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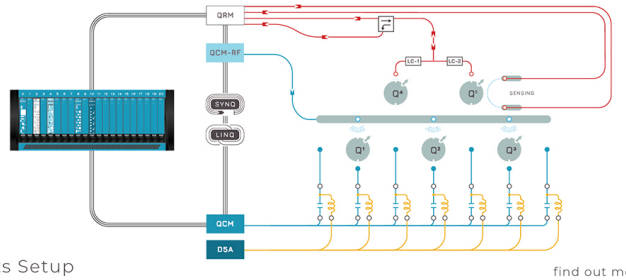

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A perspective on piezotronics and piezo-phototronics based on the third and fourth generation semiconductors

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ABSTRACT

The rapid development of semiconductor materials and devices has brought tremendous development opportunities to optoelectronics, intelligent manufacturing, Internet of Things, power electronics, and even innovative energy technologies. Among them, the third and fourth generation semiconductors represented by ZnO, GaN, SiC, and Ga_2O_3 are two kinds of emerging strategic material systems. Due to their large energy bandgaps, they exhibit excellent performance in application scenarios of high voltage, high frequency, and high temperature resistance, making them great candidates in high-power, radio frequency, and optoelectronic devices. The third and fourth generation semiconductors usually possess non-centrosymmetric crystal structures, which makes the piezoelectric polarization effect a fundamental characteristic for the third and fourth generation semiconductors in contrast to the first and second generation semiconductors as represented by Si, Ge, and GaAs. Research studies on the coupling of piezoelectricity, semiconductor, and light excitation properties were coined as piezotronics and piezo-phototronics in 2007 and 2010, respectively, by Zhong Lin Wang. The piezotronic and piezo-phototronic effects open another avenue for further improvement of the performance of electronic and optoelectronic devices. This Perspective will first introduce the basic concepts and principles of piezotronics and piezo-phototronics and the basic characteristics of the third and fourth generation semiconductors. Then, progress, challenges, and opportunities of ideal materials, comprehensive physical models, and outstanding applications based on piezotronics and piezo-phototronics are presented with emphasis. Finally, conclusions and outlooks are drawn for the piezotronics and piezo-phototronics based on the third and fourth generation semiconductors.

I. INTRODUCTION

New technology industries represented by intelligent manufacturing, Internet of Things, and new era energy needs are anticipated to grow in future years.[1–3] Among them, semiconductor materials, which have developed to the fourth generation, have been playing an extremely important role. The first generation of semiconductor materials, invented and applied in the 1950s, represented by silicon (Si) and germanium (Ge), especially Si, constituted the basis of almost all logic devices of integrated chip.[4,5] The second generation semiconductor materials, represented by gallium arsenide (GaAs) and indium phosphide (InP), play vital role in radio frequency (RF) power amplifier devices and optical communication devices.[6,7] The third generation semiconductors, represented by silicon carbide (SiC), gallium nitride (GaN), zinc oxide (ZnO), are emerging semiconductor materials with wide bandgap ($Eg > 2.3$ eV) properties, which can be widely used in high temperature, high frequency, high power, and radiation resistant electronic/optoelectronic devices.[8–11] The fourth generation semiconductors, represented by gallium oxide (Ga_2O_3) with a much wider bandgap of 4.9 eV, reveal broad application prospects in solar-blind optoelectronic devices.[12–14] From the first to the fourth generation semiconductors, the bandgap is basically increased. From the perspective of crystal structure, the first, second, third, and fourth generation semiconductors are single element cubic, compound cubic, hexagonal, and monoclinic crystal structures, respectively,[9,15,16] as shown in Fig. 1.

Compared with the first and second generation semiconductors, the third and fourth generation semiconductors are in the early stage

of development. The third and fourth generation semiconductors are great candidates for power electronic and optoelectronic devices.[14,17,18] Si is the most widely used substrate material in integrated circuit chips with the most mature technology and the largest market share. In recent years, the potentials of Si materials have almost been exhausted especially in upscale chip industry. In the fields of high voltage, high frequency, and high temperature, the market scale of the third generation semiconductor materials, represented by SiC, GaN, and ZnO, are expected to see rapid development, especially in the application fields of information, increased energy demands, electric vehicles, etc.[19] Compared to the third generation semiconductors, power devices based on Ga_2O_3 would possess many more advantages such as high voltage resistance, low loss, high efficiency, and small size due to the larger bandgap.[12,13,20] Among the five structure phases, the β-phase Ga_2O_3 is extensively used, which is usually believed to possess a centrosymmetric structure with a space group of C2/m due to no detectable piezoelectricity and pyroelectricity.[21,22] However, when the size and dimension of the β-Ga_2O_3 are reduced, piezoelectricity and pyroelectricity might be obvious with a non-centrosymmetric space group of C2, which has been seldom reported. Furthermore, a hexagonal wurtzite phase of Ga_2O_3 (ε-Ga_2O_3) is also anticipated to produce spontaneous polarization as well as piezoelectric properties.[22] The special characteristics of the third and fourth generation semiconductors are generally benefiting from the wide bandgap. Additionally important is the fact that the non-centrosymmetric structures endow (or will endow) them a fundamental piezoelectric polarization effect, which is a key property in regulating and controlling the performance of their electronic/optoelectronic devices.[8,9,23] The research fields of device manipulation by the coupling of piezoelectricity, semiconductor, and light excitation properties were coined as piezotronics and piezo-phototronics by Wang in 2007 and 2010, respectively.[24,25]

After more than ten years of development, piezotronics and piezo-phototronics have become worldwide research hotspots and have been widely used in the fields of electronic/optoelectronic devices, sensor networks, life sciences, human–machine interface integration, energy sciences, etc. Dozens of countries and regions including China, United States, South Korea, Singapore, and Europe have followed research works in these two fields. In this Perspective, we focus on basic concepts and principles based on these two research fields, then introduce recent progress, challenges, and opportunities on ideal material systems, comprehensive physics, and compelling applications of them, and finally give outlooks on their future development.

