



On Maxwell's displacement current for energy and sensors: the origin of nanogenerators

Zhong Lin Wang^{1,2}

¹ School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, United States

² Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, China

Self-powered system is a system that can sustainably operate without an external power supply for sensing, detection, data processing and data transmission. Nanogenerators were first developed for self-powered systems based on piezoelectric effect and triboelectrification effect for converting tiny mechanical energy into electricity, which have applications in internet of things, environmental/infrastructural monitoring, medical science and security. In this paper, we present the fundamental theory of the nanogenerators starting from the Maxwell equations. In the Maxwell's displacement current, the first term $\epsilon_0 \frac{\partial E}{\partial t}$ gives the birth of electromagnetic wave, which is the foundation of wireless communication, radar and later the information technology. Our study indicates that the second term $\frac{\partial P}{\partial t}$ in the Maxwell's displacement current is directly related to the output electric current of the nanogenerator, meaning that our nanogenerators are the applications of Maxwell's displacement current in energy and sensors. By contrast, electromagnetic generators are built based on Lorentz force driven flow of free electrons in a conductor. This study presents the similarity and differences between piezoelectric nanogenerator and triboelectric nanogenerator, as well as the classical electromagnetic generator, so that the impact and uniqueness of the nanogenerators can be clearly understood. We also present the three major applications of nanogenerators as micro/nano-power source, self-powered sensors and blue energy.

Self-powering

Internet of things (IoT) is a technological drive that link moving things or any things around world on internet, such as shipping objects, cargo carriers and people etc. IoT needs widely distributed sensors for health monitoring, medical care, environmental protection, infrastructure monitoring and security. The power for driving each sensor is small, but the number of such units can be huge in the order of billions to trillions. The most conventional technology is using batteries, which may not be the solution for IoT with considering the limited life time, wide distribution, high maintenance cost and environmental issues. Most of the IoT would be impossible without making the devices self-powered by harvesting energy from the working environment so that the

devices can operate sustainably. This was the original motivation for developing nanogenerators based self-powering systems [1,2].

In the last half century, the road map of electronics has been focusing on miniaturization following the Moore's law, for example, the number of devices on a chip doubles every 18 months, which is a commercial drive rather than a nature physics law. Solid state electronics has made it possible to integrate many components on a single chip. Integrated circuits set the foundation for improving the reliability, reducing size, increasing calculation speed, reducing power consumption and more. Secondly, the next revolutionary advance is the development of wireless/mobile communication technology. By conjunction with optical fiber based information transfer and computer science, the development of internet has changed every corner of the world. Thirdly, in the last decades, adding functionality to mobile devices has closely

E-mail address: zlwang@gatech.edu.

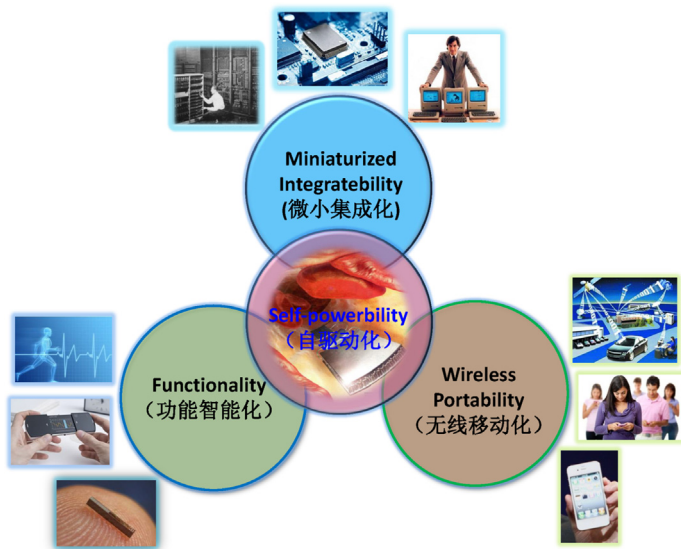


FIGURE 1

A summary about the major development stages of microelectronics and communication technologies as well as newly arising fields.

linked to medical science and medical care of every one, so that one can fully utilize modern sensor technology for living in a more security and healthy world. But all of these advances can be hugely impacted if we can make the mobile electronics self-powered so that the systems can operate suitably and continuously without interruption. This is desperately needed for IoT because we mostly care about mobile objects. Regarding whatever technology, one thing is true, no electronics works without electric power! Therefore, the last huge drive is to make devices self-powered. The above discussions are thus classified and summarized in Fig. 1 as four major technological drives toward systems with: miniaturized integratebility; wireless portability, functionality, and self-powerability. The self-powering serves as the base of the other three fields. This is what I projected future areas of exploration.

Nanogenerators

We first proposed the idea of self-powering in 2006 as a result of discovery of piezoelectric nanogenerators (PENGs) [3–5], which utilizes piezoelectric effect of nanowires for converting tiny mechanical energy into electricity. This study inspires the field of nanoenergy. The triboelectric nanogenerator (TENG) was first invented in 2012 [6–9]. Using the electrostatic charges created on the surfaces of two dissimilar materials when they are brought into physical contact, the contact induced triboelectric charges can generate a potential drop when the two surfaces are separated by a mechanical force, which can drive electrons to flow between the two electrodes built on the top and bottom surfaces of the two materials. Research in nanogenerators has inspired a worldwide interest because of its importance not only as a power source, but also self-powered sensors with applications ranging from IoT, environmental monitoring, health care, medical science, infrastructure monitoring and security [9].

