Piezo/Tribotronics Toward Smart Flexible Sensors

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Smart, flexible, and self-powered sensory systems represent the developmental trend of information technology beyond Moore’s law with versatility and diversity toward artificial intelligence. Piezo/tribotronics offer a direct linkage/triggering of the electrical output sensing signals with external mechanical actions in an active way, which is highly promising in smart and flexible sensors, intelligent human–machine interaction, and self-powered systems. Starting with the origin of piezo/triboelectric nanogenerators (PENGs/TENGs), herein, a review on the piezotronic devices based on 1D nanowires, 2D materials, 1D/2D mixed dimensional structures, PENG/TENG-gated three-terminal devices, and their applications in various multifunctional sensors is covered. In addition, a discussion is provided around how to improve the effectiveness in utilizing the piezo/triboelectric potential and fabricate smarter and more sophisticated electronic devices. Finally, future research concerns on piezo/triboelectric potential applications are summarized. There remains a massive space for the further development of piezotronics/tribotronics, which will be a multidisciplinary subject closely associated with soft electronics, neuromorphic devices, artificial intelligence, self-powered systems, and even ocean/space technologies.

1. Introduction

Moore’s law[1,2] has directed modern information technology (IT) for decades, which requires the number of transistors on silicon chips to be doubled every 18 months. Based on the complementary metal oxide semiconductor (CMOS) technology,[3,4] IT has achieved remarkable achievements with the fast-paced technical development of critical components, e.g., very large-scale integration circuit (VLSI),[5] central processing unit (CPU),[6] hard disk drive (HDD),[7] random access memory (RAM),[8] etc. One of the upcoming development directions of IT is established on the current CMOS digital technology toward further device miniaturization, higher integration density, and larger-scale CPU/RAM by following Moore’s law or “More Moore.”[9–11] In contrast, transistor scaling approaching the technology node of ≈3 nm[12] requires new techniques to transcend Moore’s law with versatility, which leads to the rapid development of multifunctional devices, active sensors, neuromorphic chips, artificial intelligence, interactive communicators/interfaces, and self-powered systems.[13,14] The demonstrated multifunctional and diversified devices toward smart flexible sensors, electronic skins (E-skins), non-Von Neumann architectures, and intelligent robotics are leading another “More than Moore” research direction. The construction of the unconventional nondigital “sensor” and “communicator” to surround the conventional digital transistor “brain” is opening up the possibility for more intelligent human life in the near future (Figure 1).

Among the reported E-skins,[15–18] epidermal electronics,[19] and mechanosensation systems,[20,21] the demonstrated flexible sensors are primarily based on the capacitor, resistor, transistor, light waveguide, piezoelectric/triboelectric devices, etc. Categorized by the way of driving, the capacitive, resistive, and transistor-type sensors require the external power source to supply the requisite energy for device operation and sensing implementation. By contrast, the piezoelectric/triboelectric devices can produce piezo/triboelectric potential[22–26] as the power source for itself, which is directly associated with the external mechanical stimuli or acts as the “intermediator” between the biomechanical action and electronic devices. The emerging low-frequency energy-harvesting technique[27] that is, piezo/triboelectric nanogenerators (PENGs/TENGs), has also been extensively investigated to modulate the transport properties of semiconductor devices for various pressures/forces/strains/stress sensors[28] and self-powered sensory systems.[29] These electronic devices which utilize piezo/triboelectric potential can be classified into a category of interactive devices, termed piezotronics and tribotronics.

Piezotronics is an interdisciplinary subject that combines piezoelectric property and the properties of semiconductor. It was first proposed by Wang[30] and has drawn a great deal of attention so far. It primarily focuses on the semiconductor materials with a noncentral symmetric lattice structure, including 1D wurtzite...
nanowires (e.g., zinc oxide [ZnO],[31] gallium nitride [GaN],[32] cadmium sulfide [CdS],[33] indium arsenide [InAs],[34] and indium nitride [InN][35]) and some 2D materials (e.g., MoS₂, MoSe₂, and other transition metal dichalcogenides [TMDCs]).[36–39]

In addition, a three terminal device (e.g., PENG-gated field effect transistor [FET])[35,40] which utilize a piezoelectric nanowire or a piezoelectric polymer as a gate, can also be classified as a piezoelectric device according to a more general definition. Analogously, tribotronics,[23] first proposed in 2014, represents an emerging branched research field of TENG applications that couple the triboelectric static effect with semiconductor devices. On tribotronic devices, the triboelectric potential induced by contact electrification and electrostatic induction acts as the “gate” to modulate the electrical performance of semiconductor materials such as silicon,[23,41] organic semiconductors,[42] 2D semiconducting materials,[21,43,44] etc. In comparison with the conventional capacitive, resistive, and transistor-type sensors, piezo/tribotronics provide a direct linkage/triggering of the electrical output sensing signals with external mechanical actions in an active way (compared with the passive driving fashion by external power source), which is highly promising for use in smart and flexible sensors,[45] human–machine interaction,[46] artificial intelligence,[29] and self-powered systems.[47]

This Review will mainly focus on the smart and flexible self-powered sensory systems based on piezotronics and tribotronics. As shown in Figure 2, starting with the origin of the piezoelectric nanogenerator (i.e., Maxwell’s displacement current),[23,51] we first list the piezotronic devices based on 1D nanowires, 2D materials, 1D/2D mixed structures, PENG-gated three-terminal devices (i.e., FETs), and their applications in smart/flexible sensors and human–machine interaction with artificial intelligence. Then, we conduct the review of tribotronics from the origin of the triboelectric potential, fundamental working principle, efficient tribotronic gating methods, and its application in intelligent tribotronic systems including logic devices,[44,54] smart touch sensors/array,[43,49,51] distance sensors,[21] materials recognition,[21] etc. Finally, we conduct the discussion around how to make use of the piezo/tri博potential more efficiently to develop intelligent flexible sensors and construct complete sensory systems with high sensitivity, precise control capacity, effective implementation, and low-power consumption.

