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TOPICAL REVIEW

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Topical Review

Progress in piezotronics and piezo-phototronics of quantum materials

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Abstract

Piezotronic and piezo-phototronic effects reveal promising applications in the third-generation semiconductors with non-centrosymmetric structures. With the size of piezoelectric materials reducing to nanoscale, quantum wave behavior and some interesting quantum effects will appear. This paper aims to offer a summary of the rapid advancements made in piezotronics and piezo-phototronics of quantum materials and present a perspective on their applications. Furthermore, several significant quantum phenomena manipulated by the piezotronic or piezo-phototronic effect are highlighted. The coupling between piezotronics/piezo-phototronics and quantum physics opens up a new avenue for next-generation high-integration, ultra-fast and hypersensitive electronic/optoelectronic systems.

Keywords: piezotronic effect, piezo-phototronic effect, quantum effect, carrier transportation, noncentrosymmetric structures

(Some figures may appear in colour only in the online journal)

1. Introduction

When a strain is applied, there are piezoelectric potential (piezopotential) and piezoelectric charges (piezo-charges) created in the piezoelectric semiconductors (e.g. ZnO, GaN, CdS, MoS_2) due to the lack of central symmetry [1–4]. The generation of piezopotential and piezo-charges influences largely on the transport behavior of electrons and holes through a metal/semiconductor (M–S) Schottky interface or a semiconductor heterojunction; electronics working depending on such an effect are coined as piezotronics [3, 5–7]. Since the creation of piezotronics in 2007 by Wang *et al* [1], fast developments have been witnessed with great significance in physical science and huge potential in device applications. Plenty of piezotronic devices have been invented, such as strain sensors [8, 9], piezotronic transistors [10, 11], piezotronic logic circuits [12], and piezotronic electromechanical memories [2]. By introducing light illumination, the coupling among the semiconductor, light excitation and piezoelectric property develops another new research area named piezo-phototronics, which was coined in 2010, also by Wang *et al* [2]. Since then, the piezo-phototronic effect is extensively applied to enhance the performance of a variety of optoelectronic devices, such as light-emitting diodes [13, 14], solar cells [15–17], and photodetectors [18, 19].

With Moore's law reaching its limit, new electronic devices based on quantum theories urgently need to be developed in order to further enhance the chip integration and reduce the energy consumption in the chip [20, 21]. Quantum mechanics is about the subject of study of quantum physics and design of quantum devices [22]. With the size of the materials shrinking to nanoscale, the quantum wave behavior and some quantum effects (such as the quantum size, quantum tunneling and quantum interference effects) of the electron will become predominant [23]. In the semi-classical theory, the first-order linear approximation was taken into account, while the quantized energy levels and the restricted carrier wave functions were totally ignored [24]. Hence, when lowering the dimension of piezoelectric semiconductors, semi-classical physics possibly become invalid while many interesting quantum phenomena might appear. In recent years, numerous researchers have been pioneering two emerging research fields, namely quantum piezotronics and quantum piezo-phototronics, which involve two main research aspects: the design and fabrication of piezotronic/piezo-phototronic quantum materials that possess space size for several nanometers or even smaller, and the piezotronic/piezo-phototronic devices illustrating significant quantum physics (e.g. spin transport, topological phase, single electron transport) [25–29].

This paper gives a brief review of recent development in quantum piezotronics and quantum piezo-phototronics. First, several representative devices based on different types of quantum structures with enhanced performance by piezotronic or piezo-phototronic effect are presented, highlighting the outstanding features and scientific significances of each quantum device. Then, the latest results of piezotronic or piezo-phototronic effect tuned quantum physical phenomena are reviewed. Finally, a brief summary is provided, and a few future perspectives are given to imagine the development of the quantum piezotronics and piezo-phototronics. This review not only reveals a comprehensive summary to recent works presenting basic physical impacts of the piezotronic or piezo-phototronic effect on quantum structures, but also sheds light on future design and fabrication for advanced quantum piezotronic/piezo-phototronic devices.

2. Piezopotential, piezo-charges, and piezotronic/piezo-phototronic effects

It is well known that most of the third-generation semiconductors possess a wurtzite structure. The lack of centrosymmetry in these crystals results in piezoelectricity. Taking ZnO as an example, there are no polarization can be found without applying external stress due to the overlap of effective centers of Zn^{2+} and O^{2-}. When a force is applied on the top of a ZnO tetrahedron, the two centers move towards opposite directions, giving rise to an electric dipole moment along the force direction (figure 1(a)). A successive stack of dipole polarization results in a macroscopic electric potential, namely piezopotential [3, 5, 7]. The piezopotential remains in existence as long as the force is applied, and its magnitude is decided by the applied force and the dosage concentration. For an M–S contact (figure 1(b)), the Schottky barrier height can be tuned by an external strain (tensile or compressive) because of the existence of piezo-charges. The electron transport can be improved thanks to the reduced barrier height, while the electron transport can be hindered because of the raised barrier height, which is the well-known piezotronic effect. Similarly, in the case of a p-n heterojunction (figure 1(c)), the positive piezo-charges in the surface of n-type piezoelectric semiconductors can tune the space charge zone moving towards the p-type piezoelectric semiconductor. The decreased energy band profile due to the positive piezo-charges in the interface leading to an increased built-in electric field, obstructing the electrical transport in p-n junction. Oppositely, negative piezo-charges will make the space charge zone shifting to the n-type semiconductor (figure 1(c)). A raised band profile leading to an enhanced electronic transportation. When a light excitation is introduced, the piezo-phototronic effect starts to work. Concretely speaking, the generation, dissociation, transport or recombination of photo-induced carriers can be effectively manipulated due to the modified band profile thanks to the strain-induced piezo-charges.

3. Piezotronic/piezo-phototronic devices based on various quantum structures

The piezotronic and piezo-phototronic effects have been extensively utilized in 1D micro-/nanomaterials and their thin-films at the very beginning [3, 5, 7, 31]. Latest research demonstrates that 2D materials (e.g. monolayer MoS_2, α-In_2Se_3, ultra-thin ZnO nanoplates) also reveal strong piezoelectric properties because of their asymmetric structures [25, 26, 32, 33]. Besides, many quantum well and quantum dot structures also show great potential in the study of piezotronics and piezo-phototronics [24, 34–38]. In this section, we review several representative piezotronic/piezo-phototronic devices which are just based on various quantum structures.

3.1. Two-dimentional (2D) piezotronic/piezo-phototronic devices

2D materials usually possess high crystallinity, excellent mechanical and piezoelectric properties, which make them fantastic candidates for designing next-generation high-performance electronic and optoelectronic devices. The investigation of piezoelectricity and piezotronic/piezo-phototronic effects in 2D materials is a prospective research area.