There are a few important forms of energy that can be harvested from our living environment for self-powered system, including

solar, thermal, mechanical and biochemical. Each of these energies offers its own uniqueness, potentials and limitations, as summarized in Fig. 2. In some cases, a device that can simultaneously harvesting multiple types of energies is desirable, so called hybrid energy technology [10,11]. Our current article mainly focus on mechanical energy harvesting, which can be accomplished using effects such as electromagnetic induction, electrostatic, piezoelectric and triboelectric. Each of these effects has its own uniqueness and applications, as summarized and compared in Fig. 3. The goal of this article is about the fundamental physics for energy harvesting using piezoelectric and triboelectric effect. We will explore the relationship between nanogenerator's output and the Maxwell's displacement current so that a clear understanding is offered about the difference between nanogenerators from classical electromagnetic generator (EMG). Finally, some key application fields of the nanogenerators will be briefly reviewed.

Maxwell's displacement current for understanding nanogenerators

Our discussion starts from the fundamental Maxwell's equations that unify electromagnetism:

$$\nabla \cdot \mathbf{D} = \rho_f \quad (\text{Gauss's Law}) \quad (1.1)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (\text{Gauss's law for magnetism}) \quad (1.2)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (\text{Faraday's law}) \quad (1.3)$$

$$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t} \quad (\text{Ampère's circuital law with Maxwell's addition}) \quad (1.4)$$

where the electric field \mathbf{E} ; the magnetic field \mathbf{B} ; magnetizing field \mathbf{H} ; the free electric charge density ρ_f ; the free electric current density \mathbf{J}_f ; displacement field \mathbf{D} ,

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P} \quad (2)$$

and polarization field \mathbf{P} , and permittivity in vacuum ϵ_0 . As for an isotropic media, $\mathbf{D} = \epsilon \mathbf{E}$, where ϵ is the permittivity of the dielectrics.

In Eq. (1.4), the second term is the Maxwell's displacement current defined as

$$\mathbf{J}_D = \frac{\partial \mathbf{D}}{\partial t} = \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}}{\partial t} \quad (3)$$

The displacement current was first postulated by Maxwell in 1861 [12], and it was introduced on consistency consideration between Ampère's law for the magnetic field and the continuity equation for electric charges. *The displacement current is not an electric current of moving free charges, but a time-varying electric field (vacuum or media), plus a contribution from the slight motion of charges bound in atoms, dielectric polarization in materials.* In Eq. (3), the first component $\epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$ in the displacement current gives the birth of electromagnetic wave, which later being taken as the approach for developing radio, radar, TV and long distance wireless communication. We now present the relationship between the second term in the displacement current and the output signal from nanogenerators, and show the contribution of displacement current to energy and sensors in the near future.


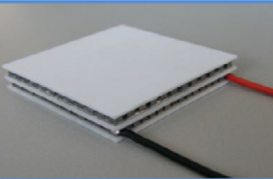
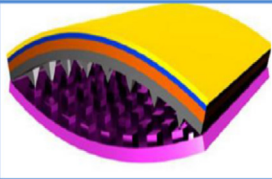
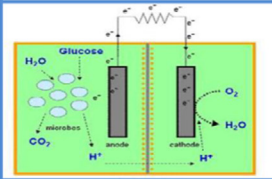
Energy source	Solar	Thermal	Mechanical	Biochemical
				
Harvesting Principle	Photovoltaic	Thermoelectric	Electromagnetic/Electrostatic/ Piezoelectric	Biochemical reactions
Approximate power density	5–30 mWcm ⁻²	0.01–0.1 mWcm ⁻²	10–100 mWcm ⁻²	0.1–1 mWcm ⁻²
Pros	Microfabrication compatible mature technology, long lifetime, DC & high power output	No moving parts required, long lifetime, high reliability, DC output	Ubiquitous and abundant in the ambient, broad frequency and power ranges, high output	Biocompatible/degradable, clean energy, environmentally friendly, abundant in biological entities
Cons	Limited by environmental conditions, not available at night	Low efficiency, large size, a large and sustained thermal gradient is required	AC output, not continuous output	Low power output, poor reliability, limited lifetime
Potential Applications	Remote sensing and environmental Monitoring	Structural-health monitoring for Engines and machines, wearable Biomedical devices	Remote sensing and monitoring, wearable systems, blue energy, internet of things	In vivo applications, environmental Monitoring/sensing, biocompatible application

FIGURE 2

A comparison about the harvesting of energy from solar, thermal, mechanical and biochemical for illustrating their merits and possible practical limitations.


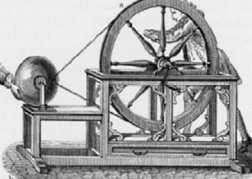
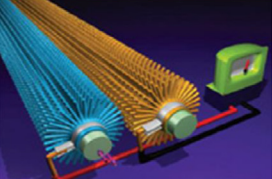
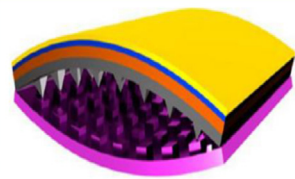
Mechanical energy harvesting	Electromagnetic	Electrostatic	Piezoelectric	Triboelectric
				
Harvesting principle	Electromagnetic induction	Electrostatic induction	Piezoelectric effect & Electrostatic induction	Contact electrification & Electrostatic induction
Impedance type	Resistive	Capacitive	Capacitive	Capacitive
Pros	High efficiency, easy to scale up	Light weight	Easy to scale down to nanoscale	Large output power, high efficiency, low weight, cost effective materials, simple fabrication
Cons	Heavy magnet required, low output for small-scale devices	Precharge required, low output, high matched impedance	Low output & low efficiency, pulsed output, high matched impedance	Pulsed output, high matched impedance

FIGURE 3

A comparison about the harvesting of mechanical energy using electromagnetic, electrostatic, piezoelectric and triboelectric effect for illustrating their merits and possible practical limitations.

