiconductor absorbs, minimizing the amount of photon energy that simply heats the material, and decreasing the reflectivity of the material's surface. Silicon is capable of absorbing about three-quarters of the wavelengths of sunlight, mostly in the visible range. Researchers are working to extend the absorption further into the near-infrared range.

Silicon comes in three forms: crystalline, polycrystalline and amorphous. The crystalline atoms are arranged in a regular, lattice-like structure; polycrystalline materials are aggregates of tiny crystals; and the atoms in amorphous materials are unordered.

Amorphous silicon is cheap to produce but less efficient at taking in photons and converting them to electricity than crystalline silicon. Polycrystalline silicon is promising because it is relatively inexpensive and it is nearly as efficient at converting photons to electricity as crystalline silicon. Crystalline silicon has a 20 to 25 efficiency rate, polycrystalline silicon's is 15 to 20 percent, and amorphous silicon's is 6 to 12 percent.

Piezoelectrics and Thermoelectrics

Tim Coutts
National Renewable Energy Labor
www.mines.edu/Academic/physics/people/pages/coutts.html

Peter Hagelstein
Massachusetts Institute of Technology
rleweb.mit.edu/rlestaff/p-hage.htm

George A. Lesieutre
Pennsylvania State University
www.personal.psu.edu/faculty/g/a/gal4/index.html

Joe Paradiso
Massachusetts Institute of Technology
web.media.mit.edu/~joep/

Zero-Point Energy

Ho Bun Chan
Bell Labs
www.bell-labs.com/org/physicalsciences/org/pr/pr.html

Umar Mohideen
University of California, Riverside
physics.ucr.edu/People/Home/mohideen.html

Beyond silicon

There are other semiconductor candidates as well. Until recently the best known photovoltaic material was a combination of gallium
arsenide and gallium indium phosphide, which has a theoretical efficiency of 32 percent, but is more expensive than silicon.

A research group recently unexpectedly found that a common semiconductor is potentially more efficient than silicon and gallium arsenide. When they measured the semiconductor indium nitride they found that standard measurements taken two decades ago that classified the material as a mediocre photovoltaic were incorrect. The new measurements peg the material's theoretical efficiency at 50 percent. (See Materials Soaks up the Sun, page 17)

Meanwhile, researchers from Sandia National Laboratories and Iowa State University have found a way to structure a tungsten element so that it emits many more visible wavelengths than heat. The material could be used to shift some of the heat of sunlight into the visible light range where it can be more easily converted to electricity by today's photovoltaic cells. (See Crystals Turns Heat to Light, page 18.)

These more efficient solar technologies could be in practical use within five years.

Researchers are also working on plastic solar cells, which would be far less expensive than silicon devices. The technology also sets the stage for paint-on solar panels. The most efficient plastic solar cell to date, however, has an efficiency of just three percent. Plastic solar cells also break down relatively quickly when exposed to air, moisture and ultraviolet light.

Researchers at the University of California at Berkeley have developed a hybrid that combines plastic with semiconductor nanorods made from cadmium selenide, a crystalline semiconductor. The device has an efficiency of 1.7 percent, but can potentially reach ten percent.

Higher efficiency plastic solar cells could be practical in five to ten years.

Splitting it up

Researchers from the University of California at Santa Barbara have completely redesigned the solar cell to make a much cheaper photon-converting device.

Key to the redesign was finding a way to efficiently transfer excited electrons from one material to another. This made it possible to carry out the two functions of a solar cell — absorbing photons and transporting electrons — using two different materials. The device uses a dye rather than crystalline semiconductors to absorb photons. The dye reflects less light than silicon. And because the semiconductor component that transports electrons is not required to absorb photons, the researchers were able to switch to a very cheap one — titanium dioxide, an ingredient of white paint.

The Santa Barbara prototype has an overall efficiency of less than one percent, but this can easily be improved by increasing the surface area. The method has the potential to produce solar cells that are about as efficient as current commercial models, but more than an order of magnitude cheaper. The technology could also lead to paint-on solar panels. (See Cheap Solar Power on Deck, page 16.)

The cost of converting photons

On the practical side, solar energy has great promise for several different types of power uses. Residential and commercial buildings, which account for 65 percent of the electricity consumed in the U.S., have abundant surface areas for harvesting sunlight. Solar energy, especially when combined with battery storage, is also well suited to powering portable, mobile, and remote devices like robots and sensors.

At 20 to 30 cents per kilowatt-hour, however, today's solar cell technology is considerably more expensive than other methods of generating energy in general use. Most other power sources, including fossil fuels, nuclear power and renewable energy sources like wind power, cost two to eight cents per kilowatt-hour. These numbers do not factor in secondary costs like environmental and health effects or boosts from government subsidies. The average retail price of electricity in 2001 was 8.5 cents per kilowatt-hour for residences and 5 cents per kilowatt-hour for industry, according to the U.S. Department of Energy.

Recycling energy

Turning light to electricity isn't the only way to convert one form of energy to another. Heat and vibration, two ubiquitous byproducts of technology, can also be converted to electricity.

Scientists discovered how to quietly and cleanly turn heat to electricity nearly a century ago. Thermovoltaic technology is not widely used, however, because it has never been very efficient. (See How It Works, page 2)

Researchers looking for clean energy sources that are appropriate for small devices are working to more efficiently convert heat from sources like power plants, car engines — and even people — to electricity.

Researchers from the Massachusetts Institute of Technology and Eneco, Inc. have produced a thermal diode that has the potential to improve the conversion rate for waste heat sources from 10 to 18 percent by more efficiently moving electrons across the device, and at the same time blocking electrons from returning. (See Chips Turned More Heat to Power, page 19.)

Researchers from the Dresden University of Technologies in Germany have made a cheap, flexible, recyclable thermoelectric generator that is about the size of a thumbtack. (See Flexible Film Turns Heat to Power, page 20.)

More efficient thermoelectric generators could be practical within a year.

Good vibrations

Regular vibrations from machines and people are also a potential energy source. Piezoelectric devices, which convert vibrations to electricity, have been around for decades, most famously as a means to power watches. As electronic devices become smaller and more power efficient, their power needs more closely match the small amount of energy generated by piezoelectric materials. At the same time, researchers are finding ways to extract more energy from vibrations.

Pennsylvania State University researchers have increased piezoelectric circuit efficiency by optimizing the converter that transfers harvested energy to a battery. The device should prove efficient enough to use a runner's motion to power an electronic music device, according to the researchers. (See Circuit Gets More Power from Shakes, page 21.)

Better piezoelectrics could be practical within a year.

Packing power away

Batteries are all about time-shifting: storing electricity for use when and where it can't be efficiently generated, and storing excess energy for later use.

Batteries' working principles are similar to fuel cells (see How It Works, page 2). And as with fuel cells, researchers are looking to make them more efficient, smaller, cheaper and less toxic.

Batteries that hold more power per ounce can be smaller, and smaller batteries will enable lighter, smaller electronic devices. Researchers from Hosei University in Japan have embedded tiny batteries on silicon chips. (See On-Chip Battery Debuts, page 22.)

This type of battery could become practical in five to ten years.

Researchers from the University of North Carolina have shown that is possible to extend battery life by making electrodes from carbon nanotubes rather than graphite. (See Nanotubes Pack Power, page 24.)

At the same time materials historically used in batteries have been fairly toxic to humans. Researchers are looking for less toxic alternatives.

A team from Bar-Ilan University in Israel has made rechargeable batteries from magnesium, which is cheap and relatively non-toxic. (See Magnesium Batteries Show Mettle, page 22.) And Massachusetts Institute of Technology researchers have drastically improved the conductivity of lithium iron phosphate, a cheap, nontoxic battery electrode material. (See Metal Mix Boosts Batteries, page 23.)

These new materials could be available for practical use within two years.

Further down the line

Two very different potential power sources have the attention of researchers doing long-term projects into power generation.

The first promises massive amounts of energy — if only it can be controlled. The second has to do with getting something from nothing.

The unfathomable force of fusion

The quest to gain energy from nuclear fusion started more than 50 years ago. Fusion promises almost unlimited power, but comes with the tremendous challenge of compressing and igniting atoms. The goal is being able to generate a fusion reaction using less energy than it yields.

Many research teams are working on the difficult problem of confining and controlling fusion, which takes place at 100 million degrees Celsius and requires a tremendous amount of energy to ignite. (See How It Works, page 2.)

In one recent development, an international team of 23 researchers showed that it is possible to use a one million billion watt laser pulse to isolate and superheat fuel in order to set off nuclear fusion. (See Huge Lasers Could Spark Fusion, page 25.)

Practical fusion energy generation is a decade or two away.

Something from nothing

At the scale of atoms — 200,000 times smaller than the human eye can distinguish — physics works differently. Space is filled with zero point energy created by subatomic particles that appear and disappear. The amount of energy created is negligible at the scale of humans, but researchers are looking to this weird quantum effect to gain enough energy to drive microscopic machines.

Researchers from the University of California at Riverside and the Federal University of Paraíba in Brazil have fashioned a device that uses zero point energy to slide one surface over another. (See Quantum Force Powers Microslide, page 26.) And researchers from Lucent Technologies' Bell Labs have built a device that measures the effect of zero point energy. (See Quantum Effect Moves Machine, page 27.)

Zero point energy could be used in practical devices in five to ten years.

Hand in glove

More than 86 percent of the energy consumed in the U.S. in 2001 was generated by fossil fuels, according to the Department of Energy. Nearly a third of that was imported.

Technology and energy have been inseparable since the start of the industrial age — technology both consumes energy and increases energy production. And so technologyFIFTH research is a fitting vehicle for making sustainable, cost-effective, clean, energy available to microscopic machines and national power grids alike.

Recent Key Developments

Advances in hydrogen generation and storage:

- A cheaper catalyst for generating hydrogen from glucose, developed by the University of Wisconsin, June, 2003
- A visible-light catalyst for generating hydrogen from water (Sunlight Turns Water to Fuel, page 10)
- A chip that extracts hydrogen from a methanol-water mixture (Hydrogen Chip to Fuel Handhelds, page 11)
- A new material that stores useful amounts of hydrogen (Hydrogen Storage Eased, page 12)
- A better metal for storing hydrogen (Metal Stores More Hydrogen, page 13)
- A method for storing hydrogen in pressurized ice, developed by the Carnegie Institution of Washington, the University of Chicago and Los Alamos National Laboratory, September, 2002

Advances in fuel cells:

- A fuel cell that gets its hydrogen from bacteria's sugar consumption byproducts (Munching Microbes Feed Fuel Cell, page 14)
- A fuel cell powered by enzymes breaking down ethanol (Alcohol Powers Fuel Cell, page 14)
- A cigarette-lighter-sized fuel cell, developed by Case Western Reserve University and the Pacific Northwest National Laboratory, April, 2003
- A chip-sized fuel cell that uses cartridges of methanol (Fuel Cell Aimed at Handhelds, page 14)
- Metal-ceramic electrodes that promise cheaper fuel cells (Alloy Lowers Fuel-Cell Cost, page 15)

Advances in solar cells:

- A solar cell based on a very low-cost semiconductor (Cheap Solar Power on Deck, page 16)
- A previously overlooked material as a light-to-electricity converter (Materials Soaks up the Sun, page 17)
- A process for etching grooves in silicon solar cells in order to increase surface area, developed by the Australian National University, May, 2003
- Plastic solar cells that are flexible and cheap, developed by the University of California at Berkeley, March, 2002

Advances in generating electricity from heat and vibrations:

- A tiny electric generator that burns hydrogen and focuses the heat on a photovoltaic converter, developed by the National University of Singapore and California State Polytechnic University, December, 2002
- A tungsten crystal that emits a narrow band of infrared energy suitable for heat-to-electricity conversion (Crystal Turns Heat to Light, page 18)
- A more efficient thermoelectric generator (Chip Turns More Heat to Power, page 19)
- A tiny thermoelectric generator made from flexible foil (Flexible Film Turns Heat to Power, page 20)
- A piezoelectric circuit that boosts the efficiency of converting vibrations to electricity (Circuit Gets More Power from Shakes, page 21)

Advances in batteries:

- A barely-visible battery for powering microelectronics (On-Chip Battery Debuts, page 22)
- Nanoscale electrodes for a microbattery, developed by the University of Florida, October, 2002
- A less toxic alternative to lithium batteries (Magnesium Batteries Show Mettle, page 22)
- A less toxic form of lithium for batteries (Metal Mix Boosts Batteries, page 23)
- More efficient battery electrodes made from carbon nanotubes (Nanotubes Pack Power, page 24)

Advances in future power sources:

- A high-power laser pulse technique that advances fusion efforts (Huge Lasers Could Spark Fusion, page 25)

- A way to make ever-present quantum zero-point energy slide one microscopic plate over another (Quantum Force Powers Microslide, page 26)
- A way to measure zero-point energy (Quantum Effect Moves Machine, page 27)
- A scheme for using hot gases from combustion engines to power lasers (Heat Engines Gain Quantum Afterburner, page 29)
- Back to the future: a tiny combustion engine capable of powering portable electronics (Engine Fires up Electrical Devices, page 29)

Sunlight Turns Water to Fuel

By Kimberly Patch, Technology Research News
January 9, 2002

Hydrogen is the ultimate green fuel because it burns in air without producing pollution. It is also abundant because it is one of the atoms that makes up water.

