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Topical Review

Dynamic carrier transport modulation for constructing advanced devices with improved performance by piezotronic and piezo-phototronic effects: a brief review

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Abstract

Carrier generation, transport, separation, and recombination behaviors can be modulated for improving the performance of semiconductor devices by using piezotronic and piezo-phototronic effects with creating piezopotential in crystals based on non-centrosymmetric semiconductor materials such as group II–VI and III–V semiconductors and transition metal dichalcogenides (TMDCs), which have emerged as attractive materials for electronic/photonic applications because of their novel properties. Until now, much effort has been devoted to improving the performance of devices based on the aforementioned materials through modulation of the carrier behavior. However, due to existing drawbacks, it has been difficult to further enhance the device performance for a built structure. However, effective exploration of the piezotronic and piezo-phototronic effects in these semiconducting materials could pave the way to the realization of high-performance devices. In general, the effective modulation of carrier behavior dynamically in devices such as light-emitting diodes, photodetectors, solar cells, nanogenerators, and so on, remains a key challenge. Due to the polarization of ions in semiconductor materials with noncentral symmetry under external strain, a piezopotential is created considering piezotronic and piezo-photoronic effects, which could dynamically modulate charge carrier transport behaviors across p–n junctions or metal–semiconductor interfaces. Through a combination of these effects and semiconductor properties, the performance of the related devices could be improved and new types of devices such as piezoelectric field-effect transistors and sensors have emerged, with potential applications in self-driven devices for effective energy harvesting and

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biosensing with high sensitivity, which are different from those traditionally designed and may have potential applications in strained triggered devices. The objective of this review is to briefly introduce the corresponding mechanisms for modulating carrier behavior on the basis of piezotronic and piezo-phototronic effects in materials such as group II–VI and group III–V semiconductors and TMDCs, as well as to discuss possible solutions to effectively enhance the performance of the devices via carrier modulation.

Keywords: carrier modulation, piezotronic and piezo-phototronic effects, non-centrosymmetric semiconductor materials, electronic and photonic devices

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

1. Introduction

Until now, more and more research has been done on low-dimensional micro/nanodevices with intelligent functionalities for POCT health and environmental monitoring. In order to construct these devices, modulated operation of electronic and photonic devices through mechanical behavior is highly expected [1]. Charge carrier transport modulation is very important for building high-efficiency devices such as light-emitting diodes (LEDs), solar cells, photodetectors, and other photonic and electronic devices [2–7]. The piezotronic and piezo-phototronic effects of non-centrosymmetric semiconductor structures are especially important to the overall charge transport modulation because they can influence the recombination velocity and chemical reaction dynamics. The piezoelectric effect, discovered in 1880, describes the ability to develop an electric polarization proportional to mechanical stress in certain crystalline materials [8], which plays an important role in tuning carrier behavior when designing special devices based on non-centrosymmetric semiconductor materials. For instance, the group II–VI semiconductor material, ZnO, with a wurtzite structure, is now widely used for constructing LEDs, photodetectors, nanogenerators, surface acoustic wave devices, sensors, and more, with modulated performances [9–12]. The conjugation of piezoelectricity, photoexcitation, and semiconductor properties (piezo-phototronic effect) of ZnO nanomaterials was fully explored by Zhonglin Wang *et al* and the mechanisms of the piezo-phototronic effect that combine these effects are well described in their report [13–16]. Their investigation demonstrated that the properties of the semiconductor materials with non-central symmetry could be tuned under piezoelectric fields, and it was expected that the performance modulation of the devices based on these materials would receive much attention in the electronic or photonic communities, and many reports would be published thereof.

