Piezotronics enabled artificial intelligence systems

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Abstract

Artificial intelligence (AI) technologies are accelerating the rapid innovations of multifunctional micro/nanosystems for boosting significant applications in flexible electronics, human healthcare, advanced robotics, autonomous control, and human–machine interfaces. III-nitride semiconductors, e.g. GaN, AlN, InN, and their alloys, exhibit superior device characteristics in high-performance opto-/electronics, due to the unique polarization effects in the non-central-symmetric crystal. Piezotronics, coupled with piezoelectric polarization and semiconductor properties, can provide a novel approach for controlling charge carrier transport across the interfacial Schottky barrier or \( p-n \) junction in these piezoelectric semiconductors. It means constructing a direct, real-time, seamless interaction between human/machine and environment, which indicates great potential in emerging AI systems. In this article, we review the research progress of piezotronics on III-nitride semiconductors, summarize the fundamental theory of piezotronics, illustrate flexible device process, present emerging piezotronic intelligent GaN-based devices, and provide innovative supports for building adaptive and interactive AI systems.

1. Introduction

With the rapid innovation and development of artificial intelligence (AI), intelligent micro/nanosystems with multifunctional features have been demonstrating significant applications in flexible electronics, human healthcare, advanced robotics, autonomous control, and human–machine interface technologies [1–3]. Multifunction/diversification is critical for emerging electronics in the post-Moore era. III-nitrides semiconductors, e.g. GaN, AlN, InN, and their alloys, have tunable direct bandgap (ranging from 0.7 to 6.2 eV) at the ambient, and exhibit superior device characteristics in high-performance opto-/electronics. Fabricating high-quality tunable InGaN/GaN or AlGaN/GaN heterojunctions have been maturely developed, and promoting some commercialized applications in solid-state optoelectronics (e.g. light-emitting diode (LED), and laser diodes (LDs)) and high-performance electronics (e.g. high electron mobility transistor (HEMT)) in the harsh environment [4].

Due to the non-central-symmetric wurtzite structure, III-nitrides demonstrate large spontaneous and piezoelectric polarization effects along the \( c \)-axis. With varying external (or internal) strain, the device performance will exhibit significant changes, owing to the additional piezoelectric polarization response. This phenomenon is defined as ‘Piezotronics’ [5–7], which is coupled with piezoelectric polarization and semiconductor properties in such piezoelectric semiconductors. Importantly, strain-induced piezoelectric polarization would act as a virtual gate to modulate the carrier transport across the metal-semiconductor Schottky interface (or \( p-n \) junction) with the modified interface (or depletion region). That is, the piezotronics can provide a new means for controlling charge carrier transport across the interfacial Schottky barrier or \( p-n \) junction, consequently affecting the device output characteristics [6, 7].
GaN-based heterojunction devices have been fabricated through the mature material growth process and the compatible micro/nanofabrication technologies, and possessing a large market. However, the rigid and brittle heterojunction layers (i.e. mechanical fatigue) show limitations for the increasing demands of flexible electronics. Specifically, GaN-based materials and devices have been promoting from basic research to practical applications, which would contribute to the significant use of piezotronics. Developing flexible configurations is highly desirable for ingeniously integrating piezotronics into the high-performance GaN-based devices, which boosts the mechanical and electrical signals in seamless interaction. In this review, we discuss the research progress of piezotronics on III-nitride semiconductors, summarize the fundamental theory of piezotronics, illustrate flexible device process, present emerging piezotronic intelligent GaN-based devices, and provide innovative supports for building adaptive and interactive AI systems.

2. The fundamental theory of piezotronics

2.1. Piezotronics in nanowires

Upon loading small forces on a ZnO nanowire by an atomic force microscopy (AFM) Pt tip, professor Zhong Lin Wang found that the induced piezoelectric potential (piezopotential) can be used to control/tune the height of the Schottky barrier (between Pt and ZnO), and presented the emerging field of piezotronics in 2007 [5]. The terminology—piezotronics (illustrated in figure 1(a)) is defined as the physical effect coupling with piezoelectric polarization and semiconductor properties in the piezoelectric semiconductors (due to the non-central-symmetric crystal structure). Such materials, e.g. GaN, InN, AlN, ZnO, CdS, and CdSe, can provide a new way to manipulate charge carrier transport under the use of mechanical stimuli and lead to unprecedented device characteristics [6–9]. With a large number of experimental demonstrations, Wang also developed the fundamental theoretical framework for Piezotronics [10]. To illustrate the static/dynamic transport of the charge carriers in the piezoelectric semiconductors, the piezotronics involves the basic equations including electrostatic equations, current density equations, continuity equations, and piezoelectric equations. More detail in the fundamental theory of piezotronics can be found in [10].

Herein, we take III-nitride semiconductors, which have been arousing wide interests by the communities both of academia and industry, as good examples to clearly elaborate the effect of piezotronics on device performance [11]. Due to the non-central-symmetry in a wurtzite crystal (e.g. GaN, figure 1(b)), the piezoelectric polarization is generated along the c-axis under internal or external strain, as schematically shown in figure 1(c). Specifically, a typical tetrahedral structure cell is composed of Ga$^{3+}$ (or N$^{5−}$) ions and the surrounding four N$^{3−}$ (or Ga$^{3+}$) ions. Without strain on the cell, the centers of anion and cation coincide in the tetrahedron. When loading a strain on the cell, the centers of anion and cation would show a relative shift and cause the piezoelectric polarization along the c-axis (figure 1(c)). As such material assembled into a metal-semiconductor Schottky (or p–n junction) based device, the piezoelectric polarization charges are produced at the Schottky barrier interface (or p–n depletion region) with the applying of strain, and the induced piezopotential can act as a virtual gate to modulate the charge carrier transport characteristics.