Hydrogen can be extracted from water using electricity, but today's electricity-generating methods usually produce some pollution. The key to using hydrogen as a clean fuel is finding a non-polluting way to get water to give up its hydrogen.

Water can also be split using photocatalysts, which use the energy of light to break the molecular bonds. This is how plants gain their energy.

The difficulty has been finding a stable photocatalyst that can harness enough light energy to split the molecular bonds of water. Visible light photocatalysts tend to either break down too soon to be used in practical products or are not powerful enough to split the water bonds. And although stable ultraviolet photocatalysts exist, there is much less energy in ultraviolet light than in the visible light spectrum. Ultraviolet light represents about four percent of the energy the sun throws off, while visible light accounts for 43 percent.

A group of researchers in Japan has taken a large step toward producing clean hydrogen by finding a stable photocatalyst that can use the energy in visible light to split water. The group's research shows that it is possible to "photocatalyticly decompose water using solar energy and an oxide semiconductor to generate clean energy hydrogen like green plants," said Zhigang Zou, a researcher at the National Institute of Advanced Industrial Science and Technology in Japan.

The researchers doped indium-tantalum oxide semiconductor material with nickel to produce the photocatalyst.

The photocatalyst splits water by absorbing a photon of light, which provides enough energy to separate the negatively-charged electrons from the positively-charged holes in the material. These charges then move to the surface of the semiconductor particle where they react with the water, splitting it into its two gases.

The key to the researchers' success is that their material has an energy gap, or bandgap, that is low enough that the energy provided by photons of visible light is sufficient to move its electrons to a higher energy band.

Electrons whiz around an atom's nucleus in certain orbits, or bands, similar to the way planets orbit the sun. Unlike planets, however, electrons can change orbits. When a material gains energy, its electrons hop to a higher band, and when it gives up energy by fueling a chemical reaction like splitting water, the electrons fall to a lower energy band. The difference in energy between the first, or valence band and, the second, or conduction band, is the energy gap.

The researchers tested the material by suspending doped indium tantalum oxide powder in water in a closed glass circulation system under a lamp, then measured the ensuing gases. The researchers material is not very efficient, using only 0.66 percent of the energy in light to split the water, but this can be improved by increasing the surface area of the photocatalyst and by changing its chemical composition, said Zou. "It is necessary to enhance the efficiency up to about 50 percent for commercial [use]," he said.

Researchers have been working on finding catalysts that split water since the first paper on the subject appeared in 1972, said Thomas Mallouk, a professor of materials chemistry at Pennsylvania State University. "This is the first bona fide report of such a photocatalyst, which carries out the reaction using visible light," he said.

There is still work to be done before the method can be made practical, he added. The paper doesn't contain much detail on exactly how the reaction works. "I think it is safe to say that neither the authors nor anyone else understands in detail how this photocatalyst really works. This does not take away from the discovery, which is quite important, it just means that more work needs to be done," he said.

The yield must also be increased for the photocatalyst to the practical. "If it could be improved by a factor of ten or so then it would become quite interesting for solar energy conversion. I expect that this discovery will stimulate more work in this area," Malick said.

The researchers are now working on increasing the efficiency of the photocatalyst; they're also looking for similar substances that may be more efficient, said Zou. It will probably be 20 years before clean water splitting devices are practical, he added.

Zou's research colleagues were Jinhua Ye, Kazuhiro Sayama and Hironori Arakawa. They published the research in the December 6, 2001 issue of the journal *Nature*. The research was funded by the Japanese Ministry of Education and Science.

Timeline: 20 years
Funding: Government
TRN Categories: Energy; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Direct Splitting of Water under Visible Light Irradiation with an Oxide Semiconductor Photocatalyst," Nature, December 6, 2001

TRN

Hydrogen Chip to Fuel Handhelds

By Kimberly Patch, Technology Research News
September 12, 2001

As the field of portable electronics matures, producing increasingly complicated handheld devices, there is a growing need for more efficient ways to power them. One alternative is to use tiny versions of fuel cells, which create power by making hydrogen and oxygen react chemically rather than burning them like an engine does.

Two groups of scientists have made separate advances toward this goal. A group of researchers at Lehigh University has worked out a way to fuel a chip-sized fuel cell. Another group at NEC Corporation has used a type of carbon nanotube to make the fuel cell reaction more efficient.

The methods could eventually be used in chip-sized fuel cells to power devices that require small, rechargeable power sources, like laptop computers and cellular phones.

A major challenge in producing a practical chip-sized fuel cell is providing the cell with a source of hydrogen. This usually involves a bulky storage device because hydrogen stored as gas or metal hydrides does not provide as much energy by volume as a liquid hydrocarbon fuel, according to Mayuresh Kothare, an assistant professor of chemical engineering at Lehigh.

One way to sidestep the storage problem is to extract hydrogen as it is needed from liquids that contain it at room temperature. The Lehigh researchers have found a way to do this by mixing methanol and water in the presence of a catalyst, said Kothare.

The Lehigh device uses tiny capillaries etched into a silicon chip to act as fuel lines to mix and carry the raw materials of the reaction—methanol and water—to channels coated with a catalyst layer of copper, said Kothare. "The channels… provide a closed path for flow of fluids. The inside of the channels will be coated with a catalyst. The reaction will take place on the surface of the catalyst."

When the mix of methanol, which contains one carbon, one oxygen and four hydrogen molecules, and water, which contains one oxygen and two hydrogen molecules, reaches the coated channels, it reacts to form hydrogen, said Kothare. "The hydrogen and unreacted methanol [and] water will flow out of the channel. [The] hydrogen will then be purified and sent to the fuel cell to produce power," he said.

The key to efficiently extracting hydrogen is controlling the size and location of the microfluidic channels as well as the environment within them in order to prevent leaks and bypasses and make the reaction efficient, said Kothare.

The channels of the device are 1 to 2 centimeters long and half a millimeter deep. The copper coating is about 33 nanometers thick. A nanometer is one millionth of a millimeter.

In order to carry out and control fluid delivery at such a small scale, the temperature of the microreactors that produce the hydrogen must be finely controlled via tiny sensors and heaters, said Kothare. The researchers are also working on optimizing the dimensions and geometry of the microreactors in order to maximize the amount of hydrogen they can extract in the reaction, he said. They are also working on ways to connect the hydrogen generator to a microfuel cell that would use the hydrogen to produce power, he said.

The Lehigh prototype has "excellent potential for mass production", said Lois Anne Zook, an assistant professor of analytical and environmental chemistry at Delta State University. "Fuel cells have the potential to be one of the most commercially viable renewable energy technologies for the electronics industry [and] the [Lehigh] hydrogen power chip work... proposes an approach to solving one of the main limitations of the hydrogen oxygen fuel cell system—the fuel supply," she said.

Although the Lehigh prototype is a good proof of concept, there are still technical challenges to address in order for the technology to become practical, she said. "The reformer is not as fuel-efficient as using pure hydrogen gas, and byproducts of the reformer reaction poison the fuel cell catalysts, degrading performance over time," she said. The biggest technical hurdle to making the extraction approach commercially viable is addressing this fuel cleanup, she said.

The Lehigh researchers' goal is to build and demonstrate the hydrogen generator portion of the microfuel plant, said Kothare. Microfuel plants that use such generators could be ready for commercial use in about five years, he said.

Meanwhile, the NEC scientists found that a type of carbon nanotube dubbed nanohorns can be used to make more efficient catalyst for a chemical reaction in the fuel cell that extracts energy from the hydrogen. The scientists found that they could coat the carbon nanohorns, which are sheets of carbon molecules rolled up in a horn shape, with a coating of platinum catalyst particles that were less than half the size supported by ordinary activated carbon. The finer grain of the platinum makes for a more efficient fuel cell reaction.

Although using nanotubes in fuel cells is not new, the nanohorn shape may make for more efficient cells, said Zook. "Typically, the higher the surface area to volume ratio of the platinum catalyst, the better it works, so putting platinum on these high-surface-area carbon tubes reduces the amount of platinum used while keeping the surface area for the reaction high," she said.

Kothare's research colleagues were Ashish V. Pattekar, Sooraj V. Karnik and Miltiadis K. Hatalis. They published the research in the proceedings of the 5th International Conference on Microreactors Technology, which was held in Strasbourg, France, in May. The research was funded by the National Science Foundation (NSF), the Pittsburgh Digital Greenhouse, and Sandia National Laboratories.

The NEC team of scientists was led by NEC research fellow Sumio Iijima.

Timeline: 5 years
Funding: Corporate; Government
TRN Categories: Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "A Reactor for In-situ Hydrogen Production by Catalytic Methanol Reforming," proceedings of the 5th International rence on Microreaction Technology held in Strasbourg, France, May 27-30, 2001

Hydrogen Storage Eased

By Eric Smalley, Technology Research News
May 21/28, 2003

One of the biggest challenges to using hydrogen as a fuel is finding a way to store it. The lighter-than-air gas makes the perfect fuel—it contains three times the energy of liquid hydrocarbons and when it reacts with oxygen to produce energy the only byproduct is water—but it isn't easy to contain.

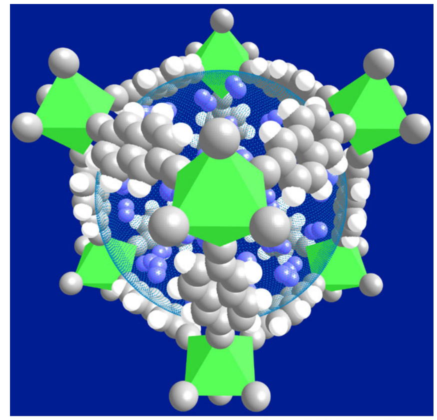
Today's hydrogen storage materials hold 2 to 4 percent of their weight in hydrogen, short of the 6.5 percent Department of Energy goal for using hydrogen as automobile fuel.

Researchers from the University of Michigan, the University of California at Santa Barbara, the University of South Florida and Arizona State University have discovered a new class of materials, dubbed metal-organic frameworks, that are relatively inexpensive to make and have the potential to reach the 6.5 percent mark. "We are in sight of the DOE goal," said Omar Yaghi, a chemistry professor at the University of Michigan.

The discovery promises to remove the principal stumbling block to hydrogen-powered cars, and the method could be ready for production use within five years.

Hydrogen storage materials act like sponges, capable of filling up with certain gases and later releasing them. The challenge is developing materials that hold useful amounts of hydrogen, and that store and release the hydrogen easily.

Current hydrogen storage systems chemically bind powdered metal hydrides to hydrogen at high temperatures. In November, researchers in Singapore developed a metal material that holds more than 11 percent of its weight in hydrogen, but requires high temperatures and pressures. Researchers are also exploring carbon-based approaches, including carbon nanotubes, but these require very low temperatures.



Source: University of Michigan

This graphic depicts a metal-organic framework, a molecular structure that can store hydrogen. The hydrogen atoms are represented by blue spheres.

It is easy to store and retrieve hydrogen using metal-organic frameworks materials, said Yaghi. "Hydrogen can be inserted into the material and then removed reversibly with no change to the storage medium," he said. When the materials are exposed to hydrogen at room temperature and under modest pressure, they take it up immediately, he said.

This is possible because hydrogen is adsorbed by rather than chemically bound to the storage material, said Yaghi. Adsorption is the process of gas or vapor atoms sticking to a surface. "The hydrogen is physically attracted to the walls of the [material's] pores," he said. "This attraction makes it possible to stuff more hydrogen molecules into a small area without requiring either low temperatures or high pressures."

Metal-organic frameworks are exceptionally porous at the molecular scale, with surface areas of more than 3,000 square meters per gram, according to Yaghi. They are "basically scaffolds of linked rods," he said.

The materials have several other advantages, said Yaghi. They're made from low-cost starting materials including zinc oxide, which is used in sunscreen lotion, and terephthalate, which is a component of plastic soda bottles. They are simple to make, and manufacturing yields are high, he said.