Piezoelectric nanogenerator

The working principle of a piezoelectric nanogenerator (PENG) is illustrated in Fig. 4a-i. An insulator piezoelectric material is covered by a top and bottom electrodes on its two surfaces. A vertical mechanical deformation results in the generation of piezoelectric polarization charges at the two ends of the material (Fig. 4a-ii). An increase of the applied force results in higher polarization charge density (Fig. 4a-iii). The electrostatic potential created by the polarization charges is balanced by the flow of electrons from one electrode to the other through an external load. This is the process of converting mechanical energy into electric power. If the density of the piezoelectric polarization charges on the surface is $\sigma_p(z)$, and the corresponding charge density of free electrons in the electrode is $\sigma(x)$, which is a function of the thickness of the piezoelectric material z with considering the strain introduced by applied force.

As for a piezoelectric material that is usually anisotropic, the piezoelectric equation and constitutive equations under a small uniform mechanical strain are given by [13–15]:

$$P_i = (e)_{ijk}(s)_{jk} \quad (4a)$$

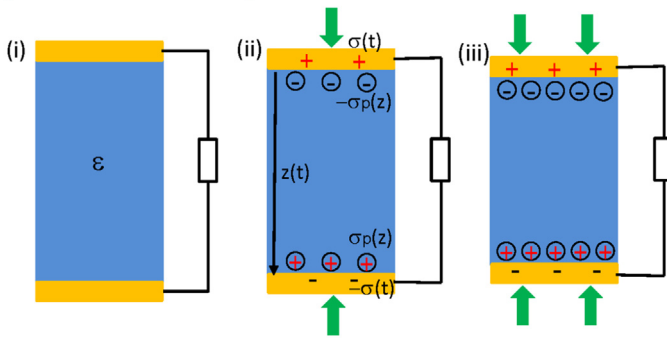
$$\begin{cases} \mathbf{T} = \mathbf{c}_E \mathbf{s} - \mathbf{e}^T \mathbf{E} \\ \mathbf{D} = \mathbf{e} \mathbf{s} + \mathbf{k} \mathbf{E} \end{cases} \quad (4b)$$

where \mathbf{s} is the mechanical strain; the third order tensor $(e)_{ijk}$ is the piezoelectric tensor; \mathbf{T} and \mathbf{c}_E are the stress tensor and the elasticity tensor, respectively; \mathbf{k} is the dielectric tensor. The displacement current from the media polarization is:

$$J_{Di} = \frac{\partial P_i}{\partial t} = (e)_{ijk} \left(\frac{\partial s}{\partial t} \right)_{jk} \quad (5)$$

Eq. (5) means that the changing rate of the applied strain is proportional to the output current density of the PENG.

(a) Piezoelectric nanogenerator



(b) Triboelectric nanogenerator

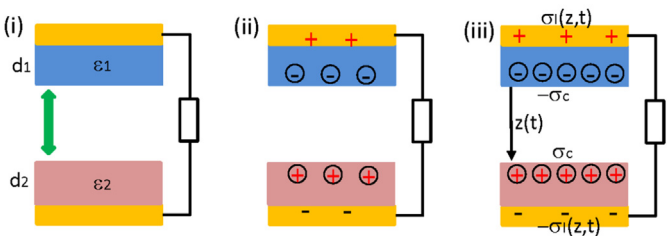


FIGURE 4

Illustrations about the working mechanisms of (a) piezoelectric nanogenerator with the increase of the applied stress, and (b) triboelectric nanogenerator with the increase of contact cycles.

For a case there is no external electric field applied as shown in Fig. 4a and the polarization is along the z -axis, the displacement field is the polarization vector, $D_z = P_z = \sigma_p(z)$ in the media, so that the displacement current is

$$J_{Dz} = \frac{\partial P_z}{\partial t} = \frac{\partial \sigma_p(z)}{\partial t} \quad (6)$$

Eq. (6) means that the changing rate of the surface polarization charges is the observed output current for a PENG. The magnitude of the open circuit voltage for PENG is

$$V_{oc} = z \sigma_p(z) / \epsilon \quad (7)$$

With considering the presence of an external load R as shown in Fig. 4a-ii, the current transport equation for PENG is

$$RA \frac{d\sigma}{dt} = z [\sigma_p(z) - \sigma(z)] / \epsilon \quad (8)$$

where A is the area of the electrode. In a case that the applied strain is a relatively slow process, so that z is a function of time t . The output characteristics of a PENG can be derived from Eq. (8). In analogy, the output of a pyroelectric nanogenerator can also be described accordingly.

Triboelectric nanogenerator

We start from the very basic model of the TENG for illustrating its theory. Starting from a four layer TENG in contact-separation mode, with two dielectrics with permittivity of ϵ_1 and ϵ_2 and thicknesses d_1 and d_2 , respectively (Fig. 4b-i). Once the two dielectrics are driven to be in physical contact, electrostatic charges are transferred to the surfaces of the two owing to the contact electrification effect (triboelectricity). The surface is partially charged and the charges are non-mobile static charges (Fig. 4b-ii), and surface charge density σ_c builds up as a number of contacts between the two dielectric media and finally reaches a saturation, and it is independent of the gap distance z . The electrostatic field built by the triboelectric charges drives electrons to flow through the external load, resulting in an accumulation of free electrons in the electrode, $\sigma_I(z, t)$, which is a function of the gap distance $z(t)$ between the two dielectrics. This is the process of converting mechanical energy into electricity.

