A Conversation with
Prof. Zhong Lin Wang, Energy Harvester

I met with Prof. Zhong Lin Wang of Georgia Tech at the Beijing Friendship Hotel, during the Nano Energy and Nano Systems meeting that he organized and hosted in Beijing, China in December 2014.

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Prof. Zhong Lin Wang of Georgia Tech discusses harvesting and recycling energy using nanostructures.

PSW: You started your research career in electron microscopy and materials structure. How did you end up in energy harvesting, capture, and recycling?

ZLW: My original training was in transmission electron microscopy (TEM). My advisor told me, "Why don't you start with a small particle?" At that time, it was not called a "nanoparticle," it was just a "small particle." I was using TEM to look at the tiny little particles, looking at the surface oxidation of cobalt particles.

PSW: With whom did you work and where?

ZLW: My Ph.D. advisor was Prof. John Cowley. He was the pioneer of modern high-resolution microscopy. He established the theory for high-resolution microscopy back in the 1950s.[1−4] He was the first person to see atomic-resolution images with transmission electron microscopy, in 1969.[5] Prof. Sumio Iijima[6−10] was my advisor's post doc, years ago. He was a man who specialized in microscopy; he passed away in 2004, at age 81.

PSW: How did you find your way into his laboratory?

ZLW: When I was a high school student, I never dreamed of going to college. The reason was that, college education was banned in China at that time; for poor kids like me, there was no chance. The last year of high school, they said there is a possibility for a college education and I said, "Maybe I should try." I tried and I made it.

PSW: Where did you grow up?

ZLW: My hometown, Gaoyang, is a two-hour drive from Xian. It's a very little town, probably 3,000 people, farmland. Both my parents farmed for their whole life. They did not even have a basic education, but they did one thing right. They wanted their kid to have the right education. This I appreciate from the bottom of my heart—they worked hard and supported me.

PSW: Are they still with you? Have they seen your success?

ZLW: My father passed away 25 years ago; he did not see any of my success. My mother passed away two years ago; she saw some of my success.

PSW: You went to university in Xi'an?

ZLW: I went to Xidian University in Xi'an; now, it is got a new name [University of Electronic Science and Technology at Xi'an].

I was 17 and I never studied English. How could I dream of studying in America? Forget about it, impossible. But, life changed. I put effort into studying English. I said, "I want to do research, I want to know English." By the year I graduated, there was a program called the US-China student exchange in physics. It was for the top 100 students in physics to study in America. The first batch was in 1980, I think. I was in the

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1983 group. I was lucky to pass the exam and went to Arizona State University.

How did I end up at Arizona State? At that time, I had no knowledge about American schools, which one is superior. I said, "Okay, I'll choose one from A and I'll choose one from B and I'll choose one from C." A total of five, no more. I chose A, Arizona State University; I thought, "They have 40 faculty in physics, they must be good." And I chose Brown University. And ASU accepted me, so I arrived on campus to study. This is great, just great. I was devoted 100% to studying at that time. That is how I ended up in the U.S.

PSW: What about your independent career?

ZLW: After I graduated, I continued to do microscopy for years, fundamental microscopy. When I got to Georgia Tech, the microscopy facility was not the best. In order to do microscopy, you have to have the best equipment, multimillion dollar equipment. So I said, okay, maybe I need to do some measurements inside the TEM. This was 1996, 1997, and I used TEM to study the mechanical properties of individual carbon nanotubes.[11−14] We had the first *in situ* measurements. Then, we measured the quantum transport of carbon nanotubes. Now, this has evolved into a small field.[15]

Then, I went to the (Georgia Tech) lawyer, and I said, "I have a TEM specimen holder; I want to apply for a US patent." He asked me, "When will you get this commercialized?" I said, "Probably three to five years." And he said, "That's too long, anything that's not commercial within two years, we're not interested. Go away."

I didn't have a single patent when I started to make nanomaterials. Looking back today, in 1999, I picked the right material, zinc oxide.[16] Over the years, I worked on nanomaterials, I applied for various patents, and today, I have 50 U.S. patents. In 2003, we made all these devices, measured these gas sensors, but how do we power this little thing? Can we make a power source to drive it instead of a battery? So, this was the original idea.