The researchers previously showed that metal-organic frameworks can absorb voluminous quantities of nitrogen and organic vapors, said Yaghi. "Given the importance of hydrogen as a fuel, we sought to examine the hydrogen storage capabilities," he said.

The researchers' showed that it is possible to design metal-organic frameworks materials that absorb incrementally more hydrogen. Their best prototypes store two percent of their weight in hydrogen, but the materials have the potential to store much more, said Yaghi. "We have shown that we can systematically increase the hydrogen storage capacity of these materials, thus identifying a clear path toward achieving the DOE hydrogen storage goal," he said.

The researchers are currently working on increasing the hydrogen capacity of the materials and also on better understanding the reasons the materials are able to absorb so much hydrogen, said Yaghi.

The researchers are also collaborating with BASF Corporation to use the materials in practical applications. It will take from two to five years of development before the material can be used in practical applications, Yaghi said.

Yaghi's research colleagues were Nathaniel Rosi, David T. Vodak and Jaheon Kim from the University of Michigan, Jurgen Eckart from the University of California at Santa Barbara and the Los Alamos National Laboratory, Muhamed Eddaoudi from the University of South Florida, and Michael O'Keefe from Arizona State University. The work appeared in the May 16, 2003 issue of *Science*. The research was funded by the National Science Foundation (NSF), the Department of Energy (DOE) and BASF Corporation.

Timeline: 2-5 years
Funding: Corporate, Government
TRN Categories: Energy; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Hydrogen Storage in Microporous Metal-Organic Frameworks," *Science*, May 16, 2003.

TRN

Metal Stores More Hydrogen

By Eric Smalley, Technology Research News
January 15/22, 2003

Hydrogen is the most abundant element in the universe, and when it is burned its only byproduct is water. One reason the world isn't running on hydrogen fuel is that it's hard to store.

Researchers from the National University of Singapore have made an accidental discovery that brings the promise of clean hydrogen energy a big step forward.

The challenges to using hydrogen as a fuel include finding a hydrogen storage system that is reasonably small and light, and finding a way to release the stored fuel quickly enough when it is needed.

The researchers have found a material that can store and quickly release large amounts of hydrogen. Lithium nitride can store 11.4 percent of its own weight in hydrogen, which is 50 percent more than magnesium hydride, the previous best hydrogen storage material. Other metal hydrides generally store only 2 to 4 percent of their weight.

The new material is not ready for practical applications because the temperature required to release the hydrogen is too high, but it points the way to a practical hydrogen storage material, according to Ping Chen, a senior research fellow at the National University of Singapore. "We think the main application might be... on-board hydrogen storage," he said.

The researchers discovered the material accidentally, according to Chen. "In the last three years we continuously pursued the task of storing hydrogen in lithium-carbon," he said. In the course of that work, the researchers treated lithium-carbon with nitrogen, and found that hydrogen absorption increased. When they studied the material, they found that lithium nitride was the substance responsible for the increased uptake.

Lithium nitride absorbs hydrogen when it is exposed to hydrogen that is under pressure. The chemistry involves one lithium nitride molecule combining with four hydrogen atoms to form lithium amide and lithium hydride. Reducing the pressure reverses the process. "Under low hydrogen pressure, lithium amide and [lithium] hydride react with each other and give out hydrogen gas," said Chen.

The current drawback to the researchers' material is that in order for the hydrogen to be released at one atmosphere of pressure, the storage material has to be heated to 270 degrees Celsius. It will release hydrogen at lower temperatures, but only at pressures below one atmosphere, which is the pressure of Earth's atmosphere at sea level. The researchers' next step is to find a way to release the hydrogen at a usable pressure and practical temperature.

The work is "the first to establish that alkali metal nitrides are worthy of serious consideration as viable hydrogen storage materials," said Craig Jensen, a professor of chemistry at the University of Hawaii at Manoa.

Although the thermodynamic parameters of the system render it impractical, "the paydirt reported by the authors is rich enough that it should attract a rush of prospectors into this area to search for the elusive hydrogen storage material that will open the door to the hydrogen era," Jensen said.

The researchers are working on improving the hydrogen storage performance of their system through both mechanical and chemical modifications, said Chen.

They are investigating the hydrogen storage potential of related nitrides and imides in order to find one with better temperature attributes, said Chen. New species, or forms of nitrides, imides and metal-nitride-hydrogen composites are emerging continuously, he said. "With abundant chemical information and well-developed synthetic and characteristic techniques, we believe there is huge scope for development of materials [that will work at a] practical temperature."

Another technical challenge to making a practical onboard hydrogen storage system is making sure the storage material is chemically stable, said Chen. The researchers' current prototype is sensitive to moisture, oxygen, carbon dioxide and other common substances, which makes strict conditions necessary for practical operation, he said.

It will take five to ten years to develop a practical metal nitride or imide hydrogen storage material, he said.

Chen's research colleagues were Zhitao Xiong, Jizhong Luo, Jianyi Lin and Kuang Lee Tan. They published the research in the November 21, 2002 issue of the journal *Nature*. The research was funded by the Singapore Agency for Science, Technology and Research.

Timeline: 5-10 years
Funding: Government
TRN Categories: Energy; Materials Science and Engineering
Story Type: News
Related Elements: Technical Paper, "Interaction of Hydrogen with Metal Nitrides Imides," *Nature*, November 21, 2002.

Munching Microbes Feed Fuel Cell

Technology Research News, July 30/August 6, 2003

Researchers from the Ernst Moritz Arndt University in Germany have found a way to harvest the energy needed to power a fuel cell from chemical reactions that occur when E. coli bacteria consume sugar.

The researchers' prototype microbial fuel cell captures the hydrogen produced when the microorganisms metabolize carbohydrates like sugar in the absence of air. Most fuel cells use hydrogen as fuel, capturing the energy released when hydrogen reacts with oxygen to produce water.

Source: Ernst Moritz Arndt University

The microbes in this container produce hydrogen, the element that powers fuel cells.

The key to the researchers' prototype, which produces up to 1.5 thousandths of an amp and can run for hours at a time, is that the anode is coated with a conducting polymer. This layer allows hydrogen to diffuse through, but blocks larger molecules. It is also involved in an oxidation reaction that cleanses the anode of excreted metabolites that would otherwise gum up the works.

The fuel cell produces enough power to continuously run the 0.4 volt motor of a ventilator, according to the researchers.

It will take the least five years to produce practical microbial fuel cells, according to the researchers. The work appeared in issue 25 of *Angewandte Chemie*.

Alcohol Powers Fuel Cell

Technology Research News, April 9/16, 2003

Researchers from Saint Louis University have developed a fuel cell that uses enzymes rather than metal and can be recharged by adding a few milliliters of alcohol. Enzymes commonly speed up chemical reactions in living cells.

In the biofuel cell, the enzymes convert ethanol to acetaldehyde, removing a proton in the process. The proton is then added to nicotinimide adenine dinucleotide. The fuel cell's electrode strips the proton back off to produce electricity.

Key to the method is a polymer membrane modified with ammonium salts to increase the size of the membrane's pores and reduce its acidity. When enzymes are added to the membrane, they become trapped in the pores, which provide them with a stable environment.

Enzymes in the researchers' prototypes remained active for several weeks. Given the proper environment, enzymes theoretically last forever, according to the researchers.

Biofuel cells could eventually be used as a replacement for any rechargeable power source, including laptop and PDA batteries, according to the researchers.

Biofuel cells could be applied practically in five to ten years, according to the researchers. The work was presented at the 225th national meeting of the American Chemical Society in New Orleans on March 27, 2003.

Fuel Cell Aimed at Handhelds

By Ted Smalley Bowen, Technology Research News
March 13, 2002

Fuel cells have been tagged as promising energy sources for everything from buildings and cars to cell phones and yet-to-emerge micro-devices.

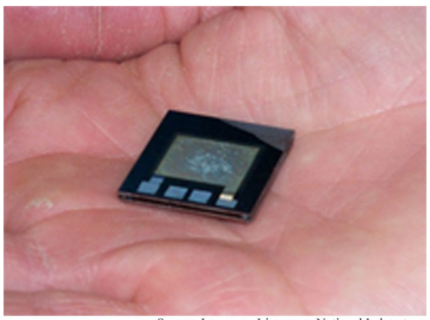
With an eye toward the small end of the scale, a researcher at Lawrence Livermore National Laboratory has made a fuel cell that could eventually power consumer electronics.

The thin-film fuel cell consumes methanol, and is smaller and would be cheaper to make than rechargeable batteries, according to Jeff Morse, a researcher in the lab's center for micro-technology engineering.

Morse made prototype fuel cells using materials and processes borrowed from computer chip manufacturing, the emerging field of microelectromechanical systems (MEMS), and microfluidics.

A fuel cell works by converting chemical energy into electrical energy and heat. Like a battery, it uses a cycle of chemical reactions between positive and negative electrodes to produce an electric current. Unlike batteries, fuel cells are supplied by fuel—commonly some form of hydrogen—and need to be refueled rather than recharged.

In a typical hydrogen fuel cell, the hydrogen fuel is flowed into the cathode, or negative electrode, and air flowed into the anode, or positive electrode. The porous metal electrodes act as catalysts to speed the reactions of hydrogen gas from the fuel and oxygen from the air with the electrolyte, a pool of chemicals bathing the electrodes. At the anode, the oxygen reacts with water in the electrolyte to form hydroxide ions. At the cathode, the hydrogen fuel reacts with the hydroxide ions to form water, releasing two electrons per hydrogen molecule.



Source: Lawrence Livermore National Laboratory

This tiny fuel cell is a prototype of an energy source that could be used to power hand-held devices.

The released electrons flow through an external circuit. This electrical current can be tapped to produce work. The chemical cycle also produces heat.

The Livermore fuel cell is designed to use replaceable fuel cartridges filled with methyl alcohol, or methanol. Each cartridge fuels the power pack for twice as long as a lithium ion battery lasts on a single charge, and could eventually last close to three times as long, according to Morse.

Fully loaded, the fuel cell weighs 8 grams and produces 1 to 2 Watts of power, or about 3,000 work hours per kilogram, according to Morse. The cells could be made as small as 5 by 3 by 3 centimeters, he said.

The small fuel cell is made from a thin polymer film, with thin-film electrodes of platinum and ruthenium. Key to shrinking the fuel cell was combining microelectronics with microfluidic plumbing. A micro-machined flow field of channels etched into silicon circulates methanol over the anode and air over the cathode. The channels range from a millimeter to one-tenth of a millimeter wide.

The fuel cell also contains electrical elements that heat the components, which speeds the ions bound from the anode to the cathode, enabling the cell to produce more power.

The researchers' design must become more efficient before it can challenge existing fuel cell designs, according to Morse. "Our fuel conversion efficiency is slightly less than conventional fuel cells. Our estimates for present designs are thirty-five percent," he said.

Conventional large fuel cells extract about 60 percent of the energy available in the fuel. Batteries, meanwhile, can convert about 75 percent of the chemical energy they contain into electrical current. Fuel cells are more often considered as an alternative to internal combustion engines, which burn fuel rather than chemically extracting electricity from it. The combustion engines in today's cars produce much more waste heat and are only about 15 to 20 percent efficient.

To date, diminutive fuel cells have not measured up well against conventional batteries, said Lutgard C. De Jonghe, professor of ceramics in the department of materials science and engineering at the University of California at Berkeley and senior scientist in the materials sciences division of Lawrence Berkeley National Laboratory. "In general, comparisons of small fuel cells with same size batteries is quite unfavorable for the fuel cell, both in power and energy density."

One inherent problem with thin-film fuel cells is seepage of fuel before it can react with the anode. "Important issues such as methanol crossover have been a problem for polymer membrane fuel cells," said De Jonghe. This methanol crossover can sap around 20 percent of a fuel cell's fuel and slightly lower its voltage, dropping its overall efficiency.

The Livermore prototype's fuel reforming devices address this by converting the methanol water-fuel mixture to hydrogen at the fuel cell anode, said Morris. This may produce another problem, however, he added. "Catalytic reforming converts the methanol to hydrogen and carbon dioxide first. Our concern is the impact of any carbon monoxide generated."

The MEMS fuel cell could find uses in portable electronics, small sensors, and military electronics, according to Morse. It could be ready for practical use within three years, he said.

Morris presented the work at the Lawrence Livermore National Laboratory NanoSIG conference in Livermore, California on Februrary 14, 2002. The work was funded by the lab.