As shown in Fig. 4b-iii, the electric field in dielectric 1 and 2 are $E_z = \sigma_I(z, t) / \epsilon_1$ and $E_z = \sigma_I(z, t) / \epsilon_2$, respectively. In the gap, $E_z = (\sigma_I(z, t) - \sigma_c) / \epsilon_0$. The relative voltage drop between the two electrodes is

$$V = \sigma_I(z, t) [d_1 / \epsilon_1 + d_2 / \epsilon_2] + z [\sigma_I(z, t) - \sigma_c] / \epsilon_0 \quad (9)$$

Under short-circuit condition, $V = 0$,

$$\sigma_I(z, t) = \frac{z \sigma_c}{d_1 \epsilon_0 / \epsilon_1 + d_2 \epsilon_0 / \epsilon_2 + z} \quad (10)$$

From Eq. (3), the corresponding displacement current density is

$$J_D = \frac{\partial D_z}{\partial t} = \frac{\partial \sigma_I(z, t)}{\partial t} = \sigma_c \frac{dz}{dt} \frac{d_1 \epsilon_0 / \epsilon_1 + d_2 \epsilon_0 / \epsilon_2}{[d_1 \epsilon_0 / \epsilon_1 + d_2 \epsilon_0 / \epsilon_2 + z]^2} \quad (11)$$

This equation means that the displacement current density is proportional to the charge density on the dielectric surface and the speed at which the two dielectrics are being separated or contacted. This is the output characteristics of the TENG.

With considering the presence of an external load R as shown in Fig. 4a-ii, the current transport equation for TENG is

$$RA \frac{d\sigma_I(z, t)}{dt} = z \sigma_c / \epsilon_0 - \sigma_I(z, t) [d_1 / \epsilon_1 + d_2 / \epsilon_2 + z / \epsilon_0] \quad (12)$$

where z is a function of time t depending on the dynamic process that the force is applied. Starting from Eq. (12), we have systematically established the theories for all of the four modes for TENG once it is connected with a load, regarding to the power output, the optimization of the experimental parameters [16–20].

Capacitive model

Both piezoelectric and triboelectric nanogenerators are referred to as the capacitive conduction, in which the displacement current is the only conduction mechanism for electricity transport. The power is transmitted not via flow of free charges across the electrodes of the capacitor, but via electromagnetic wave and induction. Based on a capacitor model, the output current of a nanogenerator can be represented by

$$I = \frac{dQ}{dt} = C \frac{dV}{dt} + V \frac{dC}{dt} \quad (13)$$

where Q is the stored charges in the capacitor, the first term is the current introduced by a change in the applied voltage; the second term is the current introduced by the variation in capacitance.

As for a PENG, the change in capacitance is rather small because the strain induced change in crystal size/thickness is extremely small, so that the current is mainly due the change in strain induced voltage

$$I \approx C \frac{dV}{dt} = \left(\epsilon \frac{A}{z} \right) \frac{d}{dt} \left(\frac{\sigma z}{\epsilon} \right) \approx A \frac{d\sigma}{dt}, \quad (14)$$

where A is the area of the electrode. Under short circuit condition, $\sigma = \sigma_p(z)$, the result from Eq. (14) is just the result derived from the displacement current in Eq. (6).

$$I = A \frac{d\sigma_p}{dt} = A \frac{d\sigma_p}{dz} \frac{dz}{dt}, \quad (15)$$

As for TENG, since the change in gap distance is rather large, so that both terms in Eq. (13) contribute to the observed output current,

$$I = \frac{dQ}{dt} = A \frac{d\sigma_I}{dt} \quad (16)$$

which will lead to the same result as for displacement current in Eq. (11). Therefore, the foundation of the capacitive model is the Maxwell's displacement current. Our study proves the equivalence of the different models. Using Eq. (16), in conjunction with Ohm's law, we have systematically established the theories for all of the four modes for TENG once it is connected with a load, regarding to the power output, the optimization of the experimental parameters [16–20].

Electromagnetic generators

In Maxwell Eq. (1.4), the first term \mathbf{J}_f is the current density as a result of free electron flow. As for EMG, the Lorentz force induced electron flow in a conductor is the power generation process

$$\mathbf{F} = -e\mathbf{v} \times \mathbf{B}, \quad (17)$$

where \mathbf{v} is the moving speed of the conductor across the electric field. The motion of the electrons is accelerated by the magnetic field, but the related resistance due to inelastic collisions with atoms and electrons limits their flow, reaching a steady state current. This means that the EMG is a resistive conduction.

Four fundamental working modes of TENG

Ever since the first report of the TENG in 2012 by Wang et al., TENG's output area power density reaches 500 W/m^2 [21], an instantaneous conversion efficiency of $\sim 50\%$ have been demonstrated [22]. TENG is effective for harvesting energy from human motion, walking, vibration, mechanical triggering, rotating tire, wind, flowing water and more. A TENG can also be used as a self-powered sensor for actively detecting the static and dynamic processes arising from mechanical agitation using the voltage and current output signals of the TENG, respectively, with potential applications as mechanical sensors and for touch pad and smart skin technologies. We now present the four basic working modes of a TENG (Fig. 5) [7,8]. The contact-separation mode uses the polarization in vertical direction. The lateral sliding mode uses the polarization in lateral direction as a result of relative sliding between two dielectrics [23,24]. The single electrode mode was introduced for harvesting energy from a freely moving object without attaching a conduction line [25]. The Freestanding triboelectric-layer mode is designed for power generation using electrostatic induction between a pair of electrode [26]. In many cases, two or more modes can work in conjunction.

Vertical contact-separation mode

A physical contact between the two dielectric films with distinct electron affinity (at least one is insulator) creates oppositely charged surfaces. Once the two surfaces are separated by a gap, a potential drop is created between electrodes deposited on the top and the bottom surfaces of two dielectric films, as demonstrated in Fig. 5a. If the two electrodes are electrically connected by a load, free electrons in one electrode would flow to the other electrode in order to balance the electrostatic field. Once the gap is closed, the potential drop created by the triboelectric charges disappears, the induced electrons will flow back. A periodic contact and separation between the two materials drives the induced electrons to flow back and forth between the two electrodes, resulting in an AC output in the external circuit [6,26]. This mode is the basic mode of TENG and it can be easily achieved in practice.