Let's see if the zinc oxide piezoelectric effect has anything to do with that. We used AFM [atomic force microscopy] to test the individual wires.[17] This was the starting point of all the research that followed, moving from single-wire devices to multi-wire devices, from smaller scales to large-scale power. Along the way, we invented piezotronics and piezophototronics, which was first published in *ACS Nano* (see Figure 1),[18−29] and that has led me to where I am today.

Also, an accident, which turned out to be a good accident, was that when we made the piezoelectric nanogenerator, we fabricated a device, but we did not package it very well and there was a little gap. When we measured it, we had a high voltage output and so we asked, why is this? With piezoelectrics, if you have a gap, you have no output, but we had 5 V. At that time, the best we got from piezoelectrics was a couple of volts. Why [was it] so large? We found that it was due to the triboelectric effect. That led us to what we invent today.[30]

> Looking back today, I picked the right material, zinc oxide.

PSW: Can you define each of those fields for us? Piezotronics, piezophototronics, and triboelectric nanogenerators?

ZLW: The first one that we worked on was *nanoenergy*: the energy required to drive sustainably, stably, and long lasting for mobile electronics, sensor networks, those small electronics. More broadly, it is the use of nanomaterials for energy sciences.

A *nanogenerator* is a device that utilizes piezoelectrics, triboelectrics, or paraelectrics, or all three of them, to convert mechanical action, thermal action, or other action into electricity for powering small electronic devices, mostly by converting mechanical energy.

Piezoelectronics utilize strain created in a piezoelectric semiconductor material as a gate voltage to tune, to control the charge transport, separation, or recombination processes.

Piezophototronics introduced optical excitation. We have semiconducting

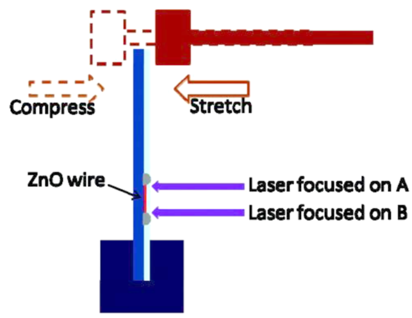

Figure 1. Studying the piezoelectric effect. Reprinted from ref 18. Copyright 2010 American Chemical Society.

piezoelectric coupling, but what happens if you introduce light? Piezophototronics has three-way coupling; we use the piezopotential to tune optoelectronic properties for achieving optimized LEDs [light-emitting diodes], solar cells, or photodetector efficiencies.

A *triboelectric nanogenerator* (TENG, see Figure 2) utilizes the electrostatic charge created due to the triboelectrification process as a driving force for electron flow to an external load. Using this process today, we can achieve 55% energy conversion efficiency, the best so far; we already submitted a paper to *ACS Nano*.[31] We have achieved a power density of 200 W/m^2. That number is phenomenal and is close to some commercial applications.

PSW: For each of these areas you have put together a roadmap. Did you do that with other people or did you do that independently to try to move the field forward?

ZLW: I did that mostly by getting my postdocs and students together to lay out the blueprint for the next 20 years. Then, I brought this blueprint to a conference I organized in June and I said, "Okay, what do you think about this?" I got some comments. I revised it, and finally I published that roadmap.[32]

> Along the way, we invented piezotronics and piezophototronics.

PSW: Even in your *ACS Nano* papers, we see many, many advances coming

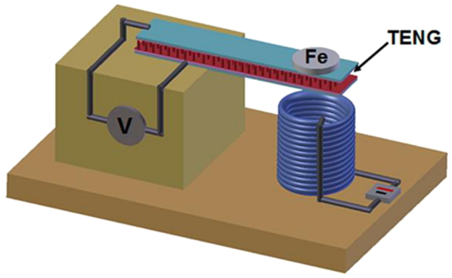

Figure 2. A triboelectric nanogenerator (TENG) uses electrostatic charge from motion and friction while in contact. Reprinted from ref 30. Copyright 2012 American Chemical Society.

along—wind power, wave power, walking, driving, typing on keyboards, and so forth.[33−39] Do you have priorities for which ones we will see around us first and a path to get there?