II. PIEZO-CHARGES, PIEZOPOTENTIAL, AND PIEZOTRONIC/PIEZO-PHOTOTRONIC EFFECTS

When non-centrosymmetric materials come across a strain, the overlapped effective centers of cations and anions will be separated, resulting in a piezoelectric polarization, which were extensively demonstrated in organic polymers,[26,27] inorganic ceramic materials,[28,29] the third and fourth generation semiconductors,[9,23,30] and two-dimensional (2D) materials,[31,32] especially in their low-dimensional structures. Taking a ZnO single crystal for example, when a normal stress along a *c*-axis of the crystalline is exerted on a ZnO tetrahedron, the effective centers of Zn^{2+} and O^{2-} will be staggered toward opposite directions, leading to a dipole moment along the applied stress [Fig. 2(a)].[33] Continuous stacking of dipole moments forms the distribution of electric potential in the stress direction, namely piezo-potential [Fig. 2(b)]. Dynamic piezo-potential can be used to drive the flow of electrons in the external circuit, so as to fabricate high-performance piezoelectric nanogenerators.[34–36] Static piezo-potential is usually applied to regulate the energy band structure of semiconductors at the interfaces to manipulate the recombination and transport of carriers in semiconductor devices. Piezo-potential exists as long as stress exists, whose magnitude is dependent on the applied stress and doping concentration. For heterostructures, such as P–N and Schottky junctions, the inner built-in energy structure can be greatly tuned by a piezoelectric semiconductor due to the presence of surface polarization charges (that is, piezo-charges) [see Figs. 2(c) and 2(d)].[24,25,37,38] It should be noted that piezo-charges exist only at the crystal surfaces as the bulk charges are neutralized. The positive piezo-charges can reduce the interface energy band level while the negative piezo-charges are opposite.[38] The transport of electrons and holes in semiconductors will be affected by the regulation of interface energy bands due to the piezo-charges, which is the well-known piezotronic effect.[24] Furthermore, the phenomenon of tuning and/or controlling the generation, separation, and recombination of photogenerated carriers at the interfaces of heterostructures were called the piezo-phototronic effect.

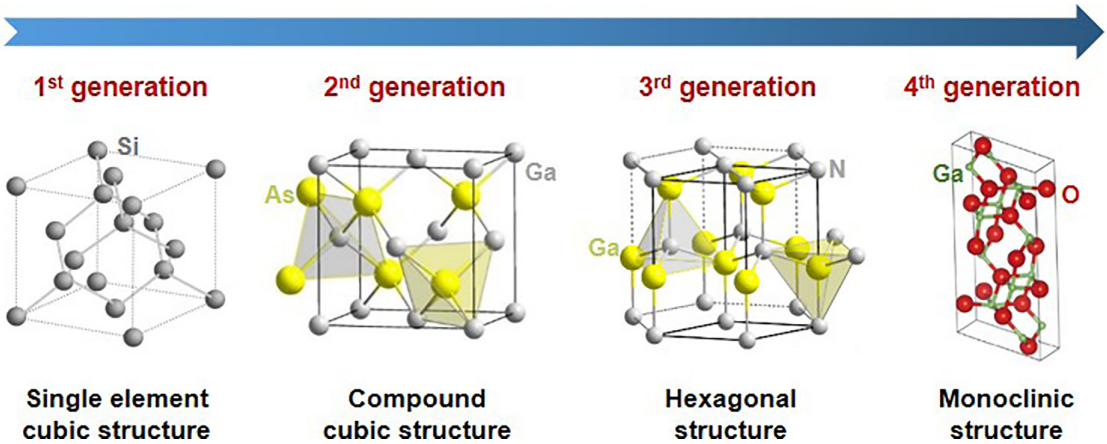

FIG. 1. Crystal structures from the first to the fourth generation semiconductors.

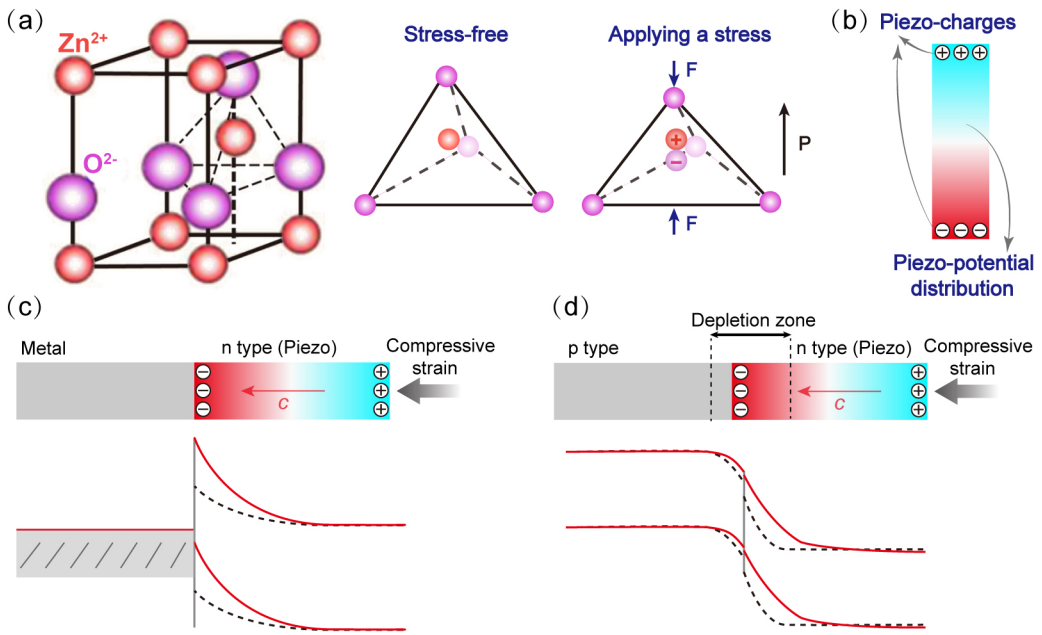

FIG. 2. (a) Schematic diagrams of the basic crystal structure of ZnO and the illustration of piezoelectric polarization when a stress along *c*-axis is applied, where F and P represent the applied vertical stress and the induced dipole moment, respectively. Reproduced with permission from Wang, Adv. Mater. **24**, 4632–4646 (2012).[33] Copyright 2012 Wiley-VCH Verlag GmbH & Co. KGaA. (b) Illustration of the distribution of piezopotential and surface piezo-charges. (c) and (d) Schematic diagrams of the piezotronic effect tuned energy band structures for metal–semiconductor (n-type) and p–n junction contacts, respectively, where *c* denotes the polarization direction of the piezoelectric semiconductor. Adapted with permission from Zhu and Wang, Adv. Funct. Mater. **29**, 1808214 (2019).[38] Copyright 2018 Wiley-VCH Verlag GmbH & Co. KGaA.