Timeline: < 3 years
Funding: Government
TRN Categories: Energy; Materials Science and Engineering
Story Type: News
Related Elements: None

TRN

Alloy Lowers Fuel-Cell Cost

Technology Research News, February 26/March 5, 2003

Scientists from Lawrence Berkeley National Laboratory have found a way to make fuel cells that are potentially cheaper and easier to manufacture than previous prototypes. The method is a step toward making the relatively clean energy-generating technology commercially viable.

Fuel cells work by converting chemical energy to electricity. The key reaction takes place in a fuel cell's electrodes, where oxygen from the air reacts with the fuel to produce a flow of electrons. The byproducts are water and carbon dioxide.

One of the main barriers to commercially-viable fuel cells is cost; fuel-cell-generated electricity costs 3 to 10 times more than other methods.

The Berkeley researchers brought down the potential cost by replacing a fuel cells' usual ceramic electrodes with a sandwich of metal and ceramic. The alloy is stronger than ceramic and can be welded, and the cost of the raw materials is considerably lower. Previous work opened the door for the alloy by decreasing the fuel-cell reaction temperature from 1,000 to 800 degrees Celsius.

The method could lead to a commercially-viable fuel cell with a materials cost of about $35 per kilowatt in about five years, according to the researchers.

TRN

Cheap Solar Power on Deck

By Kimberly Patch, Technology Research News
March 12/19, 2003

Solar cells are relatively pricey largely because the silicon they are made from is expensive to manufacture— it requires a clean room or high vacuum.

Solar cells harvest energy from light by capturing photons. The way silicon's electrons are arranged allows the material to absorb photons of visible light. The energy imparted by the photons excites the material's electrons, causing electricity to flow.

Researchers from the University of California at Santa Barbara have come up with a new type of solar cell that separates the process into two steps. The cell uses one material to absorb light that generates excited electrons, then passes the electrons on to a much cheaper semiconductor than the crystalline silicon used in most current solar cell designs.

The researchers' prototype suggests that the devices would be much less expensive to manufacture than today's solar cells and can be improved to be nearly as efficient. "It's enormously cheaper... more than a factor of 10," said Eric McFarland, a professor of chemical engineering at the University of California at Santa Barbara.

Key to the design is a very efficient way to transport electrons. The researchers were working on making sensors that use ballistic electronics when it occurred to McFarland that ballistic transport could be used to make cheap solar cells. "It was motivated and stimulated by us thinking about how electrons move across thin metal films without losing energy," said McFarland.

Ballistic transport occurs in extremely narrow wires or thin films of metal, where electrons flow straight through. In larger, ordinary wires electrons bounce around, losing energy.

Having an efficient way to transport electrons meant the researchers didn't have to use silicon to absorb the light rays, but could use any of a variety of light-absorbing substances to do so, then transport the resulting excited electrons to a semiconductor layer that is both cheaper than silicon and can be much thinner than the silicon layers in conventional solar cells.

The researchers' prototype uses a dye to capture photons, and there are several other options, including quantum dots, said McFarland. Quantum dots are tiny bits of semiconductor that trap electrons. "There are many options [and] we can have multiple absorbers," he said.

Absorbing light results in an excited electron in the dye, said McFarland. "The photoreceptor collects the light and generates what we call a hot electron, an energetic electron," he said.

The hot electron then moves ballistically across the thin metal film and into a semiconductor's conduction band. "The purpose of the semiconductor in our cell is just simply to separate the charges," said McFarland. Once charges are separated there is potential for electricity to flow to bring the charges together again.

The titanium dioxide semiconductor the researchers used to receive the electrons is very inexpensive, said McFarland. "It's used for white paint—it's a terribly cheap material," he said.

The researchers' prototype has an internal quantum efficiency of 10 percent, and it's probably possible to increase this above ninety percent, said McFarland. Today's commercial solar cells have an internal efficiency of about 95 percent, he said.

Internal efficiency is a measure of the number of all photons absorbed versus the number of photons that make it to the electric circuit, and is how researchers rate solar cells.

The researchers' prototype has an overall efficiency of less than one percent compared to about 15 percent for today's solar cells. Overall efficiency is a measure of the number of photons that hit a device versus the number of photons that make it to the electric circuit.

Increasing the overall efficiency is an engineering problem, said McFarland. "We need to make more surface area [and] coat the surface with more dye," he said.

The researchers' design is just a step toward using different mechanisms for converting solar energy into electricity, said McFarland. "It's... simply another possible route," he said.

McFarland's research colleague was Jing Tang. The work appeared in the February 6, 2003 issue of the journal *Nature*. The research was funded by Adrena Inc.

Timeline: Unknown
Funding: Corporate
TRN Categories: Energy; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, “Photovoltaic Device Structure Based on Internal Electron Emission,” *Nature*, February 6, 2003.

Material Soaks up the Sun

By Kimberly Patch, Technology Research News
December 11-25, 2002

Capturing solar energy efficiently means finding materials that absorb as many wavelengths of light as possible that the sun sends our way.

Researchers from Lawrence Berkeley National Laboratory, the University of California at Berkeley and Cornell University have discovered that measurements of the semiconductor indium nitride taken two decades ago were wrong. The measurements led researchers to erroneously classify the material as a mediocre photovoltaic.

Instead, the material’s band gap falls squarely in the solar spectrum, making it potentially more efficient than currently used photovoltaics. A material’s band gap determines which wavelengths of photons can excite electrons in the material to create a flow of electricity.

The reclassified material promises to boost the efficiency of solar cells, allowing for smaller cells or cells of the same size that collect more electricity.

The best photovoltaic material currently available, a combination of gallium arsenide and gallium indium phosphide, has a theoretical efficiency of 32 percent; indium nitride has the potential to increase that to 50 percent, said Wladek Walukiewicz, a senior staff scientist at Lawrence Berkeley National Laboratory.

The researchers’ initial testing also shows that the material withstands high energy particle irradiation without breaking down. This bodes well for satellite and other solar collectors that work in space.

When they made their surprising discovery, the researchers were investigating the mysterious lack of emissions from the material at the conventionally understood band gap of two electron volts. Instead of finding unusual reasons for the lack, they discovered that the material was simply misclassified, and instead has a band gap of 0.7 electron volts. “Once we looked at a lower energy range we could easily see all the features characteristic of [a] direct band-gap semiconductor,” said Walukiewicz.

The misclassification took place at a time when samples were prepared by sputtering the material onto a surface. “Such samples contain large amounts of oxygen, as much as 30 percent. So the samples were indium-oxygen-nitride alloys rather than indium nitride,” said Walukiewicz.

The more modern samples, in contrast, were grown by molecular beam epitaxy, a process that takes place in a vacuum. “Our material... contains undetectable levels of oxygen,” he said.

A solar cell works by separating the positive and negative charges—holes and electrons—produced in a semiconductor unit in the when photons of sunlight hit it. The atomic structure of the semiconductors used in solar cells determines how many holes and electrons they can generate. The efficiency of a material has to do with microscopic measurements: the band gap, or spacing between the levels electrons occupy in a material, and the wavelengths of solar radiation.

Materials whose electron level spacing matches up with the wavelengths of the photons hitting it can absorb the photons. When a material absorbs a photon, some of the photon’s energy causes an electron, which holds a negative charge, to change to a higher-energy position, leaving behind a positively-charged hole.

To separate these charges, the substance must be doped, or mixed with another substance to create separate paths for positive and negative charges. The separate types of semiconductor are n-type, which guides electrons, and p-type, which guides holes. “When an electron-hole pair is produced by a photon... the electron is pulled to the n-type side, and the hole is pulled to the p-type side,” said Walukiewicz.

Because the charges naturally attract each other, the charge separation creates a change in electric potential, much like rolling a rock up a hill stores energy that can be released by simply starting it on the path downhill. In a solar circuit the potential stored by the separated charges can be released in a current of electricity.

The efficiency of a solar cell depends on how much of the total solar photon flux, or flow, can be converted into charge carriers, said Walukiewicz. “For a solar cell made of one semiconductor with a specific energy-gap, only the photons close to the absorption [range] contribute to the electric current,” he said.

To increase the efficiency, however, solar cells can be made by stacking several cells of semiconductors with different band gaps to catch the different light waves. “Although each of the cells will convert the solar energy only from a limited range of photon energies, all of them together can make use of more photons,” said Walukiewicz.

Indium nitride is important because its band gap sits squarely in the middle of the light spectrum; this makes it possible to produce gallium-indium-nitride semiconductors that have any gap within the solar spectrum range, and makes it possible to put more semiconductors in tandem, said Walukiewicz. “This is a solar-cell-designer paradise [because] one can maximize... performance by optimizing the number of cells and their band gaps,” he said.

There's a lot of work to be done before practical solar cells can be made from indium nitride, however. The researchers have not yet made the p-type form of the material. "One of the biggest challenges is to make p-type doped indium nitride," said Walukiewicz. The indications are good, however. It is theoretically easier to make p-type doped indium nitride than to do the same with gallium nitride, which has already been done, he said. Gallium nitride is also a direct band-gap material.

The researchers' next step is to make p-type indium nitride. They are also working to make p-type gallium indium nitride, he said. And they are more thoroughly testing the properties of the two materials under high-energy particle irradiation, he said.

The researchers have only tested a few samples, said Cheng Hsiao Wu, a professor of electrical and computer engineering at the University of Missouri at Rolla. The reasons for the measurements are not yet clear; there could be a mechanism involved other than a different band gap, he said.

Given the benefit of the doubt, however, a 0.7 reading could be useful, but finding such a material is a long way from making a solar cell, said Wu. "For actual solar applications, either the current or the voltage of each solar cell using a particular [part of the] solar spectrum has to be matched," and this is a particularly tricky proposition for a full-spectrum solar cell, he said. If the material works out, however, it "may add another variety of the solar cell we already have for the full visible spectrum range," he said.

It will take three to four years to develop indium-nitride-based solar cell technology, said Walukiewicz.

Walukiewicz's research colleagues were Junqiao Wu and Eugene E. Haller from the University of California at Berkeley and Lawrence Berkeley National Laboratory, W. Shan, Kin Man Yu and Joel W. Ager III from Lawrence Berkeley National Laboratory, and Hai Lu and William J. Schaff from Cornell University. They published the research in the November 15, 2002 issue of *Physical Review B*. The research was funded by the Department of Energy.

Timeline: 3-4 years
Funding: Government
TRN Categories: Semiconductors; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Effects of the Narrow Band Gap on the Properties of InN," *Physical Review B*, November 15, 2002.

TRN

Crystal Turns Heat to Light

By Kimberly Patch, Technology Research News
May 29/June 5, 2002

Controlling the range of light wavelengths a material emits makes for more efficient lights. There's a lot of room for improvement in this area.

The tungsten filaments commonly used in lightbulbs, for instance, are notoriously inefficient, emitting only five to ten percent of the energy they use as light, and producing enough heat, or infrared radiation, to burn the skin of anyone unfortunate enough to touch a lightbulb that has been on for more than a few seconds.

Researchers from Sandia National Laboratories and Iowa State University have found a way to structure a tungsten filament so that, instead of emitting radiation made up of a broad mix of light and heat wavelengths, it emits 60 percent of the energy it receives in a relatively narrow band of wavelengths.

The wavelengths of visible light measure from about 400 to 700 nanometers from crest to crest, while heat wavelengths range from 700 to one million nanometers. A nanometer is one millionth of a millimeter.

Concentrating wavelengths paves the way for lights that emit more visible wavelengths than heat, drastically improving their efficiency.

The researchers' material, a type of photonic crystal, could also improve the efficiency of thermophotovoltaic devices, which convert heat to electricity, according to James Fleming, a researcher at Sandia National Laboratories.

Thermophotovoltaic devices convert heat to electricity the same way solar cells convert visible light to electricity. They produce electricity when photons from incoming light of certain wavelengths knock electrons loose from the semiconductor material that makes up the bulk of the device.

The Sandia photonic crystal promises to boost efficiencies by shifting a broad swath of wavelengths that make up the heat from a heat source to a narrower band of the optimal wavelengths for thermophotovoltaic cells to convert to electricity. When the researchers fed the properties of their material into a mathematical model of thermophotovoltaics they found that it could boost the efficiency of a thermophotovoltaic device to 51 percent, according to Fleming. By comparison, today's most efficient infrared emitters come in at just under 13 percent.

The researchers current prototype emits heat, but it is possible to shrink the crystal structure so that the narrow band it emits is within the wavelengths of visible light, said Fleming. "The structure needs to be shrunk by roughly a factor of eight to get into the visible" spectrum, he said.

