50 YEARS MRS

Nanogenerators and piezotronics: From scientific discoveries to technology breakthroughs

Zhong Lin Wang

Nanogenerators is a field that uses the piezoelectric and/or triboelectric effect for converting low-grade mechanical energy (termed as high-entropy energy) into electric power, with a great potential for applications in the Internet of Things, self-powered sensors, robotics, medical science, and even artificial intelligence. Piezotronics is a field that utilizes the piezoelectric polarization in third-generation semiconductors for controlling the charge-carrier transport in semiconductor devices. These two fields were first coined by Wang's group in 2006 and 2007, respectively. This article reviews the background and initial ideas based on which we introduced the following original discoveries and effects: piezoelectric nanogenerators; triboelectric nanogenerators; self-powered sensor; hybrid cell; nano energy; high-entropy energy; piezotronics; and piezo-phototronics. As inspired by these original discoveries, the current technologies developed based on the scientific discoveries of nanogenerators and piezotronics are also reviewed.

Introduction

Energy is the driving force of our society, which dictates the sustainable development of humankind. Today's main power still relies on fossil energy. By burning high-density fossil energy, thermal energy is converted into mechanical energy by a steam engine, which then drives an electric generator for outputting electric power. The energy is eventually dissipated in our living environment in the form of heat, wind, and mechanical and such low-density and low-quality energy is hardly to be used again. Furthermore, by considering the limited resources for fossil energy on land and the severe consequence to climate change as a result of overusage of fossil energy, searching for new energy is desperately needed. This was the goal of inventing the nanogenerator in 2006,[1] aiming at converting distributed, low-grade energy in our living environment into electric power. This original discovery has inspired numerous new fields, such as piezotronics, self-powered sensor, and nanoenergy. Based on the SCI database, there are more than 12,000 scientists (or authors) distributed in 83 countries and regions who are engaged in nanogenerator research, and there are more than 4000 scientists in the field of piezotronics. The number of papers published in these two fields each year increases consistently (**Figure 1**). A total of close to 15,000 papers have been published in international journals as of December 2022.

The objective of this article is to give a review on the original thoughts for inventing nanogenerators and piezotronics, and the novel discoveries and technology advances that have been made since the coining of the two fields. We try to show how a tiny new idea can be turned into a huge field at the end.

Piezoelectric nanogenerators

My original training during PhD study and afterward was transmission electron microscopy (TEM), and my research before 1996 was mainly focused on fundamentals of TEM such as dynamic inelastic scattering in electron–solid interaction. The materials I used for research were mainly synthesized by others. As coming to intellectual properties, I did not have any credit although I had spent a lot of time in understanding the structure of the materials. In 1999, I decided to synthesize materials myself so that our research can be more systematic and self-controlled. Based on our judgment to the near future development of the field, we started with the synthesis of one-dimensional functional oxides. By 2001, we published the first landmark paper on oxide nanobelts,[2] which totally changed my career path by focusing on ZnO nanostructures ever since. This paper has been cited close to 7400 times.

After systematically understanding the growth mechanism of various ZnO nanostructures, we started to use ZnO

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doi:10.1557/s43577-023-00576-7

for fabricating various devices and related physical property measurements.[3] The first work in 2004 was to use an atomic force microscope (AFM) to characterize the Young's modulus of vertically aligned ZnO nanowires. The idea is to correlate the deflection force with the transverse displacement distance using Hooke's Law.

A unique characteristic of the third-generation semiconductor is its piezoelectricity created due to noncentrosymmetric crystal structure. The piezoelectric effect is about the crystal lattice polarization. Once it is subjected to mechanical strain, the anions and cations in the crystal will be polarized and distributed at the two ends of the crystal along the polarization direction. We used an AFM probe to characterize the piezoelectric properties of ZnO nanowires, which is an outstanding candidate for third-generation semiconductors. Our basic assumption was to convert tiny mechanical deformation energy into electric power, based on which the piezoelectric coefficient could be derived if all of the input mechanical energy was totally converted into electric power. However, the experimental results indicated that the derived piezoelectric coefficient experimentally was much smaller than what we expected theoretically. I suddenly realized that we made a mistake in my assumption, because energy-conversion efficiency can never be 100 percent. On September 20, 2005, I simply switched the objective of the experiment from measuring the piezoelectric coefficient to energy conversion, and the new device was named piezoelectric nanogenerator (PENG).[1] Because we used individual nanowires and an atomic force microscope (AFM) tip for energy conversion and the output voltage and current of PENG were in tens mV and in pA range, we named it nanogenerator. As of today, the physics mechanism and the output power of the nanogenerator have been much improved, and the applications have far exceeded nanoscale, but we still use the original term for historical reasons. As of now, *nanogenerator is a field that uses the Maxwell's displacement current as the driving force for converting mechanical energy into electric power using either piezoelectric or triboelectric effect, whether we use nanomaterials or not.* The output of nanogenerators has been boosted from nanoscale to macroscale with many practical applications. The first paper has been cited close to 8000 times.

Triboelectric nanogenerators

The triboelectric nanogenerator (TENG) was discovered by an experimental error. Since we first reported PENG, we had been consistently trying to improve its output toward practical applications. By integrating the contribution of multiunits of PENG, we were able to raise the output power for driving LED light in 2010.[4,5] A key step for the enhanced output was to tightly integrate arrays of ZnO nanowires as a solid device without air being trapped. But accidentally, in March 2011, we had devices that were incorrectly fabricated with air gaps being trapped between the electrode and the ZnO nanowire array, which was not purposely at the first place. It was expected that such PENGs would have much lower output in comparison to that of the correctly packaged ones. In contrast, repeated measurements of more than 200 such devices gave a much higher output than the conventional PENGs, which was a surprise to us. After a systematic study in August 2011, we concluded that the output was due to a triboelectrification effect, which was not by design, and totally unexpected in our original device design. This later led to the first invention of triboelectric nanogenerators.[6]

The discovery of TENG immediately inspired much research worldwide, because of its high output, easy fabrication, diverse choice of materials, low cost, and broad applications. The