By using high-quality polarity-controlled GaN nanowires, Zhao et al proved that the height of Schottky barrier between the Pt tip and c-plane (or m-plane) GaN can be effectively modulated by the normal (or transverse) compressive force under the piezotronic effect [12]. As shown in figure 1(d), for the case of c-plane GaN nanowires, the relative change of Schottky barrier height (SBH) has an approximated linear relationship with normal compressive force. An increase of 176 meV in the SBH is found when applied a normal compressive force of 1.3 μN. However, the normal force shows no significant influence on the m-plane GaN nanowire, due to its horizontal polarity direction. It also provides solid evidence for distinguishing the difference between the piezoelectric and piezoresistive effect. Moreover, some significant works on piezotronic GaN with nonpolar growth (e.g. a-axis GaN nanobel) were reported [13, 14]. The strain-induced piezoelectric polarization along the direction perpendicular to the channel could contribute to the direct modulating the carrier transport characteristics [3].

Figure 1(e) illustrates the schematic band alignments of the metal-semiconductor Schottky contact under tensile and compressive strain, indicating the modulated change of local SBH in response to the applied mechanical inputs. Upon loading a tensile strain on the semiconductor, the barrier interface is depleted of major carriers (i.e. electrons for GaN) by the negative piezoelectric polarization charges, leading to an increase of SBH (left of figure 1(e)); Upon loading a compressive strain on the semiconductor, the barrier interface shows less depletion by the positive piezoelectric polarization charges, causing a decrease of SBH (right of figure 1(e)). Hence, the charge carrier transport across the metal-semiconductor contact can be effectively tuned with the strain-induced piezoelectric polarization. And the modified current density equation for the metal–wurtzite semiconductor contact is described as [10].
Figure 1. The basic principle of piezotronics. (a) Schematic illustration of the piezotronics, which is coupling with piezoelectric polarization and semiconductor properties in the piezoelectric semiconductors. (b) Schematic diagram of the typical GaN wurtzite crystal structure. (c) Schematic illustration on the piezoelectric polarization (i.e. the induced electric dipole moment, $P$) under a load of external force ($F$). (d) The change of Schottky barrier height ($\Delta \phi$) as a function of normal compressive force conducted by conductive atomic force microscopy (AFM) in a GaN nanowire device. The inset (left top) illustrates the schematic testing setup and the simulated piezopotential distribution along the $c$-axis of GaN nanowire (length $= 1000$ nm, and diameter $= 200$ nm at 1.0 $\mu$N normal compressive force). The inset (right bottom) shows the schematic energy band alignment diagram for the tuned Schottky barrier height under normal compressive force. Reprinted with permission from [12]. Copyright (2015) American Chemical Society. (e) Energy band diagrams for the piezotronic modulation on a metal-semiconductor Schottky contact under the strain of tensile (left) or compressive (right).

\[
J_n = J_{D0} \exp \left( \frac{q e_3 s_3 W_{\text{piezo}}}{2e_kT} \right) \left[ \exp \left( \frac{qV}{kT} \right) - 1 \right]
\]  

where $J_{D0}$ is the saturation current density without piezoelectric charges, $s_3$ is the $c$-axial strain, $e_3$ is the piezoelectric coefficient along the $c$-axis, $W_{\text{piezo}}$ is the width of piezoelectric charge, $k$ is the Boltzmann constant, $T$ is the absolute temperature, and $V$ is the applied bias. According to equation (1), it proves that the current density across the Schottky contact can be tuned/controlled in an exponential relation by the applied strain. Besides, the transport characteristics across the $p$–$n$ junction also show the piezotronic modulations as a result of strain, which is described in detail in [6, 7, 10].

Because of the coupling effects of piezoelectric polarization and semiconductor properties (i.e. piezotronics), the piezoelectric semiconductors can provide new approaches for the design and optimization of emerging devices with seamless and adaptive interactions, and boost to develop and build novel AI systems in the future.

2.2. Piezotronics in heterojunctions

III-nitrides, such as InN, GaN, AlN, and their alloys, exhibit wurtzite crystal structure and have tunable direct bandgap (ranging from 0.7 to 6.2 eV) at the ambient, and are building blocks for the important applications of solid-state optoelectronics and high-power electronics [4]. Different from the Si and GaAs semiconductors, due to the lattice-mismatch in the heterojunctions, the III-nitrides-based devices are demonstrating superior performances under the effects of spontaneous and piezoelectric polarizations. And a variety of heterostructures (e.g. quantum wells, quantum dots, and superlattices) can be fabricated by some commercialized epitaxy techniques, including metal-organic chemical vapor deposition, molecular beam epitaxy, and hydride vapor-phase epitaxy [15].

Speaking of the GaN heterojunctions, it is necessary to mention the two-type heterojunctions, i.e. InGaN/GaN, and AlGaN/GaN. Due to the strong inherent polarization behavior, the InGaN/GaN heterojunction is capable to prepare multiple quantum wells (MQWs) in high-performance optoelectronic applications, including LEDs, LDs, and solar cells; and the AlGaN/GaN heterojunction can form high concentration two-dimensional electron gas (2DEG) at the heterointerface for the high-power electronic applications, e.g. HEMTs [4].
Figure 2. GaN-based heterojunctions and the piezotronic effect. (a) Multiple quantum well (MQW) structure and energy band diagram of the InGaN/GaN heterojunction. (b) Crystal structure and energy band diagram of the AlGaN/GaN heterojunction. (c) Calculated energy band distributions of the GaN/InGaN/GaN heterojunction with different strains. (d) Schematic band distribution diagrams of the AlGaN/GaN heterojunction under a compressive (left) and tensile (right) strain. (a), (c) Reprinted with permission from [16]. Copyright (2017) American Chemical Society; (b), (d) [19] John Wiley & Sons. [Copyright © 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim].