3.1.1. Piezotronic effect on 2D monolayer chalcogenides. With the high-quality of crystal lattice and property to endure tremendous strain, 2D materials draw huge attention as promising piezoelectric materials [39–41]. It is predicted that monolayer MoS_2 possesses the piezoelectric effect, while it vanishes in the bulk due to the reversed polarization directions for neighbouring atomic layers [42, 43]. Wu *et al* demonstrated that piezoelectric signals could be measured when periodic tensile and compressive strains were applied on MoS_2 flakes with only odd atomic layers [25, 33]. Figure 2(a) shows optical images of a monolayer MoS_2 device and a polar diagram of the crystal's azimuthal angle dependence of the second-harmonic signal intensity from a monolayer MoS_2. The piezoelectric property is increased with the reduction of thickness. Transport characteristics denote a fierce piezotronic

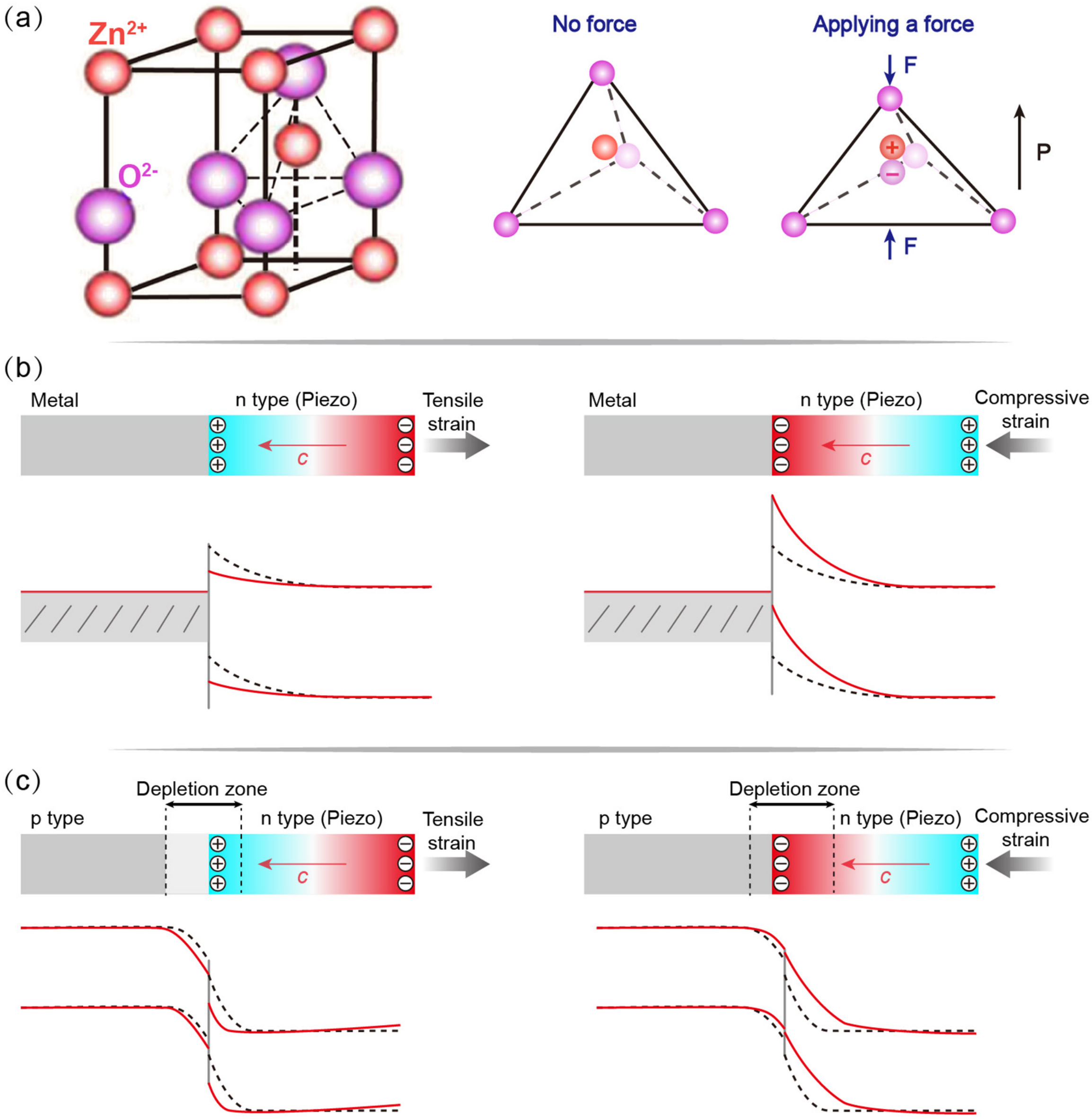

Figure 1. (a) Schematic diagrams of the lattice atomic distribution of ZnO and the illustration of piezoelectric polarization, where F and P denote the external force and the generated electric dipole moment, respectively. (b) Schematic illustrations of the piezotronic effect tuned energy band diagrams of a metal–semiconductor contact, where c denotes the polarization direction of the piezoelectric semiconductor. (c) Schematic illustrations of the piezotronic effect tuned energy band diagrams of a p-n junction contact. [30] John Wiley & Sons. © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

effect in monolayer MoS_2 (the left figure in figure 2(b)), but not in bilayer (the right figure in figure 2(b)) and bulk MoS_2. The piezo-charges distributed at the zigzag edges could influence the metal-MoS_2 contacts by tuning the local density of free electrons and affecting the charges within interface states (figure 2(c)) [2, 5, 7]. The presence of piezoelectric property in 2D semiconductor materials may develop potential applications in nano-electromechanical systems, sensitive biological probes and flexible electronics [25].

The piezoelectric property in MoS_2 and h-BN appeared only in the in-plane direction [25, 43, 44]. Recent theoretical analysis predicted the presence of piezoelectric property in monolayer α-In_2Se_3 with both in-plane and out-of-plane directions [45, 46]. In 2018, Xue *et al* verified experimentally the piezoelectricity of monolayer α-In_2Se_3 in these two directions due to the noncentrosymmetry caused by hexagonal stacking (figure 2(d)) [32]. And they found that there was still a piezoelectric property even in bulk α-In_2Se_3. The piezoelectric coefficient of α-In_2Se_3 raised from 0.34 to 5.6 pm V^{-1} when the layer number was increased from the monolayer to the bulk. It is worth noting that there was no odd–even effect. They proved that the α-In_2Se_3 can be used as a flexible piezoelectric nanogenerator based on finger bending, showing potential applications in energy-harvesting and electronic skin (figure 2(d)). The α-In_2Se_3 flakes provide good materials to realize both vertical and horizontal piezotronic devices.

When a light is coupled into the devices based on the above 2D materials, there are piezo-phototronic effect enhanced optoelectronic performances in the quantum devices, such as MoS_2/WSe_2 van der Waals heterostructure photodiodes [47],

