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AUTHOR COMMENTARIES - 2008

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Georgia Tech's Zhong Lin Wang New Power Generation

The *Science Watch*® Newsletter Interview

Imagine it's the early years of the automotive industry, and technologically savvy engineers and entrepreneurs all over the world are setting out to create passenger cars, buses, trucks, motorcycles and every other conceivable motorized vehicle without first creating the power generators necessary to drive them. That's the situation the nanotechnology industry has been in since its inception, making remarkable advances in the design and fabrication of a host of nanoscale sensors, devices, and what are known as microelectromechanical systems, without bothering first to develop the miniaturized power sources—the nanogenerators—required to power them.

Two years ago that critical gap in the technology of nanotechnology may have been solved when Georgia Tech's Zhong Lin Wang published an article in *Science* describing the creation of piezoelectric nanogenerators that offered the potential of converting mechanical, vibrational, or hydraulic energy from the environment into electricity for powering nanodevices. Wang's paper (Z. L. Wang, J.H. Song, *Science*, 312[5771]: 242-6, 2006), became a fixture in the Chemistry Top Ten, racking up well over 200 citations in just two and a half years and continuing Wang's remarkable run of influential research in the field of nanotechnology.

Wang can also take credit for pioneering work in direct *in situ* measurements of nanostructures and the use of semiconducting oxides in fabricating nanotubes, nanobelts, and other nanoscale structures. By 2002 Wang was already ranked in the top 25 most-cited authors of the decade in nanotechnology, with his 2001 *Science* paper on nanobelts of semiconducting oxides garnering over 2,100 citations (see adjoining table, paper #1). More than 50 of Wang's publications have been cited over 100 times each, and his overall citation count exceeds 23,000, with an h-index of 72. Meanwhile, the latest bimonthly file of the Hot Papers Database reveals that three of Wang's newer papers are already attracting heightened attention, including a paper debuting at #3 in the latest Chemistry Top Ten column, wherein Wang shares a few thoughts with chem correspondent John Emsley.

> *"The device alone is not enough,"* says Zhong Lin Wang of Georgia Tech. *"What we need is self-powered nanotechnology."*

Wang, 47, obtained his bachelor's of science degree in 1982 at the Northwest Telecommunication Engineering Institute (now Xidian University) in Xi'an, China in 1982. He then came to the U.S. and received his doctorate in physics from Arizona State University in 1987. For the next eight years, Wang lived a peripatetic research existence, working at SUNY Stony Brook, at the famous Cavendish Lab at the University of Cambridge, at Oak Ridge National Laboratory, and the National Institute of Standards and Technology. In 1995, Wang joined Georgia Tech, where he's now a distinguished professor in the College of Engineering.

Wang spoke to* Science Watch® *from his office in Atlanta.

SW: It wasn't until the late 1990s that you started working on nanotechnology. What were you working on until then, and what prompted the switch?

After I graduated from Arizona State in 1987, I worked for a long time on the fundamental physics of electron-solid interactions, mostly on elastic and inelastic scattering theory. I was also involved in surface-image analysis of reflected electrons, a topic on which I wrote a book in 1996. I also worked for a long time on high-temperature superconductors. I decided to switch to nanotechnology because I realized the limitation of the theory I was working on—that what we'd developed was not going to be particularly high-impact, and I needed to find a new area that could fully utilize all my strengths and where I might have a significant impact. That got me full-time into nanotechnology. Because I had worked as a student with transmission electron microscopy, always looking at atoms and surfaces at very small scales, turning to nanotechnology was a natural choice.

SW: How did you first approach the field? What did you work on first?

When I first started in 1995, people were just beginning to work on the self-assembly of nanoparticles—metallic particles of gold, silver, etc., so I worked on that. I worked on shape control of self-assembled nanoparticles and on carbon nanotubes, and I developed a method called *in situ* nano-measurement, which means that I put these nanotubes on a specimen holder inside a transmission electron microscope and could then directly image the nanotube itself while measuring its various physical properties. A lot of researchers doing measurements at the time couldn't actually see what they were measuring, and so could only explain it in terms of the assumptions of their models. With my technique I could directly determine the structure and directly measure the physical properties. There was a one-to-one correspondence between structure and property. This work was published in *Science* and has since evolved into an entire field of research—*in situ* nano-mechanics. My major effort on that was between 1997 and 2000, although we're still doing it in my lab, but it's now only a small part of our efforts.