In-plane sliding mode

When two materials with opposite triboelectric polarities are brought into contact, surface charge transfer takes place due to

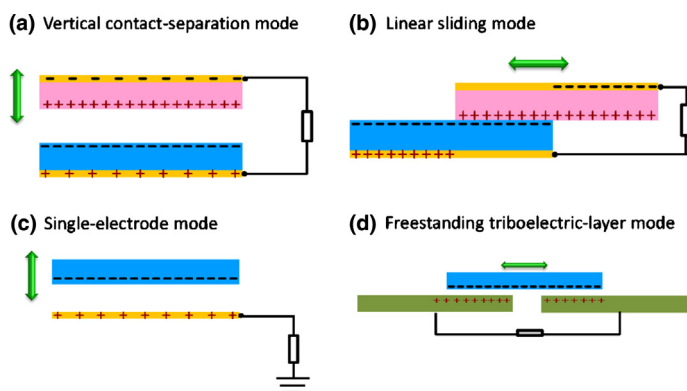


FIGURE 5

The four fundamental working modes of the triboelectric nanogenerators. (a) The vertical contact-separation mode. (b) The lateral sliding mode. (c) The single-electrode mode. (d) The free-standing mode.

the triboelectrification effect (Fig. 5b) [27]. When the two surfaces are fully matched there is no current flow, because the positive charges at one side are fully compensated by the negative ones. Once a relative displacement is introduced by an externally applied force in the direction parallel to the interface, triboelectric charges are not fully compensated at the displaced/mismatched areas, resulting in the creation of an effective dipole polarization in parallel to the direction of the displacement. Therefore, a potential difference across the two electrodes is generated. The sliding mode can be made into fully packaged and even in rotation mode so that it can operate in vacuum.

Single-electrode mode

For a dielectric and metal plate, as shown in Fig. 5c, induction current is created in the metal plate if the charged dielectric approaches it to balance the field. Once the dielectric moves away from the metal plate, the current flows back to the ground. This mode works in a way that relies on the charge exchange between ground and metal plate [25]. This mode is most useful for utilizing the energy from a moving object without attaching an electric connection, such as human walking, moving car, finger typing and more.

Free-standing triboelectric-layer mode

If we make a pair of symmetric electrodes underneath a dielectric layer and the size of the electrodes are of the same order as the size of the moving object, and there is a small gap between the object and the electrode, the object's approaching to and/or departing from the electrodes create an asymmetric charge distribution via induction in the media, provided the object was prior-charged by a triboelectric process, which causes the electrons to flow between the two electrodes to balance the local potential distribution (Fig. 5d) [28]. The oscillation of the electrons between the paired electrodes in responding to the back and forth motion of the object produces an AC current output. This mode carries the advantages of harvesting the energy from a moving object but with the entire system mobile without grounding.

Major applications of TENG

To provide a comparison, Fig. 6 gives a comparison between EMG and TENG, through which one can see the distinction differences between the TENG and EMG. The major applications of TENG are in three directions (Fig. 7): as sustainable nano/micro-power source for small devices to achieve self-powering; as active sensors for medical, infrastructure, human-machine, environmental monitoring and security; and as basic networks units for harvesting water motion energy at low frequency toward the dream of blue energy [9].

TENGs as sustainable nano/micro-power source for self-powered systems

The ultimate goal of nanogenerators is to build up self-powered systems (Fig. 8), in which multifunctional electronic devices can be powered up by the nanogenerators through collecting ambient mechanical energies [29]. TENGs can convert irregular and mostly low-frequency energy from almost any mechanical motion from human, machine to nature into electricity. Such pulsed energy cannot be directly used to drive conventional electronics that


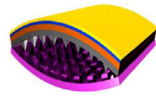
	Electromagnetic generator	Triboelectric nanogenerator
		
Mechanism	<ul style="list-style-type: none"> Electromagnetic induction; Resistive free electron conduction driven by Lorentz force 	<ul style="list-style-type: none"> Contact electrification and electrostatic induction; Capacitive displacement current arising from time-dependent electrostatic induction and slight motion of bonded electrostatic charges
Pros	<ul style="list-style-type: none"> High current, low voltage; High efficiency at high frequency; High durability, long life 	<ul style="list-style-type: none"> High voltage, low current; High efficiency at low frequency; Low cost, low density, low weight; Multiple working modes; Diverse choice of materials; Diverse use of fields; Broad use as sensors
Cons	<ul style="list-style-type: none"> Low impedance; Heavy, high density; High cost 	<ul style="list-style-type: none"> High impedance; Low durability

FIGURE 6

A comparison about the electromagnetic generator and triboelectric nanogenerator in mechanisms, advantages and disadvantages.

require a continuous and constant input. A new power management system is required for lowering the output voltage but without sacrificing energy, so that the generated electricity can be directly stored as electrochemical energy by a battery or capacitor [30]. Such a power management cannot be accomplished by a classical transformer, which usually has a very low efficiency at low-frequency. An integration of a TENG, power management circuit and storage unit form a self-charging power unit. This unit can be used as a sustainable power source for powering any electronics as long as the power output is sufficient. This is the first major applications of TENG.

TENGs as self-powered active sensors

TENG is a technology for converting mechanical energy into electricity. Reversely, the electric output signals of the TENG directly reflect the impact of the mechanical triggering, so that TENG can be used as an active sensor in responding to external excitation [31]. From Eq. (7), the output voltage is a direct measurement of the gap distance z , while the output current represents the impact speed, dz/dt . The TENG based sensor is different from the conventional sensor that has to be driven by a power, otherwise there is no output signal. In contrast, the TENG sensor gives an output electric signal itself without applying a power to the sensor tip. TENG based sensor can be used for sensing of motion, vibration, human triggering and object contacts.