The photonic crystals are made of tiny bars lined up like Lincoln logs at regular distances and angles. This artificial crystal latticework allows only certain wavelengths to pass through, and can also control the direction of those wavelengths. The material can be made using the same processes companies use to make computer chips, said Fleming.

These lattices are essentially the photonic counterparts to semiconductors. They control photon flow in a similar way to how computer chips control electron flow, said Fleming.

The researchers built the photonic crystal structure in silicon, then removed some of the silicon and exposed the structure to a chemical vapor to coat it with tungsten.

The discovery that this particular structure concentrated wavelengths was accidental, said Fleming. "The structure appears to be able to modify the range of wavelengths emitted by the filament. The odd emissive behavior was... not predicted. We came upon it in the course of other, related work," he said.

The researchers have not worked out the details of how the effect happens, said Fleming. "We need to better develop the theory behind the effect," he said.

The work is novel, said Eli Yablonovitch, a professor of electrical engineering at the University of California at Los Angeles. "It's... probably the first application of photonic crystals to the energy industry," he said.

The effect has the potential to increase the efficiency of small-scale devices that convert heat to electricity, he said. "It could lead to small portable electric generators that run on... fuel and that would produce electricity very efficiently. In general it's competitive with many other methods of producing electricity, but it's efficient even in a small unit," he said.

The research could lead to practical products in about five years, said Fleming. In terms of gaining a full understanding of the effect, "we should have a good idea of what is happening in about two years," he said. In addition, "there are... niche markets for efficient infrared sources which could benefit from what we have already demonstrated," he said.

Fleming's research colleagues were Shawn Y. Lin, Ihab El-Kady and Rana Biswas from Sandia and Kai-Ming Ho from Iowa State University. They published the research in the May 2, 2002 issue of the journal *Nature*. The research was funded by Sandia.

Timeline: 5 years
Funding: Government
TRN Categories: Materials Science and Engineering; Optical Computing,
Optoelectronics and Photonics
Story Type: News
Related Elements: Technical paper, "All-Metallic Three-dimensional Photonic Crystals with a Large Infrared Bandgap," *Nature*, May 2, 2002

Chips Turn More Heat to Power

By Kimberly Patch, Technology Research News
December 19/26, 2001

The technology to cleanly and quietly turn heat into electricity without the use of a turbine or generator has existed for nearly a century. The trouble is, it has never been efficient enough for widespread practical use.

A pair of scientists at the Massachusetts Institute of Technology and Eneco Inc. have made a device that nearly doubles the amount of electricity that can be extracted from heat. The researchers' thermal diode converts about 18 percent of thermal energy to electricity, while current thermoelectric generators convert about 10 percent.

The technology could be used to generate additional electricity from power plants, which throw off enormous amounts of waste heat, and to generate electricity using the heat from automobile engines. The technology could also produce electricity in conjunction with devices that concentrate sunlight.

In the thermal diode, heat causes electrons to flow from one semiconductor layer to another. The device operates at about 18 percent efficiency when the heat source is between 200 and 300 degrees Celsius, said Yan Kucherov, chief scientist at Eneco, Inc.

The diodes also have the potential to be more efficient. "We should be able to improve [the] existing devices to 20 to 23 percent efficiency at the same temperatures," said Kucherov. In addition, making the thermal diodes from different materials could increase the efficiency to 25 to 33 percent at 450 to 500 degrees Celsius, he said.

The researchers made their thermal diodes more efficient than existing thermoelectric devices by making two basic changes. "We demonstrated two physical mechanisms that can greatly enhance the ability of a thermoelectric to convert heat into electricity," said Peter Hagelstein, an associate professor of electrical engineering and computer science at MIT.

First, the researchers found an efficient way to move electrons across the device. Second, they found a way to block the electrons from returning, which effectively increased the voltage of the forward current, making the energy conversion more efficient. "We blocked the ohmic return current by reducing the electron concentration near the collector, so that it took more voltage to generate the same return current," said Hagelstein.

The initial results were surprising enough that the scientists did not at first understand exactly what was happening, said Hagelstein. "We had thought for a long time that these devices could be understood based on the usual semiconductor equations. The experimental results were not in agreement with the predictions of such models," he said. The results at first seemed to be in violation of the laws that govern thermoelectrics, but the scientists eventually resolved the apparent conflicts. "It became clear that we had found something new," said Hagelstein.

The principles involved increase the efficiency of thermal-to-electrical energy conversion by about eight times, and can apply to any semiconductor material, said Hagelstein. "We believe that the mechanisms are applicable to all semiconductor thermoelectrics," he said.

If the work is correct, it proves that a substantial improvement in thermal-to-electrical energy conversion is possible, said George Nolas, an assistant professor of physics at the University of South Florida. "This would open new commercial markets and consumer demand" for this type of energy, and foster further research into using energy extracted from heat sources, he said.

The research is interesting but a key challenge of using thermal diodes to generate electricity is to keep the temperature different at the two ends of the device, said Wenmin Qu, a senior engineer at the Hydac Group in Germany.

Although it is difficult to predict when these thermoelectric devices could become practical, given the resources, "we could see prototype devices within a year," Hagelstein said.

The same mechanisms that allow the diodes to generate electricity from waste heat could eventually be employed to make more efficient refrigerators, said Yan Kucherov, chief scientist at Eneco. Thermoelectric generators can be run in reverse so that electricity running through them cools the surrounding air. "It definitely can be adapted to refrigeration. Our model shows [a] possibility of going to liquid nitrogen temperatures with a single stage," said Kucherov. Nitrogen gas turns to liquid at -196 degrees Celsius.

Hagelstein and Kucherov presented the research at the Materials Research Society Fall meeting in Boston on November 27, 2001. The research was funded by Eneco and the Defense Advanced Research Projects Agency (DARPA).

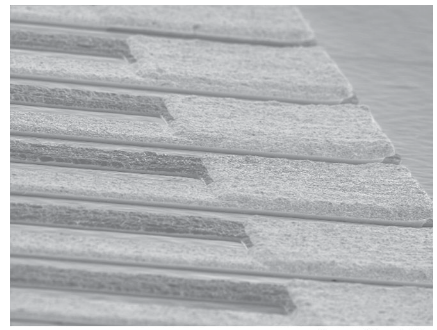
Timeline: 1 year
Funding: Corporate, Government
TRN Categories: Energy; Materials Science and Engineering; Semiconductors
Story Type: News
Related Elements: Technical paper, "Enhancement of Thermal to Electrical Energy Conversion with Thermal Diodes," presented at the Materials Research Society Fall meeting in Boston, November 27, 2001

Flexible Film Turns Heat to Power

By Chhavi Sachdev, Technology Research News
May 16, 2001

Imagine a sensor in your car warning you that your tire needs to be replaced soon. Now, imagine that the power system for the sensor was made using something that resembles what you wrapped your leftovers in - metal foil.

Researchers at the Dresden University of Technology in Germany have found a way to make tiny thermoelectric generators using copper foil as a template. The result is a cheap, flexible and recyclable generator that converts environmental heat into electricity.



Source: Wenmin Qu

These overlapping strips of antimony and bismuth make up a tiny thermoelectric generator. Researchers made the device using copper foil as both a substrate and seed layer.

The key to the process is using the copper foil template rather than silicon coated with a thin film of metal. The foil is cheaper, and using it as both the substrate - the base of any integrated circuit - and the seed layer - where the semiconductor crystals are grown - makes for a less complicated fabrication process.

Using copper foil precludes having a dedicated sacrificial layer that would have to be etched away, said researcher Wenmin Qu, a senior engineer for microsensors and microsystems at the Hydac Group in Germany.

The microsystem could use the heat produced in the axles of cars and trains by the motion of the wheels to detect damage inside the wheels or the axles, said Qu. "Ideal microsystems should be intelligent and self-powered," he said.

Because the human body is a source of heat, someday, implanted medical microdevices could also be powered with a thermoelectric generator that operates on the body's waste heat, said Qu.

"This generator could also be used in [the] reverse direction…as a cooling element," for computer chips and other electrical devices, he said. Applying electrical power to the generator cools it, he explained.

The generator, which is as flexible as copper wire, comprises 100 pairs of antimony-bismuth strips connected thermally and electrically. The entire module measures 16 by 20 millimeters square, or about the size of a thumbtack. Each strip in the module is about 10 microns high, 40 microns wide and 20 mm long.

The researchers made the generator by patterning the copper foil using photolithography, then electrodpositing antimony and bismuth on the pattern. They then added an epoxy film to the antimony-bismuth strips and hardened it using ultraviolet light. "In the last step, the initial copper sheet is entirely etched away, resulting in the antimony-bismuth strips being embedded in the epoxy film," said Qu.

The next step for Qu and his colleagues is designing a more efficient thermoelectric generator based on bismuth telluride, he said.

The antimony-bismuth module can generate 250 millivolts, or a quarter of a volt when the temperature difference between the ends is 30 degrees celsius, said Qu. The bismuth telluride version could provide five times the power of the antimony bismuth model, he said.

"Theoretically, the module with bismuth telluride will provide a voltage of about 1.6 volts at a temperature difference of 30 degrees [celsius]. The real value could be a little lower than [1.6 volts]. However, we believe it would not be lower than 1.2 volts," said Qu.

The researchers are also looking into using titanium as a substrate instead of copper foil, even though it is more expensive; in experiments, titanium did not contaminate either antimony or bismuth layers, while the researchers found small traces of copper contaminating the electrodeposited antimony layer.

They hope to have a functional, equally flexible bismuth telluride module within 2 to 3 years, according to Qu.

"There are a host of possible applications in microsystems of autonomous electrical power sources that can run on low-temperature waste heat," said Yogendra Joshi, a professor of mechanical engineering at the University of Maryland. "The key challenge is the ability to generate decent amounts of power and the ability to integrate the device with the rest of the microsystem," he said.

"The authors have shown success in doing this with [antimony-bismuth] micro thermocouples, with modest electrical power generation," said Joshi.

Qu's research colleagues were Matthias Plötner and Wolf-Joachim Fischer of the Dresden University of Technology. They published the research in the Journal of Micromechanics and Microengineering, March 2001. The research was funded by the Association of Industrial Research Organisations (AiF) in Germany.

Timeline: 2-3 years
Funding: Institute
TRN Categories: Microelectromechanical Systems (MEMS)
Story Type: News
Related Elements: Technical paper, "Microfabrication of Thermoelectric Generators on Flexible Foil Substrates as a Power Source for Autonomous Microsystems," in the Journal of Micromechanics and Microengineering, March 2001

Circuit Gets More Power from Shakes

By Kimberly Patch, Technology Research News
November 13/20, 2002

Energy is all around, the trick is finding ways to harvest it to do the work of your choosing.

Researchers at Pennsylvania State University have boosted the efficiency of piezoelectric circuits, which transfer the mechanical energy of vibrations into useful electric power. Piezoelectric circuits are commonly used to convert a watch-wearer's motion into energy to power the watch.

The Penn State piezoelectric circuit harvests four times more power from vibrational energy than the circuits currently in use, said George Lesieutre, a professor of aerospace engineering at Penn State. Key to the increased efficiency is an adaptive control technique that optimizes the actions of a converter that transfers the harvested energy to a battery for storage.

The researchers prototype generates 50 milliwatts of energy, and should be efficient enough to convert the motion of a runner into the power needed to run an electronic music device, according to Lesieutre. Fifty milliwatts is one twentieth of a watt. The circuitry could also be used to power wireless networks of tiny sensors, and to power devices that dampen vibrations, according to Lesieutre.

In principle, energy can be extracted from any place where two areas consistently hold different amounts of energy, such as the temperature difference between a warm body and the outside air or between sun and shadow. Similarly, energy can be extracted from mechanical vibrational fields such as those caused by people walking or tires running over a road. One working example is tiny light-emitting diodes on downhill skis that are powered by the motion of the skis.

Like all piezoelectric circuits, the researchers' device depends on a key property of piezoelectric crystals like quartz. These crystals do not conduct electricity, but when they are exposed to mechanical stress, electrical charges appear on their surfaces.

Piezoelectric crystal also works in reverse. When exposed to an alternating electric current, the crystal vibrates, generating high-frequency sound waves. This effect is widely used in loudspeakers, microphones and devices that control frequencies in radio transmitters.

The Penn State circuit works by capturing the alternating voltage formed by piezoelectric crystal in response to vibrations. The device includes a rectifier, which converts the alternating electrical input to a positive electrical flow, a filter capacitor that smooths the electrical flow, and a converter that allows a battery to store the harvested energy.

