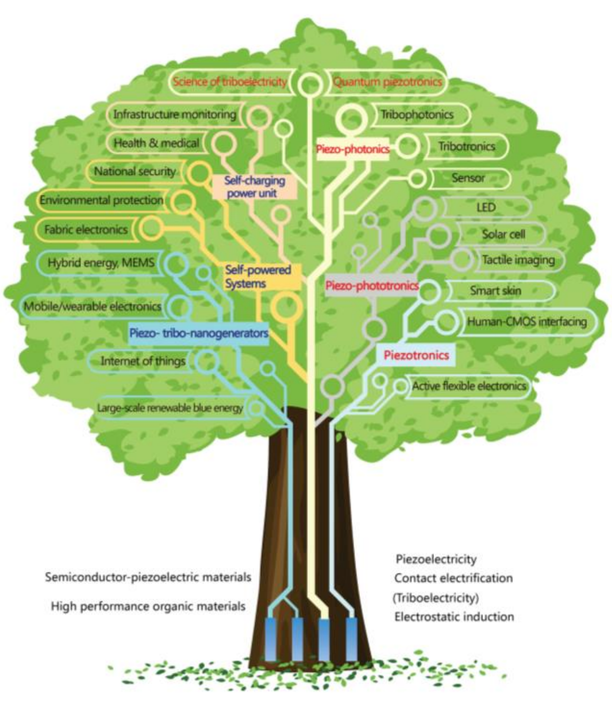
Summary of Zhong Lin (Z.L.) Wang' Achievements (1995-2015)

Dr. Zhong Lin (ZL) Wang received his PhD from Arizona State University in 1987. He is the Hightower Chair in Materials Science and Engineering and Regents' Professor at Georgia Tech.

Dr. Wang has made original and seminal contributions to the synthesis, discovery, characterization and understanding of fundamental physical properties of oxide nanobelts and nanowires, and their applications in energy sciences, sensors, electronics and optoelectronics. He is the world leader in ZnO nanostructure research. His discovery and breakthroughs in developing nanogenerators establish the principle and technological road map for harvesting mechanical energy from environment and biological systems for powering mobile sensors. His research on self-powered nanosystems has inspired the worldwide effort in academia and industry for harvesting ambient energy for micro-nano-systems, which is now a distinct disciplinary in energy science for future sensor networks and internet of things. He coined and pioneered the fields of piezotronics and piezo-phototronics by introducing piezoelectric potential gated charge transport process in fabricating strain-gated transistors for new electronics, optoelectronics, sensors and energy sciences. The piezotronic transistors have important applications in smart MEMS/NEMS, nanorobotics, human-electronics interface and sensors. Wang also invented and pioneered the *in-situ* technique for measuring the mechanical and electrical properties of a single nanotube/nanowire inside a transmission electron microscope (TEM).

Dr. Wang is a pioneer and world leader in nanoscience and nanotechnology for his outstanding creativity and productivity. He has authored and co-authored **6** scientific reference and textbooks and over **1000** peer reviewed journal articles (**16** in *Nature* and *Science*, ***8** in Nature sister journals*), **45** review papers and book chapters, edited and co-edited **14** volumes of books on nanotechnology, and held over **100** US and foreign patents. Dr. Wang is the world's top 5 most cited authors in nanotechnology. His entire publications have been cited for over **84,000** times [an updated report from SCI data base can be found at: http://www.researcherid.com/rid/E-2176-2011; from Google Scholars: http://scholar.google.com/citations?user=HeHFFW8AAAAJ&hl=en]. The H-index of his publications is **140** per SCI data base, which is the highest among his peers worldwide. He has delivered over **850** plenary, keynote, invited and seminar talks at international and national conferences as well as universities and research institutes worldwide.



A "tree" approach that summarizes Wang's major original and pioneer contributions in science and technology as well as broad impacts.

Dr. Wang is taking a leadership in commercialization of his inventions. He is the co-founder of three companies: Newnagy, Inc., a company specialized in commercialization of piezoelectric nanogenerators; Nanoenergy Sys LLC, a company devoted to the exploration of electrical measurement system for nanoenergy; and TiSES, a company dedicated to the commercialization of triboelectric nanogenerator technologies.