Figure 2(a) shows the MQW structure and the tilted energy band of the InGaN/GaN heterojunctions. The lattice-mismatch between InGaN and GaN can induce piezoelectric polarization charges at the InGaN/GaN heterointerfaces and contribute to forming the triangle-shaped potential well in the InGaN layer [16, 17]. And the piezoelectric polarization induced piezopotential would influence the energy band and bound electronic states within the MQWs, and consequently tune the device performances. Additionally, by varying the alloy composition, doping, and thickness, the tilted energy band structure of the MQWs and the transition energy of well states can be well-controlled [18].

Figure 2(b) illustrates the atomic structure model and the energy band energy of the AlGaN/AlN/GaN heterojunctions. The inserted AlN layer between GaN and AlGaN contributes to an increase of 2DEG mobility, thereby, increasing conduction band offset and 2DEG density and reducing the alloy disorder scattering [4]. Due to the non-central-symmetric crystal structure, the intrinsic polarizations including the spontaneous polarization ($P_{AlGaN}^{sp}$ and $P_{GaN}^{sp}$) and lattice-mismatch induced piezoelectric polarizations ($P_{lm}$) can be found in the AlGaN/AlN/GaN heterojunctions. These polarizations causing the net positive fixed charges accumulated at the AlN/GaN heterointerface that lead to inducing a triangle-shaped potential well in the conduction band of GaN lies below that of AlGaN, and help to drive free electrons to the heterointerface forming a 2DEG (figure 2(b)).

In addition to changing the doping and composition of the alloys and designing the heterostructures, an effective approach can be used to optimize the GaN-heterojunction-based devices by applying internal or external strain under the piezotronic effect. Figure 2(c) shows the calculated energy band distributions of the InGaN/GaN heterojunction under different strains. With the increase of external strain, the conduction band ($E_c$) at the InGaN/GaN heterointerface shifts upward. And the lattice-mismatch-induced internal strain at the heterointerface between the barrier and the well shows partial compensation under external strain [16]. Moreover, the schematic band distribution diagrams of the AlGaN/GaN heterojunction under compressive and tensile strains are shown in figure 2(d). Similarly, the external-strain-induced piezoelectric polarization charges at the AlGaN/GaN heterointerface can affect the tilted-down of the conduction band of GaN at the heterointerface. For instance, more electrons can be confined at the potential well with the influence of positive piezoelectric polarization charges under compressive strain, leading to an increased 2DEG concentration. Hence, the charge carrier transport across the heterojunctions including InGaN/GaN and...
AlGaN/GaN can be effectively modulated by applying an external strain under the piezotronic effect, showing the feasibility for the optimization of GaN-heterojunction-based devices in principle.

3. GaN-based devices and the flexible configurations

As fabricating the GaN-based heterojunction into a device, the device can exhibit unique characteristics because of large spontaneous and piezoelectric polarization induced by the non-central-symmetric wurtzite structure and the lattice-mismatch in heterojunction. The modified heterojunction structure or interlayer can lead to a change of internal strain between the heterojunctions, which thus affects device performance. Besides, an external strain can be used to induce additional piezoelectric polarization that leads to effective control for carrier transport across the heterointerface under the piezotronic effect [20, 21]. In this part, we will introduce some typical GaN-based opto-/electronic devices and further present three ways to make flexible GaN-based devices for emerging AI applications and the in-depth study of piezotronics.

3.1. GaN-based opto-/electronic devices

As a new generation of wide bandgap semiconductors, the III-nitride semiconductors have been extensively studied and demonstrate a wide range of uses in the high-power, high-frequency and high-temperature opto-/electronic devices. Capable of large breakdown voltage, high thermal conductivity, and high carrier saturation drift velocity, the III-nitride heterojunctions have been developed into instructing a variety of electronic devices, such as heterojunction bipolar transistor (HBT) [22], and high-performance filed effect transistor (FET) (e.g. junction field-effect transistor [23], metal-semiconductor field-effect transistor [24], metal-oxide-semiconductor field-effect transistor [25], and HEMT [26]).