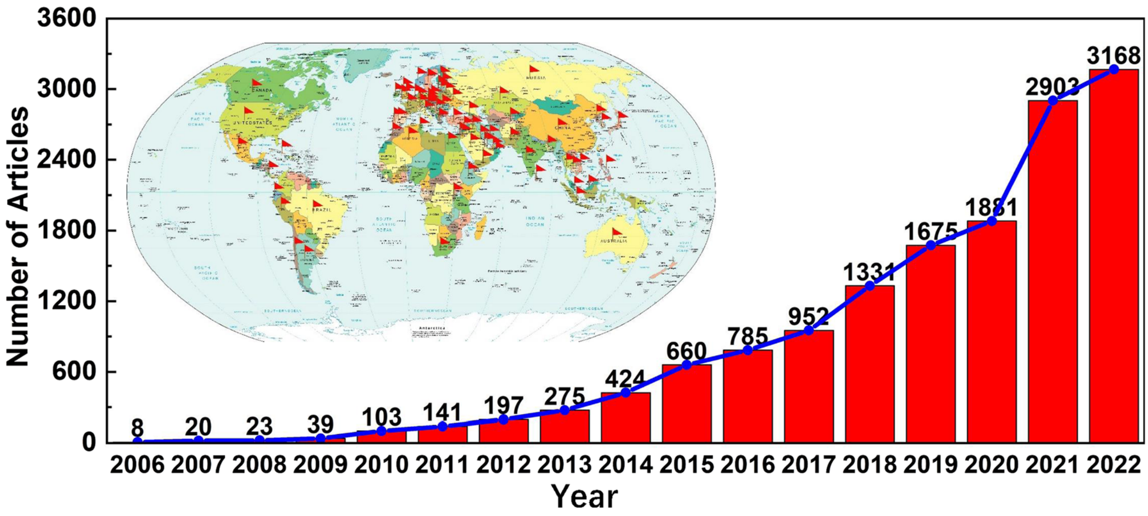

Figure 1. From Scientific citation index (SCI) database, papers that have been published in the fields of nanogenerator, piezotronics, piezo-phototronic, piezophotonic, self-powered sensor, and self-powered system since the first report of nanogenerators in 2006.

energy-conversion efficiency is 50–85%, and the output power density can reach up to 500 W/m.[7,8] TENGs have 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.[9,10]

TENG has four basic operation modes and one composed mode, as illustrated in **Figure 2**.[11] A typical TENG generally consists of two dielectric materials that tend to have opposite triboelectric charges after contacting. One or two electrodes are deposited on the surfaces of the dielectric layers that are interconnected via a load by a metal wire. The first mode is the vertical contact-separation mode (Figure 2a), in which two dielectric layers are periodically contacting and separating, and the time-dependent electric potential across the two electrodes would drive electrons to flow from one electrode to the other in order to balance the electrostatic potential drop created by the tribo-charges. The second mode is the lateral sliding mode (Figure 2b), in which one dielectric film is sliding on the top of the other; a mismatch in lateral direction between the two dielectric materials causes the electrons to flow between the two electrodes, resulting in an AC current. The third mode is a single-electrode mode (Figure 2c), in which a dielectric layer is approaching another dielectric layer at the back of which there is a metal electrode; the time-dependent potential built across the two dielectric layers results in electron exchanges between the electrode and the ground. The fourth mode is the freestanding triboelectric-layer mode (Figure 2d), in which a dielectric layer swings between and above two electrodes, electrons will be flowing back and forth across the two electrodes, resulting in an AC current. The mode shown in Figure 2e is a composed mode that can be considered as a combination of the four modes, so-called rolling mode,[7] in which rolling spheres on a dielectric surface will lead the exchange of electrons between the two electrodes, resulting in power output.

The mechanism of TENG

The classical approach for converting mechanical energy into electric power relies on the electromagnetic generator (EMG), which is based on Faraday's Law of electromagnetic induction. A conduction current is generated inside a coil as a result of Lorentz force acting on free electrons. Because the output voltage and current of EMG are linearly dependent on the mechanical cycling frequency, f, its output power is proportional to *square of* f. In such a case, the output power and efficiency increase with the increase of operation frequency, and EMG is most efficient for converting high-quality, high-frequency mechanical energy into electric power. However, for low-frequency and low-amplitude mechanical triggering, such as water wave, human activities, and gentle wind, EMG is not efficient for power generation because of its low output voltage (**Figure 3**a).

TENG utilizes a combination of triboelectrification and electrostatic induction effects (Figure 3b), and the output current is produced by the Maxwell's displacement current. Using the electrostatic charges created on surfaces due to media contacts, a space variation in the arrangement of the electrostatic charges results in a displacement current that induces the flow of electrons connected to the two electrodes as driven by an external force. Because of this, TENG has a high output voltage although the mechanical triggering frequency and magnitude are rather low. In fact, TENG can convert any form of

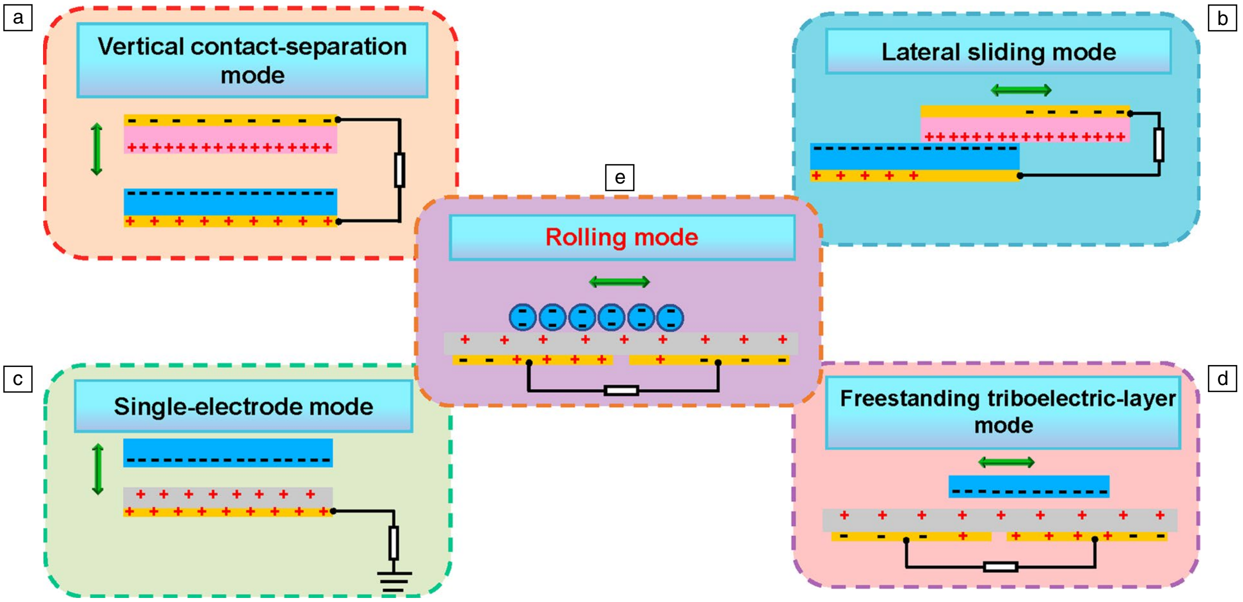

Figure 2. (a–d) The four operation modes of a triboelectronic nanogenerator (TENG) and (e) the rolling-based TENG.