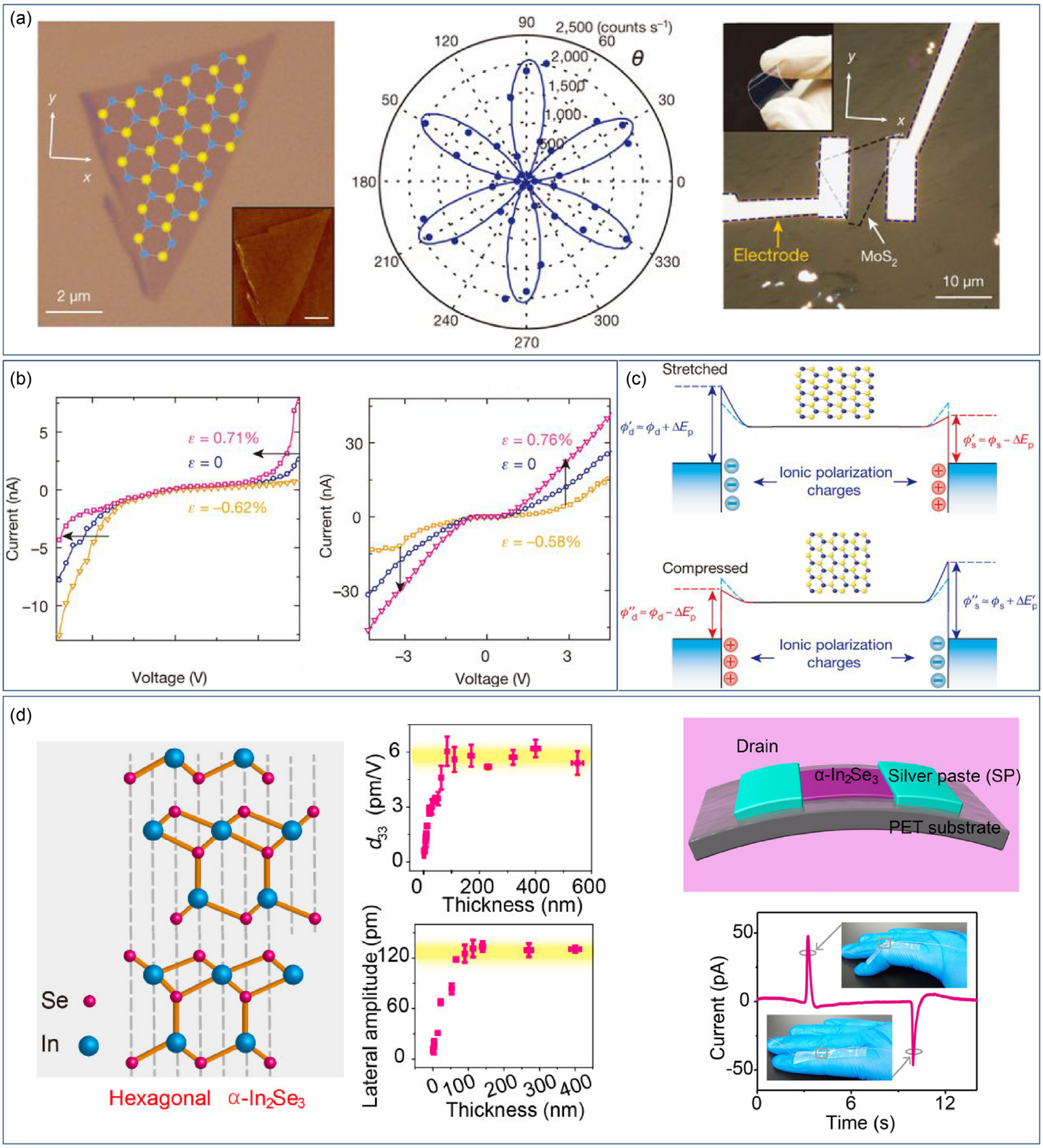

Figure 2. (a) Optical image of the monolayer MoS_2 and device. The middle one is a polar diagram of the azimuth angle dependence of the second-harmonic intensity. (b) An asymmetric variation of electrical transport characteristics under opposite bias in a monolayer MoS_2 device. A symmetrical variation of electrical transport characteristics under opposite bias in a bilayer MoS_2 device. (c) Band diagrams denoting the piezotronic effect on the changes of Schottky barrier heights for a monolayer MoS_2 device. (d) The asymmetric atom models for the hexagonal α-In_2Se_3, the thickness dependence of the piezoelectric coefficient and the lateral amplitude, and a flexible piezoelectric nanogenerator on a finger based on α-In_2Se_3. (a)–(c) [25] Copyright © 2014, Springer Nature. With permission of Springer. (d) Reprinted with permission from [32]. Copyright 2018 American Chemical Society.

p-MoS_2/n-ZnO heterostructure photodiodes [48], and MoS_2 strain-gated adaptive photodetectors [33], etc. This basic research lays the foundation for their future applications in self-powered nano-systems, flexible electronics, and high-performance optoelectronics.

3.1.2. 2D ultra-thin ZnO piezotronic transistors. The theoretical size limit of silicon transistors is 5 nm because of the quantum tunneling effect [49, 50]. Many new nanomaterials, such as nanotubes, nanowires, and 2D transition metal dichalcogenides, have been investigated in order to get

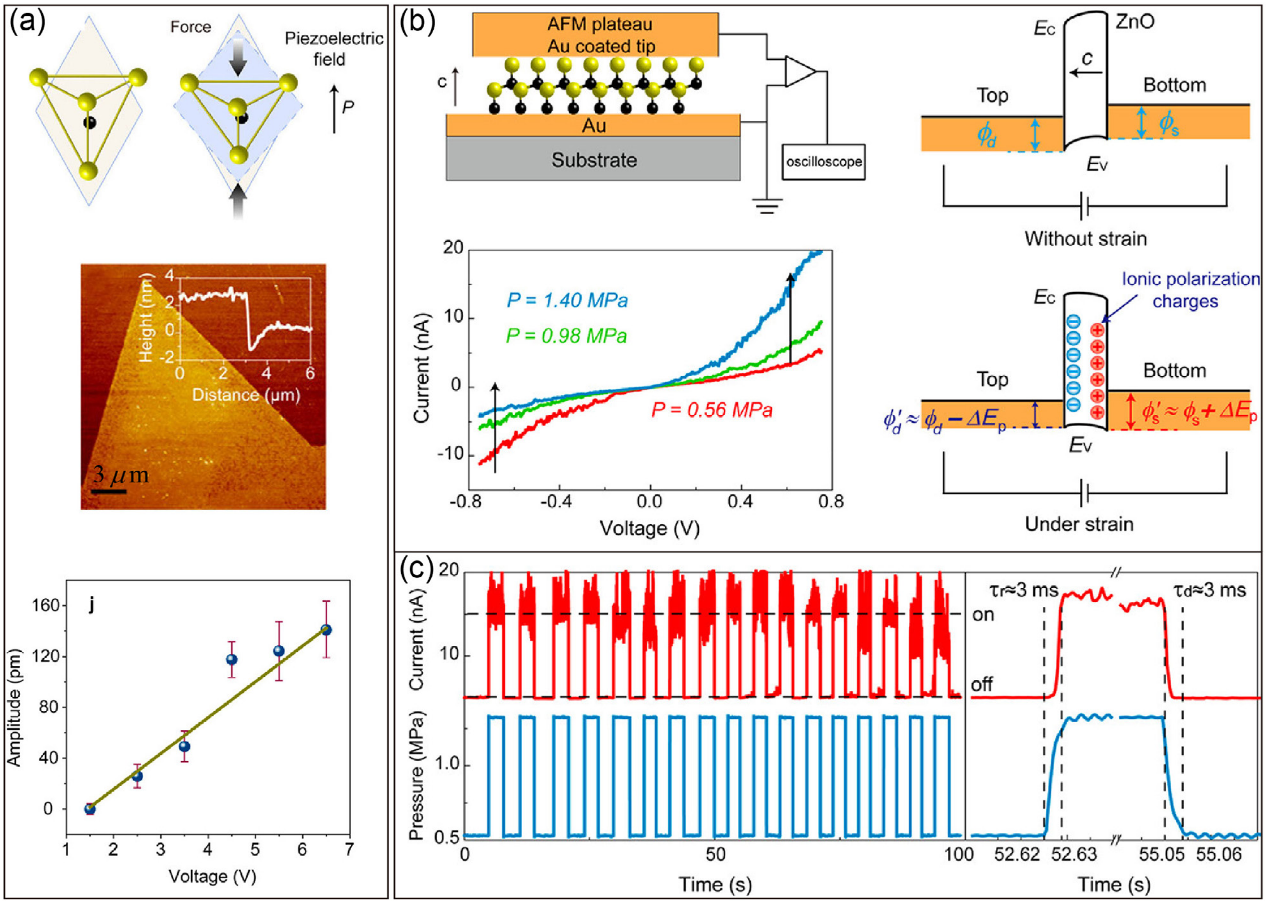

Figure 3. (a) Atom structure, morphology and piezoelectric coefficient of the 2 nm ultrathin ZnO nanoplate. (b) The measurement of piezoelectric characteristics and the modulation of energy band due to the piezo-charges. (c) The speed and stability of the piezoelectric response. Reprinted with permission from [26]. Copyright 2018 American Chemical Society.

breakthroughs [51–54]. Piezotronic transistors, which utilize piezopotential as the gate voltage instead of an external gate voltage, have been demonstrated for the ZnO micro-/nanowires [11, 55]. The equivalent gate length should be the distance between drain and source electrodes. Does it still work for the equivalent gate length below 5 nm? Recently, Wang *et al* demonstrate a 2 nm ultrathin ZnO piezotronic transistor (figure 3(a)) with out-of-plane piezopotential gating the carrier transport [26]. The device does not require the fabrication of a special gate electrode, which can easily get rid of the size limit of transistors. The 2 nm ultrathin device demonstrates an obvious piezotronic effect as well as better pressure-switching property (figures 3(b) and (c)). This study demonstrates the emerging piezotronic effect can still work even under 2 nm equivalent gate length, which is of great significance to the development of new generation transistors. This study gives a new insight on nano-electromechanical devices based on the piezotronic effect for human–machine interfacing, tactile sensors, and quantum piezotronic systems.