We use keyboard based TENG as an example [32]. Keyboard is an indispensable input component for many personal electronics like computers and cell phones. We recently invented an intelligent and self-powered keyboard as an advanced security safeguard against unauthorized access to computers. Based on the triboelectric effect between human fingers and keys, the intelligent keyboard (IKB) could convert typing motions into localized electric signals that could be identified as personalized physiological information. The core part of the IKB was composed of multilayered transparent thin film materials to form a typical single-electrode TENG. Fig. 9a shows the schematic structure and a photograph of a fully-assembled IKB with the same size as a commercial keyboard. The working principle of the IKB as an

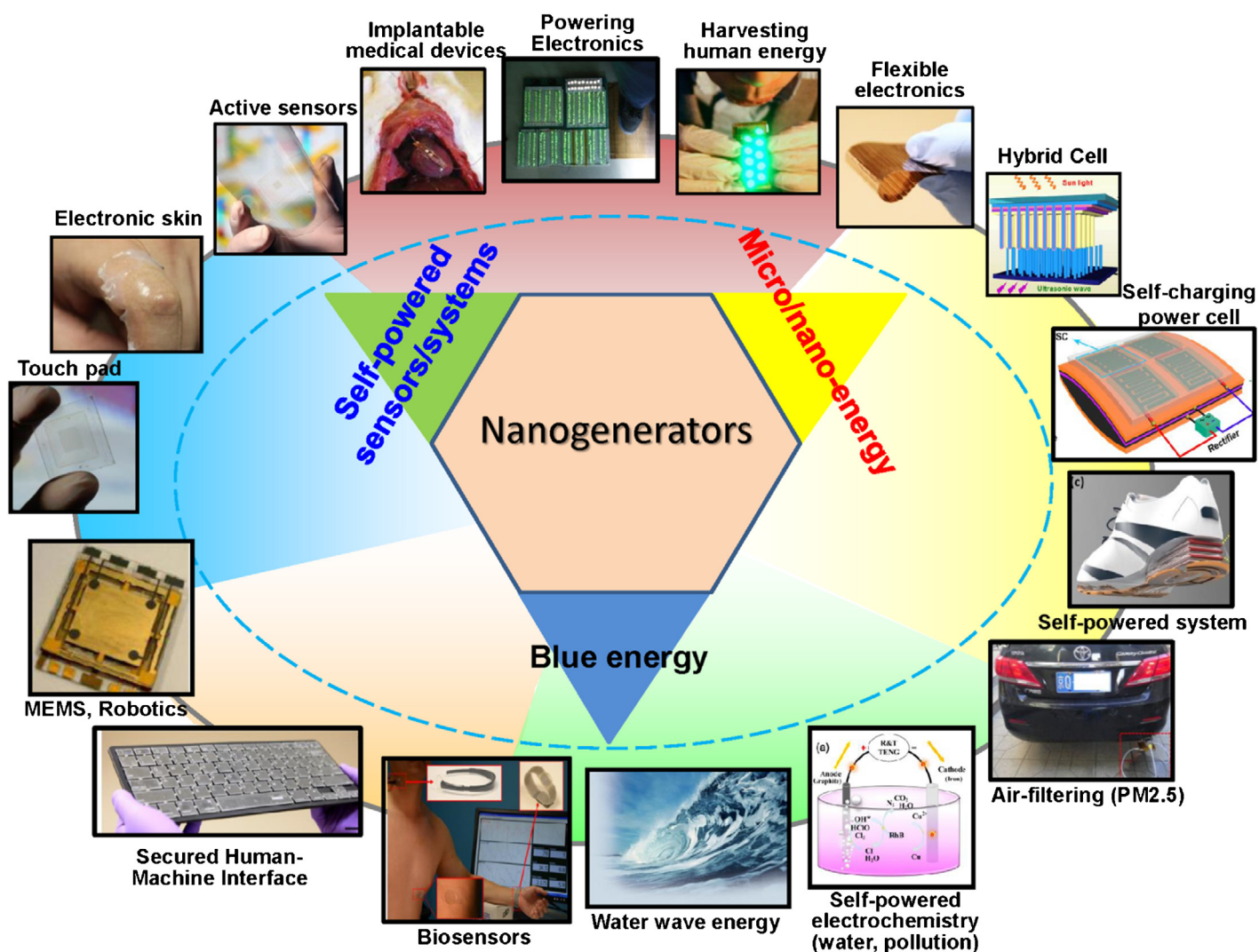


FIGURE 7

A summary about the three major application fields of nanogenerators as micro-/nano-energy source, for blue energy and self-powered sensors. The photos around the three directions are the ones we have demonstrated in our experiments in the last few years.