The key to making the device more efficient is the engineering involved in the converter, said Lesieutre. The converter includes an adaptive control technique that adjusts to find the optimal power transfer options for the moment, including an efficient duty cycle. A duty cycle dictates when and for how long a device is active. "The smarts is in the... converter, which operates at [a specific] frequency and duty cycle," he said. The adaptive technique allows the converter to transfer power more efficiently in order to maximize the power stored by the battery. "The duty cycle selection is especially critical," he added.

The researchers also sized the circuit with an eye toward maximum efficiency, said Lesieutre.

In the researchers' experiments, the adaptive converter increased power transfer by more than 400 percent, he said.

Devices that require more than 50 milliwatts could be powered using an array of several piezoelectric circuits, or they could be powered periodically, Lesieutre said.

For example, the device could power an environmental-control sensor that periodically wakes up, processes data, then communicates it to a central location via wireless transmitter, said Lesieutre. Even though it may take more than 50 milliwatts to power the sensor and transmitter, they can be operated intermittently. One can store a lot of energy in a battery, even at low charging rates, if one can wait long enough," he said.

The circuit could also be used for control and guidance robotics in manufacturing, patient monitoring and diagnostics, home security systems, and interactive toys, according to Lesieutre. Researchers are also looking to use power-scavenging techniques to power microelectrical mechanical systems (MEMS) and micro-robots.

The work is "another useful piece of analysis and engineering," said Andrew Brown, an electronics professor and head of the electronic systems design group at the University of Southampton in England. The amount of power that can be scavenged by techniques like these is still extremely small, he added.

However, recent technology has enabled the efficient and cheap extraction of these small amounts of power, and the ability to use them. "Two aspects of technology are converging to make this application workable: it's becoming feasible to mine low levels of power, and it's becoming possible to do useful things with that level of power," said Brown. "Very low power design is an enormous and growing field in its own right," he said.

The researchers' next steps are to make the system even more efficient, and to size it for various applications, including very small ones, Lesieutre said. The possibilities include powering wearable electronics, he said.

The device could be used in products in less than two years, he said. Ways to power sensors and wireless transmitters would be useful to pursue first, he said.

Lesieutre's research colleagues were Geffrey K. Ottman, Heath Hoftmann and Archin C. Bhatt. They published the research in the September, 2002 issue of *IEEE Transactions on Power Electronics*. The research was funded by the Office of Naval Research (ONR).

Timeline: < 2 years
Funding: Government
TRN Categories: Energy; Engineering
Story Type: News
Related Elements: Technical paper, "Adaptive Piezoelectric Energy Harvesting Circuit for Wireless, Remote er Supply," *IEEE Transactions on Power Electronics*, September, 2002

TRN

On-Chip Battery Debuts

Technology Research News, March 26/April 2, 2003

Researchers from Hosei University in Japan have taken a big step toward giving nano devices and biochips onboard power supplies.

The researchers etched 200- by 100- by 2-micron trenches into silicon chips to house tiny batteries. A micron is one thousandth of a millimeter, and human hair is about 75 microns in diameter.

The researchers filled the trenches with a porous glass electrolyte and electrodes made from lithium and lithium manganese oxide. The battery produces a current of electrons when lithium ions move through the glass from one electrode to the other. The researchers added numerous nano-sized pores to the inside and surface of the glass, which opened more paths for the lithium ions to travel, increasing the tiny battery's power. A nanometer is one thousandth of a micron.

The 3.6-volt batteries deliver 34.6 watt hours per square centimeter.

The researchers are working on embedding larger numbers of smaller batteries into silicon chips, and are working on materials that allow ions to diffuse more efficiently. Practical miniature batteries could be ready for use in computer chips and biochips in five to ten years, according to the researchers.

The work appeared in the December 23, 2002 issue of Applied Physics Letters.

TRN

Magnesium Batteries Show Mettle

Technology Research News, May 21/28, 2003

Researchers from Bar-Ilan University in Israel have developed rechargeable batteries made from magnesium, a cheap, abundant and relatively environmentally friendly metal.

The batteries can be recharged as many as 3,000 times, lose power slowly, and have a working temperature range of -40 to 100 degrees Celsius. They are also safe and maintenance-free, making them good candidates for large-size applications like powerplant load-leveling, according to the researchers.

The key to making batteries that use magnesium as a positive electrode was finding suitable negative electrode and electrolyte materials. Batteries use a cycle of chemical reactions between positive and negative electrodes to release energy stored in the electrolyte. The researchers' prototype uses a molybdenum sulfide negative electrode and liquid and solid electrolytes of organic, or carbon-based, and organo-metallic compounds.

The batteries have an energy density of 60 Watt hours per kilogram, which is higher than existing nickel cadmium and lead acid batteries, but lower than lithium batteries. The researchers are working to increase the energy density of the batteries.

The batteries could be used in practical devices in two to five years, according to the researchers. The work appeared in the April 9, 2003 issue of Advanced Materials.

TRN

Metal Mix Boosts Batteries

By Kimberly Patch, Technology Research News
October 2/9, 2002

A truly good battery should be made of relatively inexpensive materials, store a significant amount of electricity, and discharge this energy as quickly as an electrical device needs it. And in a world that's increasingly contaminated by the residues of technology, it should be rechargeable and nontoxic.

The common lithium batteries that power portable electronic devices like laptop computers and cell phones use lithium metal oxide electrodes. Five years ago, scientists discovered a cheaper, nontoxic lithium electrode — lithium iron phosphate. But initial promise turned to disappointment when the material turned out to be a bad conductor, and so could not discharge electricity at rates high enough to be useful.

Researchers from the Massachusetts Institute of Technology have now shown that doping, or mixing, lithium iron phosphate with positive ions of another metal can drastically boost the material's conductivity. Ions are atoms that have fewer or more electrons than electrically neutral atoms and so have a positive or negative charge.

The doping metal increased the conductivity of the lithium iron phosphate by 100 million times, making it an even better conductor than standard lithium metal oxide electrodes, according to Yet-Ming Chiang, a professor of materials science and engineering at the Massachusetts Institute of Technology.

The raw materials that go into the compound are only about one-quarter the cost of those that make up lithium metal oxide electrodes and the compound is nontoxic, Chiang said. The material gives a battery an extremely high rate of charge and discharge, "while at the same time being low in materials cost and very safe," he said.

Lithium iron phosphate batteries could bring on a new class of devices that would bridge the gap between super capacitors, which deliver short bursts of high power, but can only store limited amounts of total energy, and batteries, which have the opposite trade-off, said Chiang.

The material promises to improve batteries for electric and hybrid cars, backup power for implantable medical devices, and fuel cells, according to Chiang.

Batteries generate electricity when the pair of materials that make up the bulk of the battery react chemically, with one material giving up electrons and the other material gaining electrons. Rather than flowing directly from one material to the other, however, the electric current leaves the battery through one electrode and returns through another.

Connecting an electronic device between a battery's electrodes, which act as gatekeepers that determine how quickly the electricity flows, powers the device.

Batteries made with the researchers' new electrode material would deliver voltage similar to conventional lithium batteries, but the material's better conductivity allows for much higher power density, or rate of charge and discharge, said Chiang. A cell containing the new electrode could be charged or discharged in as little as three minutes, while typical batteries might require a half-hour or more, he said.

This is important for electric vehicles because they need a high rate of energy to accelerate and because they need to store electricity quickly in order to reuse breaking energy, said Chiang. "Battery power density is required for rapid acceleration and also to accept the regenerative breaking energy when someone slams on the brakes," he said.

The material could also eventually be used as electrodes for electrochemical applications like fuel-cells and membranes for separating hydrogen gas, according to Chiang. "These are other applications that require rapid electron transport as well as ion transport—in these cases the ion is hydrogen rather than lithium as in the battery," he said.

The team synthesized more than 50 different mixtures by adding different metals and baking the samples at temperatures as high as 850 degrees Celsius in order to change the crystal structure of the material to improve its conductivity, said Chiang. The metals included magnesium, aluminum, titanium, zirconium, niobium, and tungsten. The challenges were getting the additive to be uniformly distributed in the crystal lattice of the lithium iron phosphate at the right positions in the lattice to have the necessary effect on conductivity, he said.

They knew they were on to something when something strange happened. "Lithium iron phosphate is normally medium gray color, not surprising for an electronic insulator," Chiang said. When one of the samples came out jet-black, "we realized that something special had happened," he said. "Highly conductive materials are usually either metallic in luster—gold, silver, copper, aluminum—or black in color—carbon, oxide superconductors, magnetic ferrites."

The material has a nanoporous crystal structure, said Chiang. Nanoporous materials contain holes nearly as small as atoms. "The nanoporous structure allows for rapid lithium transport into the electrode without impeding the electronic conductivity," he said.

The formulation has proven very stable in abuse tests. This is "especially important for batteries that pack a lot of energy and will be used under a wide range of temperatures and electrical conditions," Chiang said.

Lithium iron phosphate is also the basic formulation of a mineral found in the earth's mantle. Both this and the dopants the researchers added are considered nontoxic compared to nickel-cadmium or lead acid batteries, said Chiang. "We expect no environmental issues concerned with disposal," he said.

The new type of lithium iron phosphate "looks like a major breakthrough," said John Owen, a reader in electrochemistry at the University of Southampton in England for. "This discovery will certainly bring forward the arrival of a new type of lithium battery in its the next year or two," he said.

Once the scope and mechanism of the effect are fully understood, "the way will be open to use a similar technique to improve many other materials in the field of energy conversion, [including] fuel cells and solar cells," he said.

If the result turns out to be reliable, then this is most certainly interesting, said Josh Thomas a professor of solid-state electrochemistry at Uppsala University in Sweden, and director of the university's Advanced Battery Centre. The material "is at the absolute front line... in implementing new materials for developing better, cleaner, more powerful batteries for ever larger applications—ultimately for traction applications in electric and electric/hybrid vehicles," he said.

The researchers are currently working to understand exactly how the material conducts so well, said Chiang. "We want to understand the crystal chemistry and mechanisms of conduction in this material at a deeper level, to know where the atoms and electrons are and why the conduction is as high as it is," he said. The researchers are also planning to investigate similar compounds, he said.

Because batteries based on the new electrode can use existing materials for the rest of the battery, the material could find its way into products within two years, Chiang said.

Chiang is co-founder of A123Systems, which has licensed the technology from MIT and is working to commercialize it, according to Chiang.

Chiang's research colleagues were Sung-Yoon Chung and Jason T. Bloking. They published the research in the September 22, 2002 issue of *Nature Materials*. The research was funded by the Department of Energy (DOE).

Timeline: 2 years
Funding: Government
TRN Categories: Energy; Materials Science and Engineering
Story Type: News
Related Elements: Technical Paper "Electronically Conductive Phopho-Olivines as Lithium Storage Electrodes," *Nature Materials*, September 22, 2002.

TRN

Nanotubes Pack Power

By Chhavi Sachdev, Technology Research News
February 27, 2002

While there may be no way to keep batteries going forever, researchers at the University of North Carolina have shown they can extend battery life by replacing a graphite electrode in the common rechargeable battery with a related carbon form: the nanotube.

Most portable electronic devices, including cell phones and laptops, draw their power from lightweight, rechargeable lithium-ion batteries. Each battery has a graphite electrode and a metal oxide electric. The charge, or current, stored by the battery is released when lithium ions move from one electrode to the other.

The researchers found a way to increase the amount of charge a battery can hold and, consequently, its lifespan, by replacing the carbon electrode with single-walled carbon nanotubes. Nanotubes are microscopic, rolled-up sheets of carbon atoms.

"When processed right, single-wall carbon nanotubes have twice the storage capacity [of] the graphite electrode," said Otto Zhou, an associate professor of physics and materials science at the University of North Carolina at Chapel Hill.

Naturally formed nanotubes are cylindrical and closed at either end. The researchers tested the storage capacities of both open-ended and closed-end single-walled carbon nanotubes.

The closed-end nanotubes were 1.4 nanometers in diameter and 10,000 nanometers long. The open-ended nanotubes were shortened to either 500 or 4,000 nanometers. A nanometer is a millionth of a millimeter; a red blood cell measures about 5,000 nanometers across.

Closed-end nanotubes were able to hold the same amount of charge as graphite electrodes, but the shorter, open-ended nanotubes held twice as much. "Open-end single-walled nanotubes can store, reversibly, twice the amount of lithium than the regular graphite electrode and closed-end single-walled nanotubes," said Zhou.

A possible reason for the higher capacity of the shorter nanotubes is that lithium ion uptake can occur more quickly through the open ends, according to Zhou. Additionally, the sidewalls of the shortened nanotubes could have defects that allow the ion to diffuse into the inner spaces more freely, he said.