2. Piezotronics

Piezotronics describe the devices that take the piezopotential as a “gate” voltage to modulate the carrier transportation properties or Schottky barrier height (SBH) at the metal–semiconductor contact (M–S contact)/p–n junction.[55–59] In essence, piezopotential is an external strain-induced local electric field originating from the nonmobile and nonannihilative ionic charges in a noncentrosymmetric crystal. As shown in Figure 3a,b, when a tensile strain is applied on the semiconductor with an asymmetric structure, a negative piezopotential, which is induced by the negative piezoelectric polarization charges, will repel the electrons away from the M–S interface/p–n junction, thus resulting in an increase in local SBH. Conversely, when a compressive strain is applied, the positive piezopotential induced by positive piezoelectric polarization charges will attract the electrons toward the M–S interface/p–n junction. Consequently, the positive piezopotential causes electrons to be less depleted at the interface/junction and local SBH to decrease. Due to the induced piezopotential under external strain, the piezotronic effect can be taken advantage of by both strain-gated two-terminal devices and piezopotential/strain-gated transistors.

The rationale of a PENG-gated three-terminal device is shown in Figure 3c. The piezoelectric material (piezomaterial) is sandwiched between two metal electrodes to constitute a PENG. The basic theory of the nanogenerator stems from the Maxwell equations. The second term $\frac{\partial}{\partial t}$ in Maxwell’s displacement current is directly associated with the output current of the PENG.[52] Piezopotential represents an intrinsic inner crystal field induced by electric dipole (composed of positive and negative charges) moments in piezomaterial under external stress.[22] The stress along different directions will lead to the rearrangement of

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electric dipoles. The applications of tensile and compressive stress to the piezomaterial are equivalent to applying negative and positive gate voltages ($-qV_{PENG}$ and $qV_{PENG}$) to the FET, thus resulting in the bending of energy band and carrier depletion (or accumulation) in the channel.

2.1. Piezotronics in 1D Wurtzite Nanowires

Plenty of studies have been conducted on two-terminal devices based on 1D wurtzite nanowires, such as ZnO, GaN, CdS, etc. According to the electromechanical conversion, the nanowires constructed in different architectures (vertical, horizontally aligned, and arrayed) are applicable in piezoelectric devices with excellent mechanical and electrical properties, for example, nanogenerators,[31,60–62] strain sensors,[28] and pressure imaging.[63–65]

2.1.1. Piezoelectric Nanogenerators Based on Vertical 1D ZnO Nanowires

The first PENG based on vertical ZnO nanowires was proposed in 2006 (Figure 4a).[31] The measurements are carried out by atomic force microscope (AFM) scanning across the ZnO nanowire array grown by the vapor–liquid–solid (VLS) process.[66,67] As the AFM tip scans over the vertically aligned nanowires in the contact mode, the nanowires are bent continuously. A notable output voltage peak can be observed in each scan of the tip. The coupling between piezoelectric and semiconducting properties in ZnO nanowire leads to charge separation across the NW as a result of the applied strain. The corresponding output voltage image of the ZnO nanowire array is recorded when the AFM tip scans over the nanowire array. The output voltage amplitudes are primarily distributed between 6 and 9 mV. The energy efficiency of the ZnO nanowire-based piezoelectric nanogenerator ranges roughly from 17% to 30%. This method first demonstrates the conversion of micro-/nanoscale mechanical energy into electrical energy through the piezoelectric ZnO nanowire array, from which the current well-developed, self-powered systems and technologies originate.

2.1.2. Strain Sensors Based on Single ZnO Nanowires

Relying on the interface charge carrier modulation, the coupling effect between piezoelectricity and electronic transport in piezoelectric semiconductors is the core of piezotronic effect.[30,57,58,68] A typical flexible strain sensor based on horizontal ZnO micro-/nanowires and the piezotronic effect is shown in Figure 4b.[28] This strain sensor is fabricated by bonding a single-crystal piezoelectric ZnO micro-/nanowire onto a polystyrene (PS) substrate. Volt–ampere characteristics ($I–V$ curves) are highly sensitive to strain as the induced remnant piezoelectric charges can have a significant impact on SBH. Notably, the piezotronic effect (e.g., nonlinear rectifying $I–V$ curve, asymmetric effect on end contacts, strong polarity, interface effect, and switch function) has to be distinguished from the piezoresistive effect, which is commonly existent in conventional semiconductor materials. In general, there are a number of parameters which can be used to evaluate the performance of a strain sensor, including sensitivity/gauge factor, response time, and durability. Gauge factor is defined as the curve slope of the normalized current versus strain ($\Delta I/I_0/\varepsilon$), where $I_0$ indicates the initial current, $\Delta I$ denotes the current variations at a certain strain, and $\varepsilon$ refers to the...
applied strain. The response time is defined as the time interval related to the current variation from 10% to 90%. The gauge factor of the ZnO piezotronic strain sensor is 1250, whereas the response time is 10 ms.