3.2. Based on nanowire heterojuction electron gas (HEG) and quantum wells (QWs)

III-nitride heterostructures are prospective material systems for designing HEG and QWs. More importantly, these materials usually possess a strong piezoelectric polarization due to the intrinsic polarization, lattice mismatch or external stress, showing potential applications in quantum piezotronics/piezo-phototronics.

3.2.1. Piezotronic effect modulated AlGaN/AlN/GaN HEG. One-dimensional (1D) semiconductor nanowires (NWs) have drawn huge attention for a good deal of applications thanks to the particular crystal structures and increased carrier mobility as a result of the quantum confinement effects [56–62]. But the carrier mobility can be scattered inevitably by the doping centers, which can be settled by introducing low-dimensional heterostructure carrier gases at the interface of the NWs [60–62]. Due to the spontaneous polarization and lattice mismatch, the transport of carriers is isolated in a space far away from the impurities, hence the scattering from the impurities is sharply weakened. As a result, the carrier mobility is significantly strengthened. AlGaN/GaN is one of the most popularly used heterostructure for inducing HEG deriving from its strong spontaneous polarizations [63], which has been extensively used in high electron mobility transistors (HEMTs) [61] and other quantum devices [64].

Recently, Wang *et al* fabricated some AlGaN/AlN/GaN heterostructured microwires by metal organic chemical vapor deposition (figure 4(a)) [35]. They demonstrated both

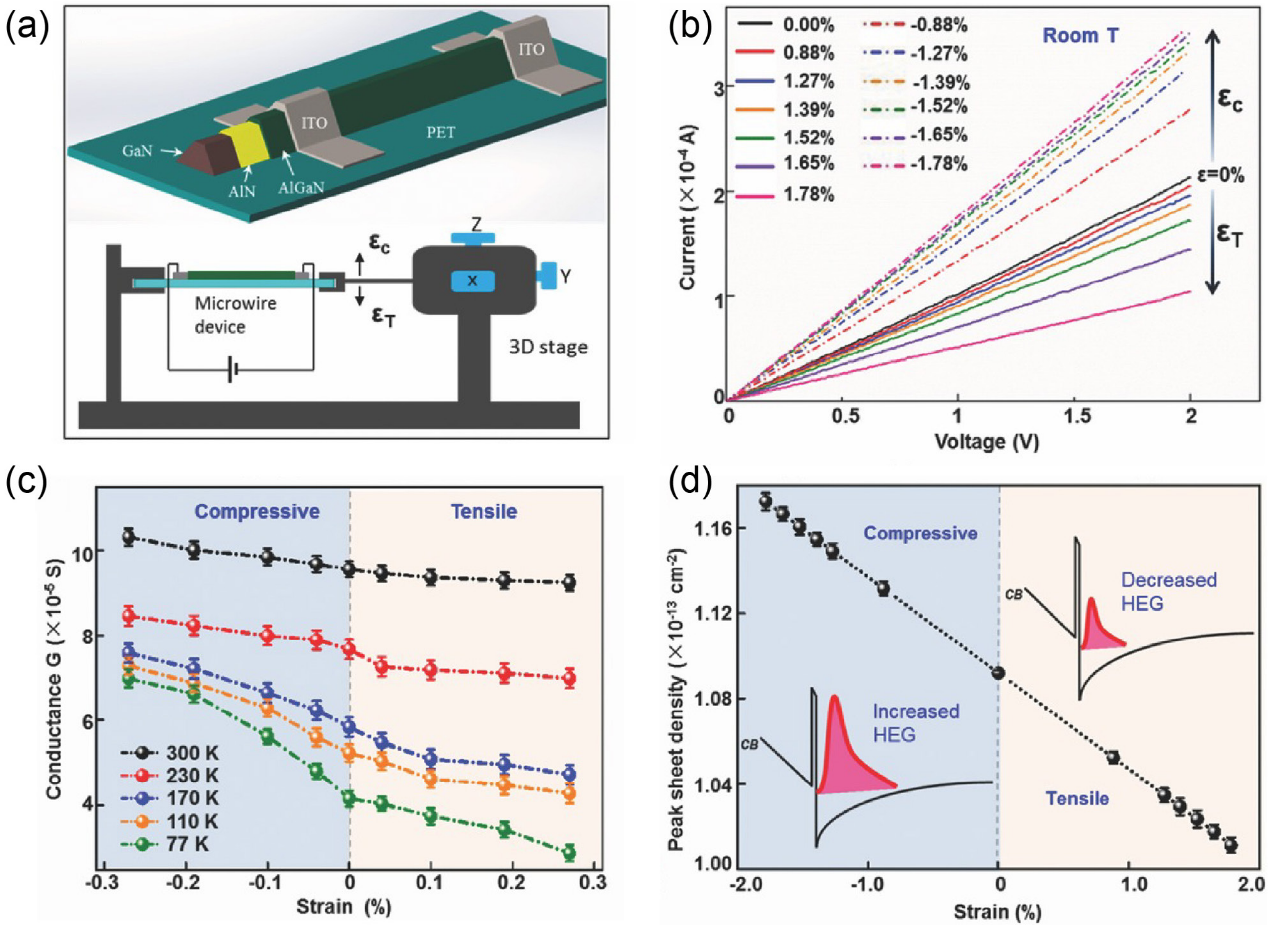

Figure 4. (a) Schematic device and experimental setup diagrams. (b) Modulation of *I–V* characteristics of the devices by the piezotronic effect under different compressive and tensile strains. (c) External strain dependence of the conductances of the devices under different temperatures. (d) The peak values of sheet density of HEG under different strains. [35] John Wiley & Sons. © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

experimentally and theoretically that the HEG was indeed existed in the AlGaN/AlN/GaN heterojunction. The piezotronic effect was proven to be an effective way to tune the HEG with temperatures varying from 77 K to 300 K (figures 4(b) and (c)). Specially, the conductance at room temperature was enhanced by 165% and decreased by 48% under 1.78% compressive and tensile strains, respectively; while at 77 K, the modulation was strengthened by 890% and 940%, respectively. The finite element analysis and self-consistent numerical simulation were applied to verify these modulation effect, from which the sheet density of HEG was demonstrated to be increased under compressive strains but decreased under tensile strains (figure 4(d)). The work gives a deep insight on the enhanced HEG via the piezotronic effect, indicating potential applications of quantum piezotronics in HEMTs and micro-/nano-electromechanical systems (MEMS/NEMS) based on III-nitride heterostructures.