SW: What happened in 2000 to change the direction of your research so radically?

I'd been working on carbon nanotubes for three or four years when I started wondering how much they'd ever be used for electronics, considering the difficulty people have controlling the chirality of nanotubes. Nanotubes can be metallic or they can be semiconductors, and this can depend on the chirality, and usually it would be random as to which way they go. Even today people have difficulty with that. So I thought, why not start using oxides? Ultimately, most of my work focused on zinc oxide.

SW: What is it about oxides and particularly zinc oxide that makes it such an ideal compound for these nanoscale structures and devices?

Oxides have very interesting properties. First, they have well-controlled structures. An oxide is a semiconductor, it's piezoelectric—meaning that it has the capacity to convert a mechanical signal to an electric signal and vice versa—and it has a well-controlled morphology, orientation, and structure. So that makes a lot of applications really easy to do. Zinc oxide, which we've focused on now for eight years, has some particularly useful properties: it's an optically transparent, wide band gap semiconductor. A second advantage is that it's semiconducting and piezoelectric, so you can use it to transmit energy. And the third advantage is that you can make nanostructures from it at temperatures as low as 50° to 80° Celsius. You can grow this material in chemical beakers on any shape of

Highly Cited Papers by Zhong Lin Wang and Colleagues, Published Since 1996
(Ranked by total citations)

Rank	Papers	Cites
1	Z.W. Pan, Z.R. Dai, Z.L. Wang, "Nanobelts of semiconducting oxides," *Science*, 291 (5510): 1947-9, 2001.	2,188
2	S. Frank, *et al.*, "Carbon nanotube quantum resistors," *Science*, 280(5370): 1744-6, 1998.	925
3	T.S. Ahmadi, *et al.*, "Shape-controlled synthesis of colloidal platinum nanoparticles," *Science*, 272(5270): 1924-6, 1996.	805
4	P. Poncharal, *et al.*, "Electrostatic deflections and electromechanical resonances of carbon nanotubes," *Science*, 283(5407): 1513-6, 1999.	620
5	R.L. Whetten, *et al.*, "Nanocrystal gold molecules," *Adv. Materials*, 8(5): 428-33, 1996.	541

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substrate. And it's biologically
compatible—it’s bio-safe. There are
no environmental side effects. It’s a green material. You put all this together, and it's got all the properties you need to do a lot of very, very creative work.

SW: If they're so useful, why wasn’t anyone else working on oxides?

Everyone was working on carbon nanotubes. You have to have the courage to shift your focus to something completely new. We left carbon nanotubes completely when we started working on this. In retrospect, we obviously made the right decision, but there was no way to know it for sure at the time.

SW: How did you come on the idea for nanogenerators and self-powered nanodevices?

We were working on oxide nanobelts, on nanowire growth, trying to understand the fundamental science. Then, in 2004, I was thinking about what’s missing in all this. We grow all kinds of nanostructures—everybody's making nanomaterials, nanodevices, these extremely small devices, but how do we power them? Where’s the extremely small power source for these devices? Maybe we should figure out how to build self-powered nanodevices. So how can we harvest energy from the environment to power these devices? Maybe we should not only make the device but provide the energy. Over the long term, the device alone is not enough. What we need is self-powered nanotechnology. That was my vision.

SW: Okay, that’s the vision. How do you go about making it a reality?

You start by looking at what can be converted into energy. What’s the advantage of nanotechnology? Small size, small power consumption. What sources of energy are available to us? There's solar energy, but to convert solar energy you need a solar panel, and a lot of applications are inside biological systems, or indoors, or other places where solar isn’t an option. So how about mechanical energy? A lot of things generate mechanical energy. When we talk about sonic waves, those are mechanical energy. Walking. My foot step is mechanical energy. A heart beat is mechanical energy. Muscle stretch is mechanical energy. Air flow is mechanical energy. Traffic noise. Your air conditioner blowing. Curtain movements. All are mechanical energy. Can we convert this energy to electricity? That was my idea. So the first question was: is this possible? In 2005, I asked my students, if we use an atomic force microscope, AFM, to bend a single nanowire, can we convert the bending into electric power? We know zinc oxide has this piezoelectric effect. So can we demonstrate this using an AFM and a single zinc-oxide nanowire?

