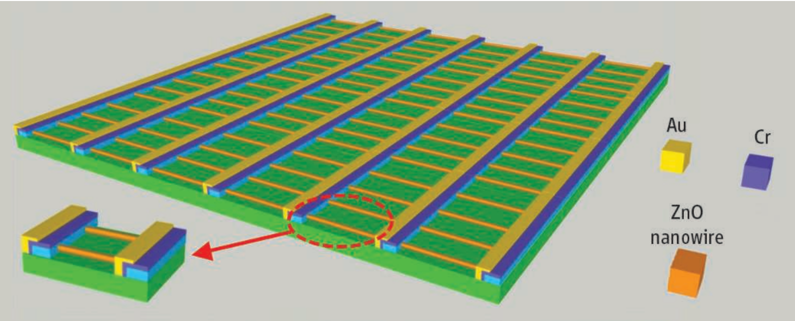
ENGINEERING

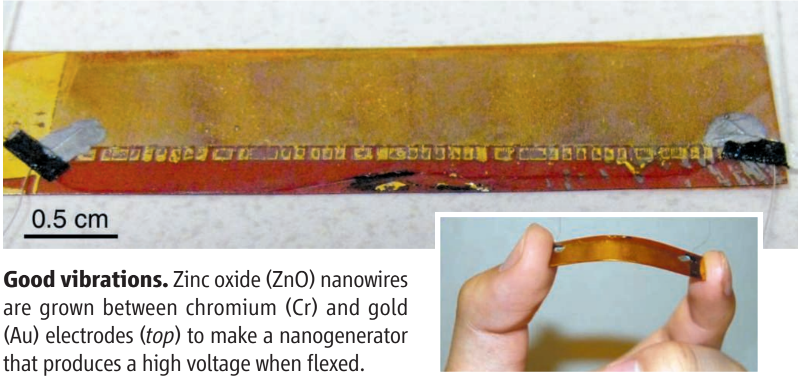
Nanogenerators Tap Waste Energy To Power Ultrasmall Electronics

Tiny devices that convert movements into electricity won't power cities. But they may soon be efficient enough to power arrays of invisible sensors and hand-held electronics

In the corner of a conference center on the main campus of Microsoft in Redmond, Washington, engineers have built a small four-room apartment. Called MS Home, it serves as both a testing ground and a showcase for how the future home may look and, well, behave. In Microsoft's vision, that home will be run by a computer system that turns on lights, controls the heat, and manages the appliances. An array of invisible sensors would do everything from tracking your movements (in order to know when to turn the lights on in the next room) to monitoring whether your plants need water.



Good vibrations. Zinc oxide (ZnO) nanowires are grown between chromium (Cr) and gold (Au) electrodes (*top*) to make a nanogenerator that produces a high voltage when flexed.



Uses of sensor networks have been talked about for years. One stumbling block has been figuring out how to power the devices. Sure, each one could be plied with batteries or wired to the grid. But that is expensive and requires periodic maintenance, which often upends such proposals. Now, however, the rise of a new technology to scavenge power from vibrations and other ambient sources may finally usher this vision of the future into the present.

Power scavengers have actually been around for some time. Companies, for example, already make larger scale devices that harness vibrations to monitor the structural health of buildings and bridges. But over the past few years, researchers have been progressively shrinking these scavengers to nanoscale dimensions in an effort to power everything from minuscule sensors inside the body to arrays of self-powered environmental sensors to monitor things such as air quality and stream flows. This miniaturization push has been aided by the steady progress of microelectronics technology, which now turns out sensors and computing devices small enough and frugal enough with their energy needs that many can be powered with just nanowatts to microwatts of power.

Today, the field "has now reached a critical mass and momentum," says Zhong Lin Wang, a physicist at the Georgia Institute of Technology (Georgia Tech) in Atlanta. "I am confident that with the way things are progressing, this will one day soon impact our daily lives."

Although several technologies are competing to power such devices, most nanogenerators are made from piezoelectric materials that convert mechanical motion into electricity. Piezoelectric materials, such as crystals of the ceramic lead zirconate titanate (PZT), are made of subunits that separate electrical charges. Mechanical strain, such as bending a thin piezoelectric wire, changes this electric polarization of the material and causes positive and negative charges to migrate to opposite faces of the material, creating an electric voltage that can be used to do work. The effect can also be reversed: Applying a voltage across a piezoelectric crystal causes it to move. This effect—first discovered in 1880—is behind decades of technology; sonar detectors, loudspeakers, autofocusing cameras, atomic force microscopes, and many other gadgets.