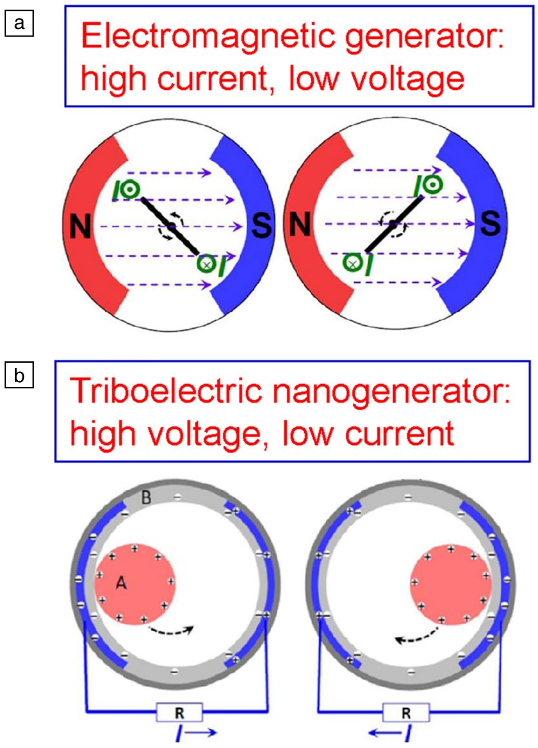

Figure 3. Comparison of the mechanisms of (a) the electromagnetic generator (EMG) based on Faraday's Law of electromagnetic induction and (b) the triboelectric nanogenerator (TENG) that is based on a combination of triboelectrification and electrostatic induction effects. EMG has the characteristic of high current but low voltage, and TENG has a high output voltage but low current. Both EMG and TENG can be applied in tandem.

mechanical energy into electric power with a high energy-conversion efficiency especially at low frequency. TENG is *a field that uses Maxwell's displacement current as the driving force for effectively converting mechanical energy into electric power/signal.*[9,10]

Theory of TENG

The driving force for TENG is the Maxwell's displacement current, which is caused by a time variation of electric field plus a media polarization term according to the classical electrodynamics. The displacement vector that is responsible to the displacement current is

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P}, \tag{1}$$

where the first term polarization vector $\boldsymbol{P}$ is due to the existence of an external electric field $\boldsymbol{E}$. It must indicate that Equation 1 holds if all of the media are at stationary and there is no moving boundary. However, for TENG, the dielectric media are moving under mechanical triggering and thus a polarization term should be introduced to account for the polarization produced by medium movement especially with considering its surface being charged due to the triboelectrification effect. To account for the contribution made by the contact electrification-induced electrostatic charges in Maxwell's equations, an additional term $\boldsymbol{P}_\mathrm{s}$ is added in displacement vector $\boldsymbol{D}$ by Wang,[12,13] that is

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P} + \boldsymbol{P}_\mathrm{s}, \tag{2}$$

where the term $\boldsymbol{P}_\mathrm{s}$ is called the mechano-driven polarization due to the movement of charged objects.

For a general TENG device, the charged dielectric medium can move with an arbitrary velocity distribution under mechanical excitation. For a medium that has a time-dependent volume, shape, and surface, moves at an inhomogeneous velocity $\boldsymbol{v}(\boldsymbol{r}, t)$ along an arbitrary trajectory distribution, the *Maxwell's equations for a mechano-driven slow-moving medium system* (MEs-f-MDMS) are developed.[14,15] The expanded MEs-f-MDMS are derived from the integral forms of four physical laws, which include the mechano-electro-magnetic interaction fields. The electromagnetic behavior inside the moving object is governed by the MEs-f-MDMS.[16]

$$\nabla \cdot \boldsymbol{D}' = \rho_\mathrm{f} - \nabla \cdot \boldsymbol{P}_\mathrm{s}, \tag{3a}$$

$$\nabla \cdot \boldsymbol{B} = 0, \tag{3b}$$

$$\nabla \times (\boldsymbol{E} + \boldsymbol{v}_\mathrm{r} \times \boldsymbol{B}) = -\frac{\partial}{\partial t}\boldsymbol{B}, \tag{3c}$$

$$\nabla \times [\boldsymbol{H} - \boldsymbol{v}_\mathrm{r} \times (\boldsymbol{D}' + \boldsymbol{P}_\mathrm{s})] = \boldsymbol{J}_\mathrm{f} + \rho_\mathrm{f}\boldsymbol{v} + \frac{\partial}{\partial t}(\boldsymbol{D}' + \boldsymbol{P}_\mathrm{s}), \tag{3d}$$

where the moving velocity of the unit charge can be split into two components: the moving velocity $\boldsymbol{v}$ of the moving reference frame and the relative moving velocity ($\boldsymbol{v}_\mathrm{r}$) of the point charge inside the medium with respect to the moving reference frame. Note the movement can have acceleration and there is the assumption of an inertia reference frame here, as long as the moving velocity is much less than the speed of light. The propagation of the electromagnetic waves in free space is described by the classical Maxwell's equations. The two sets of solutions meet at the medium interface as governed by the boundary conditions. The term that contributes to the output current of TENG is $\frac{\partial}{\partial t}P_\mathrm{s}$, which has been applied to calculate the output of TENG.[17,18] Equations 3a–d are the fully electrodynamics for moving objects and associated electromagnetic waves generated by the moving media.