The coupling of piezoelectricity, semiconductor, and light excitation in electronic and optoelectronic devices has been attracting much attention from all around the world, which had been coined as frontier fields of piezotronics and piezo-phototronics.[24,25,39] Although advanced materials or new demands for application are based on the third and fourth generation semiconductors, the basic principles of piezotronics and piezo-phototronics are mainly the same.

III. PROGRESS, CHALLENGES, AND OPPORTUNITIES: INNOVATION IN MATERIALS PHYSICS AND APPLICATIONS BASED ON PIEZOTRONICS AND PIEZO-PHOTOTRONICS

A. Material systems ideal for piezotronics and piezo-phototronics

The most popular one-dimensional (1D) nanomaterials that are mainly used for piezotronics and piezo-phototronics are ZnO nanomaterials due to their large-scale, low-cost, biologically compatible, and environmentally friendly properties. Thermal evaporation (vapor–liquid–solid) method in a tube furnace was usually used to grow long ZnO nanowires/nanobelts with several hundreds of micrometers.[40,41] Patterned growth could be realized when an Au catalyst was introduced.[36] ZnO nanowire arrays could also be grown at any substrate with any shape even under low temperature by using a hydrothermal method.[42–44] The hydrothermal method could also be modified to synthesize ZnO nanoplatelets.[45,46] Pulse laser deposition (PLD) was another method to grow well-aligned vertical ZnO nanowires at a high temperature.[47] Similarly, CdSe nanowires and nanowire arrays grown by an Au-catalyzed vapor–liquid–solid method were also demonstrated in applications of piezotronics and piezo-phototronics.[48,49] CdS nanowire arrays grown by a hydrothermal method are also ideal candidates, especially for piezo-phototronic light-emitting diodes (LEDs) and photodetectors (PDs).[50,51] GaN films grown by metal organic chemical vapor deposition (MOCVD) are other vital materials used for piezotronics and piezo-phototronics.[52,53] Piezo-phototronic effect enhanced photoluminescence was discovered in a single GaN/InGaN quantum well.[54] By using hydride vapor phase epitaxy (HVPE) and MOCVD, GaN-based piezoelectric nanowire, microwire, and nanobelt were also obtained.[55–57] By the state-of-the-art top–down fabrication from an epitaxial InGaN/GaN multilayer, piezoelectric nanowire arrays based on GaN quantum wells were explored for photoluminescence imaging.[58,59] Furthermore, single-atomic-layer materials, such as MoS_2 and In_2Se_3, were proven to possess piezoelectricity.[31,60,61] In the past few years, organic–inorganic perovskites have aroused extensive attention due to their excellent piezoelectric property, which could help them to enhance optoelectronic performance by the piezo-phototronic effect.[62,63] As a strategic third semiconductor materials, SiC has been widely used in various fields including energy vehicles, photovoltaic inverter, 5G communication, etc. Recently, 4H-SiC nanowires/nanoholes have revealed to possess obvious piezoelectricity compared with those of thin films, which endows them with a great potential to be used in piezotronics and piezo-phototronics.[35,64,65] Additionally, as the fourth wide bandgap semiconductor, β-Ga_2O_3 and ε-Ga_2O_3 are other candidate piezotronic and piezo-phototronic materials, while related study has been rarely reported. Therefore, SiC and Ga_2O_3 crystals especially for their low-dimensional structures offer enhanced opportunities in piezotronics

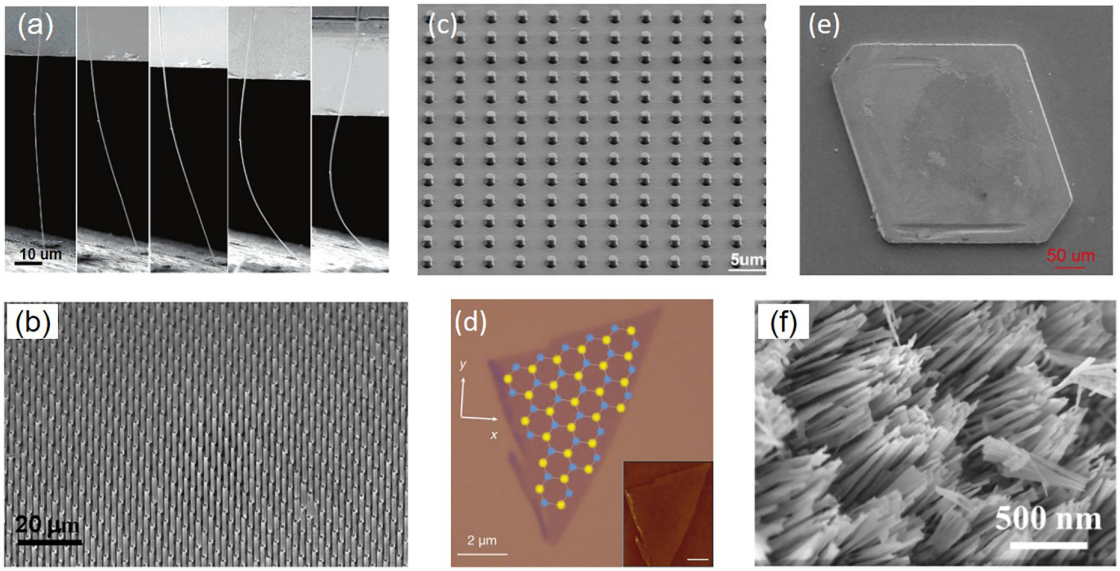

FIG. 3. (a) SEM (scanning electron microscopy) images of the ZnO nanowire grown by a thermal evaporation in a tube furnace. Reproduced with permission from Wang *et al.*, Nano Lett. **6**, 2768–2772 (2006).[41] Copyright 2006 American Chemical Society. (b) SEM image of the ZnO nanowire array grown by low-temperature hydrothermal method. Reproduced with permission from Wei *et al.*, Nano Lett. **10**, 3414–3419 (2010).[43] Copyright 2010 American Chemical Society. (c) SEM image of the GaN-based nanowire array. Reproduced with permission from Peng *et al.*, ACS Nano **9**, 3143–3150 (2015).[58] Copyright 2015 American Chemical Society. (d) Optical image of the single-atomic layer MoS_2 flake. Reproduced with permission from Wu *et al.*, Nature **514**, 470–474 (2014).[31] Copyright 2014 Nature Publishing Group. (e) SEM image of the $MAPbI_3$ single crystal. Reproduced with permission from Lai *et al.*, ACS Nano **12**, 10501–10508 (2018).[62] Copyright 2018 American Chemical Society. (f) SEM image of the 4H-SiC nanowire array. Reproduced with permission from Zhou *et al.*, Nano Energy **83**, 105826 (2021).[35] Copyright 2021 Elsevier Ltd.