Dr. Wang has received numerous honors award. They include: 2014 World Technology Award (Materials); 2014 Distinguished Professor Award (Highest faculty honor at Georgia Tech); 2014 NANOSMAT prize (United Kingdom);

China International Science and Technology Collaboration Award, China,中华人民共和国国际科学技术合作奖 (2014); The James C. McGroddy Prize in New Materials from American Physical Society (2014); ACS Nano Lectureship (2013); Edward Orton Memorial Lecture Award, American Ceramic Society (2012); MRS Medal from Materials Research Soci. (2011); Dow Lecture, Northwestern University (2011); Hubei Province Bianzhong award (2009); Purdy award, American Ceramic Society (2009); John M. Cowley Distinguished Lecture, Arizona State University (2012); Distinguished oversea scholar lectureship (教育部海外名师讲坛计划), Tsinghua University (2008); Lee Hsun Lecture Award, Institute of Metal Research, China (2006); NanoTech Briefs, Top50 award (2005); Sigma Xi sustain research awards, Georgia Tech (2005); Georgia Tech faculty outstanding research author award (2004); S.T. Li Prize for Distinguished Achievement in Science and Technology (2001); Outstanding Research Author Award, Georgia Tech (2000); Burton Medal, Microscopy Soc. of America (1999); Outstanding Oversea Young Scientists award from NSF China (杰出青年) (1998); NSF CAREER (1998).

Dr. Wang was elected as a foreign member of the Chinese Academy of Sciences in 2009, member of European Academy of Sciences in 2002, fellow of American Physical Society in 2005, fellow of AAAS in 2006, fellow of Materials Research Society in 2008, fellow of Microscopy Society of America in 2010, fellow of the World Innovation Foundation in 2002, fellow of Royal Society of Chemistry, and fellow of World Technology Network 2014. He is an honorable professor of over 10 universities in China and Europe. Dr. Wang is the founding editor and chief editor of an international journal *Nano Energy*, which now has an impact factor of 10.2.

Dr. Wang's breakthrough researches in the last 15 years have been featured by over 50 media world wide including *CNN, BBC, FOX News, New York Times, Washington Post, Reuters, NPR radio, Time Magazine, National Geography Magazine, Discovery Magazine, New Scientists, and Scientific America*. Dr. Wang is the #25 in the list of the world's greatest scientists (http://superstarsofscience.com/scientists). Recent news reports are:

> Wang interviewed by *CNN* for his research in self-charging power pack being among the top 10 breakthroughs in 2012 by *Physics World*: http://www.cnn.com/video/#/video/tech/2012/12/29/intv-clancy-battery-breakthrough.cnn
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> Reuters: http://news.yahoo.com/video/researchers-tap-power-motion-energy-013803650.html
> Georgia Tech: http://www.news.gatech.edu/2013/12/07/harvesting-electricity-triboelectric-generators-capture-wasted-power

Dr. Wang has received funding from NSF, DOE, DARPA, NIH, NASA, Airforce, Samsung, NIMS (Japan) and industry. The total funding for supporting his research from 1995 to day is **$22M**.

Wang invented the piezoelectric nanogenerators and initiated the field of nanoenergy. Developing novel technologies for wireless nanodevices and nanosystems are of critical importance for in-situ, real-time and implantable biosensors, environmental science, personal electronics and national security. It is highly desired for wireless devices to be self-powered without using battery; otherwise 90% of internet of things would be impossible. A groundbreaking research by Wang in 2006 is the invention of the piezoelectric nanogenerators for self-powered nanodevices (*Science*, 312, (2006) 242; >2400 citation). He demonstrated an innovative approach for effectively converting mechanical energy into electric energy by piezoelectric zinc oxide nanowire arrays. This research opens up the area of nanoenergy, a field that uses nanomaterials and nanodevices for high efficient harvesting of energy from ambient environment, which is now a focal area of research for applications in sensor networks, mobile electronics and internet of things. This research was chosen as the world top 10 most outstanding discovery in science by the Chinese Academy of Sciences. Wang was featured by *Science Watch* in Dec. 2008 issue for his pioneer work in nanogenerator.

Wang pioneered the original idea of self-powered systems. Wang developed the first microfiber-nanowire hybrid nanogenerator (*Science* 316 (2007) 102, citation 850; *Nature* 451 (2008) 809-813, >510 citation; *Nature Nanotechnology* 4 (2009) 34), establishing the basis of using textile fibers for harvesting mechanical energy. The principle and technology demonstrated converts mechanical movement energy (such as body movement, muscle contractions, blood pressure), vibration energy (such as acoustic/ultrasonic wave), and hydraulic energy (such as flow of body fluid, blood flow, contraction of blood vessel) into electric energy that may be sufficient for self-powering nanodevices and nanosystems. Wang has made ground-breaking progress in scale up the output of the nanogenerators through three-dimensional integration, so that the output voltage reached 3-10 V and the continuous output power reaches 10-100 uW (accumulative output power is 50 mW) (*Nano Letters*, 10 (2010) 5025; *Nano Letters*, 10 (2010) 3151), clearly demonstrating its outstanding potential for powering sensors and personal electronics. The prototype technology established by the nanogenerator sets a platform for developing self-powering nanosystems with important applications in implantable in-vivo biosensors, wireless and remote sensors, nanorobotics, MEMS and sonic wave detection (*Scientific American*, January issue (2008) 82). The nanogenerator is selected by *New Scientist* as the top 10 most potential technologies in the coming 30 years, which will be as important as the invention of cell phone, is among the top 20 featured nanotechnologies by *Discovery Magazine* in 2010, and is the top 10 scientific discoveries by *Physics World* in 2012. The fiber based nanogenerator was selected as the top 10 most important emerging technologies in 2008 by the British *Physics World*, *MIT Technology Review*, and *Beijing Daily* newspaper.