2.1.3. Large-Area-Integrated Piezotronic Transistor Array Based on Vertical ZnO Nanowires

Integrating nanodevice arrays into a functional system plays a critical role in realizing high-resolution sensation, propelling the nanoscience to practical nanotechnology. Wu et al. presented a massive area of integrated piezotronic transistor arrays with the vertical ZnO nanowires taken as an active taxel-addressable matrix for tactile imaging (Figure 4c). A two-terminal strain-gated vertical ZnO nanowire piezotronic transistor is treated as the basic unit of the integrated device. Different from the operation mechanism of the traditional voltage-gated transistor, the strain-gated piezotronic transistor is capable of tuning carrier transport/SBH by strain-induced polarization charges at the interface between electrodes and nanowire. Therefore, the fabrication processes of piezotronic transistors in circuitry array integration are significantly simplified due to the removal of gate electrodes. A large-scale integration of piezotronic transistor arrays with a device density of 92 × 92 can be achieved by combining the bottom-up growth of vertically ZnO nanowires and top-down microfabrication techniques. Such a piezotronic matrix can enable self-powered sensing and tactile pressure imaging by applying external mechanical stimuli in the absence of gate voltage. Furthermore, the simplification of the matrix integration provides a significant route to the development of multifunctional and diversified large-scale smart sensors.

2.2. Piezotronics in 2D Materials

2D semiconductor materials have attracted much attention for the development of electronic devices due to a combination of
their excellent electronic transport properties, optical properties, thermal properties, and mechanical properties. A large proportion of the presented 2D materials, e.g., TMDCs (MoS$_2$, MoSe$_2$, etc.), hexagonal boron nitride (hBN), layer-phase group III monochalcogenides (GaS, GaSe, and InSe), and group IV monochalcogenides (MX, M = Sn or Ge, X = Se or S), exhibit piezoelectric properties because of the inner-asymmetry crystal structure when the thickness is reduced to monolayer or a few number of odd layers. As predicted in theoretical research, the strain-induced polarization/piezoelectricity exists in the atomically thin semiconductors, which may also be applicable to modulate charge carrier transport at the Schottky contact. The piezotronic effect in the mechanically exfoliated monolayer MoS$_2$ was first observed experimentally in 2014 (Figure 5a). The asymmetric output currents at the opposite drain biases under external strain are observed in monolayer MoS$_2$, which is a scientific evidence of the piezotronic effect. As shown in the energy band diagram drawn under different strains, strain polarization causes a change to SBH, thus leading to the piezotronic behavior in single-layer MoS$_2$ devices. By contrast, the piezoresistive effect (the symmetrical currents) is observed in a bilayer and bulk MoS$_2$ flakes. As a strain sensor, the gauge factors for the piezotronic MoS$_2$ and bulk MoS$_2$ devices are 230 and 200, respectively. The piezotronic effect has been observed as well in a multilayer α-In$_2$Se$_3$ flake as shown in Figure 5b. As a proof of concept, a self-powered piezotronic sensor based on α-In$_2$Se$_3$ flake operates in a direct coupling way, has massive advantages in the detection of breath state due to synchronization occurring between current signals and breath sequences.

2.3. Piezotronics in 1D/2D Mixed Structure

Recently, the piezopotential-/strain-modulated devices in 1D/2D mixed dimensional structures have provided an alternative to achieving electromechanical conversion and developing more sophisticated piezotronic sensory devices. In these 1D/2D mixed structured devices, the piezopotential of 1D nanowires (e.g., ZnO and GaN) can act as “gate voltage” to tune the carrier transport in the 2D semiconductor channel or the SBH at the M–S contact or heterostructures. The fabrication process of the 1D/2D mixed dimensional hybrid structure through the self-aligned method is shown in Figure 6a. First, 1D p-type GaN nanowires are transferred onto monolayer MoS$_2$ flakes grown on SiO$_2$/Si substrate. Second, all the electrodes are patterned by means of standard e-beam lithography and metal deposition. Finally, 10 nm Au thin film is deposited on the MoS$_2$ channel to create the nanoscale channel by following a self-aligned process. The 1D GaN nanowire plays the role as a self-aligned local gate for 2D MoS$_2$ FET, as shown in Figure 6b. A p–n junction is formed at the 1D/2D (GaN/MoS$_2$) interface, which can reduce the gate leakage current due to the formed depletion region located at the GaN/MoS$_2$ interface. Another example is the strain-gated FET based on 1D ZnO nanowire array and 2D MoS$_2$ flake mixed dimensional hybrid structures. Under external strain, the ZnO nanowires provide the gate voltage for MoS$_2$ flakes conductive channel. The electrical performance of both the ZnO–MoS$_2$ stacked structure (Figure 6c) and ZnO–Al$_2$O$_3$–MoS$_2$ sandwiched

Figure 3. The piezotronic effect and piezo/triboelectric potential modulation. Schematic energy diagrams of the piezotronic effect at the metal-semiconductor contact a) and p–n junction b) under tensile and compressive strains. Adapted with permission. Copyright 2016, Springer Nature. c) Piezoelectric and triboelectric potential modulations in FET.
structure (Figure 6d) is investigated. When the external strain applied to the ZnO nanowire is on the increase, the output current of the ZnO–MoS$_2$ structure would decline due to the depletion of charge carriers in the MoS$_2$ channel. In contrast, the output current of the ZnO–Al$_2$O$_3$–MoS$_2$ structure increases as a result of the accumulation of charge carriers. Other examples of the piezotronic 1D/2D mixed structure are premised on ZnO/graphene heterostructure. By combining the piezoelectric property of ZnO the nanowire, the transfer of ultrafast electrons in graphene, and excellent photoresponse of the heterostructure, a success is achieved in the development of the strain-modulated high performance photosensor, as shown in Figure 6e. When the tensile strain on the ZnO nanowire is applied at 0.44%, the photoresponsivity of the device is enhanced by as much as 26%.