The AlGaN/GaN heterojunction shows superior advantages in the HEMT applications. Due to the non-central-symmetric wurtzite structure and the large lattice-mismatch at the AlGaN/GaN heterointerface, high spontaneous and piezoelectric polarizations are inherently induced at local heterojunctions, causing the high 2DEG concentration. In 1993, Khan et al. developed the first AlGaN/GaN HEMT [27]. Figure 3(a) illustrates the typical device structure of the AlGaN/GaN HEMT. Ohmic contacted drain and source electrodes and Schottky contacted gate electrode were fabricated on the AlGaN/GaN heterojunction. Nowadays, the development of AlGaN/GaN heterojunctions has achieved remarkable progress. In 2011, Transphorm introduced the first-generation 600 V cascaded GaN HEMT to the market. Then in 2015, VisIC announced that an enhancement-mode (E-mode) GaN HEMT with high gate threshold voltage (>3 V) and high breakdown voltage (650 V) was successfully developed [28]. In radio-frequency (RF) applications, Chung et al. has demonstrated a gate-recessed HEMT device with an ultra-high power-gain cut-off frequency ($f_{\text{max}} = 300$ GHz) in 2010 [29]. Figure 3(b) shows the typical device structure of the gate-recessed HEMT. The observed T-shaped gate is critical for RF performance. Then in 2016, by using a self-aligned asymmetric process, HRL fabricated a better-performed HEMT device (T4-A GaN HEMT) with $f_t > 320$ GHz,
performances (e.g. light emission efficiency in micro-disk LEDs). The pronounced changes in the non-uniform residual internal strain would cause the corresponding strain distribution on the micro-disk, while the compressive strain in the InGaN layer gradually increases. The flexible HEMTs can endure a large mechanical deformation, and be significantly modulated by the piezotronic effect. The external strain-induced piezoelectric polarization could deform the energy band structure at the heterointerface and result in a change in 2DEG concentration. And thus, the output current shows a significant increase (or decrease) as the increase of compressive (or tensile) strain [19]. As mentioned above, the GaN-based heterojunction electronic devices exhibit excellent properties and have been widely used in the important fields of RF, wireless communication, and high-power applications.

Besides, the III-nitride semiconductors with direct energy bandgap also show great potential in the applications of solar cells [34], LEDs [35], and LEDs [36]. It is mainly attributed to the excellent optoelectronic properties of these materials, including high internal/external quantum efficiencies, wide tunable wavelength coverage from 0.7 to 6.2 eV, and fast response time [37]. In practical applications, the highly controlled and tunable InGaN/GaN MQWs are commonly used in the GaN-based heterojunction optoelectronic devices, resulting in similar epitaxial structures of these devices (i.e. solar cells, LED, and LEDs). A typical structure of the InGaN/GaN p-i-n double heterojunction solar cells is shown in figure 3(e), in which the intrinsic region can be replaced by the MQWs to improve the device efficiency. Figure 3(f) shows a schematic diagram of an AlGaN-cladding-free non-polar m-plane InGaN/GaN LDs, which was fabricated by Feezell et al. [38]. This device was grown directly on a non-polar GaN substrate to avoid the polarization-induced electric fields and thread dislocations, thereby improving the device performance. Liu et al fabricated a semi-floating micro-disk LED array [33], and systematically analyzed the non-uniform strain distribution on the micro-disk GaN-based heterojunction (figure 3(g)). After the release of the micro-disk by etching Si substrate, the in-plane tensile strain in the GaN layer shows a decreasing trend from the center to the edge of the micro-disk, while the compressive strain in the InGaN layer gradually increases. The pronounced changes in the non-uniform residual internal strain would cause the corresponding piezoelectric polarization (under the piezo-phototronic effect) and could be applied to modulate the device performances (e.g. light emission efficiency in micro-disk LEDs).

### 3.2. Emerging flexible configurations

Developing a lattice-matched and thermal-compatible substrate remains a challenge for the high-temperature growth of III-nitride high-quality crystal materials. Up to the present, sapphire and silicon carbide (SiC) are the promising and widely used substrate materials, and silicon (Si) has been also used to develop the low-cost and compatible epitaxial process [4]. However, these rigid substrates inevitably hinder the potential applications in flexible electronics and piezotronics. The III-nitride-based devices with flexible configurations not only greatly improve the toleration for mechanical deformations, but also provide an effective approach for device optimization under piezotronics. Hence, it is highly desirable to fabricate the III-nitride-based flexible devices for satisfying the research requirements of piezotronics and boosting the growing applications in wearable electronics, human healthcare, human–machine interface, and other AI fields.

Commonly, the fabricated GaN-based heterojunction devices can be made into flexible ones by using the mature laser or chemical lift-off process [39, 40]. Figure 4(a) illustrates the fabrication of a flexible GaN-based HEMT array. During the lift-off process, a sacrifice carrier is adhered to the device surface to protect the epitaxial layers from cracking as a result of the release of internal strain. And then, the device can be transferred onto an arbitrary flexible substrate. As shown in figures 4(b) and (c), the large-scale AlGaN/GaN HEMT array was transferred from the rigid Si substrate to a flexible copper substrate by the wet chemical etching [41] (i.e. the chemical lift-off process). And the electrical properties of the flexible HEMTs still reached a comparable level but showed a small degradation when compared with the case before transferred. The flexible HEMTs can endure a large mechanical deformation, and be significantly modulated the device performances by applying external strain under the piezotronic effect. In addition, substrate thinning [42] is also an approach to make the GaN-based heterojunction device to make a flexible attribute withstanding large mechanical deformation. But the heterojunction films (with high elastic modulus) are...
easy to brittle in the process. Moreover, 2D materials based van der Waals epitaxy method (e.g. graphene) has been recently developed for the facile transfer of GaN-based heterojunctions [43–45].

Being widely used in the micro-electro-mechanical system (MEMS), fabricating microstructures (e.g. cantilever) are capable to provide GaN-based heterojunction devices with flexible features. The schematic illustration for the fabrication of a cantilever-structured GaN-based HEMT array is shown in figure 4(d). And the unique device structures are shown in figures 4(e) and (f), including the cantilever-structured GaN-based HEMT [2] and the micro-disk LED array [33]. The microstructures can be achieved by the fabrication process of the etching Si substrate with the wet, dry or combined method [2, 33, 41, 46–48]. For instance, Zhang et al developed a fully dry etching process to fabricate cantilever-structured HEMTs [2]. These microstructured devices show the changes of internal strain in the GaN-based heterojunctions resulting in the electrical properties variations, and can also be tuned/controlled by inputting external strain.