Piezotronic and piezo-phototronic effects have been systematically explored in many non-centrosymmetric semiconductor materials in groups II–VI/III–V, transition metal dichalcogenides (TMDCs), etc. Heavily studied materials such as 1D wurtzite-structured ZnO nanowires [17–22] and the 2D atomically thin TMDC, MoS_2 [23–26], have been applied in building different kinds of photo-electric devices. Other materials, such as $ZnSnO_3$ with a rhombohedral structure [27–29] and CdTe in the zinc blende phase [30], have also been explored for constructing related devices by using their piezoelectric properties. Through a combination of piezoelectricity, semiconductivity, and photoexcitation, the novel properties of these materials and the fundamental theoretical principles were further studied using these effects [31–35], which may have potential applications in the next generation of photonic and electronic devices [13, 35–42]. As piezoelectric semiconductor material's polarization is produced under a mechanical strain, an accumulation of polarized charges appear at the surface of the material; the presence of these polarization charges gives rise to the piezoelectric potential (piezopotential) for realizing piezotronic and piezo-phototronic effects. Carrier transport thus could be easily modulated under the piezoelectric effect, and the created piezopotential at the interface can be applied for enhancing charge combination/separation, regulating barrier height, and modulating reaction kinetics. Devices with a high performance, such as LEDs, photodetectors, and field-effect transistors (FETs) are designed by considering these effects [16]. The modulation of carrier transport is very important for tuning the performance of these devices. Through application of piezotronic and piezo-phototronic effects, carrier transport modulation can be achieved through the induced piezopotential by applying a strain [31, 33, 35, 43–45]. However, how to best utilize these advantages for building high efficiency devices remains a key challenge for researchers. Here, a brief review on the principles, piezoelectric semiconductor materials, and photonic and electronic devices is made (see figure 1) focusing on the charge carrier modulation; and illustrations on how to modulate carrier transport by these effects for improving the performance of the devices are reviewed by designed device structures. The principle of carrier modulation by piezotronic and piezo-phototronic effects is first examined, followed by a discussion of the most widely studied semiconductor materials with non-centrosymmetry. The review is then concluded with a survey of semiconductor devices based on piezoelectric materials. Moreover, the perspectives of the research field are briefly provided, which may serve to guide future research.

2. Principles and applications of piezotronics and piezo-phototronics

Piezotronics modulates charge carrier transport characteristics for basic structures such as p–n junctions or metal–semiconductor contacts; while piezo-phototronics combines piezoelectricity,

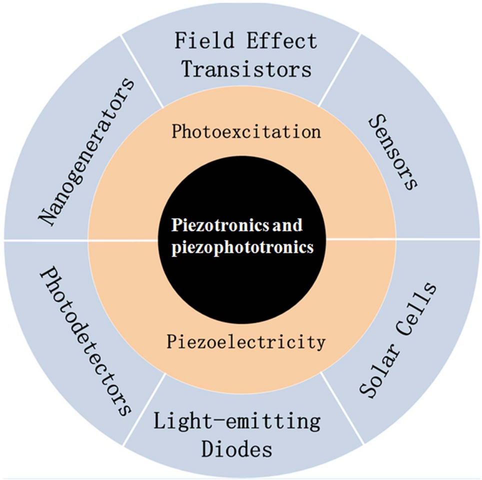

Figure 1. The applications of piezotronics and piezo-phototronics.

semiconducting and photoexcitation properties together to deal with carrier behaviors such as generation, transport, separation/recombination for modulating performance of the designed devices. As mentioned in the introduction, piezotronic and piezo-phototronic effects are of particular interest for utilizing the strain-induced piezoelectric potential to modulate the charge carrier transport behavior, which offers a pathway for engineering the energy band structure for improving the performance of many electronic, optoelectronic, and photovoltaic devices. The generated piezopotential that considerably affects the carrier transport and optical properties in the crystal is the key to piezotronic and piezo-phototronic effects. Through coupling of piezoelectric polarization and the intrinsic electric field, the charge carrier transport behavior in a space charge region could be effectively tuned for semiconductor devices. In order to illustrate the modulation capabilities of piezotronics, the principles and applications of these effects are explored first.