2.4. Piezotronics in PENG-Gated Transistors

Compared with 1D piezoelectric materials, the solution-treated polymer piezoelectric materials also show significant advantages due to remarkable flexibility, low-temperature processability, and chemical inertness. In addition, it is highly applicable to flexible, wearable, and conformable strain sensors. Based on capacitive coupling, the piezoelectric polymer can be used to achieve piezopotential/strain-gated (or PENG-gated) transistor by simply patterning it at the designated position of the extended gate region with the assistance of solid-state electrolyte dielectrics. For the piezotronics based on the PENG-gated transistor, poly (vinylidene fluoride-co-trifluoroethylene) P(VDF-TrFE) film (a typical piezomaterial) is highly desirable as the “gate” to modulate the transport properties of the semiconductor channel due...
to the preferential ferroelectric β phase with the addition of a third fluoride into the TrFE monomer unit (internal polarization phenomenon), which has been widely reported in the relevant literature.\cite{15,22,81}

2.4.1. PENG-Gated Transistor for Modulating Schottky Barrier Height

The piezopotential originating from PENGs is readily available to modulate the density of charge carriers (or Fermi level) of the FET semiconductor channel.\cite{81} Nevertheless, the intrinsic insulating properties of the piezoelectric polymer have restricted its practical application in the direct modulation of the energy barrier at heterojunctions (such as M–S contacts or p–n junctions) due to the broad bandgap in insulating piezoelectric polymer when compared with semiconductors (i.e., bandgap mismatch between insulator and semiconductor). The combination of the PENG and vertical Schottky barrier transistors delivers a way to ensure efficiency in tuning the SBH at M–S contact in the piezotronic graphene barristor. The piezopotential generated in PENG performs two major functions in the piezotronic graphene barristor. One is to modulate the charge carrier density in IGZO channel and the other is to tune the SBH formed between graphene and IGZO by modulating the work function of graphene. The feasibility of piezopotential modulating the SBH in graphene barristor is mainly determined by the linear energy dispersion relationship in the graphene band structure and efficient piezopotential-gating properties through electrical double layers (EDLs)\cite{82} in ion gel. Multilevel modulation for SBH can also be realized by integrating double PENGs to single ion-gel-gated transistors, as shown in Figure 7a. The piezopotentials initiate the accumulation of electrons in graphene (the Fermi level, $E_F$ shifts upward), when the external strains are continuously applied to the two PENGs, which lead to a stepped increment of the output current. Conversely, the release of the strain for PENGs causes a downward shift of the $E_F$ in graphene, which causes the current in the transistor to decrease. Combined with the piezopotential modulation of charge carrier density in the FET channel, the efficient modulation of SBH by piezopotential achieves the strain modulation of typical semiconducting characteristics while widening the range of piezotronics for more sophisticated smart sensor designs.

2.4.2. PENG-Gated Transistors for Static and Dynamic Modulation

To further extend the application of piezotronics, a piezoelectret coupled with MoS$_2$ FET has been demonstrated to achieve both static and dynamic piezopotential modulation (Figure 7b).\cite{22} The remnant polarization in piezoelectret can statically modulate the Fermi level of the MoS$_2$ channel to initialize the current level of MoS$_2$ FET (initial current varying from $10^{-9}$ to $10^{-7}$ A by changing the direction of prepolarization stress). With regard to the dynamic transfer characteristics (current vs strain), the on/off ratio of the piezoelectret-gated MoS$_2$ FET tuned by external strain exceeds four orders of magnitude. Moreover, the strain dynamically induced piezopotential is capable to further tune the Fermi level of MoS$_2$ and create a high-performance strain sensor (large gauge factor of 4800, fast response time at 0.15 s, and good durability over 1000 s). The static and dynamic piezopotential modulation diversifies the application of the piezotronic effect and can be extended to the devices based on pyroelectret materials for multifunctional sensory systems and the harvesting of highly efficient energy.

Figure 5. Piezotronics in 2D piezoelectric materials. a) Monolayer MoS$_2$ piezoelectric device and energy band diagrams. Reproduced with permission.\cite{38} Copyright 2014, Springer Nature. b) Self-powered piezoelectric sensors based on a multilayer α-In$_2$Se$_3$ flake for real-time monitoring of breath signals. Reproduced with permission.\cite{16} Copyright 2019, American Chemical Society.
2.4.3. PENG-Gated Graphene Transistors for Strain Sensors

A strain sensor based on a single PENG-gated graphene transistor and the corresponding output characteristics is shown in Figure 8a.\textsuperscript{[15]} The PENG-gated graphene transistor consists of a P(VDF-TrFE)-based PENG and a coplanar ion-gel-gate graphene transistor. The strain-induced piezopotential in PENG tunes the Fermi level of the graphene channel and affects the output drain current. According to equivalent positive piezopotential, the drain current of the strain-gated graphene transistor increases as the applied strain is on the rise. The opposite output current behaviors of the PENG-gated graphene transistor under tensile (0.06\%) and compression (−0.06\%) strain are shown in Figure 8b. The tensile and compressive strains contribute to opposite piezopotentials in PENGs. Consequently, the number of holes in the graphene channel increases under tensile strain but declines under compressive strain. The gauge factor for the PENG-gated graphene transistor is 389.

Moreover, an active matrix strain sensor array based on PENG-gated graphene transistors is integrated into a flexible and transparent substrate, as shown in Figure 8c. The output currents of 4 × 4 pixels and the quantitatively visualized 2D color mapping of strain distribution on the active matrix are recorded. In addition, the demonstrated flexible and transparent strain-gated sensors can be fabricated on the elastic substrate and applied in wearable mechanical actions monitoring.