Applications of TENG

TENG has inspired worldwide research in energy-harvesting and self-powered sensing, simply because of its superior performance, cost-effective, wide range choice of materials and broad applications, including but not limited to medical science, environmental science, wearable electronics, textile-based sensors and systems, Internet of Things, security, and many more. TENG was born at the right time that the world is

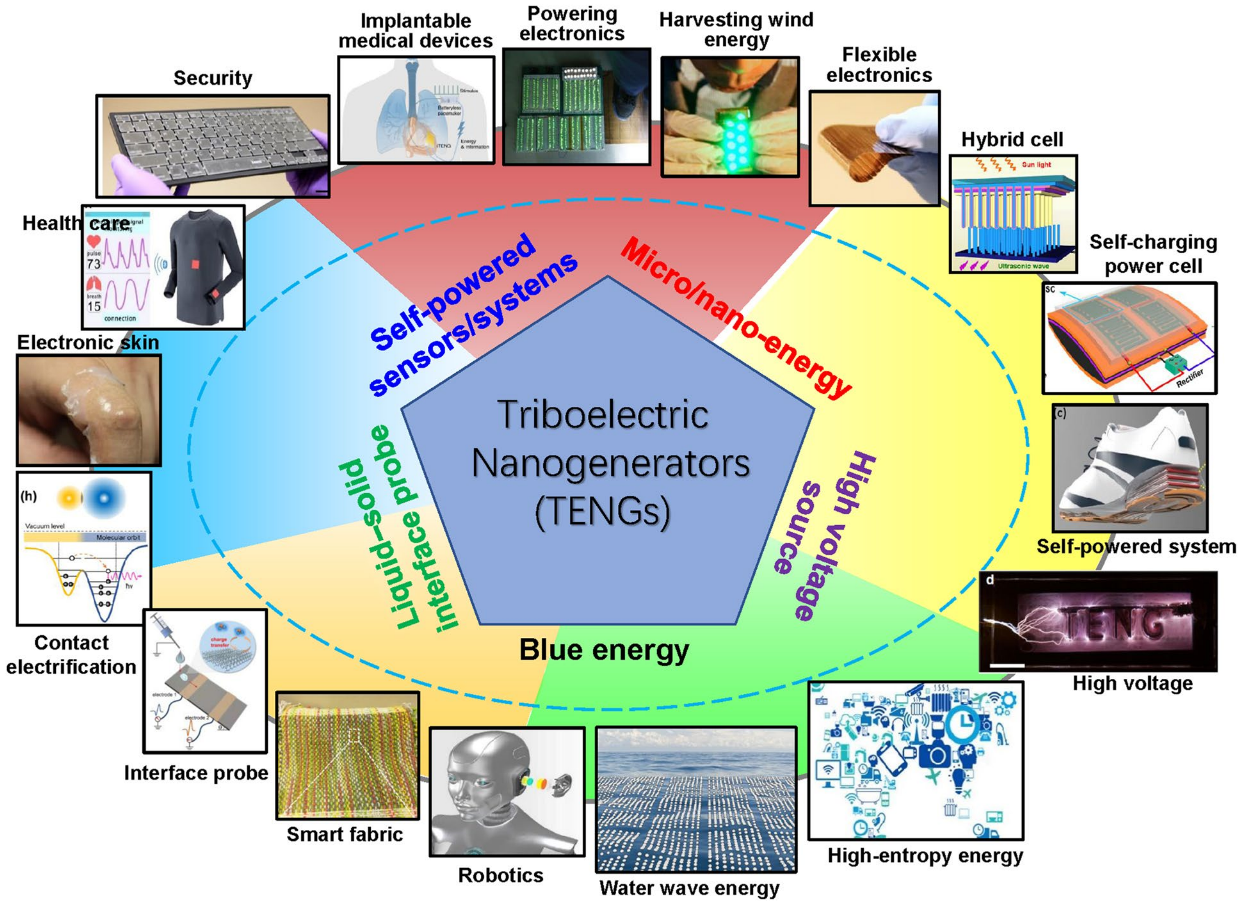

Figure 4. Five major application fields of triboelectric nanogenerators (TENGs), covering flexible electronics, human–machine interfacing, robotics, wearable electronics, medical science, environmental science, and blue energy.

marching into the era of artificial intelligence, Internet of Things, and big data. The major application fields of TENG are summarized in **Figure 4**, as elaborated as follows.[9,10]

As nano- and micro-power sources

The original objective for inventing the nanogenerator was for powering small electronic components by harvesting the distributed energy in our living environment. Since the fast development of the Internet of Things and sensor networks, all electronics have to be powered, which is a major challenge for many applications. TENG makes this possible due to the fast increase in the output power and efficiency of TENG, and the rapid reduction of the operation power of small electronics. Many of the electronics can operate at a power input of tens of milliwatts and even lower, so it can be effectively powered by TENG. In general, a TENG has to be integrated with a power management circuit and an energy-storage unit in order to be applied as a functional power unit. The power management circuit is used to lower the output voltage of the TENG and raise the output current[19] so that it can be effectively used for charging an energy-storage unit. An energy-storage unit is required in order to regulate the power for stably driving electronics. A typical example of micro-power is to use human breathing for driving a pacemaker. Using a TENG of 3 cm × 2 cm × 1 mm size, the triggering from breathing-driven muscle motion can drive a commercial pacemaker.[20]

As self-powered sensors

Today's society fully relies on big data, and collection of data needs sensor networks. Because each sensor may work independently and be widely distributed, with the possibility of highly mobile and wireless, powering such a sensor is a major task. Since most sensors are passive and they will not sense anything without an input power, it is important to make the sensors work without supplying an external electric power. It is essential to have sensors that respond to environmental changes without power (e.g., active sensors). As for motion, vibration, and triggering sensors, PENG and TENG can be an ideal choice, which produces output signals as it is mechanically triggered. The signals can be wirelessly transmitted even without an external power source. Because the output voltage of TENG is rather high even with very gentle mechanical triggering, typically in tens to hundreds of volts, a detection system with a sensitivity of millivolts is sufficient; thus, it is an ideal choice for mechanical sensing. Because the output voltage of TENG depends on the magnitude of triggering and the output current depends on the triggering velocity/acceleration, TENG is ideal for sensing dynamic triggering.