Today the most widely used piezoelectric material is PZT, as it is the most efficient material at converting mechanical strain to electricity. But PZT has its drawbacks. For starters, it is brittle and breaks easily. It also contains lead, a toxic metal, which makes it a poor choice for powering medical sensors in the body.

Now, researchers may have found a way around PZT's shortcomings. In the 10 February issue of *Nano Letters*, researchers led by Michael McAlpine, a chemist at Princeton University, reported the creation of a flexible PZT nanogenerator encapsulated inside a biocompatible plastic. McAlpine notes that whereas large crystals of PZT are brittle, ultrathin ribbons of the material can bend and flex without breaking. So McAlpine's team grew a thin layer of PZT atop a crystal of magnesium oxide (MgO) and then used a lithographic patterning technique, akin to that used to pattern microchips, to pattern the PZT into an array of long ribbons. They then dissolved the MgO substrate, leaving the ribbons behind, and pressed a rubbery plastic known as PDMS on top, transferring the PZT nanoribbons to the plastic (see bottom figure, p. 305). Several characterization studies showed that the transferred PZT nanoribbons retained their same piezoelectric properties, and they were roughly four times as efficient at transferring mechanical strain to electricity as were competing nanogenerators.

Still, flexible PZT nanoribbons have a way to go before they are ready to power real devices, McAlpine says. Among the steps still needed is to refine the PZT nanowire growth techniques. McAlpine says it should be possible to improve the power output of the devices 10-fold. Also, he says, scaling the technique up to make larger arrays would help to power more types of devices.

If efforts to make PZT nanogenerators more flexible and biocompatible don't succeed, alternatives are moving in to pick up the slack. Wang and his colleagues at Georgia Tech, for example, have pushed nanogenera-

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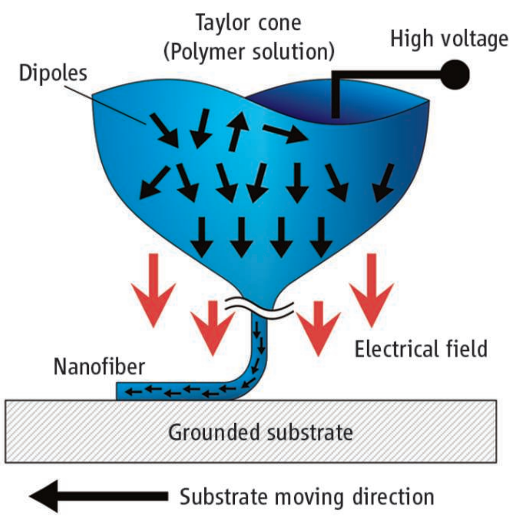


Power threads. A large electric field orients electric dipoles in a polymer being drawn into fibers.

tors made from zinc oxide (ZnO) nanowires considerably further than their PZT cousins. In 2006, Wang and his student Jinhui Song reported in *Science* that they grew arrays of vertical ZnO nanowires that when bent to the side created a small electric voltage (*Science*, 14 April 2006, p. 242). In the years since, Wang's team has developed successive iterations of their ZnO nanogenerators in an effort to increase the power output and robustness.

Last month, they raised the bar to the highest point yet. In a paper posted online in *Nature Nanotechnology* on 28 March, Wang and colleagues reported making two new nanogenerators. One produced the highest voltage of any nanogenerator to date; the other produced a lower voltage but was rigged up to power either a pH sensor or an ultraviolet detector without need for any outside energy. Both nanogenerators were made by growing arrays of long, thin zinc oxide nanowires. In the version wired to the sensors, these nanowire collections resemble a bed of nails with thin electrodes placed on the top and bottom. When the researchers then squeezed their device—thereby bending the nanowires—it produced 0.24 volts, with enough current to run their sensors. "That's pretty cool," says McAlpine, who credits Wang for pioneering several nanogenerator concepts.