and piezo-phototronics. However, the fabrication processes of low-dimensional structures would be a big challenge (Fig. 3). Material systems ideally for piezotronics and piezo-phototronics are summarized and listed in Table I.

B. Innovation in physical models associated with piezotronics and piezo-phototronics

Electrons possess several intrinsic degrees of freedom, including charge, spin, and valley. Traditional device manipulations are generally based on charge degree, which is no exception for those of piezotronics and piezo-phototronics.[23,33,39,66] Apart from traditional manipulation of charges transportation, there are still additional physics tuned by the piezotronic and piezo-phototronic effects. The first demonstration of spins that can be manipulated by the piezotronic effect was carried out by Zhu *et al.* in 2018, which shed light on the coupling research of flexible-piezo-spintronics [Fig. 4(a)].[67] By controlling the spin–orbit coupling (SOC), which is the most important factor in semiconductors to achieve generation, manipulation, and detection of spins, spin transportation could be effectively manipulated. A spin-related photocurrent derived from the spin splitting of energy band and the spin transportation could be realized in a ZnO/P3HT nanowire array structure by using a technology based on the circular photogalvanic effect (CPGE) [Fig. 4(b)].[67] The piezo-phototronic effect could even manipulate light polarization, including linear and circular light polarizations, due to the tuned spin splitting of energy band.[63,68,69] Topological quantum states have great potential in emerging applications such as next-generation spintronics and quantum computing. The piezotronic effect was also demonstrated theoretically to tune topological quantum states in a GaN/InN/GaN quantum well and a CdTe/HgTe/CdTe quantum well [Figs. 4(c) and 4(d)], respectively.[70,71] In recent years, the discovery and manipulation of valley degree of freedom have made it possible for valley electronic devices to become the mainstream.[72–74] Therefore, the manipulation of valley degree of freedom by the piezotronic and piezo-phototronic effects are much anticipated in the future. Other physical phenomena, such as superconductivity[75] and single electron transport,[76] may also be tuned by the piezotronic effect. The physical models described above will not only broaden fundamental research of energy band engineering in the third and fourth semiconductors but also expand the range of applications of piezotronics and piezo-phototronics.

TABLE I. A summary of material systems ideal for piezotronics and piezo-phototronics.

Structures	Materials
1D	ZnO, CdSe, CdS, GaN, etc.
2D	MoS_2, In_2Se_3, etc.
Film	ZnO, GaN, 4H-SiC, organic–inorganic perovskites, etc.

C. Killer applications based on piezotronics and piezo-phototronics

Compared with the first and second generation semiconductors, devices based on the third and fourth generation semiconductors also hold other outstanding properties, such as high thermal conductivity, high breakdown electric field strength, high saturation drift speed,

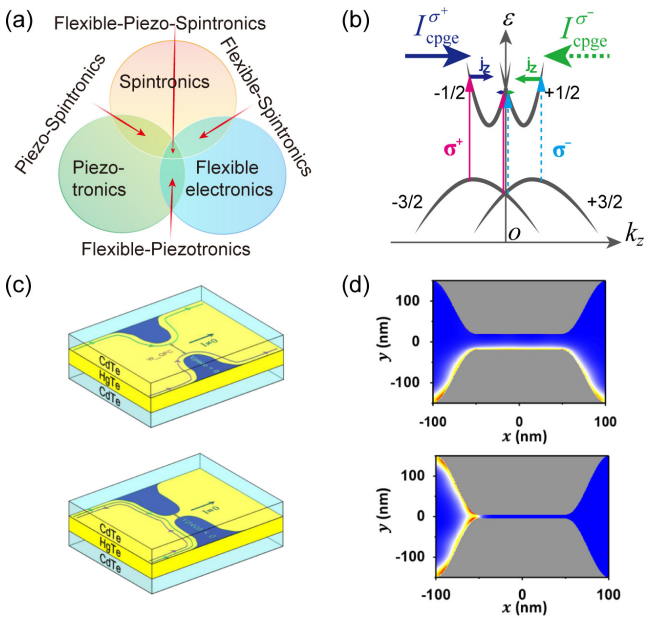

FIG. 4. (a) Cross-over study of piezotronics, spintronics, and flexible electronics. (b) Schematic diagram of CPGE current due to the spin split band structure. Reproduced with permission from Zhu *et al.*, ACS Nano **12**, 1811–1820 (2018).[67] Copyright 2018 American Chemical Society. (c) Schematics of electronic transport in the CdTe/HgTe/CdTe topological insulator. (d) The local densities of states of spin-down electrons for "OFF" (upper one) and "ON" (lower one) states. Reproduced with permission from Hu *et al.*, ACS Nano **12**, 779–785 (2018).[71] Copyright 2018 American Chemical Society.

high thermal stability, chemical inertness, etc. In addition to high frequency, high voltage, and high temperature working scenarios, they usually possess advantages of easy heat dissipation, small size, and low energy consumption. Piezotronics and piezo-phototronics have attracted much attention in transistors, LEDs, PDs, solar cells, gas sensors, chemical catalysis, etc. Here, we will just introduce three representative killer applications, including flexible high-electron-mobility transistors (HEMTs), high-power LEDs, and self-powered ultraviolet (UV) and infrared (IR) PDs, as all of them are exhibiting great application potentials in the fields of intelligent manufacturing, Internet of Things, and emerging era of increased energy demand.