Wang invented triboelectric nanogenerator for internet of things. Although triboelectrification is known for thousands of years, it is rarely used for power generation. In 2011, Wang has made a discovery of utilizing the conjunction of triboelectrification effect and electrostatic induction for electricity generation using organic thin film materials. The triboelectric nanogenerator (TENG) is a simple, low cost and effective approach for power generation using human motion, which is fabricated by stacking two polymer sheets made of materials having distinctly different triboelectric characteristics, with metal films deposited on the top and bottom of the assembled structure. Later, Wang has systematically invented the modes and theories for the TENG to meet a variety of needs. TENG has been demonstrated to exhibit an unprecedented conversion efficiency of 50-85%, an area power density of 313 W/m^2 and a volume power density of 340 kW/m^3 (*Nature Communication*, 5 (2014) 3456; *Nano Letters*, 12 (2012) 3109; *Nano Letters*, 12 (2012) 4960; *Nano Letters*, 12 (2012) 6339; *Nano Letters*, 13 (2013) 847; *Adv. Mater*. 26 (2014) 3788). TENGs have the revolutionary applications for harvesting energy from human activities, rotating tires, mechanical vibration and more, with great applications in self-powered systems for personal electronics, environmental monitoring, medical science and even large-scale power.

Wang developed triboelectric nanogenerator as a new energy technology for potentially large-scale blue energy. Wang invented the four working modes of the TENG, using which it becomes technologically feasible to harvest energy from the tide and waves in ocean, which is unrealistic using the traditional generators. By constructing a unit of TENG in the size of a baseball that gives an output power of 1 mW as driven by water kinetic energy, connecting and integrating many such units into a "fishing net" structure would give a large power output (*Faraday Discussions*, DOI: 10.1039/c4fd00159a); it is estimated to produce an output power of 1.1 MW from 1 km square surface area of ocean. This type of energy is stable and has less dependence on day or night, good weather vs poor weather in comparison to solar energy, so that it has the potential to be integrated with major power grid. This research opens a new chapter in exploring the blue energy to meet the needs of large-scale power.

Wang first discovered the piezotronic effect and coined the field of piezotronics. Owing to the polarization of ions in a crystal that has non-central symmetry, a piezoelectric potential *(piezopotential)* is created in the material by applying a stress. This internal field created inside of a ZnO nanowire can effectively tune the Schottky barrier height between the nanowire and its metal contact, which can effectively tune and gate the charge carrier transport process across the interface. This is the *piezotronic effect* first proposed by Wang in 2007 (*Advanced Materials*, 19 (2007) 889), based on which piezoelectric field effect transistor, piezoelectric diode and strain gated logic operations have been developed by Wang. The electronics fabricated by using the piezopotential as a gate voltage is coined *piezotronics* (*Science*, 340 (2013) 952). The design of piezotronics fundamentally changes the design of traditional CMOS transistor in three ways: the gate electrode is eliminated so that the piezotronic transistor only has two leads; the externally applied gate voltage is replaced by an internally created piezopotential so that the device is controlled by the strain applied to the semiconductor nanowire rather than gate voltage; the transport of the charges is controlled by the contact at the drain (source)-nanowire interface rather than the channel width. Wang is also the first who demonstrated the piezotronic effect in 2D materials (*Nature*, 514 (2014) 470). Piezotronics has applications in human-computer interfacing, smart MEMS, nanorobotics and sensors. Piezotronics was chosen as the top 10 emerging technology in 2009 by the *MIT Technology Review.*

Wang first discovered the piezo-photonic effect, which is about the piezoelectric field induced photon emission from a semiconductor material under mechanical straining (*Adv. Funct. Mater.* 2008, *18* , 3553; *Nano Today* 2010, *5* , 540). Wang demonstrated the first mechanoluminescent ZnS:Mn particles (ZMPs) based, self-powered pressure sensor matrix for securer signature collections by recording both the handwritten signatures and the force/pressure applied by the signees at each pixel during signing, leading to an invention of high security electronic signature system (Adv. Mater. DOI: 10.1002/adma.201405826). This large-area, flexible sensor matrix can in-situ map two-dimensional pressure distributions ranging from 0.6~50 MPa either statically or dynamically within 10 ms, with a spatial resolution of 100 m (254 dpi). Utilizing strain-induced piezoelectric polarization charges to tune the band structure and facilitate the detrapping of electrons within ZMPs. This device is applicable to real-time pressure mapping, smart sensor networks, high-level security systems, human-machine interfaces and artificial skins.