For blue energy utilization

Oceans have huge energy, and they offer the possibility of substituting fossil energy in the future.[21] But harvesting water wave energy from the ocean is challenging because of the low frequency, wide distribution, and complex and difficult environment. Harvesting ocean wave energy by EMG has a rather low efficiency, so that it is impractical for large-scale application. Because TENG has an outstanding output efficiency at low-frequency and low impact amplitude in comparison to EMG, it is unique for harvesting water wave energy from the ocean. By integrating many units of TENGs into a network, it is possible to harvest energy from ocean water waves, which is referred to as blue energy that is expected to be stable, dependent, and sustainable.[11] Recently, TENG has reached an energy-harvesting efficiency of 28% by triggering in water.[22] Because TENG networks can be built into 3D so that they can be extended to deep water, we anticipate that TENG can be a power source in the ocean. The peak output of TENG networks can be as high as 80 W/m^3.

As high-voltage sources

Because a unique characteristic of TENG is its high-output voltage, a high voltage can be generated using a small device. This can have some applications in cases where a high-output voltage is required, such as driving electrostatics and excitation of plasma.[23–25]

As a probe for studying the charge transfer at liquid–solid interface

Contact electrification (CE) can occur not only at a solid–solid interface, but also at a liquid–solid interface in which electron transfer can be a key component. Using the principle of a single-electrode TENG, one can probe the charge exchange between a water droplet with a solid surface using the charge transport in TENG. Using an array of TENGs as pixels, it is possible to map the charge transfer *in situ* and at real time. This provides a basic tool for fundamental studying of liquid–solid interface charge transfer and associated dynamics.[26–28]

Self-powered sensor/systems

Conventional gas, chemical, and biological sensors are usually passive and operate only when an external power source is applied. A sensor system is made of three parts: sensor tip, control electronics, and power supply. The original idea of developing the PENG was to explore the possibility of building self-powered systems,[27] by which we mean that a system is self-sufficient in energy by harvesting energy from its working environment. The self-powering idea was first proposed in the 2006 paper on nanogenerators.[1] For mechanical triggering, PENG and TENG can be sensor tips that automatically self-generate electric signals once they are triggered. Furthermore, energy can be harvested from the working environment using mechanical motion/stimulation so that the power unit can be self-charged. The sensor system can work in a mode of active-standby-active-standby. During the standby mode, the electronics work at the minimum power, and energy is harvested from the environment using TENG and stored. During the active mode, the sensor system fully operates by collecting data, analyzing data, and transmitting data. Self-powering is a major idea that can enable the system to operate sustainably, which is now well received in many fields in the area of sensor networks, Internet of Things, and implantable medical devices.

Hybrid cell

Our living environment has several forms of energy, such as mechanical energy, solar/light energy, thermal energy, and even chemical/biochemical energy. To make a mobile unit sustainably operating in the environment that has widely distributed, low-grade energy, we need to use whatever is available. During the course of developing PENG, we were wondering if one device can simultaneously harvest two or more different types of energy. This idea was first realized experimentally in 2009 by harvesting mechanical and solar energy using a hybrid cell.[28] Later, the idea was further developed and expanded for harvesting multiple types of energy and the same type of energy using various approaches.[29,30] This is the beginning of the hybrid cell.

Nano energy

Traditionally, when using the term energy, people usually mean large-scale energy, aiming at solving the world energy supply. This is a long-term goal, but for today's society, mobile electronics and distributed electronics are vital for the Internet of Things, artificial intelligence, and sensor network for big data. Sustainable driving of these large number, low power consumption, widely distributed, and possibly wireless units need distributed energy. We called this type of energy Nano Energy. The field of nano energy was phrased as early as 2006, which *is about the harvesting, storage, and effective utilization of energy in our living environment using nanomaterials, nanodevices, and nanosystems.* Today, nano energy includes, but is not limited to, nanogenerators, fuel cells, solar cell, energy storage, thermoelectrics, photocatalysis, water splitting, and more. It is an active and important field that has drawn a lot of research interest.

High-entropy energy

Based on the first law of thermodynamics: the conservation of energy, the electricity generated by fossil energy will eventually be dissipated into and distributed in our environment, at least in part, in the form of heat, wind, and other mechanical energies. Although the total amount of energy may be conserved, the conversion of such energy into electric power is considered as secondary energy, the efficiency of which is rather low. This process can be understood from the second law of thermodynamics: increase of entropy in energy distribution. Therefore, the energy is transformed from concentrated and high-quality fossil fuels into electric power, which is transmitted via cables to millions of factories and will eventually be dissipated into heat, becoming low quality and not readily reusable energy. In other words, the energy is transformed from concentrated and high-quality sources into distributed and low-quality energy sources. Together with the harvested solar and wind energy, *all of such distributed energies are referred to as high-entropy energy*.[31] The key challenge is how to effectively convert the high-entropy energy into electric power. We believe that in the future, the world should be run by a conjunction of fossil energy dominated power grid together with high-entropy energy.

Piezotronics

The mechanism of PENG is based on an assumption that there exists piezoelectric charge-generated potential across the piezoelectric material. *For piezoelectric semiconductors, such as ZnO and GaN, the piezo-charges created piezopotential by strain can act as an internal "gate" voltage for tuning and controlling the transport process of charge carriers, which is referred to as the piezotronics effect*. With the presence of this piezopotential at a metal–semiconductor interface, a diode can be made by applying a strain in the nanowire, and the height of the Schottky barrier can be freely controlled by the applied strain.[32] As inspired by the study available then, the concept of piezotronics was proposed in 2007.[33] **Figure 5**a and b shows the tuning of the piezopotential to the local Schottky barrier height due the existence of one layer of piezoelectric charges at the interface.[34] This is the principle that applying a strain can turn on or off of a diode.