ZLW: We separated these into three stages: near, middle, and long term. What's near term? Near term is utilizing a self-powered sensor. For example, we build this as a security system. We build it under the carpet and if somebody walks over it, we would detect it. No external power for the sensor. It generates the signal itself on the door triggers, on security locks; this can come first because it doesn't need that much power.

PSW: It's like the squeaky nightingale floors at Nij-j in Kyoto, only electric?

ZLW: Yes, electric. I think it's three years away or so. Then, the middle term–powering cell phones, sensors, large-grid sensors–is five years out.

Long term is major power. We make individual units, which give 1 mW. You say, it's not much, right? But, we will make a 3D grid on 1 km^2 of water surface area, to give 1 MW. This involves a lot of issues–material optimization, dielectrics, surface wearability, durability, and also triboelectric charge generation. Nano plays all roles in this one. The materials are so diverse. I wrote a review for *ACS Nano* last year on this idea.[40]

PSW: Would commercialization be through licensing and collaboration, or are you trying to start a company or companies?

ZLW: How are we going to do it? I think there are a number of ways. Number one is somebody licenses the technology and does it themselves. That would be easier than for me to do it.

> We use that power to drive a pacemaker now. If you can drive a pacemaker, you can drive a lot of *in vivo* biomedical devices.

Number two is that we have a start-up. I have some students who started a company; we have a couple companies registered. If somebody wants to license a particular part of it, we'll license it to them, but some parts, we want to try ourselves.

There is a lot of company interest — Samsung, Phillips, and LG—they already have a research group. Worldwide, we have 40 groups working on triboelectric nanogenerators now. We have at least five or six in the U.S., 15 in China, 20 in Korea, and five or six in Europe.

I want to see impact on society and impact on the quality of life, that we and our future generations will leave.

PSW: How robust in the environment do you imagine the ultimately produced devices will be? Is there much more work to do? In terms of packaging, is that something that still requires a great deal of attention, or are the basic materials going to be a good starting point for functional working devices?

ZLW: The basic materials are a good starting point. They already have substantial durability. Let me give you one example. We do this kind of testing, rotation [rubbing hands]. We do this 10 million times, there's no degradation in performance. So conventional materials work and work well. But for technology applications you can improve it dramatically. There's work to do. What I anticipate is that there are some hurdles we will need to overcome because packaging people never thought about this. It's the field they need to think about right now. I think those problems will be solved, but we can handle some applications already.

PSW: What about *in vivo* applications? You have started to explore those in your laboratory. Do you see those as viable?

ZLW: We started *in vivo* in 2009; we published the first papers in 2010.[41,42] We used a single wire on a heart-driven device. Today, we use the triboelectric generation and we stick [the device] to the wall of the lung. When the lung contracts, the breathing, the air compression, drives it. We use that [power] to drive a pacemaker now. This field draws a lot of attention because if you can drive a pacemaker, you can drive a lot of *in vivo* biomedical devices. I think there is a lot of research because we can have self-powered *in vivo* medical systems.

PSW: Along those lines, is there built-in energy storage in these devices? They generate power, but then say you needed to use the pacemaker. Presumably, one's heart would not be beating and that would be the reason it needed to act. How much power can be stored, or is that a separate part of the device?

ZLW: That's why I call it a "system"—we have an energy-generating device and we have a storage unit. This battery will never drain out. It will keep charging and then keep driving the pacemaker. If you solely used a battery, it probably could only last 3 to 5 years, but this system can buy you 10, 15 years, maybe even longer. It is making a lifetime much longer and sustainable.

PSW: You have something like an alternator in a car that charges the battery whenever your body is operating.

ZLW: Yes.

PSW: What gives you the most pleasure in this work?

ZLW: The most pleasure I get from this work is that I feel excited that what we do today can impact the future of human civilization, in a broad sense. Let's say 20, 30, 50 years from now, when somebody uses this technology, I'll feel very happy about that. So that's why, just like you, we work day and night persistently. Hopefully, one day we can contribute to the large scope of energy requirements and also solve part of the problem of sensor networks and the internet of things. Then, as nanoscience and nanotechnology outcomes, I'll feel happy.