2.1. Piezotronic and piezo-phototronic effects

A piezopotential is generated through the piezotronic effect in semiconductor materials with non-central symmetry due to the polarization of ions caused by the application of an external stress or strain [46]. Zhonglin Wang *et al* clearly elaborated on the piezopotential by using ZnO with a wurtzite structure [31, 32, 34, 47]. For example, in wurtzite ZnO, Zn^{2+} cations and O^{2-} anions form a tetrahedral structure with the combined centers of positive and negative ions overlapping each other. If a stress is induced at the apex of a tetrahedron, the centers of the positive and negative ions shift relative to one another, hence creating dipole moments (see figure 2(a)). The crystal produces an electric polarization and generates opposing charges on the opposite surfaces at the same time. The dipole moments of the units in the crystal result in a potential drop along the direction of the strain in the crystal; this is the so-called piezopotential [31, 34]. The piezopotential is maintained in the crystal as long as the force remains; when the external force is removed, the crystal reverts to a state of non-polarization. However, if the direction of the external force is changed, the charge polarity also changes (see figure 2(b)). The charge induced in the crystal is proportional to the size of the external force. It is instructive to introduce energy band theory for illustrating the effects of the piezotronic properties on the carrier transport behavior. The band diagram of a piezoelectric semiconductor material at 0 K without an internal electric field is shown in figure 3(a). An electric field gradient proportional to that of the induced piezoelectric potential φ_{PZ}, follows the presence of a piezoelectric field (see figure 3(b)). Free charge carriers that exist in the semiconductor material will be separated to the opposite sides of the material; thus, an electric field is created [43, 48]. The influence of this piezopotential on the behavior of the carriers is significant for piezotronic devices. The piezopotential remains under strain-induced piezoelectric field without free charge carriers for open circuits, and the existing free carriers will rely on the conditions of factors such as temperature, band structure, light interaction and doping situations. Under switching of the piezopotential, the free carriers will segregate under modification of the enery band stucture. The piezoelectric field will vary in degrees of the built-in electric fields in the semiconductors, thus, charge carrier behavior could be effectively modulated by piezopotential created by applying external strain on the piezoelectric semiconductor materials. By exploring piezoelectric polarization on modulating charge carrier behaviors such as generation, transport, seperation/recombination in photodetectors, LEDs and solar cells, the performances of the devices could be effectively modulated by piezo-phototronic effects under light interation with externally applied strain.

2.2. Carrier modulation with the piezotronic effect

As a new research field, through combining the advantages of piezoelectricity with semiconducting properties, the built-in piezopotential that is created by the piezotronic effect in the semiconductor materials serves as a 'gate' voltage to tune/control the charge carrier transport behavior. Therefore, the carrier transport modulation can be realized by using the piezotronic effect through mechanical inputs [31, 34, 35, 49]. A better understanding of the carrier modulation of the piezotronic effect can be illustrated by building fundamental semiconductor device structures, for example, metal–semiconductor contacts or p–n junctions. The so called metal–semiconductor contact is essential for fabricating devices such as solar cells and FETs. In the modulation of the inflow and outflow of the charge carrier transport/recombination in semiconductor devices, the piezotronic effect can be invoked for effectively modulating the carrier behavior, which can be dynamically modulated through an external force. Once a tensile strain is induced in the n-type piezoelectric semiconductor, the negative piezopotential induced at the semiconductor side can increase the local interface barrier height (see figure 4(a)). The interface barrier can thus deplete major carriers in n-type semiconductors. Conversely, if the strain is induced inversely, the positive piezopotential created will decrease the local barrier height (see figure 4(b)). The barrier interface is less depleted of major carriers [16]. Therefore, the transport of the carriers at the metal–semiconductor interface