1. Piezotronic effect enhanced flexible HEMTs

HEMTs, one of the important power devices, are capable of working in the information field with ultra-high frequency and ultra-high speed due to the high mobility of two-dimensional electron gas (2DEG) inside heterostructures.[56,77,78] AlGaN/GaN is the most commonly used HEMT structure, whose interface 2DEG density can reach up to $1 \times 10^{13}\,\mathrm{cm}^{-2}$, while the electron mobility can reach up to $2300\,\mathrm{cm}^2/(\mathrm{V\,s})$. Flexible power devices provide higher flexibility for high-power system integration and installation. Zhu *et al.* have developed a low-damage and wafer-scale substrate transfer technique and successfully fabricated a flexible AlGaN/GaN HEMT with excellent electrical properties [Fig. 5(a)].[79] This device could bear a larger mechanical deformation. The piezotronic effect was demonstrated to effectively enhance the electrical performance of the flexible HEMT, revealing great application potential in mechanical sensing and human–machine interaction. Recently, Chen *et al.* fabricated large-scaled ($> 2\,\mathrm{cm}^2$) flexible HEMTs based on AlGaN/AlN/GaN heterostructures [Fig. 5(b)].[80] The piezotronic effect was then applied to optimize the electrical performance and to suppress the thermal degradation by modulating the 2DEGs and phonons. The saturation current could increase by 3.15% under a 0.547% tensile strain. Hsu *et al.* also fabricated a flexible AlGaN/GaN HEMT with a short gate length of 2 μm on a Kapton tape by using a wet etching technology.[81] The piezoelectric field within the AlGaN under a tensile strain could increase the 2DEG density, hence enhancing the maximum drain current density and the maximum transconductance.[81,82] Niranjan *et al.* reported a flexible AlGaN/GaN HEMT using a gold-free process.[83] When the device was bent with a curvature radius of 2.1 cm, the electrical performance increased by 5%–10% for the ON-current, while it remained constant for the OFF-state. In general, the piezotronic effect has a vital effect in enhancing the performance of flexible HEMTs, which is of great significance in wearable electronic devices, non-

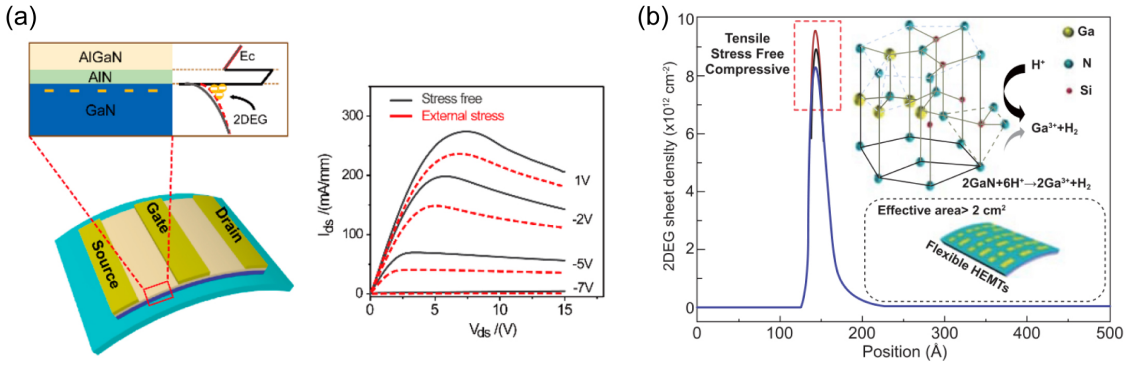

FIG. 5. (a) Schematic device structure of the flexible AlGaN/GaN HEMTs (left inset) and piezotronic effect modulated electronic transport of the device (right inset). Reproduced with permission from Zhu *et al.*, ACS Nano **13**, 13161–13168 (2019).[79] Copyright 2019 American Chemical Society. (b) Piezotronic effect modulated 2DEG sheet density for a large-sized flexible AlGaN/AlN/GaN heterostructure-based HEMTs. Reproduced with permission from Chen *et al.*, Nano-Micro Lett. **13**, 67 (2021).[80] Copyright 2021 Springer.

planar electronic devices, implantable devices, human–computer interaction, and other technological frontiers. It should be noted that the yield of HEMTs transferring from hard substrates to flexible substrates should be promoted, because dislocations and defects during transferring would weaken the performance of the HEMTs. Actually, when the HEMTs are transferred to flexible substrates, the performance of the HEMTs will be under high restrictions of the properties of the flexible materials. Therefore, high performance flexible substrates with features such as high-temperature resistance, high-voltage resistance, and resistance to irradiation damage should be developed. To pursue more applications, research works on the piezotronic and piezo-phototronic effects on power devices, such as insulated gate bipolar transistor (IGBT),[84,85] metal-oxide-semiconductor field effect transistor (MOSFET),[86,87] and P–N and Schottky barrier diodes (SBDs),[88–90] may be great attempts.