Figure 6. Piezotronics in 1D/2D mixed dimensional hybrid structure. a) Schematic illustrations of the GaN nanowire-gated MoS\textsubscript{2} FET through the self-aligned method. b) Schematic energy band diagrams and working principle of a GaN nanowire-gated MoS\textsubscript{2} FET. Reproduced with permission.\textsuperscript{[77]} Copyright 2016, American Chemical Society. c) Strain-gated FET based on ZnO–MoS\textsubscript{2} hybrid structure. Reproduced with permission.\textsuperscript{[40]} Copyright 2015, American Chemical Society. d) Strain-gated FET based on ZnO–Al\textsubscript{2}O\textsubscript{3}–MoS\textsubscript{2} hybrid structure. Reproduced with permission.\textsuperscript{[40]} Copyright 2015, American Chemical Society. e) Strain-modulated photoreponse performance of the ZnO nanowire-graphene mixed dimensional van der Waals heterostructure. Reproduced with permission.\textsuperscript{[48]} Copyright 2017, Tsinghua University Press and Springer-Verlag GmbH Germany.
2.4.4. PENG-Gated Strain Sensors with Memory Functions

A piezopotential-programmed nonvolatile memory array based on PENG-gated (indium gallium zinc oxide) IGZO FETs has been developed, as shown in Figure 8d. The writing and erasing process of the IGZO-based memory can be fulfilled by applying the external mechanical strain, which is closely associated with the induced piezopotential in the PENG component. With change made to external strain, the piezopotential-programmed memory is capable of achieving multilevel data storage with an excellent memory performance, including a large writing/erasing current ratio of $10^3$, multilevel data storage of 2 bits (over 4 levels), cycle stability over 100 times, and consistent data retention of over 3000 s. The real-time output currents (top panel) and the strain distribution in 2D color maps (bottom panel) of the eight memories during scanning over the target alphabet pattern “OEDL” are shown in Figure 8e. It is noteworthy that the piezopotential-programmed nonvolatile memory is effective in reducing the energy consumption due to the absence of gate voltage, which plays a crucial role in the practical applications for E-skins and advanced human–machine interactions.

2.4.5. PENG-Gated Transistors for Artificial Synapse

Synapse$^{[83]}$ plays an important role in information delivery for biological somatosensory system, as shown in Figure 9a. The mechanoreceptors fitted in the skin are capable of receiving mechanical stimulus and converting it into the presynaptic potentials. The presynaptic potentials are transmitted to the central nervous system through neurons and synapses. It remains a challenge to develop sophisticated artificial synapses with a high performance, simplified fabrication process, and low power consumption. A piezotronic graphene artificial synapse based on the PENG-gated graphene transistor was first demonstrated by Sun and coworkers and is shown in Figure 9c.$^{[29]}$ The schematic diagram of signal processing steps for the artificial somatosensory systems is shown in Figure 9b.$^{[84]}$ The strain-induced piezopotential in PENG leads to the formation of EDLs in the ion-gel dielectric layer, which tunes the charge carrier transport in the graphene channel. In the transistor-type artificial synapse, the source–drain current is treated as postsynaptic current (PSC). The synaptic weights$^{[85]}$ can be modulated by carrying out external mechanical stimulation. The typical behaviors of the biological synapse are observed, such as excitatory postsynaptic currents (EPSCs), excitation/inhibition, and the paired pulse facilitation (PPF) as activated by external mechanical stimulation. Similar to the electrical behavior in biological synapse, the peak value of EPSCs increases as the external strain/duration time is extended in the piezotronic graphene artificial sensory synapse. Such behaviors are also observed in a dual-organic-transistor-based tactile perception system (strain sensors-gated organic synaptic transistors), as shown in Figure 9d.$^{[84]}$ Moreover, the dynamic modulation of a sensory synapse can be achieved by integrating double presynaptic PENGs to a single postsynaptic transistor. Such piezotronic synaptic devices provide a new insight into the progress made in the research field of flexible...
smart sensors for mechanical stimulation, self-powered electronic skins with artificial intelligence, and neuromorphic interfaces for neurorobots.

3. Tribotronics

An emerging field of tribotronics\textsuperscript{[21,86,87]} was proposed using triboelectric potential in TENGs as the “gate” to regulate charge carrier transport in semiconductor devices (middle panel in Figure 3c). Due to the excellent functionality and material diversity,\textsuperscript{[88–90]} tribotronics has been extensively demonstrated in a variety of different applications, such as tribotronic logic circuits,\textsuperscript{[44,54]} integrated organic light-emitting diodes (OLEDs),\textsuperscript{[42]} organic memory,\textsuperscript{[91]} smart touch sensors,\textsuperscript{[43,49,92]} and flexible/wearable distance sensors.\textsuperscript{[21,93]}

3.1. The Origin of Contact Electrification

The triboelectrification generated from the contact made between two different materials is a commonly seen phenomenon in our daily life, including lightning during thunder and the rubbing of a plastic rod and animal’s fur (Figure 10a).\textsuperscript{[94]} The TENG based on the triboelectrification phenomenon (electrical charging by friction between two different materials) has achieved substantial progress since its first-time introduction in 2012.\textsuperscript{[90]} The TENG can be effective in converting mechanical energy from ambient environment into electricity and has thus been extensively applied in various self-powered systems\textsuperscript{[96,67,80,95]} and triboelectric potential-modulated semiconductor devices.\textsuperscript{[87,96]}

The physical model\textsuperscript{[52]} of the basic mechanism of the TENG proposed in 2017 is derived from Maxwell’s displacement current, which is defined as follows.
Herein, the second term $\frac{\partial P}{\partial t}$ represents the polarization-induced current, which is the origin of the nanogenerator (including both PENG and TENG). Figure 10b shows the fundamental model of a TENG working in the contact-separation mode. It contains two dielectric layers with different levels of electronegativity for contact electrification and two electrodes connected to the external load. The working mode and material option of TENG are very broad, which is beneficial for the development of multifunctional and diversified electronics. Four basic working modes of TENGs including vertical contact-separation mode, lateral-sliding mode, single-electrode mode, and freestanding triboelectric-layer mode are shown in Figure 10c. It is worth noting that the utilization of TENG is not restricted to one working mode. It is free to design multimode combination on demands depending on specific

$$j_D = \frac{\partial D}{\partial t} = \varepsilon_0 \frac{\partial E}{\partial t} + \frac{\partial P}{\partial t}$$
applications. Within the broad range of materials, the friction materials at the opposite ends of the triboelectric series can produce a superior output performance. For example, polytetrafluoroethylene (PTFE) is a common electronegative material and makes it easy to generate negative triboelectric charges. In comparison, nylon or metal (Au, Cu, Al, etc.) is more likely to generate positive triboelectric charges.