3.2.2. Piezo-phototronic effect tuned photoluminescence imaging. The design and fabrication of high-resolution dynamic pressure imaging is promising for potential applications in human–machine interfaces, biomechanical detection, and encrypted signatures [11, 65–67]. Most of the commonly used pressure sensors are based on electrical measurements, illustrating the change in capacitance or resistance when applying pressures on the devices. The measuring circuit is complicated, and the response speed is reduced sharply with the increase of the number of pixels. Besides, electro-optical conversion can also be used as pressure imaging, but problems of fabrication complexity and uneven current distribution when increasing the density of matrix still exist [68, 69]. Therefore, a large-scale, high-density, and quick imaging for pressure distribution is urgently needed. Recently, Peng *et al* utilized an all-optical imaging to address this issue [70]. Although some previous reports have demonstrated the change of intensity of photoluminescence (PL) in several semiconductor nanowires at room temperature, such change usually needs a relatively large pressure [71, 72]. Peng *et al* fabricated InGaN/GaN multiple quantum well (MQW) nanowire arrays, and indicated that the array PL intensity can be modulated sharply via a little strain (0%–0.15%) because of the piezo-phototronic effect (figure 5(a)). The PL variation can reach up to 60% linearly with the pressure increased to 16 MPa (figure 5(b)). The pixel density of the sensor can reach up to 6350 dpi. Figure 5(c) shows the PL imaging with a pattern 'BINN' as the pressure stamp. The PL imaging for tactile/pressure can be

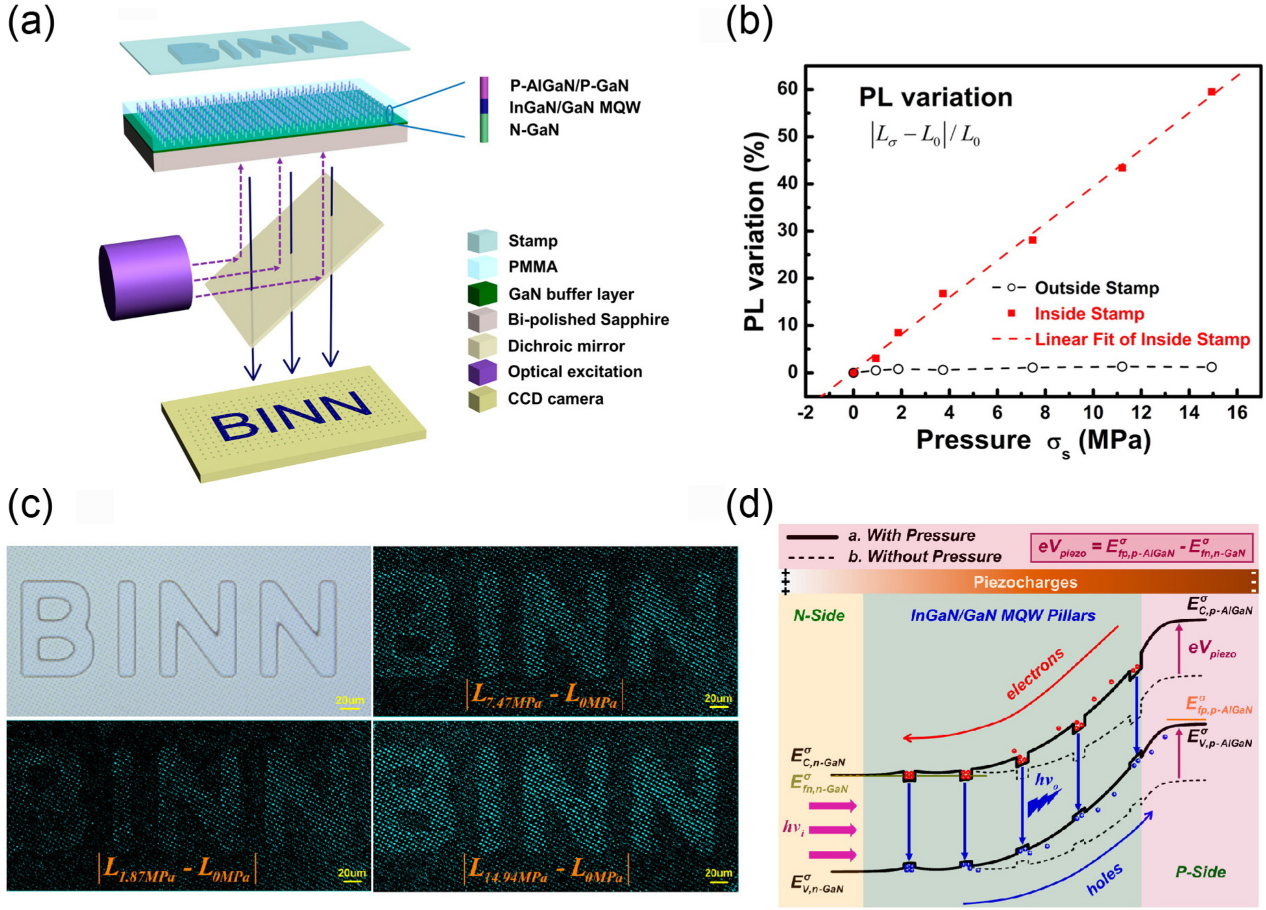

Figure 5. (a) Schematic diagram of piezo-phototronic effect modulated PL imaging. The InGaN/GaN MQW pillars is the core for pressure imaging. (b) Variation of PL intensity when applying a BINN patterned compressive pressure. (c) Differential images of 2D PL intensity. (d) Schematic change of the band profile due to the piezo-phototronic effect, illustrating the modulated PL by pressure. Reprinted with permission from [70]. Copyright 2015 American Chemical Society.

timely presented without any mutual interference. From the energy band point of view, an applied pressure can raise up the energy band of the P-side (right side) GaN, which weakens the carrier recombination in the quantum wells, hence the intensity of PL is dramatically reduced. That is, the change of the intensity of PL is enhanced (figure 5(d)). The all-optical pressure imaging provided by them possesses high pixel-resolution, better sensitivity, great uniformity, and ultrafast response speed, which indicates a wonderful way for man–machine interaction, optical MEMS/NEMS.

3.3. Based on 0D quantum dots (QDs)

3.3.1. Piezotronic effect enhanced Stark tuning of single InAs (211)B QDs. Semiconductor QDs are vital materials to produce single photons [73], entangled photon pairs [74], as well as indistinguishable photons [75]. Among them, piezoelectric QDs provide peculiar advantages compared with QDs without a piezoelectric property, such as high single-photon emission temperatures [76] and high preserved symmetry of the confining potential [77]. Recently, Germanis *et al* demonstrated improved Stark shifting of single exciton lines in InAs QDs resulting from remarkable a nonlinear piezotronic effect in polarization directions, which leads to this system extraordinary sensitive to a small external bias (figures 6(a)–(c)) [38]. The Stark shifts are measured to be 2.5 times larger than those obtained in (100) InAs QDs with no piezoelectric property. They applied a graded In-component potential profile to explain the measured transition energies and Stark shifts (figure 6(d)). The direction of the measured red shifts obviously certifies that the piezoelectric field is inversed with that speculated from bulk InAs piezoelectric coefficients. This work demonstrates directly the importance of a piezotronic effect on the Stark modulation of QDs, showing potential applications in quantum encryption and quantum information. It has also been predicted theoretically that the piezotronic effect could enhance the luminescence of QDs under a micro-/nano-newton force measurement [37]. The study revealed that CdS and CdSe QDs had much higher tunability of emission spectrum, making them suitable for applications in biological sensors and high-resolution force imaging.

4. Piezotronic/piezo-phototronic effect tuned quantum phenomena

Piezotronic/piezo-phototronic effects are universal phenomena that cannot only be applied in third-generation and 2D monolayer semiconductors lacking lattice centrosymmetry