2. Piezo-phototronic effect enhanced high-power LEDs for lighting and displaying

LEDs with high power have begun to be used in the field of lighting on a large scale due to their advantages in high electro-optical conversion efficiency, energy saving, environmental protection, long life, small size, etc.[91] At present, white LEDs are mainly realized by using blue LED chips to excite yellow phosphors. Therefore, the improvement of the performance of blue LED chips plays a vital role in improving the lighting efficiency and energy saving. High-power blue LEDs are mainly based on GaN materials. In 2011, Yang *et al.* first reported a p-GaN/n-ZnO nanowire LED and demonstrated that the piezo-phototronic effect could effectively tune the energy band structure at the heterostructure interface and, hence, increase the electro-optical conversion efficiency by 4.25 times.[92] Furthermore, a high performance two-dimensional (2D) stress displaying device was obtained with a spatial resolution of 2.7 μm and a stress response time of 90 ms, respectively, by using n-ZnO/p-GaN nanowire array LEDs.[93] Recently, micro LEDs based on GaN have been attracting much attention and are regarded as the next generation display technology by several famous information technology companies.[94] Liu *et al.* have developed an innovative semi-suspended InGaN/GaN micro LED array by combining the isotropic and anisotropic dry etching process that greatly enhanced the stability of LEDs.[95] The micro LED greatly improved the efficiency of light extraction. A gradient stress distribution from the center to the edge of the micro-disk LED chip resulted in a corresponding non-uniform piezo-phototronic effect, which led to a maximum wavelength shift of 16 meV. In 2021, a nanowire LED array based on the InGaN/GaN multiple quantum well (MQW) was fabricated, which could realize real-time, rapid, dynamic, and high-resolution displaying of the traction of cardiomyocytes using the piezo-phototronic effect.[59] The study of piezo-phototronic effect enhanced high-power LEDs can innovate the design concept of industry lighting and highly sensitive tactile displaying. For high-power LEDs, accurate construction of internal stress inside the heterostructures is a big challenge; hence, for the growth kinetics of LEDs, more attention should be paid in future. For tactile displaying, the stability and service life of LEDs should be optimized, and higher resolution is much more desired. So far, the homogeneity of strain inside the micro LEDs is seldomly reported, which will deeply influence the lighting uniformity and should be considered seriously. Additionally, the encapsulation processes of static strain into LEDs also need to be exploited (Fig. 6). Piezo-phototronic effect enhanced high-power LEDs for lighting and displaying are summarized in Table II.

3. Piezo-phototronic effect enhanced self-powered PDs

a. UV PDs. Self-powered PDs use photoelectric effect to convert optical radiation into electrical signals without the need of an extra bias. UV light is a high-energy light with a short wavelength, which has been intensively applied in sterilization, item identification, health and medical treatment, etc. UV light detectors using semiconductors with wide bandgaps hold many advantages such as anti-electromagnetic interference, anti-radiation damage, high efficiency, simple structure, light weight, etc.[96] The third and fourth generation semiconductors are naturally great candidates in self-powered UV light detection used in high security communication technology, military warning and tracking, natural disaster prediction, etc., where the piezo-phototronic effect can also play a crucial role. In 2010, based on a ZnO nanowire/Ag Schottky structure, a self-powered UV PD was fabricated and studied. The photoelectric response was improved by 5.3 times at a −0.36% compressive strain and a 4.1 pW low light power.[97] In 2015, Han *et al.* further designed a self-powered Schottky array PD based on ZnO nanowire and metal Au [Fig. 7(a)].[98] When the device was irradiated with an UV light, the shape of the spot could be imaged in real time. The strain-induced piezo-phototronic effect was used to adjust the Schottky band barrier at the interface to improve the photoelectric response and imaging quality. In 2016, a GaN-based self-powered UV PD was reported, where the piezo-phototronic effect effectively enhanced the sensitivity of the device with a photoswitching ratio increased to 1.54 times at a 1% tensile strain.[53] Piezoelectricity in SiC is usually very low in its bulk crystalline. Recently, piezoelectricity in 4H-SiC has been reported in the nanowire/nanohole structures,[35,64] which opens up an avenue for piezo-phototronic effect enhanced self-powered UV PDs. Zhang *et al.* demonstrated the presence of a piezo-phototronic-like effect, the pyro-phototronic effect, in an n-type 4H-SiC crystal, which could be used to enhance the performance of a self-powered UV PD [Fig. (b)].[99] For the fourth generation semiconductor Ga_2O_3, it is very suitable for solar-blinded PDs due to the ultra-wide bandgap of 4.9 eV.[100] Chen *et al.* developed a solar-blinded PD based on a ZnO/Ga_2O_3 core–shell heterojunction nanowire, which was extremely sensitive to deep UV light of 261 nm [Fig. (c)].[30] A three times enhancement of current responsivity was discovered under a −0.042% compressive strain due to the piezo-phototronic effect, where a bias was needed when the PD worked. The development of self-powered solar-blinded PDs based on Ga_2O_3 are very appealing. There is room for improvement regarding high-performance UV PDs. For instance, the sensitivity, detectivity, and response speed of UV PDs need to be further improved. Large-scaled PD chips and emerging technologies of precise strain construction and fixing inside the PDs need to be developed in the future.

b. Infrared (IR) PDs. Self-powered IR PDs is of great significance to night spectral monitoring, infrared guidance, optical communication, etc.[101] The piezo-phototronic effect can even enhance self-powered IR PDs. In 2017, Dai *et al.* fabricated Si/CdS heterojunction near-infrared (NIR) PDs. By introducing the piezo-phototronic effect, the photoresponsivity and the detectivity of the PD were enhanced by