3.2. Tribotronic Transistor and Working Mechanism

Wang’s group has reported the first tribotronic transistor based on contact electrification FET (CE-FET) through the combination of TENG and a bottom gate metal-oxide-semiconductor FET (MOSFET) (Figure 11a). The traditional gate is completely replaced with contact-separation-induced triboelectric potential, which is effective in reducing the energy consumption in CE-FET. The equivalent circuit diagram of the tribotronic transistor is shown in Figure 11b. As for CE-FET, the basic output characteristics at different vertical displacements ($D$) are shown in Figure 11c. Dissimilar from the conventional electrical behavior of FETs based on gate voltage ($I – V_C$), the drain current of the CE-FET increases gradually as the displacement increases from 0 to 80 $\mu$m. The working principle and the energy band diagram based on the tribotronic transistor are shown in Figure 11d. At the initial state ($D = D_0$), there is no transfer of charges that occurs between TENG and FET. When $D$ increases or decreases at a slow pace, positive/negative charges generated in TENG are transferred to the top gate electrode. In the meantime, the induced positive/negative potential ($\sigma^+ / \sigma^-$) on the top gate electrode increases, thus leading to the accumulation/depletion of the charge carrier or energy band bending in the semiconductor channel. In comparison with the threshold voltage ($V_{th}$) and subthreshold swing (SS) of traditional transistors, tribotronic transistor can be evaluated by the tribotronic threshold value ($D_t$) and tribotronic subthreshold swing (SS$_t$). The tribotronic threshold value ($D_t$) is the minimum distance of TENG which is considered necessary to create a conductive path between the source and drain terminals. The tribotronic subthreshold swing ($SS_t$) is defined as $SS_t = \delta (D_t) / \delta (\log_{10}(I_D))$, which suggests that the TENG displacement increment ($\Delta D$) could contribute to the variation in drain current ($I_D$) via an order of magnitude.

3.3. Triboiontronics

To develop high-performance tribotronic transistors, it is a pressing need to conduct in-depth research on the technical
engineering of TENG, corresponding semiconductor devices, and their coupling characteristics. Nevertheless, due to the previous complex manufacturing process and relatively poor electrical performance (especially, on/off current ratio < 10), there remains a massive space to develop tribotronics by improving the performance and broadening the applications toward smart flexible sensors. What is critical lies in how to improve the effectiveness in taking advantage of the triboelectric potential to gate transistor devices.

To achieve efficient triboelectric potential gating on transistors and explore the more diversified applications of FETs, a high-performance tunable tribotronic dual-gate logic device has been developed by integrating an n-type MoS\(_2\) transistor and a p-type black phosphorus (BP) transistor to a sliding-mode TENG.\(^4\)\(^4\) The tribotronic n-MoS\(_2\) and p-BP transistors produce excellent performance, such as a high current on/off ratio exceeding \(10^6\), a cutoff current below 1 pA \(\mu\)m\(^{-1}\), and a low energy consumption at about 1 nW. Figure 12a shows its schematic diagram, simplified equivalent circuit, working mechanism, and the electrical performance of the tribotronic complementary inverter based on tribotronic n-MoS\(_2\) and p-BP transistors. The triboelectric potential generated in TENG tunes electrons and holes transportation in n-type MoS\(_2\) and p-type BP channels, respectively. The tribotronic MoS\(_2\) FET works in the depletion mode, whereas BP FET works in the enhancement mode.

Furthermore, with the top-gate input voltage as the driving force of the tribotronic logic device, the triboelectric potential through the bottom gate is capable of tuning the electrical performance of the inverter, such as threshold voltages, gain values, inversion points, and static energy consumption. This study lays a foundation for the development of more sophisticated tribotronic logic circuits (such as AND, OR, NAND, NOR, etc.) which are based on tribotronic 2D electronics.

Taking advantage of the EDLs\(^8\)\(^,\)\(^9\)\(^,\)\(^9\)\(^9\)\(^9\) (≈ 1 nm thickness with ultrahigh capacitance of \(≈ 10 \mu \text{F cm}^{-1}\)) in electrolyte dielectrics, tribotronic gating regulation in a strong electric field provides another effective way of developing the high-performance tribotronic transistors. Recently, Sun and coworkers\(^2\)\(^4\) have reported a triboiontronic transistor of MoS\(_2\) to bridge triboelectric potential and ion-controlled 2D material transistors, as shown in Figure 12b. The carrier transport in MoS\(_2\) channel is modulated by the ion migration and arrangement, as activated by external mechanical stimuli. A triboiontronic MoS\(_2\) transistor capable of superior performance has been demonstrated according to the figures of merits of tribotronics, such as a higher current on/off ratio \((10^7)\), a lower triboelectric threshold value \((75 \mu \text{m})\), and steeper triboelectric switching properties \((20 \mu \text{m dec}^{-1})\).