The GaN-based heterojunction devices can be designed into flexible configurations by the lift-off process or fabricating microstructures. However, due to the large elastic modulus and brittle features, the GaN-based heterojunctions cannot bear large bending under a certain condition, leading to the devices not meet the specific occasions in the practical applications. As well known, low-dimensional nanomaterials, such as nanowires, nanobelts, and nanoribbons, have a large aspect ratio and contribute to obtaining a more flexible design and greater deformation tolerance [49]. Figure 4(g) illustrates the fabrication of GaN-based micro/nanowire devices, which can be fabricated by well-developed nanowire transfer technology [50, 51]. For the synthesis of GaN-based micro/nanowires, the top-down and bottom-up approaches have been intensively investigated [12, 52]. The surface morphologies of the top-down etched GaN nanowires and the bottom-up grown GaN micro/nanowires are demonstrated in figures 4(h) and (i), respectively. In recent years, different kinds of GaN-based devices based on nanowire structures have been demonstrated, such as transistors, logic devices, strain sensors, memristors, and synapses. Meanwhile, how the piezotronics influence on device performance is also systematically studied.

The flexible design of the GaN-based device is capable to increase the application direction and freedom for the nitride-based piezoelectric semiconductors, help to conduct the piezotronic modulation of the device.
performance, and will lead to important applications in wearable electronics, human healthcare, human–machine interface, and other AI fields.

4. Piezotronic intelligent GaN-based devices

With the fast evolution of AI technologies, the fundamental hardware including devices and systems have been increasingly driving into the trend of miniaturization, integration, and intelligentization. The emerging AI applications are dramatically changing our daily life. And the intelligent devices and systems are recommended to provide us a seamless, real-time, adaptive, and interactive connection to the surroundings. Recently, neuro-inspired architecture has creatively been used to guide the construction of novel intelligent devices and systems [1, 2]. Moreover, piezotronics, coupling with piezoelectric polarization and semiconduction properties, in the piezoelectric semiconductors is capable of bridging the fast linking between human and the outside environment [3]. Using the piezotronics will add novel functions into intelligent devices, which is very critical for the development of emerging AI applications. With the in-depth study of piezotronics in III-nitride semiconductors, a large number of works have focused on the fabrication of novel piezotronic devices with unconventional functions and novel structures. In this part, we will demonstrate five types of piezotronic intelligent GaN-based devices, and also show the promising in the applications of emerging AI systems.

4.1. Piezotronic transistors and logic devices

Strain-induced piezopotential can be used as a virtual gate to tune/control the charge transport across the Schottky interface, i.e. the modified SBH under strain. Different from the conventional three-terminal transistors, the piezotronic transistors are typically fabricated by using the horizontal or vertical oriented nanowires to form the two-terminal structure of metal-semiconductor-metal (M-S-M) [12, 13, 53, 54]. As a result of the piezopotential modulating the SBH, the carrier transport characteristics of the strain-gated piezotronic transistors can be directly tuned/controlled by applying external force/strain. Impressively, Wu et al invented the first large-array piezotronic transistor circuit with 92 × 92 crosspoint array of vertical ZnO nanowires, which was fabricated by combining the conventional micro/nanofabrication techniques [55]. This piezotronic transistor array shows the good capability of converting mechanical stimulation into local electrical signals and achieving shape-adaptive and high-resolution tactile sensing. In addition, several kinds of piezotronic transistors are also demonstrated by the GaN-based nanomaterials, including c-axis GaN nanowire [12], a-axis GaN nanobelts [13], and a-axis GaN nanowire [14]. By employing strain-controlled cracking of thin solid GaN films, Yu et al presented single-crystal GaN nanobelts [54], whose SEM and HRTEM images are shown in figure 5(a). The polar c-axis is along the longitudinal direction of the GaN nanobelt. After assembled a single GaN nanobelt into the piezotronic transistor, the output current of the GaN-nanobelt-based piezotronic transistor is effectively tuned by the applied external strain (compressive and tensile), and also indicates the asymmetric response for the negative and positive bias, as shown in

![Figure 5](https://example.com/fig5.png)

Figure 5. Piezotronic transistors and logic devices. (a) SEM and transmission electron microscopy (TEM) images of GaN nanobelts. (b) Current–voltage characteristics of GaN-nanobelt-based piezotronic transistor under various strains. (c) Current-strain curve of the piezotronic transistor (at a bias of 2 V). The inset shows the relation between SBH change and strain. (d) The typical logic operation—inverter, implemented by two piezotronic transistors, in response to the input strain. Reprinted with permission from [54]. Copyright (2013) American Chemical Society.
figure 5(b). The current–strain ($\varepsilon_g$) curve of the GaN-nanobelt-based piezotronic transistor indicates that the output current shows a decrease with the increase of $\varepsilon_g$ (figure 5(c)), resembling the typical voltage-gated transistor characteristics. The corresponding change of SBH with $\varepsilon_g$ obviously exhibits the strain modulated on contact characteristics (inset of figure 5(c)), verifying the piezotronics in the strain-gated transistor.