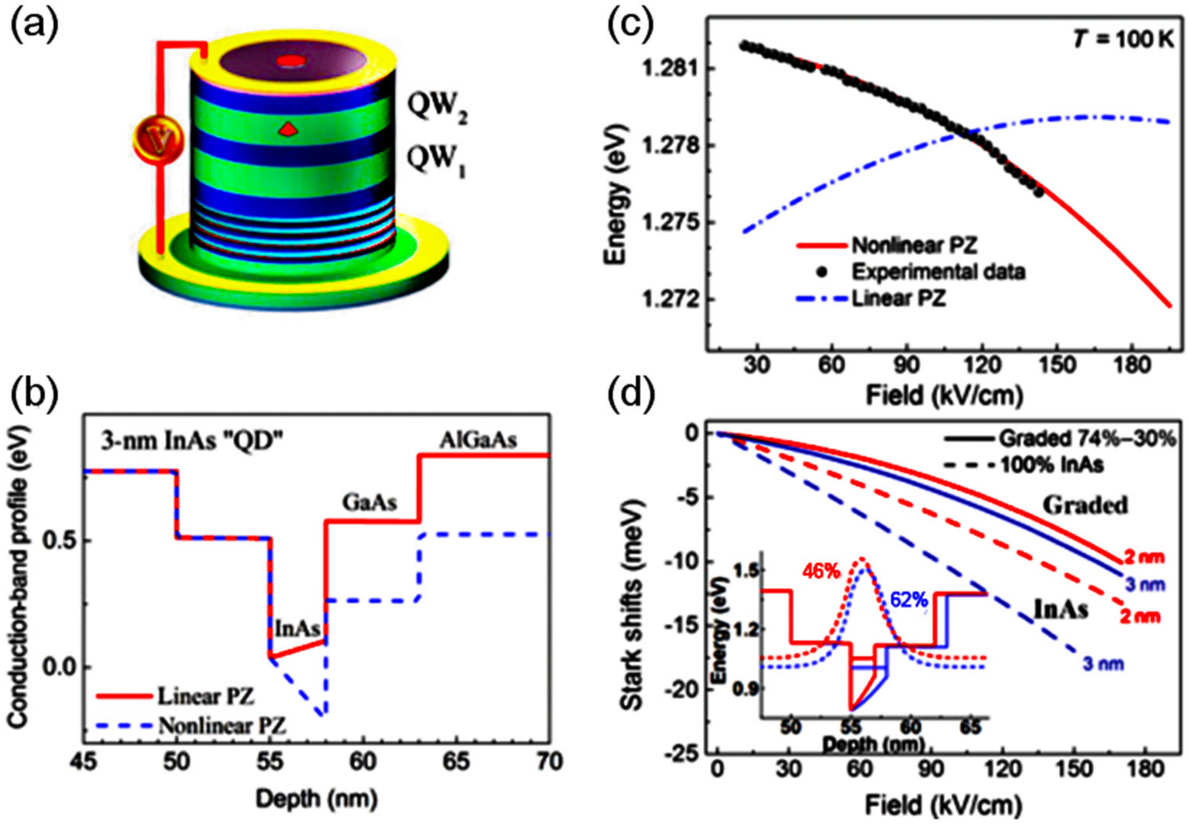

Figure 6. (a) Schematic diagram of the device. (b) The difference of the nonlinear and linear piezoelectric effects for the impacts on conduction-band profiles. (c) Experimentally measured energy (dots) corresponding to the QD X-transition as a function of external field and simulated plot consisting of nonlinear piezoelectric effect. A simulated curve including linear piezoelectric terms is also illustrated (dashed line). (d) Simulated Stark shifts, for pure InAs (dashed lines) and graded 74% to 30% In-component (solid lines), of the X-transition energy of 2 and 3 nm QDs. The conduction-band diagrams and wave-functions of the ground states without applying electric field are shown in the inset. Reprinted figure with permission from [38]. Copyright 2016 by the American Physical Society.

but also be used to tune some interesting quantum phenomena, such as laser emission, spin transport and topological quantum states, showing great potential in applications of quantum computation, quantum memory and quantum communication.

4.1. Piezo-phototronic effect tuned laser emission

The proposal of light quantum hypothesis boosted greatly the development of the laser. Lasers have a mass of applications in industrial, medical, commercial, scientific, information and military research fields [78, 79]. If the wavelength of micro-/nano-lasers can be tuned by certain ways, the micro-/nano-lasers can have great optical applications, such as optical communication devices, optical sensors, and spectral analysis technique [80, 81]. However, former ways, such as energy-band engineering [57, 82], intrinsic self-absorption process [83, 84], and Burstein–Moss effect [85], to tune the lasing modes are generally nonreversible modulations. Recently, Lu *et al* demonstrated a dynamic modulation on lasing modes in a ZnO microwire via the emerging piezo-phototronic effect (figure 7) [27]. The output lasing usually includes both TE and TM polarization. In this ZnO microwire, only TE mode is obtained. Figure 7(a) illustrates the PL spectrum and corresponding mapping of lasing emission under a 15.6 mW pumping power. The mode number is decided by the resonant wavelength, the diameter of cavity, and the wavelength dependent refractive index for a hexagonal whispering-gallery mode (WGM) cavity [27]. The calculated WGM TE mode numbers from 67 to 71 are plotted as blue triangles (upper panel in figure 7(a)), which match well with the experimental resonant wavelengths. An enhanced refraction index at room temperature was demonstrated due to the strong piezoelectric polarization in ZnO microwires when a tensile strain was applied, leading to a red shift of the whispering-gallery mode (figures 7(b) and (c)). As the line widths of the lasing modes are relatively narrow, the spectral resolution for strain was enhanced by an order of magnitude compared with PL spectra. This work proves that the piezo-phototronic effect can be effectively used in tuning the modes of micro-/nano-lasers, making it a potential in applications in high-resolution, high-sensitivity, and dynamic strain sensing.

4.2. Piezo-phototronic effect enhanced spin transport

Spintronic devices reveal significant advantages, such as high speed, allowing for much smaller sizes, and ultra-low power consumption, compared with traditional electronic devices [86–88]. The spin–orbit coupling (SOC) in semiconductors is the most important physical parameter to realize the creation, control, and detection of spins. Compared with

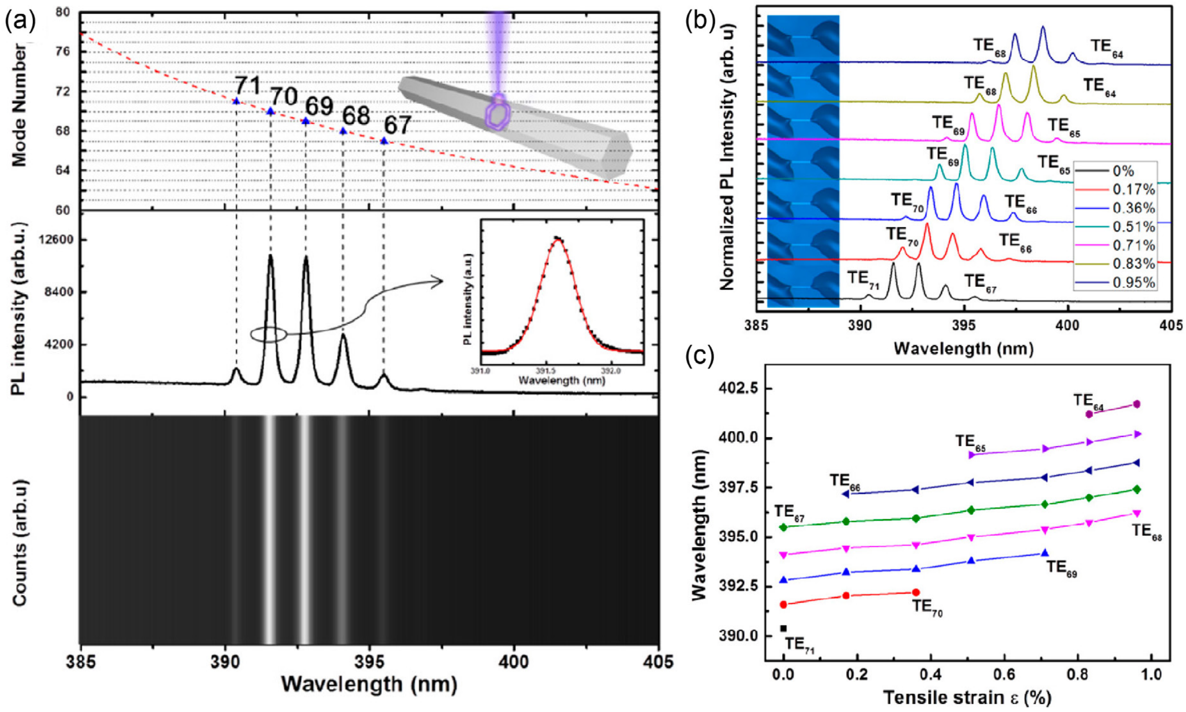

Figure 7. (a) PL spectrum (middle panel) and mapping (below panel) of light emission. And the corresponding TE mode numbers for each peak position (upper panel). (b) Red shifts of lasing spectra with increased bending strains. (c) The peak movement with the increase of tensile strain for each TE mode. Reprinted with permission from [27]. Copyright 2018 American Chemical Society.