The area of piezotronics has developed quickly into a field for third-generation semiconductors, such as ZnO, GaN, and SiC and even the fourth generation of semiconductors,

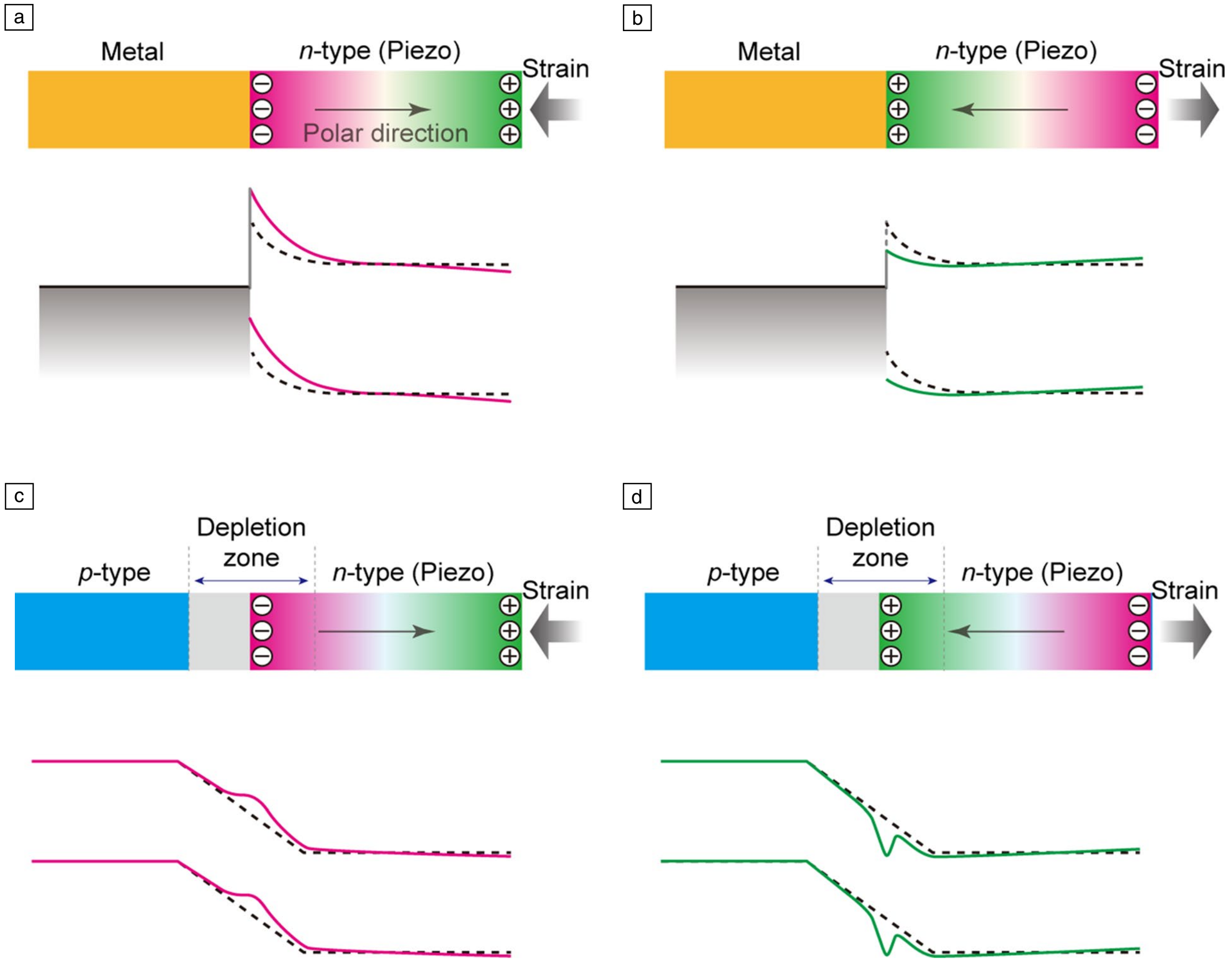

Figure 5. The effect of piezotronic effect at (a, b) a metal–semiconductor interface and (c, d) a *p*–*n* junction, and how it modifies the local energy band structure.

such as Ga_2O_3. Systematic work has been completed regarding the theory of piezotronics. Arrays of piezotronic transistors have been fabricated and integrated, setting a key step toward a piezotronic chip.[35] The piezotronic effect has also been observed for 2D materials.[36] The principle of piezotronics has fundamentally changed the design of the traditional field-effect 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; and the transport of the charges is controlled by the interface at the electrode–nanowire interface rather than the channel width. Piezotronics has potential applications in human–computer interfacing, smart MEMS, nanorobotics, and sensors, but the current research is still focusing on fundamental science.

Piezo-phototronics

In 2009, we experimentally found that the Schottky barrier height at a metal–semiconductor contact can be decreased by laser irradiation due to the increased free carrier density.[37] In contrast, we have used the piezoelectric effect to raise the height of the Schottky barrier in order to optimize its sensitivity as a photodetector.[38] The coupling of piezoelectric effect and photon excitation effect triggered us to define *the piezo-phototronic effect, which is to utilize the piezoelectric polarization charges at the interface for effectively tuning the charge-carrier separation or recombination process in optoelectronics*. A key progress in the field was the utilization of the piezo-phototronic effect to enhance a ZnO-GaN-based LED[38] and an array of LEDs.[39] The mechanism was proposed as that the presence of a layer of piezoelectric polarization charges at the interface can create a local energy dip within the carrier depletion zone of a *p-n* junction, as shown in Figure 5c and d, which can effectively increase the electron–hole recombination rate for enhancing LED efficiency by a factor of 4.25. Piezo-phototropic effect-based electronics has been extensively developed in the last 15 years, which has been effectively used to enhance the efficiency of various solar cells, efficiency of photon detectors from infrared to UV. The associated theory has been systematically established.[40] **Figure 6** is a summary of the applications of piezotronics and piezophototronics in various fields.