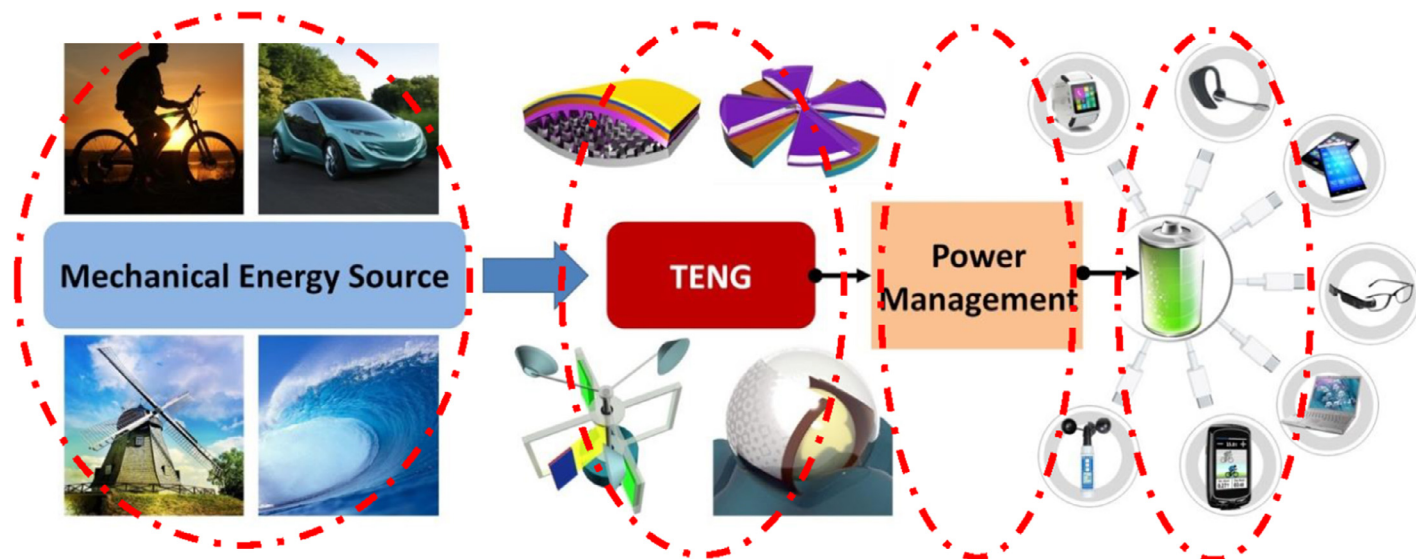
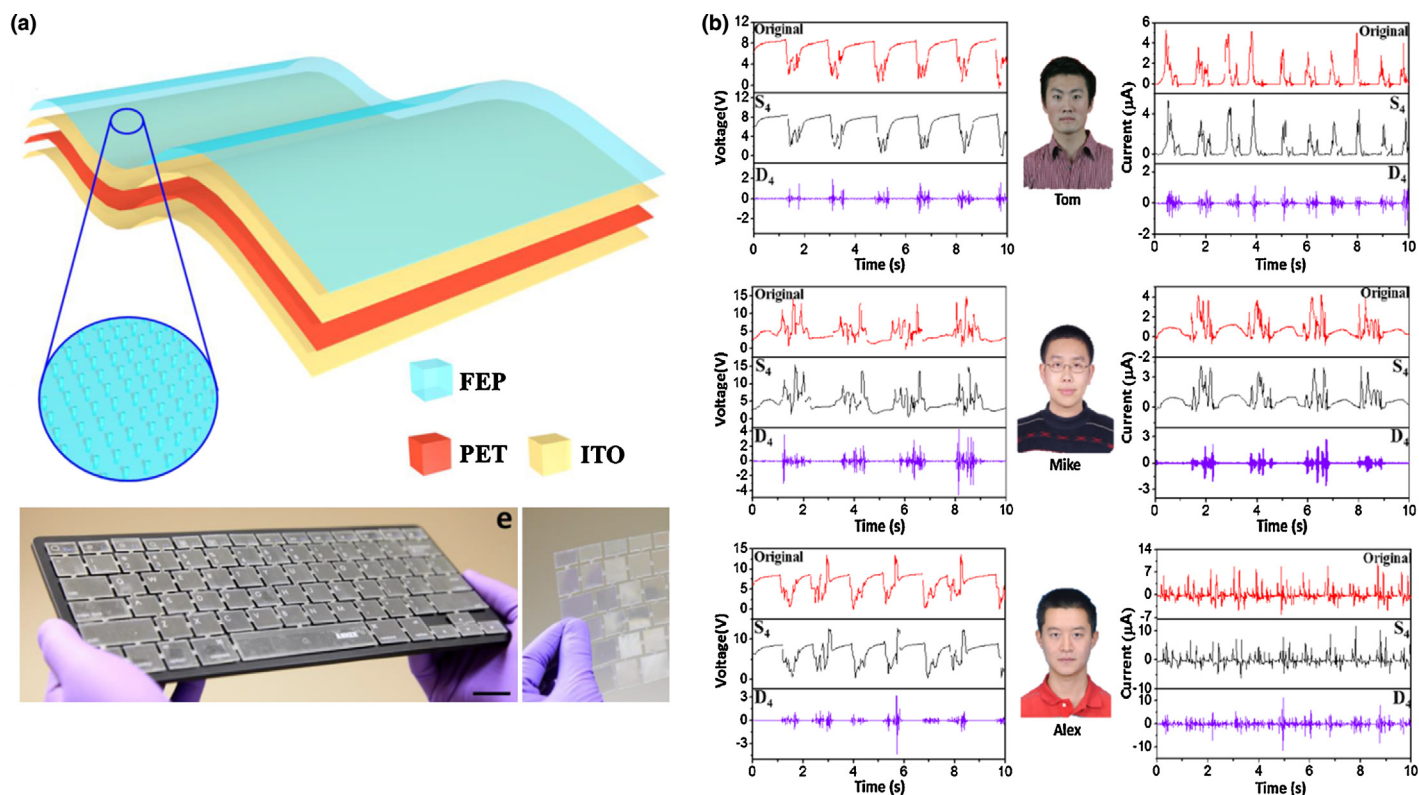


FIGURE 8

A self-powered system by integrating a nanogenerator, power management circuit and energy storage unit as a self-charging power cell.

**FIGURE 9**

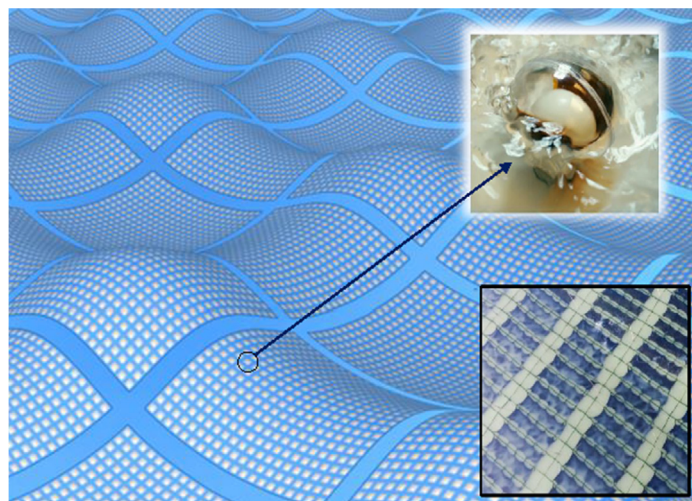
Personalized keystroke dynamics for self-powered human-machine interfacing. (a) Schematic illustrations of the keyboard. (b) Evaluation of the performance of the biometric authentication system using triboelectrification enabled keystroke dynamics by repeatedly typing the same phase of words by three different people. The output electric signals are completely different from one person to the other, but each person's pattern is self-reproducible.

energy harvester was similar with the single-electrode TENG. A finger movement during typing would then induce change of the potential difference between the pair of ITO electrodes, driving electrons flow through the external load or data collection system. The electric signals generated by three people by typing the same phrase or words are completely different, which can be used to identify the user of the computer for system protection (Fig. 9b).