> The technology we develop will have broad impact for environmental science, energy science, sensor technology, and many others.

PSW: You have an enormous and growing effort in China where you have set up a new institute here.[43] Where do you see that going? How do you manage your laboratories at Georgia Tech and the institute here? There are a few people that have this split life now and many people are curious about how it is possible and how one does it, logistically.

ZLW: I have two bases: one is at Georgia Tech and the other is in Beijing. Georgia Tech is still my main base; my family is there. How I manage it is that I make trips back to Beijing to take care of business, to supervise the students with face-to-face meetings, and also use Skype meetings, telephone, and email. Those let me interact effectively with students. I have 25 people at Georgia Tech; I have 20 directly supervised people in Beijing. So, I have 45 directly interfacing with me and I also have some administrative responsibilities.

I just try to do things efficiently. Just like you, there's no trick. Once it's in my hands, I process it right away, no waiting. Then, I utilize modern communications to speed up the interaction. I've found that it works well and both sides effectively move forward. I think it adds a lot of me for the travel. Even with jet lag, I think it's working well on both sides and I think this will go on for some time, but we'll see.

PSW: How do you see the Beijing institute filling out? What will it look like in a few years when it is set up? Right now, you are renting space—can you describe it?

ZLW: The technology we develop, the science we develop will have broad impact for environmental science, energy science, sensor technology, and many others. I need a large team to do that, but the resources I have, the reduced funding in the U.S., does not allow me to do it. In the U.S., I felt that I was a single horse rider. I love this country. I worry about the U.S. and our educational system. Now, in Beijing, I have the resources. I want to use those resources to achieve my dream to advance the technology, to advance the science. Those are the goals I want to see [met].

What's the future? We started this institute from scratch—absolute zero. We had the first meeting with three people in a coffee room about three years ago. Now, we have a total of 250 people—about 150 students, 70 researchers, and 25 administrative staff. We're still in a rental place, but hopefully in three years, we'll move to a new home that's going to be beautiful. That's the best estimate I have right now.

PSW: It's quite a large facility; you showed a schematic of it at the meeting.

ZLW: The estimated size will be 70,000 m^2. This includes research labs, central facilities, administration, and also a student dormitory, entertainment, sports, all in one place. The anticipated investment by the city of Beijing is about U.S. $100 million.

PSW: And the Chinese Academy of Sciences?

ZLW: The Chinese Academy contributes the research and operations budget. The city of Beijing is paying for the construction of the building.

PSW: When it's complete, how many people will be there? How will it operate?

ZLW: We anticipate having about 700 researchers, staff, and visiting researchers. We anticipate having 500 of our people that will be called researchers, including postdocs, assistant, associate, and full professors, and then an additional 400 students. So, 1100 local people and 200–300 visitors. We will have international exchange programs for students, postdocs, and researchers.

PSW: Was this meeting that you are holding now part of the vision for the institute, for the field?

ZLW: This meeting has several objectives. Number one is that we have this institute, but we lack visibility because it's just too new; people don't know. This meeting will help us to promote the institute. Number two, it will also help us to promote the field we're interested in—nanoenergy and nanosystems are very broad. We have brought distinguished speakers from around the world to this conference and that is very important for us. At the same time, I think we can use other means to promote our institute and field. This is the first meeting. The second one will be in two years, then another one; it will continue for years. As long as I can do it, it will continue.

PSW: The rooms were packed at this meeting. At every session I attended, it was hard to find a seat.

ZLW: I took a lot away from the U.S. on how to organize conferences. This time, we anticipated 300 people at the beginning and 600 turned out. I think next time will be 1000, easily. I borrowed from the MRS [Materials Research Society] how to increase participation for posters. I said bring food, bring drinks. People were talking and discussing until the very end. That's what happened yesterday. In China, most people leave before the posters. They don't ever look, but yesterday, it was full, packed.

PSW: Do you have any advice for young scientists, someone who wants to do what you've done?