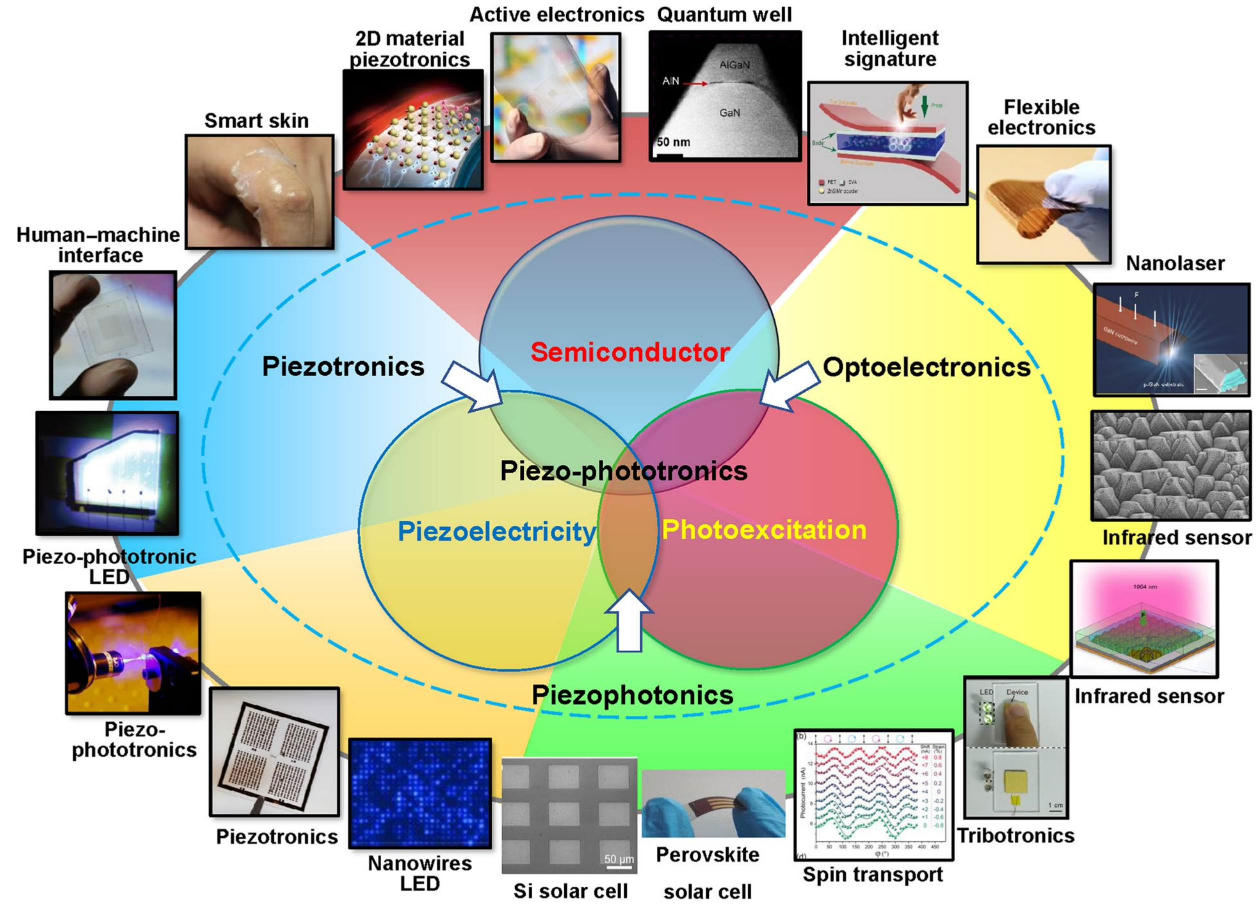

Figure 6. A summary of piezotronics, piezo-phototronics, and piezophotonics fields coined and pioneered by Wang's group and their potential applications in third-generation semiconductors and various fields. LED, light-emitting diode.

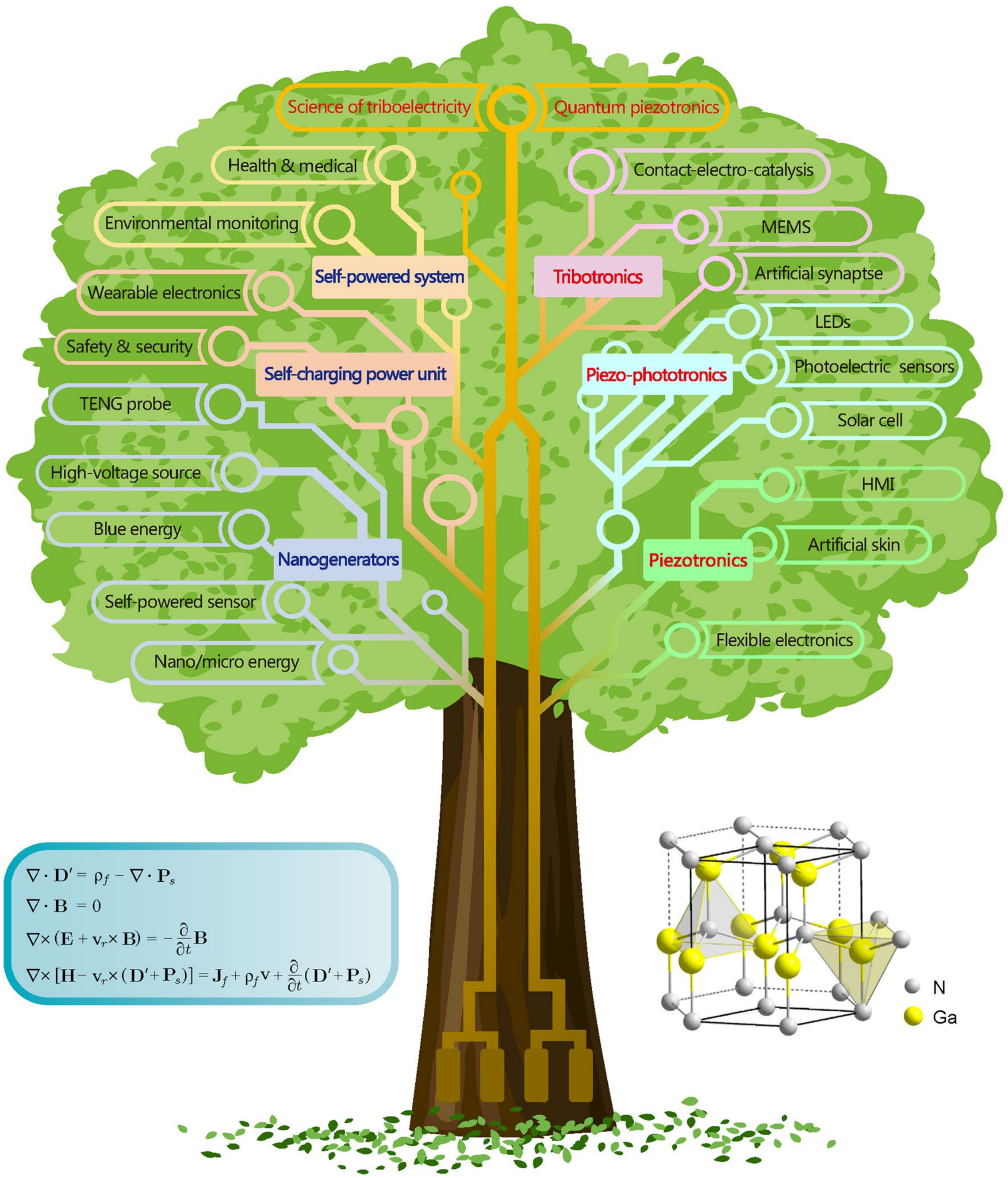

Figure 7. A summary of Wang's research by a "tree" idea (simply referred to as "ZhongLin Wang's tree"). The left-hand side is the nanogenerator-based high-entropy energy field. The right-hand side is the piezotronics and piezo-phototronics of third-generation semiconductors. MEMS, microelectromechanical systems; LEDs, light-emitting diodes; HMI, human-machine interface.