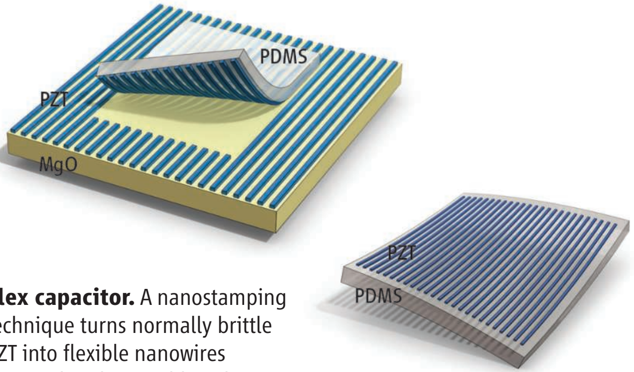
One of those was Wang's higher voltage nanogenerator. Pushing the output is important, Wang says, because most devices today need more than one-quarter of a volt to run. Standard AA battery–powered devices, for example, require up to 1.5 volts to operate—well beyond what most nanogenerators can generate.

To make a higher voltage device, Wang and his colleagues needed to find a way to make the voltage output of individual nanowire devices add up. To do so they needed to orient the crystallographic axis of each ZnO nanowire in the same direction so that when force was applied to them all collectively, the polarity of charges on each wire would be aligned, producing a higher output voltage. Wang's team patterned an array of parallel chromium wires atop a substrate. They then grew thousands of ZnO nanowires laterally between these wires, like rungs in a ladder, under conditions that ensured they all grew with the same crystallographic orientation. Finally, they soldered the ZnO nanowires to the chromium by depositing gold at the connection points (see figure, p. 304). The scheme worked. When they flexed their array, it generated 1.26 volts. That's not quite the 1.5 volts of a AA battery, but in the months since their paper was submitted, Wang says his team has upped that output to 2.4 volts. "This enables us to operate true technology," Wang says.

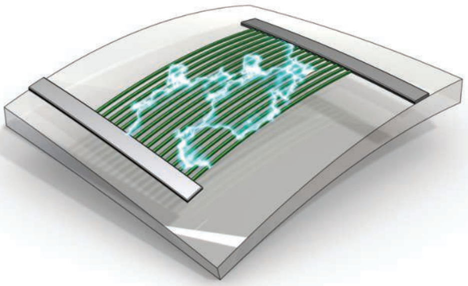
The Georgia Tech group isn't the only one closing in on that goal. At the University of California, Berkeley, another nanogenerator group, headed by mechanical engineer Liwei Lin, is making nanogenerators out of long polymer fibers that one day may be woven into cloth. "This technology could eventually lead to wearable 'smart clothes' that can power hand-held electronics through ordinary body movements," Lin says.

For their nanogenerators, Lin and his colleagues start with a polymer called polyvinylidene fluoride (PVDF) that can be processed to separate electrical charges. Other groups have previously made PVDF generators from thin films of the polymer. But PVDF films are typically inefficient, converting only 1% to 2% of kinetic energy to electricity. Lin and his colleagues also reported in the 10 February issue of *Nano Letters* that when they used a technique called electrospinning to spin PVDF into threadlike fibers as little as 500 nanometers across, the resulting fibers converted 10 times as much kinetic energy to electricity as the thin-film PVDF devices did.

Although Lin and his colleagues are still trying to understand exactly why that is, Lin says part of the explanation probably has to do with the electrospinning technique. The method draws out the polymer fibers in the presence of a large electric field, which seems to orient individual polymer molecules better than the filmmaking techniques do (see figure, left). And once the fibers are formed and solidify, this arrangement is locked in place. The output is high enough, Lin says, that calculations suggest that 1000 or so fiber generators incorporated into the cloth of a shirt would capture enough energy from a person's movements to charge a cell phone or an iPod. Although Lin says he hasn't yet formed a company to commercialize his power-suit material, he's already taking visits from venture capitalists looking to do just that.



Flex capacitor. A nanostamping technique turns normally brittle PZT into flexible nanowires encapsulated in a rubber sheet.



If nanogenerators of any sort succeed, could they possibly be scaled up to generate large amounts of power? After all, most of the handwringing about energy these days is about how to generate terawatts, rather than microwatts, of carbon-free power. Lin, Wang, and McAlpine agree that for now that doesn't seem likely. Nanogenerators simply produce too little power to change our civilization. For now, they'll be working on the small scale, which might still be enough to change our lives.

–ROBERT F. SERVICE

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