SW: It worked, obviously.

That’s right. We published this in *Science* in 2006 (312[5771]: 242-6, 2006). We used an AFM to push a nanowire and got a voltage output of 3 to 12 millivolts from a single wire. That’s not a lot, but then how big is this wire? Thirty nanometers in diameter, 2 microns in length. This is only the first step. The next step toward making this useful was to make millions, billions of nanowires convert energy. And then we wanted to get rid of the AFM in order to apply this technology *in vivo*. We wanted to use ultrasonic waves or any indirect way to provide the mechanical energy. A year of effort solved those problems, and we published our next big paper in 2007 in *Science*. [Note: as mentioned above, currently #3 in the Chemistry Top Ten.] We used a zigzag electrode to replace the AFM tip; we now have multiple v-shaped electrodes, making a zigzag shape. And that makes hundreds and thousands of nanowires generate electricity, so we’ve immediately established that this technology can be scaled up.

SW: Can you describe for us the state of the technology, circa 2008?

We followed that work with an ultrasound wave-driven nanogenerator. We used fabric, and we grow these nanowires on fibers, textile fibers, and when one fiber brushes against another, we convert body-movement energy to electricity. That's targeted at a lower frequency, a couple of hertz. We got tremendous publicity for this work, which we published in *Nature* (Y. Qin, *et al.*, *Nature*, 451(7180): 809-13, 2008).

SW: What has to be done to translate this to applications and a working technology?

What we have to do now is raise the voltage that we can generate with this nanogenerator. If we can reach fractional volts, like half a volt, it can become really useful. We also want to integrate them into three-dimensional nanogenerators: one layer is not enough. So how about 10 or 20? That way we can raise the voltage and current. We can also integrate this into biological systems—try to use muscles to generate electricity, to use blood flow, sonic waves, noises, wind.

SW: How close are you now to the half a volt necessary?

We started at 10 millivolts, .001 volts. We've increased it by a factor of 100, so we're now at about .1 volts. Our goal is .3 or .4 volts. If we can get there we can use it for biologic sensors, such as cancer-detection sensors, blood-sugar measurement sensors, and other kinds of chemical sensors.

SW: You've mentioned the piezoelectric properties of oxides several times, and what you call "piezotronics" is a major focus of your research. What is piezotronics and what role does it play or will it play in nanotechnology?

This is another field I've now created. In my work on bending nanowires with an AFM, one side of the wire is stretched—tensile—and this tensile surface has a positive piezoelectric potential. The other side is compressed and has a negative piezoelectric potential, so across the wire there's a potential drop. This can serve as a gate voltage to gate current through a transistor. So now I can build piezoelectric field-effect transistors, a piezoelectric diode. Instead of using a classic semiconductor p-n junction to make a diode, we can now use a piezoelectric junction. These devices use force or pressure to trigger a transistor or a diode. Now you have a transistor or a diode that is very sensitive to mechanical force deformation, to strain. It's a new electronic component. What do you use it for? You use the coupled piezoelectric and semiconductor properties. Traditionally these are two different fields. Semiconductors and piezeoelectric devices are two different things. I've now combined them into one device, using zinc-oxide nanowires to achieve this objective. We can now make these devices to measure strains—strains in muscles, in buildings, in structures. I call it piezotronics.

SW: In five years' time, what real applications would you expect to see emerging from your research?

In five years I want to be able to provide a nanogenerator that can harness energy and power tiny devices—little units that can operate themselves, harvest energy from the environment, drive themselves, and operate wirelessly, remotely, sustainably. Devices you can use for whatever applications you desire. That should be possible. I also hope, in five years, to furnish little biological sensors that will harvest energy from muscle movement and power themselves. In five years, I should be able to provide tiny transducers, sensors, based on piezotronics that can measure pressure and force. Actually, I can probably do that in two years. In the long run, I want to make piezotronics truly into a field of its own. I want to make nanogenerators fully useful for a lot of people and a lot of applications.

Related Information: read a Fast Breaking Paper, and two Fast Moving Front commentaries from Zhong Lin Wang 1 ¦ 2.

Keywords: Zhong Lin Wang, Georgia Institute of Technology, Georgia Tech, nanotechnology, nanowires, piezotronics, nanogenerator, biosensors.