Nanotubes have more theoretical potential to store charge than graphite because, while graphite electrodes allow a battery to store one charged lithium ion for every six carbon atoms, nanotubes allow one charged lithium ion to be stored for every three carbons, according to Zhou. "This is shown convincingly by electrochemistry and nuclear magnetic resonance measurements," he said.

This is a very high quality piece of work, said Michael Heben, a senior scientist at the National Renewable Energy Laboratory. Building on previous efforts to use single-walled carbon nanotubes as anodes in lithium batteries, Zhou and his colleagues have demonstrated lithium capacity beyond what is normally thought to be the limit, Heben said.

The work, "underscores the potential for single-walled carbon nanotubes in battery applications [and] adds significantly to a small but growing body of work," Heben said.

It will be at least two years before carbon nanotubes can be used in lithium-ion batteries, Zhou said. "We show the potential but there are many practical issues that need to be solved," he said.

Zhou's research colleagues were Hideo Shimoda, Bo Gao, Xiao-Ping Tang, Alfred Kleinhammes, Leslie Fleming, and Yue Wu. They published the research in the January 7, 2001 issue of the journal Physical Review Letters. The work was funded by the Office of Naval Research and the National Science Foundation (NSF).

Timeline: > 2 years
Funding: Government
TRN Categories: Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, Lithium Intercalation into Opened Single-Walled Carbon Nanotubes: Storage Capacities and Electronic Properties," in Physical Review Letters, January 7, 2001

TRN

Huge Lasers Could Spark Fusion

By Kimberly Patch, Technology Research News
September 18/25, 2002

Finding ways of producing useful energy is an age-old problem, and the ways humans have come up with often seem to involve some type of pollution.

Scientists have been working for more than 50 years to harness nuclear fusion, the reaction that powers both the sun and hydrogen bombs, as a clean, controllable energy source.

When a pair of atoms are forced together they fuse to create a new type of atom; this reaction gives off a tremendous amount of energy. The trick to setting off the reaction is compressing the fuel atoms enough, generating enough ignition energy, and coordinating the process.

A second challenge is containing the reaction, which, at one hundred million degrees Celsius, is hot enough to burn through any type of material. And to be a useful energy source, the reaction must produce more energy than is used to ignite it.

An international team of researchers has shown that it is possible to use very high-powered lasers to isolate and heat very dense fuel to the incredibly high temperatures necessary to set off nuclear fusion.

The method could eventually be used to generate power on an industrial scale, according to Peter Norreys, physics group leader at Rutherford Appleton Laboratory in England. "We can now seriously consider the construction of full-scale fast ignition facilities... that bring the commercial realization of fusion energy a lot closer," he said.

The effort is one of several aimed at developing fusion as a power source.

Hydrogen, the first element, has a nucleus made up of just one proton. When a pair of hydrogen atoms fuse they become one helium atom, which contains two protons.

It takes a lot of energy to meld two atoms because the positively charged protons contained in atomic nuclei repel each other. The force keeping atomic nuclei apart— the Coloumb force—is proportional to the product of the two charges divided by the square of the distance between them, meaning the closer two nuclei are, the more difficult it is to bring them closer still.

Teams of scientists across the globe are working on an approach that involves heating and compressing a large pool of the hydrogen isotope tritium using powerful electromagnetic fields, which also isolate the hot plasma.

The two hydrogen isotopes, deuterium and tritium, contain one proton plus one and two neutrons, respectively. Neutrons have no charge. This makes deuterium twice as heavy as hydrogen, and tritium three times as heavy and also more reactive.

One of the challenges of the electromagnetic field approach is precisely synchronizing the heating and compressing to occur at same time.

The laser method involves a small amount of deuterium fuel, and ignites the fuel more quickly than the usual approach, according to Norreys. "The idea of laser fusion is to compress the matter to ultra-high density so that the material does not have time to respond to the increase in temperature generated by the spark before the fusion process is complete," Norreys said.

The concept was proposed by scientists from the Lawrence Livermore National Laboratory eight years ago. "Their idea was to separate the two processes of compression to high density and heating to thermonuclear temperatures," and to use an ultra-fast laser pulse to ignite fusion, he said.

The general set-up is similar to the internal combustion engines cars use, said Norreys. "Fuel is periodically compressed, and a spark is administered to ignite the fuel. The fuel explodes and releases energy," he said.

The challenge to proving the scheme possible was finding a way to allow the ignition laser beam to come close to the compressed fuel, or plasma, without being deflected, said Norreys.

The researchers got around the problem by using a hollow gold cone to insure that exhaust from the plasma did not interact with the laser pulse, allowing the laser energy to be deposited as close as possible to the compressed fuel.

The researchers inserted the guide cone into a polystyrene-deuterium shell seven microns thick and 500 microns in diameter, and used nine laser beams to implode the shell and hold the plasma in place. A micron is one thousandth of a millimeter.

The implosion compressed the fuel to about 100 grams, or just under a quarter pound, per cubic centimeter. They shot a petawatt laser pulse into the cone, depositing a large number of energetic electrons at its tip, which was about 50 microns from the center of the fuel, said Norreys.

One petawatt is one million billion watts, which is more than a billion times the watts used by the 500-odd high-power lights that illuminate Syracuse University's 50,000-seat Carrier Dome.

The energetic electrons slowed down in the compressed material, Norreys said. And "as they slowed down they transferred their energy to the plasma in the form of heat," he said.

The experiments confirmed that at least 20 percent of the petawatt laser energy was transferred to the plasma in the form of heat, proving the method viable, said Norreys.

One of the advantages of using lasers rather than magnetic fields to spark and contain fusion is the compression process does not have to be as precise, according to Norreys. Strict implosion symmetry, where the fuel compresses into an exactly round ball, is not necessary under this scheme, he said.

The research efforts into magnetic-field contained fusion, however, are more advanced. The laser experiment was possible only because scientists now have access to petawatt lasers capable of depositing enough energy into the fuel, said Norreys.

Now that the laser scheme has been proven possible "we can... seriously consider the construction of full-scale fast ignition facilities that will greatly reduce the size of the drive laser needed for ignition," said Norreys. Refining the method so that less power is needed to ignite the fuel is a step toward making fusion energy generation commercially viable, he said.

The researchers plan to perform the same experiments on a similar laser in order to confirm that the results can be reproduced, said Norreys. "We're starting these experiments in the next three weeks at... the Rutherford Appleton laboratory," said Norreys.

Longer-term, the researchers are aiming to demonstrate that it is possible to fully ignite a fusion reaction using this method, and that it is possible to produce a net gain of energy from such a reaction, said Norreys.

The research is a valid demonstration, and an experiment well done, said Hector Baldis, director of the Institute for Laser Science and Applications at Lawrence Livermore National Laboratory and a professor of applied science at the University of California at Davis. "It does... give credibility to the idea of using what we call fast ignition," he said.

It is one thing to achieve ignition, and another to generate power from laser fusion, Baldis added.

It will take ten years of work to demonstrate ignition, and 20 years before the method could be ready for commercial use in a laser-fusion power plant, said Norreys.

In the near term, the method can be used to study fusion in the laboratory, Norreys said. "Applications in nuclear physics and laboratory-based astrophysics are much closer," he said.

Norreys' 23 research colleagues were Ryosuke Kodama and his fast-igniter Consortium team at Osaka University in Japan, Thomas Hall from the University of Essex in England, Hideaki Habara from Rutherford Appleton Laboratory, Karl Krushelnick from Imperial College in England, Kate Lancaster from Rutherford Appleton Laboratory and Imperial college, and Matthew Zepf from Queens University in Northern Ireland.

They published the research in the August 29, 2002 issue of the journal *Nature*. The research was funded by the Japanese Ministry of Education (Monbusho), the Japan Society for the Promotion of Science, and the UK Engineering and Physical Sciences Research Council.

Timeline: < 1 year, 10 years, 20 years
Funding: Government
TRN Categories: Energy; Physics
Story Type: News
Related Elements: Technical paper, "Fast Heating Scalable to Laser Fusion Ignition," *Nature*, August 29, 2002

TRN

Quantum Force Powers Microslide

By Eric Smalley, Technology Research News
May 1/8, 2002

Researchers have coaxed two tiny metal parts to slide past each other powered only by the shapes of the parts and an oddity of quantum physics. The effect could be used to move microscopic machinery.

According to quantum physics, a vacuum is actually seething with zero-point energy, which is created by subatomic particles constantly popping in and out of existence. Many of the particles are photons, which means much of the energy is electromagnetic like light, x-rays and radio waves.

When two parallel plates are positioned closely enough that the gap between them is smaller than some electromagnetic wavelengths, some of the zero-point energy is shut out of the gap. Because there is more zero-point energy acting on the outer surfaces of the plates than the inner surfaces, the plates are drawn together, a phenomenon termed the Casimir effect.

Researchers at the University of California at Riverside and the Federal University of Paraíba in Brazil have found a way to use this effect to cause one surface to slide over another.

"The normal Casimir force acts perpendicular to the two interacting surfaces, pulling them together," said Umar Mohideen, an associate professor of physics at the University of California at Riverside. "The lateral Casimir force acts tangential to the two surfaces, leading to the horizontal sliding of one surface with respect to the other," he said.

In theory, if two corrugated plates are aligned parallel to each other and positioned closely enough, the Casimir force will come into play. But unlike two flat plates that are drawn together, the corrugated surfaces are at angles to the plate as a whole, and so when the surfaces are drawn together they move the plates laterally.

Because it is very difficult to keep two plates perfectly parallel when they are separated by less than a micron, the researchers replaced one of the plates with a gold sphere one-fifth of a millimeter in diameter. The researchers imprinted the sphere with corrugations by pressing the plate into it.

The researchers moved the plate sideways less than half a nanometer at a time and measured the lateral force exerted on the sphere at each step. A nanometer is one millionth of a millimeter. The researchers started with the plate and sphere separated by 221 nanometers. They increased the distance between them in 12 nanometer increments and repeated the lateral steps at each distance. As expected, the Casimir effect weakened as the distance increased.

The researchers are studying other shapes to use in their next experiment, said Mohideen. "The Casimir force depends strongly on the shape of the [surfaces] and can be repulsive or attractive," he said. "The force between two parallel metallic plates is attractive, [but] that between two hemispheres is repulsive."

As microelectromechanical systems (MEMS) become smaller, the Casimir effect could gum up the works. But researchers could also harness the effect. The lateral Casimir force could be used to provide sliding motion, said Mohideen.

The lateral Casimir effect is not surprising, said Steve Lamoreaux, a physicist at the Los Alamos National Laboratory. "[However], the experiment must have been extremely difficult and as such the result represents a real tour de force, no pun intended. This effect might be useful in nano-machines; it could be used as a lateral spring of some sort," he said.

"On the other hand, there is also a large force between the surfaces trying to pull them together, so there is a limitation on the usefulness of the effect," Lamoreaux said.

The lateral Casimir force could be applied in MEMS technology now but it is likely to take five to ten years before practical devices make use of it, said Mohideen.

Mohideen's research colleagues were Feng Chen of the University of California at Riverside, and Galina Klimchitskaya and Vladimir Mostepanenko of the Federal University of Paraíba in Brazil. They published the research in the March 11, 2002 issue of the journal *Physical Review Letters*. The research was funded by the National Science Foundation (NSF), the National Institute of Standards and Technology (NIST) and the Brazilian government.

Timeline: 5-10 years
Funding: Government
TRN Categories: Microelectromechanical Systems (MEMS); Nanotechnology
Story Type: News
Related Elements: Technical paper, "Demonstration of the Lateral Casimir Force," *Physical Review Letters*, March 11, 2002

TRN

Quantum Effect Moves Machine

By Eric Smalley, Technology Research News
February 14, 2001

According to classical physics, a vacuum at a temperature of absolute zero contains no matter or energy. But according to quantum physics, this emptiness isn't really empty. It is filled with fluctuating energy.

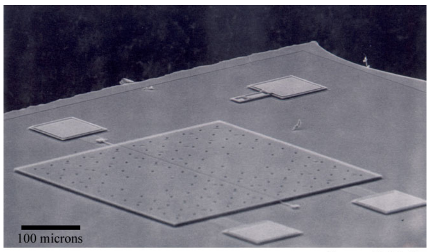
Classical physics, as epitomized by Newton's laws, describes how matter and energy operate in the everyday world. Quantum physics describes the very different conditions that exist in the realm of atoms and subatomic particles.