TENGs as basic units for large-scale blue energy

Our earth is largely covered by water. Energy offered by ocean can be huge, but harvesting such energy is extremely challenging because the low efficiency of electromagnetic generators, especially at low frequency [33]. TENG is much more effective than EMG for harvesting energy in the frequency range of <5 Hz, which is ideally suited for our daily life and in nature (not EMG works only effective at relatively high frequency such as >5 Hz). More importantly, the EMGs are heavy and high cost, and they are not easily to be installed in sea floor or at water surface for collecting the water wave energy. I proposed the idea of using TENG networks for harvesting water motion energy at a large scale in 2014 [34]. The idea is that the TENG is made of mostly organic materials and it is partially filled up with air, so that the network made of millions of TENGs as fishing net would flow at the vicinity of the water surface (Fig. 10). Any wave motion would drive the TENG to perform contact-separation and sliding motions, so that the mechanical energy can be collected. Our initial estimation indicates that the power can be generated on average is 1 MW/km^2 , which could be improved for at least 10 times based on near future progress in

materials and structure design [35]. The advantage offered by TENG networks is low-cost, occupy no land, no natural disaster, independent of day, night or even weather, and there is no big security concern. I believe that this blue energy dream will offer a new energy path for human kind.

**FIGURE 10**

A blue energy dream by networking millions of spherical balls based triboelectric nanogenerators for harvesting low-frequency water wave energy. The inset is the designed spherical TENG. The lower-right corner is an imaginary structure of the networks.

Summary

The goal of this review article is to present the linkage between the Maxwell's displacement current and the output of nanogenerators, so that the differences between EMG and PENG/TENG are clearly elaborated. The displacement current has two components (Fig. 11). The first component $\epsilon_0 \frac{\partial E}{\partial t}$ represents the electricity to magnetism induction effect, so that it represents the existence of electromagnetic waves and the theory of light. As a result, it is the foundation of antenna, telegram, radio, TV, and most recently wireless communication technology. It means that the first component of displacement current is the foundation of today's wireless information technology, which has driven the development of the world for the last 50 years.

In parallel, the second term $\frac{\partial P}{\partial t}$ in the displacement current is related to the polarization of media, from which the fundamental characteristics of piezoelectric nanogenerator and triboelectric nanogenerator can all be derived. Besides the applications in capacitors, the second term gives the birth of new energy technology and self-powered sensors, for example, our nanogenerators, which could have extensive applications in IoT, sensor networks, blue energy and even big data. The industry as generated by the second component of the displacement current could possibly drive the development of the world in energy and sensors in the next 50 years at least!

Our study indicates that the second term $\frac{\partial P}{\partial t}$ in the displacement current is directly related to the output electric current of the nanogenerator. In other words, the applications of displacement current in energy and sensors are our nanogenerators. Based on this future prediction, we like to emphasize here is a lacking of

fundamental understanding about the phenomenon of triboelectrification. Although this phenomenon is known for over thousands years, its basic physics interpretation is unclear. Why? I believe that there was not enough study devoted to it because triboelectricity has been attributed as a negative effect, so people would think that it is not important or rather difficult to understand. However, as now, triboelectric nanogenerator finds the true applications of contact electrification and it is time to study this phenomenon and explore the core physics, for example, the physics each and every one of us experiences every day! We now have the urgency and practical implication for studying charging effect at dielectric surfaces. Once a clear physical picture is presented, developing effective triboelectrification process and structure would hugely impact the technological development of nanogenerators and their commercial products.

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Displacement current:

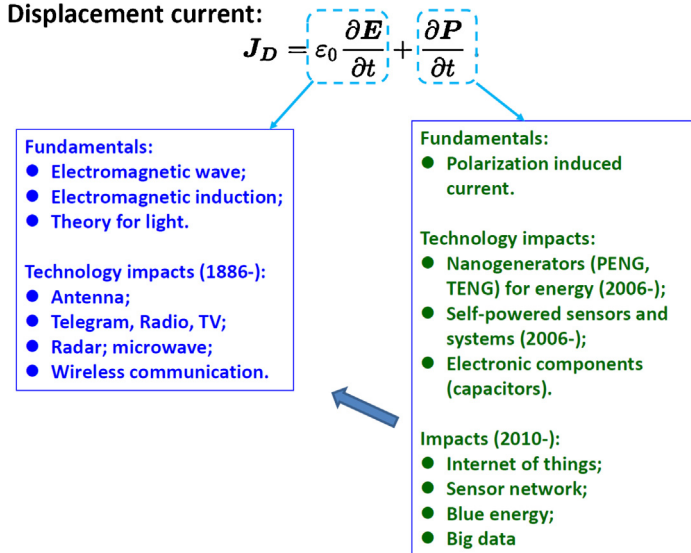


FIGURE 11

Major fundamental science, technologies and practical impacts that have been derived from the two components of the Maxwell's displacement current. The left hand-side column is the electromagnetic wave that has impacted the development of the world in the last century in communication; the right-hand side is the new technologies derived from displacement current for energy and sensors that are likely to impact the world for the future.