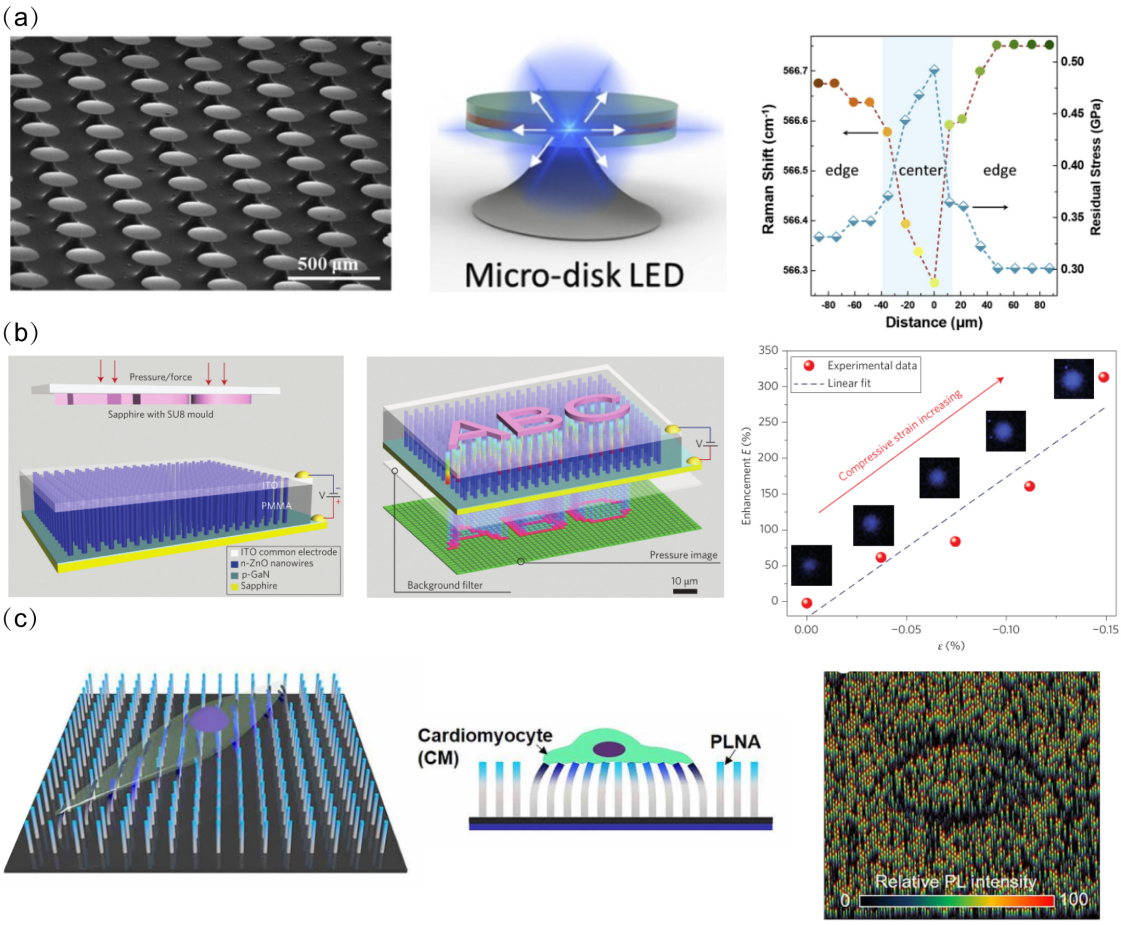

FIG. 6. (a) Piezo-phototronic effect in InGaN/GaN semi-floating micro-disk LED arrays. Images from left, middle, to right the SEM image of the semi-floating micro-disk LED arrays, schematic lighting image of the micro-disk LED, and residual stress and Raman shift of a micro-disk LED. Reproduced with permission from Liu *et al.*, Nano Energy **67**, 104218 (2020).[95] Copyright 2019 Elsevier Ltd. (b) High-resolution electroluminescent imaging of pressure distribution using a piezoelectric LED array based on n-ZnO nanowire/p-GaN. Images from left, middle, to right are schematic device structure, schematic electroluminescent imaging, and electroluminescent intensity as a function of strain. Reproduced with permission from Pan *et al.*, Nat. Photonics **7**, 752–758 (2013).[93] Copyright 2013 Nature Publishing Group. (c) Dynamic real-time imaging of a living cell traction force by piezo-phototronic light nano-antenna array based on InGaN/GaN MQWs. Images from left, middle, to right are schematic three-dimensional device structure when a living cell onto it, schematic nano-antenna array bent by cardiomyocyte, and PL intensity imaging when a cardiomyocyte onto the nano-antenna array. Reproduced with permission from Zheng *et al.*, Sci. Adv. **7**, eabe7738 (2021).[59] Copyright 2021 American Association for the Advancement of Science.

two orders of magnitude under a 1064 nm illumination, and the response speeds are increased effectively under external compressive strains.[51,102] Based on CdS/P3HT microwires, a self-powered NIR PD was fabricated, whose performance could be enhanced when a strain was applied on the CdS microwire by the piezo-phototronic effect.[103] In 2018, a high-performance self-powered flexible PD based on ZnO/CdS/CIGS heterojunction was developed. By exerting the piezo-phototronic effect, the photoresponsivity, detectivity, and response time (light ON) were increased by 2.35, 2.27, and 2.4 times, respectively.[104] Recently, P–N junction PDs were constructed by

TABLE II. Piezo-phototronic effect enhanced high-power LEDs for lighting and displaying.

Structure	Dimension	Application	Resolution (μm)	Ref.
p-GaN/n-ZnO	Microwire	Lighting		Yang *et al.*[92]
InGaN/GaN	Micro-disk array	Lighting		Liu *et al.*[95]
p-GaN/n-ZnO	Nanowire array	Stress displaying	2.7	Pan *et al.*[93]
InGaN/GaN	MQW nanowire array	Stress displaying	4.8	Zheng *et al.*[59]