Furthermore, the logic devices controlled by inputting external strain can be achieved by connecting some strain-gated piezotronic transistors. Yu et al also presented a piezotronic logic device based on the GaN-nanobelt-based piezotronic transistors, and demonstrated the universal logic operations, including AND, OR, NOT, NAND, NOR, and XOR gates [54]. Figure 5(d) shows the typical logic operation—inverter (NOT gate) in response to the input strain, implemented by the two piezotronic transistors separately placed on both sides of the flexible substrate. As the inverter bent upward or downward, the logic ‘1’ or ‘0’ could be correspondingly obtained, and the truth table and the relation between the output voltage and strain are observed in figure 5(d). Such a mechanical–electrical coupled inverter is capable to implement functions like the conventional inverter does. Besides, the computing architecture is also constructed with the piezotronic logic devices. Specifically, the basic arithmetic operation, such as one-bit binary addition by half-adder, is demonstrated to do computations, as inputting external strain and obtaining corresponding output voltage. With the ingenious coupling of mechanical stimulation and electrical properties, the strain-gated piezotronic transistor and logic device would contribute to making great progress and guiding the intelligent device design in flexible electronics, MEMS/NEMS, and human–machine interface technologies.

4.2. Piezotronic memristors

Memristor is a two-terminal resistive-switching-typed device whose internal resistance controlled by the history of applied voltage or current, and has been demonstrating fascinating applications in nonvolatile data storage and neuromorphic computing [56–59]. A large number of oxide materials have been investigated to develop the oxide-based memristors (e.g. HfO$_x$, TaO$_x$, and TiO$_x$ [60]) with good capabilities of on/off ratio, retention, endurance, and multi-level characteristics. Moreover, III-nitride materials show the potential promising for offering high-speed and low-energy switching behavior. Impressively, Choi et al demonstrated an AlN-based memristor with a record 85 ps ultrafast switching and 15 $\mu$A low switching current, and revealed the Al-rich conduction channel in the AlN causing highly reliable resistive switching behavior [61]. Such nitride-based memristors are also capable of directly integrating into the current HEMTs technology for novel ultrafast power control applications.

Commonly, the memristive switching characteristics can be achieved by modifying the metal-electrolyte interface or controlling the defects in the electrolyte layer. Liu et al synthesized bamboo-like GaN micro/nanowires via chemical vapor deposition (CVD) with a liquid Ga source precursor and 50 sccm flowed NH$_3$ at high-temperature conditions (950 °C, 8 h) [52]. As shown in the SEM image of figure 6(a), the typical GaN micro/nanowires with pronounced bamboo-shaped knots. And the c-axis growth of the single-crystal GaN microwire is clearly illustrated in the TEM image of figure 6(b). In the growth process, the Ga vapor pressure would change and cause the Ga-rich regions, resulting in the further radial formation of the bamboo-shaped knots. The knot regions are characterized to be nitrogen-deficient defects, which is critical for memristive switching. As shown in the inset of figure 6(c), the GaN-microwire-based piezotronic memristor (M-S-M structure) is fabricated with the single GaN microwire transferred onto the flexible substrate (polystyrene) and Ag paste formed source/drain contacts. Figure 6(c) shows the typical I–V characteristics of the piezotronic memristor, and indicates the bipolar resistive switching characteristics with the pronounced SET and RESET operations. Moreover, with the increase of compressive strain (from 0% to −0.76%), the SET voltage shows a positive shift from 1.42–2.15 V, as shown in figure 6(d). Under the piezotronic effect, the external-strain-induced piezoelectric polarization could contribute to the effective modulation of the SET voltage, due to the modified barrier interface at the knot region. The piezotronic memristor introduces an alternative approach to optimize the memristor (e.g. operation voltage), and helps to design and fabricate a novel intelligent device with interactive features based on the emerging memristive systems.

4.3. Piezotronic sensory memory devices

Sensory memory automatically illustrates an accurate and very brief buffer for the external stimulations (e.g. light, voice, and touch), and is very critical for the interaction between human and the surroundings. As shown in figure 7(a), the sensory memory in human skin illustrates that the mechanical stimulation is quickly memorized with the combination of a sensory receptor and a memory unit. To emulate the biological sensory memory function, the bamboo-shaped GaN micro/nanowire can be used to simplify the combined functions of sensation and memory into a single device (figure 7(b)), as a result of integrating with the piezotronics and memristive characteristics in such piezotronic semiconductor. Hence, the piezotronic...
sensory memory based on a single GaN microwire is demonstrated to sense and memorize the input strain impressions [62], which greatly reduces the complexity of artificial sensory systems. As shown in figure 7(c), the resistance of the device can transit to a high-resistance state (HRS, 100 MΩ scale) with the strain program (−1.57%), from the original low resistance state (LRS, 10 kΩ scale). Specifically, the device shows a good capability of memorizing the resistance even with the release of strain, which exhibits an emulator for the basis of the biological sensory memory. Besides, the resistance can be reversibly swept back to the low-resistance state (LRS) under the erase of voltage sweep (figure 7(d)). Additionally, the device is capable to tolerate over 100 cycles of test with the strain program and electrical erase operations and shows good retention property over 300 s for multilevel-state. Furthermore, the device working mechanism can be explained by using the trap-controlled space-charge-limited-conduction theory [63, 64]. The nitrogen vacancies at the knot region can be a variable barrier and influence the electron transport in the bamboo-shaped GaN-microwire-based device. Under the piezotronic effect, the strain-induced piezoelectric polarization (i.e. piezopotential) would cause the formation or rupture of the conductive channel. It shows a difference from the widely reported piezotronics cases at the interfacial Schottky barrier or $p$–$n$ junction. Furthermore, a touchable haptic memory panel in $3 \times 3$ pixels is demonstrated a pronounced external strain sensing/retaining spatial mapping with the operations of strain program and electrical erase in a highly reliable manner. The piezotronic sensory memory will boost the integration of sense and memory functions in a single micro/nanowire design, and shows the promising applications in tactile sensation, touchable haptic technologies, in-sensor computing, and bio-realistic AI systems.