Figure 11. Tribotronic transistor and working mechanism. a) Schematic illustration of a typical tribotronic transistor. Reproduced with permission.\(^2\)\(^3\) Copyright 2014, American Chemical Society. b) Equivalent circuit diagram of the tribotronic transistor. Reproduced with permission.\(^9\)\(^7\) Copyright 2017, American Chemical Society. c) Output characteristics of tribotronic transistor under at different TENG displacements. Reproduced with permission.\(^2\)\(^3\) Copyright 2014, American Chemical Society. d) Working principle (top panel) and energy band diagrams (bottom panel) of the tribotronic transistor at three modes: accumulation mode, flat-band mode, and depletion modes. Reproduced with permission.\(^2\)\(^4\) Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.
stability has been developed. This effective tribotronic gating method will accelerate the development of tribotronics, which show a massive potential in various fields like iontronic logical devices, ionic skins, human–machine interaction, and wearable smart electronics.

3.4. Tribotronic Tunneling

The large-scale integration of tribotronic transistors remains a challenge due to the bottleneck in matching the size of the TENG and transistor with effective tribotronic gating and the difficulty in further engineering the architectures of the fabricated tribotronic devices.⁹⁰ Therefore, nanoscale triboelectric potential gating is of great significance to explore more sophisticated tribotronic characteristics. Graphene and other 2D materials have the potential of application in tribotronics because of their unique and excellent properties of electronic transport. A rewritable ghost floating gate has been discovered in CVD-grown graphene under tunneling triboelectrification, which is only observed in the monolayer sample rather than the mechanical exfoliated flake or in bulk materials. Tunneling triboelectrification is the rubbing-induced charges tunneling between a graphene monolayer and an insulator substrate in the presence of air gap. Figure 13a,b shows the rubbing process, as measured by a Kelvin probe force microscope (KPFM). The distribution of surface potential before and after rubbing is shown in Figure 13c. Except the random fluctuation (due to crystal defects), the initial surface potential in the triboelectric area is in an equipotential state. After rubbing, the surface potential in the rubbed graphene area (0.5 × 0.5 μm²) is roughly 50 mV higher than that in the unrubbed area. Moreover, the charges caused by tunneling triboelectrification show a longer lifespan over two orders of magnitude. As a proof of concept, the rewritable p/p⁺ and p/n⁺ junctions and the rewritable ghost floating gates have been defined by a reset bias voltage on the rubbing AFM platinum tip (Figure 13d). The top panel is p/p⁺ junction under AFM tip rubbing and a bias of -10 V. The bottom panel is p/n⁺ junction upon the AFM tip biased with 10 V, whereas the p/p⁺ and p/n⁺ junctions can be repeatedly drawn, modified, and erased by the rewritable ghost floating gates. This charge-only, reversible, and rewritable method is essential for the development of the novel 2D materials-based on-demand tunneling tribotronic devices.

3.5. Tribotronic Applications Toward Smart Flexible Sensors

Due to the advantages of multiple working modes,⁹⁶ various optional materials,⁹⁸ and definable/reconfigurable structures,⁹⁰
the tribotronic transistor has been extensively applied in diversified multifunctional devices and sensors, such as tribotronic logic circuits, OLED-based tribotronic tactile sensors, tribotronic memory devices, tribotronic phototransistors, smart touch sensors, distance sensors, flexible wearable devices, and the likes.

3.5.1. Tribotronic Transistors Integrated with Functional/flexible Devices

Logic circuit can achieve the integration of discrete signals and has been commonly used in computers, communications, digital control, and instruments. In spite of this, the implementation of logic operation requires the activation by external gate voltage. A tribotronic logic device based on two opposite tribotronic MOSFETs has been developed by Wang and coworkers. The basic functions (NOT, AND, OR, etc.) are fulfilled by converting external mechanical stimuli into logic signals.

An organic tribotronic transistor (OTT) developed by coupling a TENG in vertical contact-separation mode and an organic thin-film transistor (OTFT) has also been shown (Figure 14a). Through further integration with an OLED, a TENG-gated light-emitting system is capable of enabling the direct and flexible interaction between the external mechanical stimuli and electroluminescence characteristics. This OTT device may have a massive potential of application in interactive display, pressure imaging, flexible tactile optoelectronics, and microoptical electromechanical systems.

Another flexible and transparent tribotronic transistor developed by coupling a TENG in the freestanding mode with an OFET is shown in Figure 14b. The electrical output currents show a steady and linear increase from 2 to 20 $\mu$A as the sliding distance increases from 0 to 6 mm under bending (the bottom in Figure 14b). The device can be applied to modulate the conventional electronics such as LEDs, magnetic devices, audio amplifiers, and microcontrollers.

3.5.2. Tribotronic Transistor Array

A $10 \times 10$ tribotronic transistor array (TTA) is fabricated for touch sensing by integrating TENG and FET active matrix on a flexible substrate, as shown in Figure 14c. Based on the modulation of triboelectric potential originated from the integrated TENG, the variation of the drain current in each transistor unit upon mechanical stimuli has been investigated. The size of the transistor unit can be scaled down to $0.5 \times 0.5 \text{ mm}^2$ with a high level of sensitivity and resolution. The touch sensing of the device is accessed by placing the shaped objects onto the tribotronic
transistor array. The 2D and 3D mappings of the output current distribution in the tribotronic array upon an “A”-shaped plastic alphabet are demonstrated. The tribotronic transistor array enables an active touch sensing by coupling the external mechanical stimuli and integrated circuits, which is suitable for large-area flexible/wearable devices, active matrix E-skin, and interactive applications.