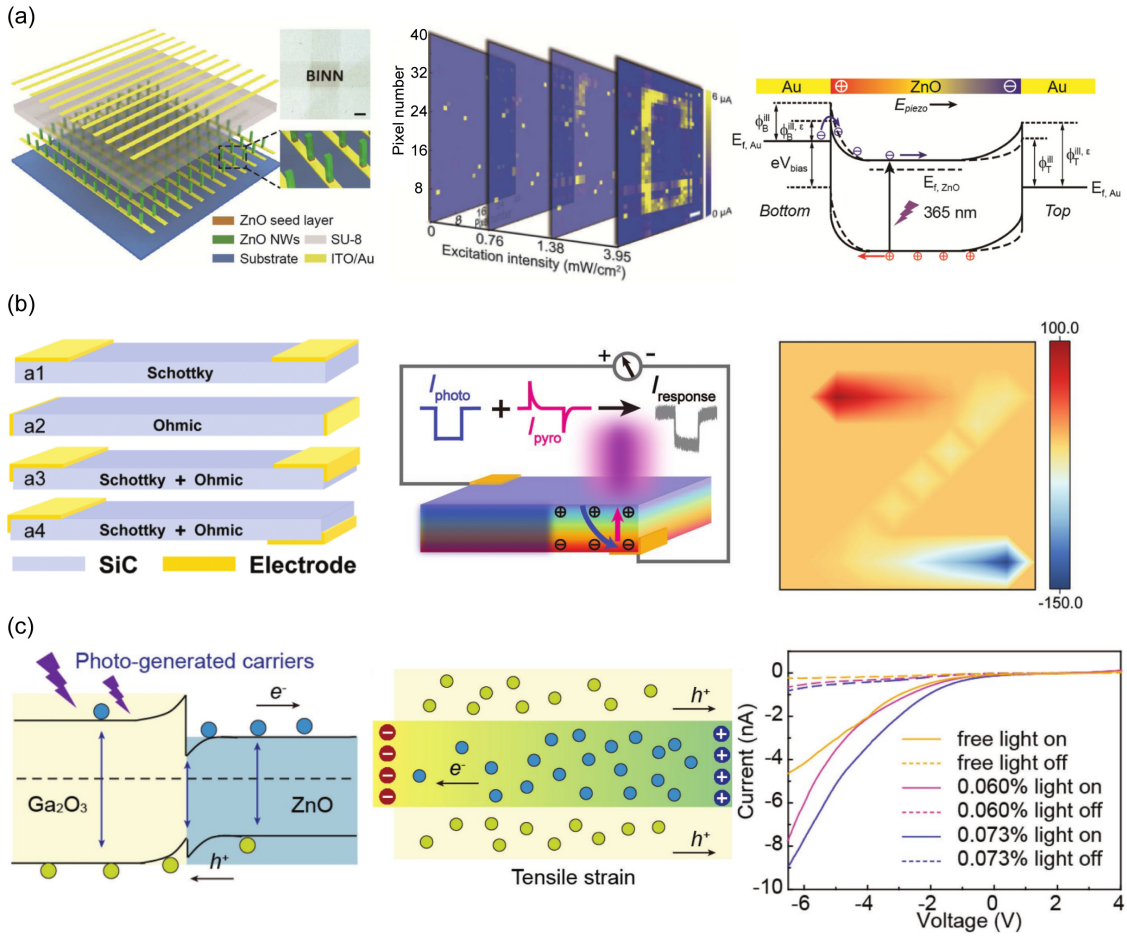

FIG. 7. (a) UV response and imaging of the illumination distributions by the ZnO PD array. Insets from left to right are schematic device structure, UV imaging, and schematic shifting of energy band by piezo-phototronic effect, respectively. Reproduced with permission from Han *et al.*, Adv. Mater. **27**, 7963–7969 (2015).[98] Copyright 2015 Wiley-VCH Verlag GmbH & Co. KGaA. (b) Highly sensitive photoelectric detection and imaging enhanced by the pyro-phototronic effect in 4H-SiC. Insets from left to right are schematic device structure, schematic device working principle, and UV imaging, respectively. Reproduced with permission from Zhang *et al.*, Adv. Mater. **34**, 2204363 (2022).[99] Copyright 2022 Wiley-VCH GmbH. (c) The piezo-phototronic effect on the solar-blinded microwire PD based on ZnO-Ga_2O_3 heterostructure. Insets from left to right are schematic working mechanism, carriers transport under strain, and I–V characteristics of the device, respectively. Reproduced with permission from Chen *et al.*, Adv. Funct. Mater. **28**, 1706379 (2018).[30] Copyright 2018 Wiley-VCH Verlag GmbH & Co. KGaA.

hydrothermal synthesis of n-type vanadium doped ZnO nanosheets (VZnO NSs) on p-type Si substrates.[105] By introducing ferroelectricity into ZnO, spontaneously ferroelectric polarized charges in the same direction as the applied external electric field could be obtained, which could also improve the transportation process of photogenerated carriers with a 12-fold increase in light responsiveness compared with non-ferroelectric ZnO/Si PDs. These findings provide essential insight of effective modulation on the performance of self-powered IR PDs by the piezo-phototronic effect. Infrared PDs usually need semiconductors with narrow bandgap; hence, technologies of materials coupling between narrow and wide bandgap semiconductors need to be developed. The investigations of piezo-phototronic effect in narrow bandgap semiconductors, such as organic–inorganic perovskites, are also good ways, where we do not need to combine a wide bandgap semiconductor. The piezo-phototronic effect enhanced self-powered UV and IR PDs can be found in Table III.

IV. CONCLUSIONS AND OUTLOOKS

The third and fourth generation semiconductors provide great opportunities for the revolution of information technology and are the strategic highland of most countries in the world. The piezotronic and piezo-phototronic effects create alternative pathways for performance manipulation of electronic/optoelectronic devices based on the third and fourth generation semiconductors, which leave lots of development space, especially for SiC and Ga_2O_3. Furthermore, breakthroughs in physical understanding including charge, spin, topological quantum states, etc., tuned by the piezotronic and piezo-phototronic effects are ongoing. Although large innovations have been made in applications

TABLE III. Piezo-phototronic effect enhanced self-powered PDs.

Structure	Enhanced responsivity (times/strain)	Light source (nm)	Ref.
ZnO/Ag	5.3/−0.36%	365	Yang *et al.*[97]
ZnO/Au	7/40 MPa	372	Han *et al.*[98]
GaN	1.54(ON/OFF)/1%	<400	Peng *et al.*[53]
ZnO/Ga_2O_3	3/−0.042%	268	Chen *et al.*[30]
Si/CdS	Two orders enhanced	1064	Dai *et al.*[100]
ZnO/CdS/CIGS	1.754/−0.75%	808	Qiao *et al.*[104]
VZnO/Si	12/ferroelectric polarization	1064	Li *et al.*[105]

based on piezotronics and piezo-phototronics, especially for power, energy saving, and information devices, such as flexible HEMTs, high-power LEDs, and self-powered PDs, there are still many important scientific and technical problems or challenges remaining, which are as follows:

(1) As the introduction of strain manually is inconvenient, innovative technologies of precise strain construction and fixing are much desired. The encapsulation processes of static strain into electronic/optoelectronic devices also need to be exploited.
(2) With the size of devices decreasing, quantum effects may become obvious; hence, the discoveries of quantum physics effects, such as valley degree of freedom, superconducting quantum states, and single electron transport, manipulated and/or controlled by piezotronic and piezo-phototronic effects are in great demand for potential quantum devices.
(3) Innovative piezotronic devices, especially for power devices, need to be developed urgently. Piezotronics and piezo-phototronics in power devices such as IGBT and MOSFET may get big breakthroughs in terms of energy conversion and transmission. Moreover, high-power diodes, represented by P–N and Schottky barrier diodes (SBDs), have crucial applications in the fields of high frequency and high voltage. The research on piezotronic effect enhanced power devices will bring new application opportunities.
(4) As large-scale integrated chips require extremely high uniformity, the methods for fabricating piezotronic and piezo-phototronic devices with wafer level nanoarrays need to be developed.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Laipan Zhu: Project administration (lead); Writing – original draft (lead). **Zhong Lin Wang:** Supervision (lead); Writing – review & editing (lead).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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