Wang first discovered the piezo-phototronic effect. Due to the polarization of ions in a crystal that has non-central symmetry, a piezoelectric potential *(piezopotential)* is created in the crystal under stress. The presence of polarization charges at an interface can largely tune the local band structure as well as shift the charge depletion zone at a pn junction, which can be effectively used to enhance the separation or recombination of charge carriers at the junction as excited by photon. This is the *piezo-phototronic effect* first introduced by Wang in 2009 for tuning and controlling optoelectronic processes by strain induced piezopotential. Using this effect, his team has demonstrated individual-nanowire light-emitting-diode (NW-LED) based pressure/force sensor arrays for mapping strain at an unprecedented resolution of 2.7 μm and density of 6350 dpi (*Nature Photonics*, 7 (2013) 752-758), high sensitive UV sensors (*Adv. Mater.*, 24 (2012) 1410), largely enhancing LED efficiency (*Nano Letters*, *11* (2011) 4012; *Nano Letters*, 13 (2013) 607), and high performance solar cells (*Nano Letters*, 12 (2012) 3302). Piezo-phototronic effect is a newly found physics effect, which has a broad range of applications in optimizing the performance of optoelectronic devices.

Wang discovered oxide nanobelts (*Science*, 209 (2001) 1947; > 4500 citation). The nanobelts are a new class of one-dimensional nanostructures denoting a wide range of semiconducting oxides with cations of different valence states and materials of distinct crystallographic structures. This landmark paper is among the list of the top 30 most influential papers published in *Science* in the last 10 years, the top 10 most cited paper in materials science in last decade. The rational approach outlined in this work has subsequently served to nucleate a large body of studies by other researchers worldwide. As a result, ZnO is the most exciting type of one-dimensional nanostructures for oxides that holds equal importance to Si nanowires and carbon nanotubes. Wang has been the world leader in studying of ZnO nanostructures.

Wang first proposed the growth processes of novel oxide nanostructures. Owing to the positive and negative ionic charges on the zinc- and oxygen-terminated ZnO basal planes, respectively, a spontaneous polarization normal to the nanobelt surface is induced. As a result, helical nanosprings/nanocoils are formed by rolling up single crystalline nanobelts and nanorings (*Science*, 303 (2004) 1348; > 1000 citation; *Science*, 309 (2005) 1700; >550 citation). These are the first papers that described the spontaneous polarization-induced novel nanostructures and they open a new direction of research for studying piezoelectric properties at nano-scale.

Wang pioneered the field of in-situ nanomeasurements in transmission electron microscopy on the mechanical, electrical and field emission properties of 1D nanomaterials. Characterizing the physical properties of carbon nanotubes is limited not only by the purity of the specimen but also by the size distribution of the nanotubes. Traditional measurements rely on scanning probe microscopy. Based on transmission electron microscopy, Wang and his colleagues have developed a series of unique techniques for measuring the mechanical, electrical and field emission properties of individual nanotubes in 1999. His in-situ TEM technique is not only an imaging tool that allows a direct observation of the crystal and surface structures of the material at atomic-resolution, but also an in-situ apparatus that can be effectively used to carry out nano-scale property measurements (*Science*, 283 (1999) 1513; >940 citation). A nanobalance technique and a novel approach toward nanomechanics have been demonstrated (*Phys. Rev. Letts*. 85 (2000) 622), which was selected by APS as the breakthrough in nanotechnology in 1999. This study creates a new field of in-situ nanomeasurements in materials science and mechanics.

Wang has made fundamental contribution to materials science and electron microscopy. His textbook entitled of *Functional and **Smart** Materials - structural evolution and structure analysis* (Plenum Press, 1998) is "a unique, cutting-edge text on smart materials ... it is recommended as an adjunct to device design books used for engineers as well as scientists during the development of smart devices and structures" (*Physics Today* , Nov. 1998, p. 70). His textbook on *Elastic and Inelastic Scattering in Electron Diffraction and Imaging* (Plenum Press, 1995) is "a noteworthy achievement and a valuable contribution to the literature" (*American Scientist*, 1996). His textbook on *Reflected Electron Microscopy And Spectroscopy For Surface Analysis* (Cambridge University Press, 1996) is “a book that any materials science or physics library should be holding" (*MRS Bulletin*, Oct., 1998).