3.5.3. Tribotronic Transistors for Smart Touch Sensors

Up to now, touch sensors have been widely used in smart phones, interactive monitor/displays, human-machine interface, and artificial robotics. A tribotronic MoS$_2$ transistor developed by vertically integrating a single-electrode mode TENG on a MoS$_2$-based FET is shown as a smart tactile switch (Figure 15a). The triboelectric charges induced by the displacement of the external electrode in TENG are taken as the gate potential to tune the charge carriers transport in MoS$_2$ FETs. The tribotronic device realizes the direct tactile switch using fingers. The on/off ratio of the tribotronic device is $\approx 16$, which is considered sufficient to light double LEDs for tactile indication functions.

In addition, a tribotronic graphene tactile sensor based on a single-electrode mode TENG-modulated planar ion-gel-gated graphene FET is fabricated on a flexible substrate (Figure 15b). The poly(dimethylsiloxane) (PDMS) friction layer coated with indium tin oxide (ITO) electrode is selected as the back electrode of the TENG, whereas the triboelectric charges induced by the external electrode in TENG are used as the gate potential to tune the carrier transport in graphene FET. The tribotronic graphene transistor shows an excellent performance in tactile sensing, for example, a minimum detection limit of 1 kPa, a sensitivity of 2% kPa$^{-1}$, a response time of 30 ms, and an excellent stability for several thousand cycles. Furthermore, the spatial mapping in terms of the current modulation by finger touch has been demonstrated with the tribotronic graphene transistor array. To realize approaching sensation and material recognition, a mechanosensation active matrix is fabricated by integrating the direct-contact tribotronic planar graphene transistor array (Figure 15c). The adopted ion gel can be viewed as both the friction layer of TENG component and dielectric layer of graphene transistor for the direct-contact tribotronic sensing process to be completed. It shows the sensitivity of 0.16 mm$^{-1}$, fast response time of 15 ms, and good durability over 1000 cycles. With contact made with different triboelectric materials, such as Al, Cu, skin, PTFE, polyethylene terephthalate (PET), and fluorinated ethylene propylene (FEP), the corresponding output sensing performances have also been characterized according to the triboelectric series. As revealed by the results, the tribotronic planar graphene transistor can enable the sensing of contact distance and the identification of different electronegative materials. The 2D mapping of
the sensing signals’ distribution of the mechanosensation-active matrix is measured by making contact with an “L”-shaped plastic plate. The proposed tribotronic graphene transistors satisfy the following requirements: 1) noninvasive sensing based on triboelectrification and charge transfer; 2) simplification of the fabrication process of tribotronic transistor; and 3) effective reduction of power consumption through EDL gating by the triboelectric potential. It is thus demonstrated that the emerging applications of simplified and low-power consumption triboelectric transistors based on flexible semiconductor materials are more desirable for interactive touch screens, intelligent sensing systems, flexible multifunctional electronics, and even neuromorphic prosthesis.

4. Perspective

Toward smart and flexible sensors, piezo/tribotronics relying on piezo/triboelectric potential-modulated semiconductor devices have made a significant progress based on 1D nanowires, 2D materials, 1D/2D mixed structures, and PENG/TENG-gated transistors. Piezotronics and tribotronics have attracted plenty of attention from scientists in different fields. It will continue to play a more important role in the new era that features Internet of Things (IoT) and artificial intelligence. The coupling of piezoelectricity/triboelectricity and semiconducting properties in low-dimensional nanomaterials and three-terminal devices has provided an alternative to the development of flexible and wearable multifunctional devices, micro-/nanopower source, self-powered systems, human–machine interface, and low-power consuming neuromorphic devices, and robotic electronics (Figure 16).

Considering the future development directions and research trends of piezotronics and tribotronics toward functional soft electronics and sensors, plenty of efforts are still required for the collective contributions to be made by multidisciplinary scientific researchers and engineers.

Looking into the developmental history of piezotronic sensors from 1D nanowires to 2D materials, 2D materials with superior mechanical properties in atomic thickness may be more advantageous in terms of lifespan and durability for the practical
piezotronic applications in the future. On the one hand, the developing theoretical predictions of piezoelectricity in emerging novel 2D materials\(^\text{[102–105]}\) indicates the direction of exploring new materials for piezotronics and further demonstrates the massive potential of piezotronic sensors. The atomic thickness also offers an ideal platform for the study on the fundamental piezoelectric properties to develop sophisticated electronic devices. One the other hand, the flexible integration of piezotronic sensors is an eternal topic toward large-area wearable sensory matrix, high-resolution spatial recognition of stimuli, and precise feedback functions.

Originating from Maxwell’s displacement current, the sensory applications based on piezo/triboelectric potential-gated three-terminal FETs intensively broaden the development of piezotronics and tribotronics. The PENG-/TENG-gated transistor is in essence a capacitive coupling of piezo/triboelectric potential and metal–insulator–semiconductor (MIS) structure. It takes advantage of the excellent pairing between the two components under high impedance. Therefore, the critical issue related to the fabrication of high-performance piezotronic/tribotronic FETs lies in how to ensure effectiveness in utilizing the piezo/triboelectric potentials. For example, EDLs developed in piezo/triboiontronic FETs can be conducive to coupling ultralarge piezo/triboelectric potential to the semiconductor channel and to delivering a highly efficient charge carrier control capacity\(^\text{[24,59]}\). Through ion migration and arrangement initiated by mechanical interaction, triboiontronics show a massive potential to initialize the mechanical behavior derived by high-performance printable organic electronics, magnetic anisotropy, and the superconductivity induced by phase transition.

In summary, piezo/tribotronics act as an “intermediator” between the biomechanical action and electronic devices and directly link the electronic properties with external mechanical stimuli, thus offering an optimal self-powered sensing and interactive strategy toward soft electronics, artificial intelligence, E-skins, IoTs, biomedical engineering, and human–machine interfaces.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

field-effect transistors, piezotronics, piezo/triboelectric potential coupling, smart flexible sensors, tribotronics
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