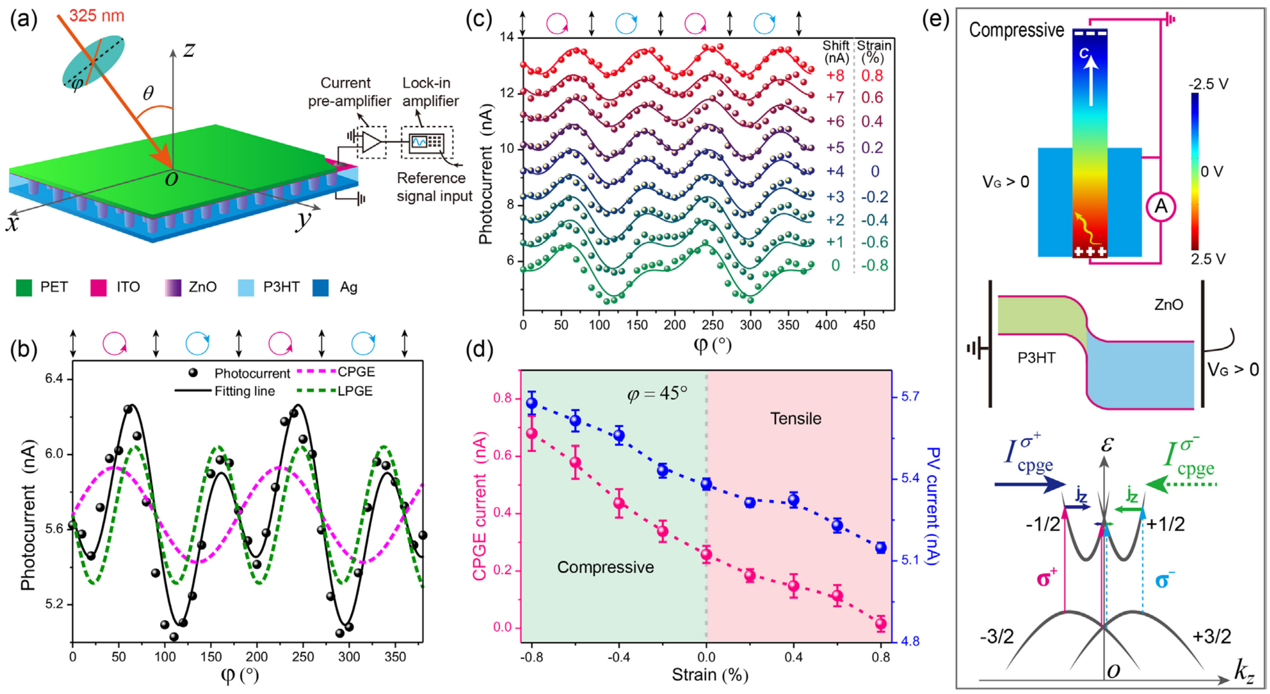

Figure 8. (a) Schematic diagram of the measuring setup. (b) Phase angle dependence of the photocurrent at room temperature, denoting that the total photocurrent consists of CPGE current, linear photogalvanic effect current and photovoltaic (PV) current. (c) Phase angle dependence of the photocurrent under various bending strains. (d) The abstracted CPGE current and PV current changing with the applied stain. (e) Schematic diagrams showing the enhanced CPGE current under a compressive strain. Reprinted with permission from [28]. Copyright 2018 American Chemical Society.

Dresselhaus SOC, Rashba SOC has drawn more attention due to the strength of Rashba SOC can be manipulated through designing artificial microstructure or exerting an external bias [89–91]. Previously, giant Rashba SOC have been detected in semiconductor nanowires (e.g. Ge/Si NWs and InAs NWs) and manipulated by gate voltages [89, 91], whereas a power source for the electric field will easily give rise to background noise or result in a short circuit in the nano-scale spintronic

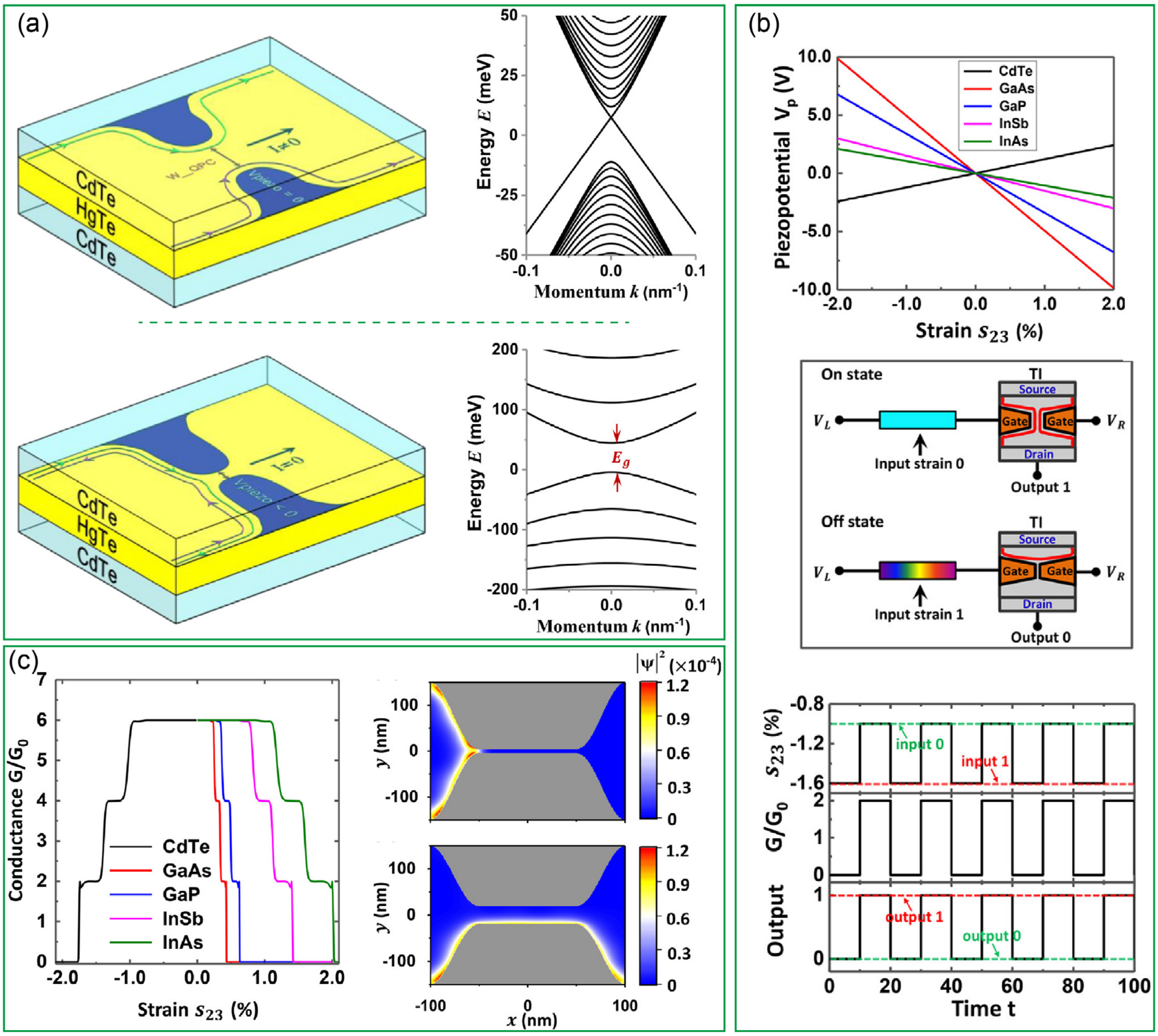

Figure 9. (a) Schematic diagrams of the manipulation of carrier transport and the energy band with and without strains. (b) The characteristics of the piezotronic switch based on a topological insulator. (c) Strain dependence of the conductance for various piezoelectric materials; wave functions of the edge states corresponding to OFF (upright figure) and ON (downright figure) states for a CdTe quantum well device. Reprinted with permission from [29]. Copyright 2018 American Chemical Society.