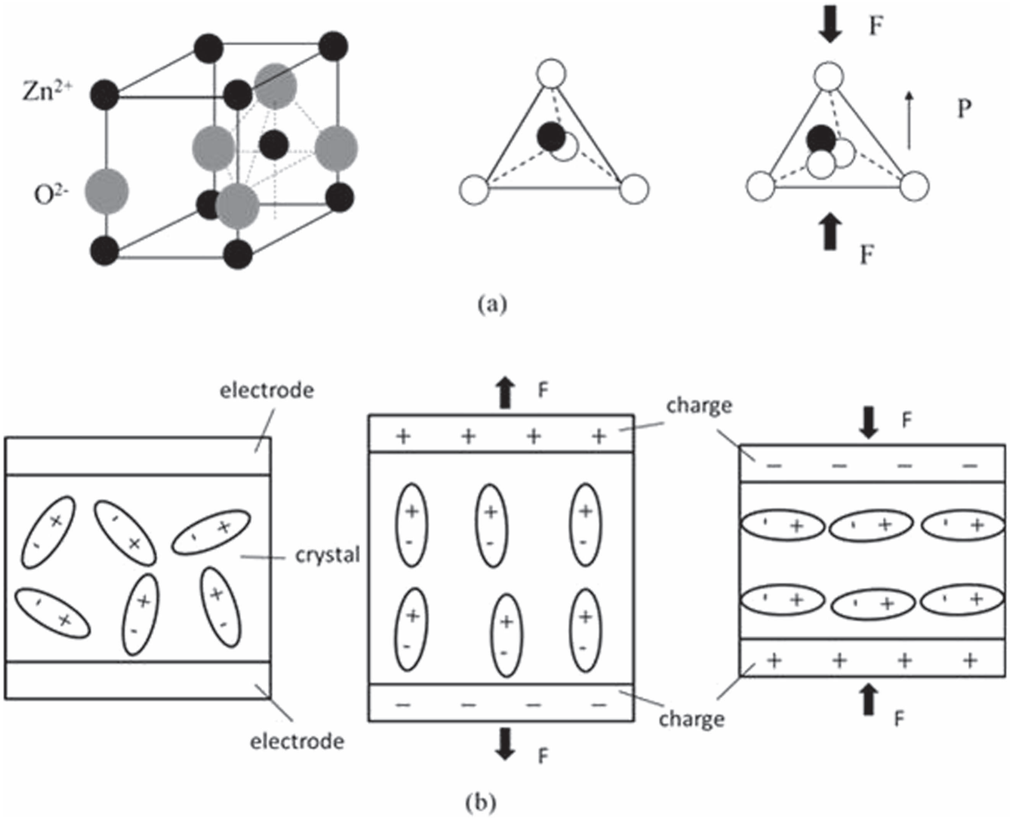

Figure 2. (a) Atomic model of the wurtzite structured ZnO. (b) Schematic diagram for illustrating electric polarization phenomenon. [43] John Wiley & Sons. [Copyright © 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim].

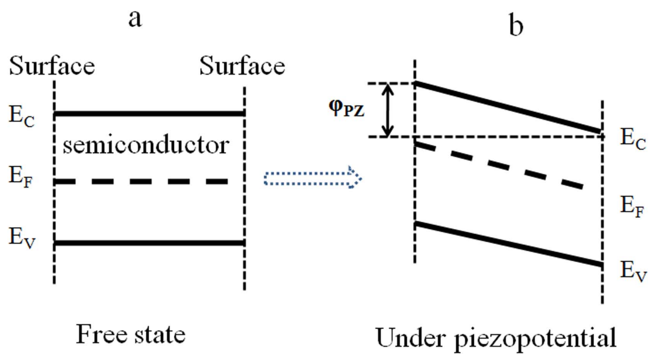

Figure 3. Schematic band structure diagrams of a semiconductor (at $T = 0$ K). (a) Without the piezopotential. (b) With the piezopotential.

can be effectively modulated by the strain-induced piezopotential, which is the core of the piezotronic effect.

The p–n junction consists of p-type and n-type semiconductor regions with opposite major carriers (viz., the holes in the p-type side and the electrons in the n-type side). They tend to diffuse interactively from another semiconductor side; consequently, the holes diffused into the n-type semiconductor side will recombine with electrons, while electrons diffused into the p-type side will recombine with holes. Hence, a built-in electric field restrains the diffusion progress at the interface of the p-type and n-type semiconductors. However, if a p–n junction includes a piezoelectric semiconductor material, the depletion region can be tuned by a strain-induced piezopotential, which could be applied for modulating the charge carrier transport behavior. Once a compressive strain is applied, the positive piezopotential induced in the n-type region near the junction interface will increase and decrease the depletion layer widths of the p-type and n-type sides, respectively [31, 34, 35]. Therefore, the depletion region expands and shifts towards the p-type semiconductor side (see figure 4(c)). In contrast, once the tensile strain is induced, the negative piezopotential generated in the n-type side repels electrons away from the junction interface, the depletion layer width of the p-type and n-type sides reverses direction, and the depletion region expands and shifts towards the n-type piezoelectric semiconductor side (see figure 4(d)). In the former case, electron–hole recombination might be promoted, and in the latter case, a suppressed phenomenon could be observed [14]. Therefore, the carrier recombination rate could be modulated for building highly efficient light-emission devices.

2.3. Carrier modulation with the piezo-phototronic effect

The effect by coupling piezoelectricity, light interaction and semiconducting properties together is called the piezo-phototronic effect, which could be applied to modulate charge carrier behaviors such as generation, transport, separation/recombination by external strain built piezopotential. For example, a p–n junction or metal–semiconductor contact could be a basic structure for a single nanowire photodetector. The external electric field is usually distributed in the depletion