ZLW: Over the years, my experience has been, do what you love to do. Pick out the interest that you think you can work on day and night and

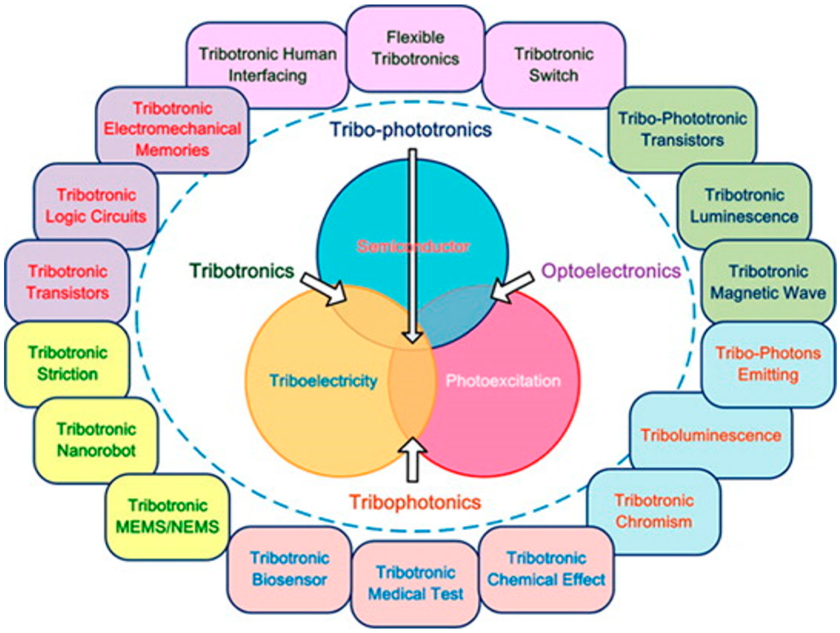

Figure 3. Schematic of the three-way coupling among triboelectricity, semiconductor properties, and photoexcitation, including "tribotronics (triboelectricity–semiconductor coupling), tribophotonics (triboelectricity–photon excitation coupling), optoelectronics, and tribo-phototronics (triboelectricity–semiconductor–photoexcitation)."[45] Reprinted from ref 45. Copyright 2014 American Chemical Society.

never get tired. This is the only driving force for you to advance. It's not for the money; it's not a job requirement; it is interest—I like it and I have a curiosity for it, number one.

Number two, for young people, do things persistently. Success doesn't come in one day or even one year; you have to be consistent in advances. In due course, people may question you, argue with you about what you do, and sometimes not believe what you say, but if you believe in yourself, you will keep doing the right thing. Let the data speak; eventually, they'll accept you. Persistence is very important. Be confident. If you believe you're right, just work toward your goal, regardless of whatever other people say about you.

Number three, make sure to work hard. We have a lot of young people, smart and talented. There are a lot of talented people in the world. Make sure you work for it. If you don't work for it, your talent won't go very far.

For example, when I had the idea for piezoelectronics, [people asked] what is this? Could it be wrong? They didn't understand it, and, *I* only had a vague idea. My definition was not as accurate five years ago, when I started, as it is today. I felt that this is something emergent and I should define it; I should give it a name.

Even at that time, you feel confident in what you do, but you don't have enough data. I only published two or three papers—okay, this is a new phase I should start. Over the years, you keep working, publish 40 or 50 papers, and then you form something substantial. Maybe people, at the beginning, don't believe you. That's okay, just keep working on your dream. And you'll be there, some day.

PSW: Are your definitions still evolving or have you now set where you think these fields and devices are going? Not that you have explored them completely, but are you still evolving your definitions now?

ZLW: I think the definitions for nanogenerator, nanoenergy, piezotronics, piezophototronics are all done. I even wrote a book three years ago.[44] Those are well defined from fundamental science, physical pictures, even in potential applications. We have many demonstrations. But, tribotronics (see Figure 3), which I just described in *ACS Nano*,[45] is still at a very early phase, the idea is evolving. We can give a definition for tribotronics, but there are more specifics to be defined in the next few years. That's how exploration is being advanced.

PSW: We look forward to capturing those advances and that evolution.

ZLW: You know, Paul, *ACS Nano* has been one of the major journals to publicize those ideas. You trust me; you trust my understanding. We try to make the best contributions to science, to educate younger generations of scientists. They are the ones who will work together with me in the future, and last a lot longer than me, to advance the field.

—Paul S. Weiss

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