4.4. Piezotronic synapses

Tactile information is efficiently captured and processed through a complex sensory system combined with mechanoreceptors, neurons, and synapses in human skin. Synapses are essential for tactile signal transmission between pre-/post-neurons, as schematically shown in figure 8(a). Learning from the complex biological model, the artificial synapse has been developed by employing a memristor (e.g. metal-oxides [60], and metal-nitrides [61]). Benefiting from the piezotronics, low dimensional piezoelectric semiconductors boost the design and fabrication of artificial synapses with strain sensing dynamics. A single
Figure 7. Piezotronic sensory memory devices. (a) The schematic sensory memory illustration. Mechanical stimulation is memorized with the combination of a sensory receptor and a memory unit. (b) The equivalent circuit of the sensory memory can be simplified into a single device with the piezotronic GaN micro/nanowire. (c) I–V curves of the GaN-microwire-based piezotronic sensory memory under the operation of strain program, including the original state. (d) I–V curves of the device under the operation of electrical erase (at 1 μA compliance current). The inset indicates the I–V curves before/after electrical erase. (e) Touchable haptic memory panel in 3 × 3 pixels, with the operations of strain program, electrical erase, and strain reprogram. Reprinted from [62], Copyright (2020), with permission from Elsevier.

GaN-microwire-based piezotronic synapse is demonstrated [65], with the simultaneously achieving strain sensing and synaptic functions coupled into the simple device, and the optical image of the piezotronic synapse is shown in the inset of figure 8(b). The dynamics of the piezotronic synapse is measured by inputting a certain pulse (1 ms, 2.5 V) in figure 8(b). The resistance shows a transition from HRS to LRS with incubation, and illustrates a relaxation back to HRS as the pulse bias reducing to 0.1 V. The dynamical transitions of the resistance state are caused by the field-driven electron trapping (in nitrogen vacancies) and the interfacial energy/stress effect induced detrapping, respectively. The piezotronic synapse illustrates the short-term plasticity synaptic functions. As shown in figure 8(c), the paired-pulse facilitation (PPF) is demonstrated with the use of pulse trains (2.7 V, 1 ms; ∆τ: 3 ms). As ∆τ increasing from 0.5 to 10 ms, the piezotronic synapse illustrates the PPF characteristics in pulse trains, meanwhile the relative change in the synaptic weight (∆w) shows a smaller slope (about 7 times reduction). However, the paired-pulse depression (PPD) characteristic is found for the case of ∆τ = 100 ms (in figure 8(d)), as a result of the synaptic relaxation behavior at low-frequency stimuli.

Due to the piezotronics, the conductance of the piezotronic synapse illustrates an obvious increase with pulse trains when applying −0.99% compressive strain (figure 8(e)), indicating the strain-controlled synaptic weight updates in the pulse mode. As schematically illustrated in figure 8(f), the nitrogen vacancies in the knot region would be modified and redistributed as the strain-induced piezopotential, affecting the synaptic functions. With the increase of compressive strain, the accumulation and transport of electrons will weaken under the influence of piezopotential. Figure 8(g) shows the updates of synaptic weight are pronouncedly tuned by applying different compressive stress (0, −0.25%, and −0.36%) with pulse trains, and the largest 330% enhancement is also observed for the strain cases between 0% and −0.36%. In addition, from the ∆w enhancement state, the applied strain conditions could be easily derived, and the achieved gauge factor (GF) is ∼736, as shown in figure 8(h). Notably, the piezotronic synapse shows the promising to build a single micro/nanowire-based neuromorphic hardware system for achieving tactile sensation and processing, and promote the development of bio-realistic AI systems.
Figure 8. Piezotronic synapses. (a) Illustration for mechanical stimuli perceived and processed through the afferent nerve in human skin. Synapse is the key to sensory information processing. (b) The time response curve for the bamboo-like GaN-microwire-based piezotronic synapse with an input pulse (1 ms, 2.5 V). The inset shows the optical image of the piezotronic synapse. (c) Paired-pulse facilitation (PPF) behavior of the piezotronic synapse. Input pulse trains (2.7 V, 1 ms pulse time, and 3 ms interval time Δt). (d) The PPF and PPD demonstration (with different Δt ranging from 0.5 to 100 ms). (e) The synaptic weight (current change) shows a remarkable increase with pulse trains under a compressive strain of −0.99%. (f) Schematic illustration for the nitrogen vacancies (VN) at the knot of the GaN microwire can be controlled and redistributed by the induced piezopotential under the compressive strain. (g) The relative change of synaptic weight is improved by different compressive strain (0, −0.25%, and −0.36%) with pulse trains (2.7 V, 1 ms; Δt: 3 ms). (h) A high gauge factor (GF = 736) for strain sensing is derived from the relation between Δw enhancement and compressive strain. Reprinted with permission from [65]. Copyright (2020) American Chemical Society.

4.5. Piezotronic intelligent power devices

Intelligent power devices are widely used in power solutions ranging from the most basic level of intelligent power control/integration to the most advanced digital control topologies. The power devices used in the conventional control system are commonly implemented in a complex signal processing chain, which contains analog-to-digital (A/D) or digital-to-analog (D/A) converter, strong/weak electricity isolation, and CPU computation. It should be noted that the intelligent power devices directly modulating output power in response to external stimuli at a rapid speed is highly desirable for the practical use of emerging AI applications, e.g. self-driving car, and humanoid robotics.