Third-generation semiconductors are distinct from first and second generations of semiconductors in crystal structure and of course in properties. By considering the wurtzite GaN and ZnO family, the piezotronic effect and piezo-phototronic effect are inevitably in device designs and their operations owing to the noncentral crystal symmetry. The tuning of piezoelectric properties at the interface introduces a new mechanism for designing new types of transistors. The effectiveness of piezotronic and piezo-phototronic effects at room temperature is another advantage for their practical applications. The piezotronic transistors are potentially useful for sensors, robotics, and artificial intelligence. The piezo-phototronic effect could be utilized for improving the efficiency of commercial LEDs and solar cells. We anticipate that the piezotronic effect can tune spin transport, single electron transport, and even topological insulators.

Summary

The research fields we have established in the last 20 years can be summarized using a "tree" design, as shown in **Figure 7**, the first version of which was published in 2012.[3] In comparison to a natural tree, a field must have its deep science as the "root," based on whether the field can be long-lasting. A breakthrough in science will lead to broad technological innovations. A field requires many years to develop, like the age rings of a tree, which means that it must experience various environmental challenges. The location of the tree cannot be frequency moved, otherwise it will eventually die. The impact and applications of the field are similar to the span of the tree branches, which can be high, broad, and out of reach. A science tree is only possible after being focused on the field for many years before major technological breakthroughs can be seen.

The scientific accomplishments by Wang's group in the last 35 years can be summarized as "1–2–3–4–5–6–7":

Established one system: The high-entropy energy system based on nano energy and distributed energy.[31]

Pioneered two fields: Pioneered the fields of nanogenerators for self-powered systems and blue energy,[3] and the piezotronics and piezo-phototronics of third-generation semiconductors.[40]

Coined three scientific majors: Piezotronics is about the devices made using a piezotronic effect for tuning the carrier transport in semiconductors; piezo-phototronics is about the devices made using a piezo-phototronic effect for tuning the carrier separation or recombination in optoelectric processes; and tribotronics is about the devices fabricated using the electrostatic potential created by triboelectrification as a "gate" voltage to tune/control charge-carrier transport in semiconductors.[40–42]

Achieved four technology innovations: Nano-micro-energy, self-powered sensor/system, blue energy, and high voltage source based on TENG.[24,43]

Developed five potential commercial application areas: Medical, health, and environmental protection; self-powered security system; micro-energy and blue energy; self-powered sensors; and piezotronics and piezo-phototronics of third-generation semiconductors.

Discovered six new physics effects:

1. **Piezotronic effect:** In piezoelectric semiconductors, piezoelectric polarization charges can act as a gate voltage to tune/control the charge transport process at the interface/junction.
2. **Piezo-phototronic effect:** Piezoelectric polarization charges can tune electron–hole separation or recombination in optoelectronic processes.
3. **Piezophotonic effect:** Piezoelectric polarization potential can induce the photonemission process.[44]
4. **Tribovoltaic effect:** Once an *n*-type semiconductor slides on a *p*-type semiconductor, the newly formed atomic bond at the interface releases an energy quantum, named "bindington," which excites electron–hole pairs at the *p*-*n* junction. The electrons and holes are separated by the internal built-in electric field, generating a DC output.[45]
5. **Pyro-phototronic effect:** For the pulsed incident light, local generated heating results in a strong pyroelectric effect, which gives a high output voltage and current. This effect can be used for high-sensitive photon sensing.[46]
6. **AC photovoltaic effect:** A photovoltaic effect that generates AC in the nonequilibrium states when the illumination light is periodically shined at the junction/interface of materials. It is suggested to be a result of the relative shift and realignment between the quasi-Fermi levels of the semiconductors adjacent to the junction/interface under the nonequilibrium conditions, which results in electron flow in the external circuit back and forth to balance the potential difference between the two electrodes.[47]

Made seven scientific contributions:

1. Developed the mechano-driven Maxwell's equations for a multi-object moving system possibly with acceleration, established the fundamental theory for TENG and beyond.[15,16]
2. A unified model is proposed for elaborating the dominant role played by interatomic electron transition in contact electrification between solid–liquid–gas phases.[48,49]
3. Established that interatomic/molecular electron transition is a popular and unified charge-transfer mechanism among phases of gas–liquid–solid. First demonstrated the contact electrification-induced interface light emission spectroscopy (CEIILES) and contact electro-catalysis.[50,51]
4. Established the electron transition process between liquid–solid and proposed a two-step model regarding the formation of electric double layer (EDL): electron transfer occurs first due to liquid–solid contact electrification, then followed by ion adsorption as a result of electron transfer at the interface. This is a new explanation about the formation of EDL based on contact electrification.[52]
5. Systematically and comprehensively developed the dynamic theory regarding phonon scattering (thermal diffuse scattering) in high energy electron diffraction and imaging. First proposed the theory for simulating high-angular annular dark-field images in scanning transmission electron microscopy (HAADF STEM).

6. Discovered a method for weighing a single nanoparticle and initiated *in situ* nanomeasurements in transmission electron microscopy.
7. Discovered oxide nanobelts and pioneered the research on nanostructures of zinc oxide.

The nanogenerator and piezotronics fields that we have coined are likely to have a broad and long-lasting impact. They are not only paradigm shift technologies for energy, but also innovative approaches for sensors. We anticipate they will have key applications in the Internet of Things, robotics, medical science, human–machine interfacing, artificial intelligence, and security.

Acknowledgments

I would like to thank our group members and collaborators for their outstanding contribution in the course of developing the reported fields in the last 35 years.

Data availability

Not applicable.

Conflict of interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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