A team at Lucent Technologies' Bell Labs has shown that as researchers make ever smaller machines, the quantum effect of zero point energy could come into play. The researchers built a microelectromechanical device similar to those used as tiny sensors and actuators, and measured how this energy affected it.

Zero point energy is created by subatomic particles that appear out of nothing, then rapidly disappear. Because many of the particles are photons, much of the energy is electromagnetic like light, x-rays and radio waves. "This energy pervades all space. It's everywhere," said Ho Bun Chan, a physicist at Bell Labs.

The energy becomes a factor in the world of devices when two parallel plates are positioned closely enough that the gap between them is smaller than some electromagnetic wavelengths. This means that some of the zero point energy is shut out of the gap. Because there is more zero point energy acting on the outer surfaces of the plates than the inner surfaces, the plates are drawn together.

The phenomenon, predicted in 1948 by the Dutch physicist Hendrik Casimir, observed in 1958 and measured in 1996, is called the Casimir effect. "This force arises merely because of the existence of the two plates," said Chan.



Source: Bell Labs

This half-millimeter-square plate pivots like a seesaw. The quantum-mechanical Casimir effect causes the end of the plate to tip up toward a sphere lowered to within 300 nanometers of the plate.

Though the force is very small at the micro scale, it increases rapidly as the distance between the plates decreases. The force between parallel plates can be as large as an atmosphere, or 14.7 pounds of pressure per square inch, at a distance of 10 nanometers, said Umar Mohideen, an associate professor of physics at the University of California at Riverside.

The Bell Labs' device consists of a 500-micron-square, 3.5-micron thick silicon plate suspended above a silicon wafer. The plate pivots, seesaw fashion, between two tiny rods. Electrodes sit on the wafer under each end of the seesaw. As the plate tilts, the capacitance on the lower side increases while that of the higher side decreases, allowing the researchers to measure very small changes in the position of the plate.

The researchers induced the Casimir effect in their device by lowering a 200-micron-diameter sphere over the plate. "When the plate is actuated by the Casimir force, the rotation is only about a thousandth of a degree. It's a tiny rotation, but it's detectable," said Chan.

The Bell Labs research "is the first step in the design and fabrication of novel MEMS devices based on the Casimir force," said Mohideen. "Finally, devices based on quantum fluctuations... are coming to fruition. This is very exciting."

The researchers used a sphere rather than a second plate because it's easier to work with even though the Casimir effect is less pronounced between a sphere and a plate, said Chan.

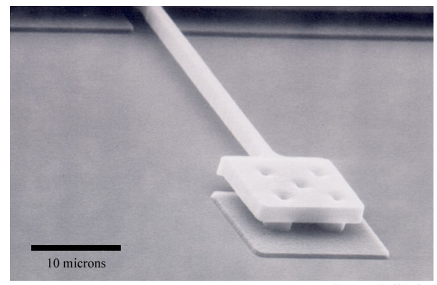
"We are talking about separations [of] less than a tenth of a micrometer," he said. "It's very difficult to keep two plates perfectly parallel. If you use a sphere there's only one point where it's closest to the plate. It basically gets rid of the alignment problem," he said.

The plate tilted due to the Casimir effect when the sphere was 300 nanometers above one end of the plate. The tilt increased sharply as the researchers moved the sphere closer to the plate.

"We can speculate [about] making very sensitive position sensors, for example, because this force rises very quickly with distance," said Chan.

As Bell Labs' use of a sphere illustrates, the effect is not limited to parallel plates.

"The Casimir force is strongly shape dependent and can be repulsive as well as attractive," said Mohideen. "It can be further modified with subtle texturing on the surfaces, like putting in corrugations. Incorporating the shape-dependent Casimir force should give an additional knob for engineers to turn in future MEMS designs," he said.



Source: Bell Labs

This tiny rod and its twin on the opposite side of the plate form a fulcrum that lets the plate pivot like a seesaw.

A NASA-funded project is even exploring how to use the Casimir effect in a propulsion system for spacecraft.

The Casimir effect is already a problem for fabricating MEMS devices because at very short distances free surfaces tend to stick together, said Mohideen. "During the fabrication step, it is very hard to make free moving surfaces such as cantilevers [and] bridges which are separated by short distances," he said.

It's difficult to predict how the Casimir effect will be used in microelectromechanical systems, said Chan. "Our work is trying to demonstrate that if the device sizes continue to shrink then we might have to take into account quantum effects," he said.

The Casimir effect could be a factor for MEMS designers in five years, he said.

Chan's research colleagues were Vladimir A. Aksyuk, Raphael N. Kleiman, David J. Bishop and Federico Capasso of Bell Labs. They published the research in the February 8, 2001 issue of *Sciencexpress*. The research was funded by Lucent Technologies.

Timeline: 5 years
Funding: Corporate
TRN Categories: Microelectromechanical Systems; Physics
Story Type: News
Related Elements: Technical paper, "Quantum Mechanical Actuation of Microelectromechanical Systems by the Casimir Force," *Sciencexpress*, February 8, 2001

Heat Engines Gain Quantum Afterburner

By Eric Smalley, Technology Research News
March 6, 2002

Considering the heat a car engine gives off, it's pretty clear that a lot of the energy it produces goes to waste. Even the hot gases produced by the most efficient engine possible are a significant source of wasted energy.

The trick to tapping these hot gases is using them for something other than mechanical work.

A physicist at Texas A&M University has figured out how to use the hot gases produced by an Otto engine, a piston engine similar to those in automobiles, to drive a laser. The laser produces energy from the hot gas and therefore increases the total amount of energy derived from the engine. The theoretical work can be applied to any engine that produces hot gases, said Marlan Scully, a professor of physics and electrical engineering at Texas A&M.

Heat engines use heat to expand a gas by causing its atoms to move faster. The expanding gas, contained within a chamber, pushes a piston, which, in turn, rotates a shaft.

This classic setup ignores the quantum nature of the atoms, however. "Atoms are not just little hard balls, but actually have internal structure," said Scully. "The internal energy levels that the electron occupies inside the atom are also a source of energy. The electron can fall from a high state to a lower state and emit light. That's how we have light. It's going on in the sun... all the time," he said.

In a laser, the photons emitted by the atoms of the laser material are trapped between two parallel mirrors and bounce back and forth, which causes them to hit other atoms that in turn release additional photons. This amplifies the light and produces the familiar intense, monochromatic beam.

Ordinarily, starting a laser requires pumping energy, usually electricity, into the laser to charge up, or excite, more than half of its atoms. "You've got to have more atoms in the excited state than the ground state because atoms in the excited state emit light but atoms in the ground state absorb light," said Scully. "You've got to have more emitters than absorbers on average in order to get a net laser action."

Scully and other researchers previously found a way to start laser action without first exciting more than half of the atoms in the laser. The method, lasing without inversion, uses a second laser to block the majority of atoms from absorbing light, which allows laser action to occur more readily in the remaining atoms.

That work led him to look at the atoms in a hot gas as a potential laser source. The atoms in a hot gas like the gas in a heat engine are in the lowest energy, or ground state. Exciting more than half of the gas atoms would take more energy than would be produced by the laser. Using lasing without inversion, however, requires less energy, allowing for a net gain.

The quantum afterburner follows the laws of thermodynamics, which dictate that you can't get any more energy out of a perfect heat engine, according to Scully. When he applied his theory to the Carnot engine, which is a mathematical representation of a perfect heat engine, it did not extract any additional energy, he said.

But even the most efficient real-world heat engine is not perfectly efficient, and so can produce at least a little more energy using the quantum afterburner. The question is how to develop practical applications.

"Maybe it would be effective to have a different kind of mechanism for powering a nano engine," said Scully. For example, the laser could trigger chlorophyll molecules in cells, causing the cells to do useful work, he said.

Lasing without inversion could be put to use within the next couple of years, said Scully. Using the lasers to power nano engines is "way off in the future," he said.

The research was funded by the National Science Foundation (NSF), the Office of Naval Research (ONR), the Air Force Office of Scientific Research, the state of Texas and the Robert A. Welch Foundation.

Timeline: < 2 years; Unknown
Funding: Government; Private
TRN Categories: Applied Technology; Physics
Story Type: News
Related Elements: Technical paper "Quantum Afterburner: Improving the Efficiency of an Ideal Heat Engine," *Physical Review Letters*, 4, 2002

TRN

Engine Fires up Electrical Devices

By Eric Smalley, Technology Research News
May 30, 2001

On a plane trip in the not-too-distant future, the hum you hear coming from your seatmate's laptop computer might not be its hard drive but rather its power source.

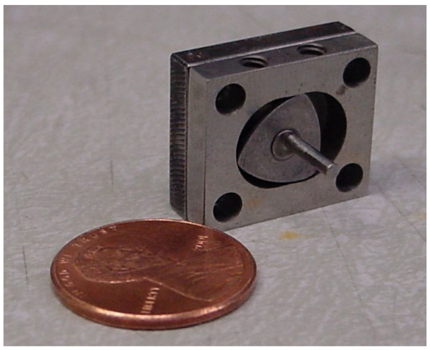
Researchers at the University of California at Berkeley have developed an internal combustion engine that could replace batteries as the power source for portable electronic devices.

Though internal combustion engines are a decidedly 19^{th}-century technology, the Berkeley engine's small size — about the size of three stacked pennies—opens up a new range of potential applications. The researchers are also building a still smaller micro engine from silicon components that could power microelectromechanical systems (MEMS).

The researchers' aim is to take advantage of the high energy density of liquid hydrocarbon fuels like butane, propane and gasoline to produce electrical and mechanical power for small-scale devices. A particular volume of a liquid hydrocarbon fuel can produce about thirty times as much energy as a battery of the same size, according to the researchers.

The mini engine will run for about two hours on one fluid ounce of fuel, and the micro engine could run for about 67 days on the same amount of fuel, said Aaron Knobloch, a graduate student at Berkeley.

"The long-term objective of this research is to develop a millimeter-scale rotary internal combustion engine that produces tens of milliwatts [of power]," he said.



Source: UC Berkeley

This miniature internal combustion engine could be used to power electronic devices.

The mini engine, which is made of steel and aluminum, turns at 3000 revolutions per minute and produces about half a watt of power. The engine weighs 22 grams, or about 4/5 of an ounce, and its combustion chamber measures 12.5 by 9.5 by 3.6 millimeters, said Knobloch.

Like the engine in your car, the mini engine works by igniting a mixture of fuel and air to create a series of small explosions. The Berkeley engine is a Wankel engine, which, instead of using the force of the explosions to drive pistons, uses it to spin a triangular rotor inside an oval chamber.

Of course, it remains to be seen whether people will be willing to trade changing batteries for loading flammable liquids into their laptop computers. "Safety is definitely a concern. However, we envision the engine, with its fuel, to be equivalent to a Bic lighter," said Knobloch, adding that people are allowed to carry butane lighters on airliners.

Batteries also have the advantage of not producing air pollution in their immediate environments. The main pollutant produced by combustion engines is carbon dioxide, which is a greenhouse gas.

"The mini engine produces as much carbon dioxide as one person at rest," or about one 400th the exhaust of an automobile traveling at 60 mph, said Knobloch. One hundred micro engines would produce the same amount of carbon dioxide as one mini engine, he added.

The researchers' next step is producing the prototype micro engine out of silicon and silicon carbide with the photolithography fabrication process used to make computer chips. The combustion chamber of the prototype will measure 3.3 by 3 by 1 millimeter, said Knobloch. The micro engine could be used to generate electricity and to drive small robots and other mechanical devices.

The mini engine could be used in practical applications within a couple of years, said Knobloch. The researchers expect to build a prototype of the micro engine within six months and aim to use it to power devices within four years, he said.

Knobloch's research colleagues were Carlos Fernandez-Pello, David Walther, Kelvin Fu, Fabian Martinez, Bryan Cooley and Dorian Liepmann of Berkeley, and Kenji Miyaska of Fukui University. They are scheduled to present their work at the 35th National Heat Transfer Conference in Anaheim in June. The research was funded by the Defense Advanced Research Project Agency (DARPA).

Timeline: < 2 years
Funding: Government
TRN Categories: Microelectromechanical Systems (MEMS)
Story Type: News
Related Elements: Technical paper, "Micro-Scale Combustion Research for Applications to MEMS Rotary IC Engines," 35th National Heat Transfer Conference, June 10-12, 2001, Anaheim, CA

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Kimberly Patch
Editor
kpatch@trnmag.com

Eric Smalley
Editor
esmalley@trnmag.com

Ted Smalley Bowen
Contributing Editor
tbowen@trnmag.com

Chhavi Sachdev
Contributing Writer
csachdev@trnmag.com