Interestingly, the reflex arc is a rapid and involuntary movement in response to a stimulus without additional conscious thoughts, as schematically shown in figure 9(a). As inspired by the biological model, Zhang et al demonstrated a strain-controlled power device based on a cantilever-structured AlGaN/GaN HEMT [2] that can provide the direct modulation of output power responses to input strain at a rapid speed (in figure 9(b)). The SEM image of the cantilever-structured AlGaN/GaN HEMT is shown in the inset of figure 9(c). And the simulated strain distribution of the device under 16 mN strain is also illustrated. With the increase of loading strain (from 0 to 16 mN) on the free-end of the cantilever, the output current of the device shows an increasing trend of 17.5% at a gate voltage (Vgs) of 1 V (figure 9(c)). Moreover, figure 9(d) describes the relations between the output power density and the input strain or Vgs in 3D plots. Similarly, the output power also shows the increasingly linear relation with the applied strain, as a result of an increase of 2DEG concentration under the piezotronic effect. And the output power is sensitive to the input Vgs.
which contributes to tuning the rapid response capability with strain. In analog to the reflex arc, the external strain (i.e. knock stimulation) can cause output power changes (like the knee reflex response) in a rapid manner. Remarkably, the gate still dominates the ultimate control for changing output power, as the invention function of the brain. Furthermore, the acceleration-feedback-controlled output power is capable of real-time reaction to the acceleration (1–5 G), as shown in figure 9(e). Developing the piezotronic chip with strain-controlled power devices could help to promote the rapid self-tunable power response controls for unexpected conditions, especially in autonomous driving and advanced robotics (figure 9(f)). Notably, by using the conventional GaN-based heterojunction devices featured with new microstructure, novel functions can be obtained to meet the demanding requirements of emerging AI applications.

5. Perspective

III-nitride semiconductors have unique heterojunctions, controllable fabrication processes, and superior device performances, showing promising potential in emerging AI systems. Despite the lack of suitable substrates and the need for high-temperature growth processes, GaN, AlN, InN, and their alloys exhibit excellent properties with tunable direct bandgap, and the high-quality tunable InGaN/GaN or AlGaN/GaN heterojunctions are maturely developed for high-performance opto-/electronics. AlN is typically used in mechanical signal sensing, energy harvesting and converting applications (due to the piezoelectric properties), acts as a good candidate for deep ultraviolet detection/emission (due to its large bandgap), and is suitable for preparing high-speed and low-power memristive devices. InN is commonly alloyed with GaN to form the InGaN ternary alloy and construct MQWs structures for high-performance LEDs and solar cells.
Due to the spontaneous and piezoelectric polarizations, III-nitride semiconductors would show more significant advantages in piezotronics than other piezoelectric materials (e.g. ZnO), especially for the explicit intelligent application scenarios (e.g. intelligent sensing and control).

Intelligent GaN-based devices, including piezotronic transistors and logic devices, piezotronic memristors, piezotronic sensory memory devices, piezotronic synapses, and piezotronic power devices, are introduced to exhibit the recent progress and advances in emerging AI applications. The fundamental hardware is increasingly driving into the trend of miniaturization, integration, and intelligentization. Coupling piezoelectric polarization and semiconductor properties, the piezotronics shows the virtual gate control capability (with inputting strain) for modulating the carrier transport across the metal-semiconductor Schottky interface (or $p$–$n$ junction), leading to effectively controlling the device output characteristics. Developing the flexible configurations is capable of ingeniously integrating the piezotronics into the high-performance GaN-based devices, boosting the mechanical and electrical signals in seamless interaction. Promoting from basic research to practical applications, GaN-based materials and devices would exhibit the significant use of piezotronics. Up till now, the recent advances of piezotronic devices still focus on individual basic devices; And, there are no universal and standardized device designs of piezotronics for practical applications in the field of AI. Hence, a compatible piezotronic device architecture should in principle be developed for the emerging AI systems; The piezoelectric chips integrated with multifunctional features should be further explored for specific AI applications.

The perspective for the piezotronics in emerging AI systems is illustrated in figure 10. Based on the piezotronics, the piezoelectric semiconductors with exquisite device designs are very suitable for building seamlessly adaptive and interactive AI systems, including the fields of logic, memory, sense, computation, communication, control, and their combinations. More impressively, neuro-inspired architecture is creatively used to guide the construction of novel intelligent devices and systems. For instance, the piezotronic synapse, resembling the sensation and processing of tactile information in the biological skin, is capable of simultaneously implementing synaptic functions and strain sensing. And it adds a novel function.
dimension of sensing capability into the artificial synapse under the use of piezotronics, realizing the fully integration of sensing, memory and computing functions in an individual micro/nanodevices (i.e., in-sensor computing architecture). A novel energy-efficient neuromorphic hardware could be achieved by using piezotronic synapse in micro/nanowires, with the optimizations of device functionalities (e.g. sensitivity; analog characteristics, conductance level, variability, etc). Furthermore, constructing a multifunctional micro/nanosystem integrated with diversified capabilities of sensing, memory, computing, communication and control is highly desirable for promoting the rapid development of bio-realistic AI systems. Based on the multi-disciplinary perspective (combining with physics, materials, electronics, biology, and other disciplines), intelligent AI systems with piezotronics will be rapidly developed, and dramatically changing our daily life.

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