devices. What is more, the material growth and device fabrication are usually intricate and expensive. Recently, we reported a spin-dependent photocurrent in a easily fabricated and low-cost ZnO/P3HT NW array structure [28]. We used the circular photogalvanic effect (CPGE), one quick and hypersensitive technology [92–95], to investigate the SOC in our devices (figure 8(a)). The CPGE current reflects the strength of SOC. We demonstrated a big Rashba SOC at the heterointerface due to the interface-induced structure inversion asymmetry (figure 8(b)). What is more surprising, the Rashba SOC was manipulated by the inner-built piezopotential introduced in the ZnO nanowires without an external applied bias (figure 8(c)). The strength of Rashba SOC was increased by 2.6 times with a moderate compressive strain (figure 8(d)). From the energy band point of view, the positive piezo-potential at the bottom part of ZnO nanowires increased the inner electric field in the heterojunction, which further raised the structure inversion asymmetry (figure 8(e)). Hence, the energy band splitting was enlarged due to the enhanced Rashba SOC at the heterointerface. As a result, the CPGE current was increased. This study illustrates a large-scale flexible spintronic device based on heterostructured nanowire arrays and confirms that the piezo-phototronic effect is a promising method of tuning spin transport.

4.3. Piezotronic effect tuned topological quantum states

Topological insulators (TIs) have gapless surface states and an insulating bulk, which have been extensively investigated due to their promising applications in low power consumption devices and quantum computing [96, 97]. A steady strain can bring in or break topological surface states, such as HgTe and Bi_2Se_3 topological insulators [98, 99]. Miao *et al* demonstrated theoretically the creation of a TI state in a GaN/InN/

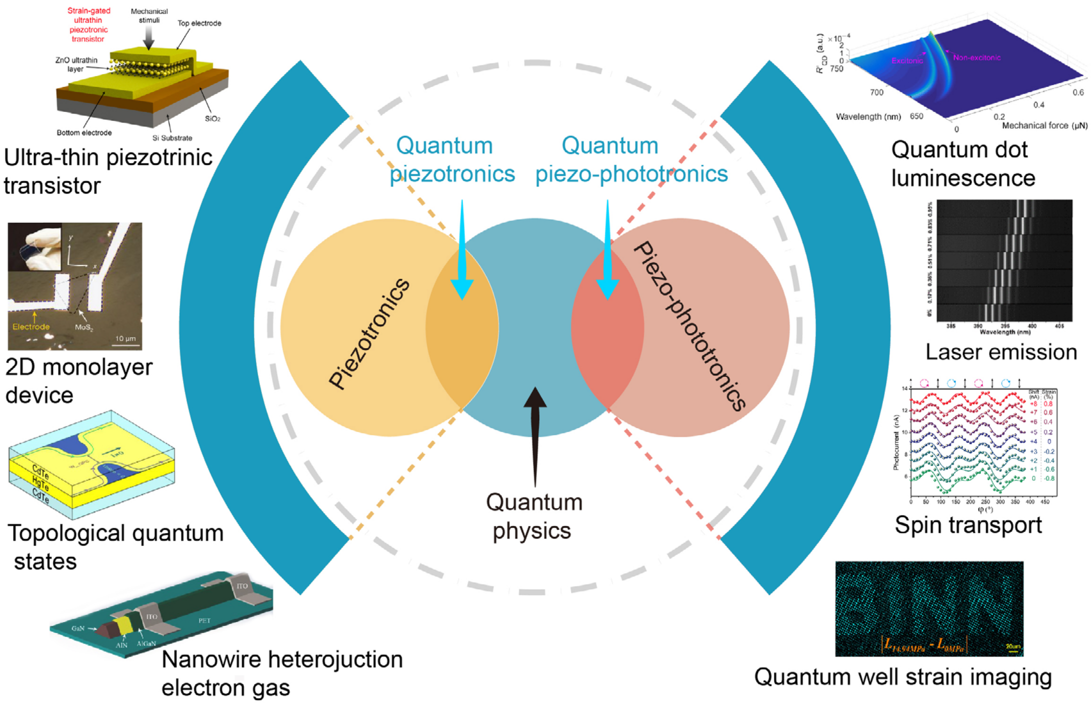

Figure 10. The coupling between piezotronics/piezo-phototronics and quantum physics coined quantum piezotronics/piezo-phototronics. This diagram illustrates the demonstrated applications of quantum piezotronics and piezo-phototronics in many promising fields.

GaN quantum well due to the piezoelectric polarization arising from the large strain in the ultrathin InN layer [36]. Recently, Hu *et al* designed in theory a TI piezotronic transistor using a CdTe/HgTe/CdTe quantum well structure (figure 9(a)) [29]. The HgTe/CdTe quantum well is extensively used for topological insulators, where the zinc-blende structure CdTe grown along the [1 1 1] direction possesses a good piezoelectric property. The strain-induced piezoelectric field is parallel to the surface of the topological insulator. Figure 9(a) illustrates the HgTe/CdTe quantum well structure with separated gates on the surface of HgTe. The constriction between the two gates can be regarded as a quantum point contact (QPC). The width of the QPC is approximately linearly dependent on the piezopotential created in the QPC region, controlling the electrical transport characteristics of the piezotronic transistor (figure 9(a)). The HgTe/CdTe quantum well can also be grown on other zinc-blende-structured piezoelectric semiconductors, such as GaAs, GaP, InSb, and InAs. The piezo-potential is linearly dependent on shear strain with different piezoeletric semiconductors. As the piezoelectric coefficient is opposite, the piezo-potential decreases with the applied strain for GaAs, GaP, InSb, and InAs (figure 9(b)). The ON/OFF ratio of conductance for a device based on piezoelectric semiconductor CdTe can reach up to 10^{10} (figure 9(b)). Based on this point, high-performance logical circuit and hypersensitive strain sensor could be fabricated. What is more, they found several conductance shoulders for the case of higher Fermi energy (figure 9(c)). This study demonstrates a good way of using piezotronic effect to tune topological quantum states, showing potential applications in high-performance switches, logical circuits, and strain sensors.

5. Summary and perspectives

The piezotronic and piezo-phototronic effects are universal effects and play a key role in the third-generation semiconductors as well as 2D materials. Here, we review recent advances in these two fields when quantum materials and quantum effects are considered (figure 10). Firstly, the piezotronic and piezophototronic devices based on various quantum structures are summarized. Then, some vital quantum phenomena tuned using the piezotronic and piezo-phototronic effects are discussed. Further developments are urgently needed to comprehend basic quantum physics, discover new quantum effects and explore novel applications for quantum piezotronic and piezophototronic devices. In addition, the design, manufacture, and characterization of quantum materials and devices are especially essential to attempt new applications. Low temperatures and high magnetic fields are required to seek more quantum devices based on piezotronic and piezo-phototronic effects. Apart from the demonstrated laser emission, spin transport, and topological states, many other quantum phenomena, such as single electron transport, valleytronic effect and superconducting effect, etc, are anticipated to be manipulated using the piezotronic and piezo-phototronic effects. The study of quantum piezotronics/piezo-phototronics is beneficial to the realization of next-generation high-integration, ultra-fast and hypersensitive electronic/optoelectronic systems, with potential applications in quantum computing, quantum communication, artificial intelligence, and wearable devices.

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