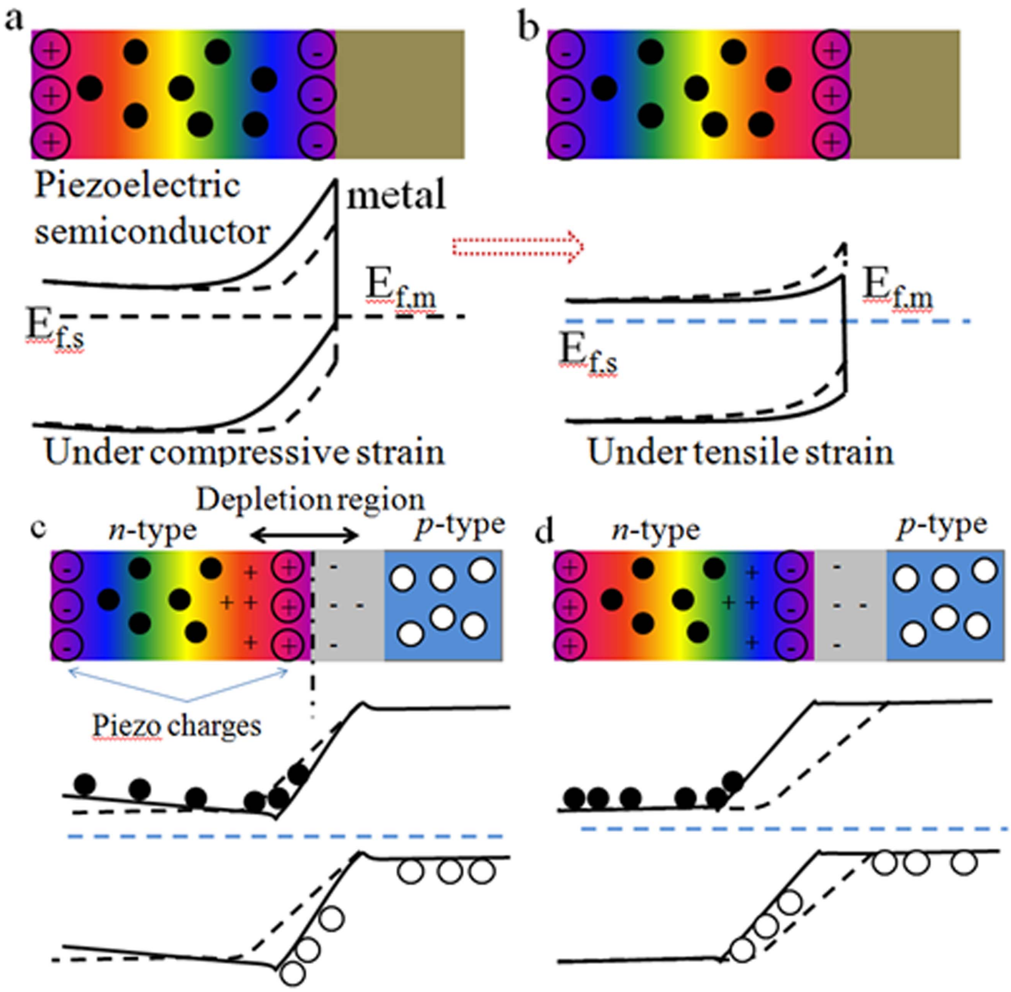

Figure 4. Schematic of the energy diagram showing carrier modulation of the piezotronic effect in a metal–semiconductor contact and p–n junction. (a), (b) Carrier modulation in a metal–semiconductor contact under compressive or tensile strain. (c), (d) Carrier modulation in a p–n junction under compressive or tensile strain.

region of the detector for efficient separation of carriers generated by photon excitation, which is the fundamental working principle. Through creation of the piezopotential, the energy band structure will be significantly modified at the interface by external strains, the carrier generation, separation, and transport at the interface thus could be effectively modulated for improving the performance of the cell. Carrier behavior control could be well modulated for improving the performance of optoelectronic devices by the piezo-phototronic effect through coupling the semiconductor properties, photon excitation with piezoelectricity together. Here, the carrier modulation with the piezo-phototronic effect is illustrated by an ideal p–n junction photodetector based on an n-type piezoelectric material. The working principle of p–n junction photodetectors is as follows: when light irradiation occurs, the photogenerated electrons and holes in the depletion region will be transported towards the n-type and p-type sides under the built-in electric field, which induces a photocurrent. Meanwhile, when a compressive strain is applied, the depletion area in the p-type side increases due to the presence of the positive piezoelectric charges, giving rise to the expansion and shift of the depletion region towards the p-type side. Thus, a charge channel in the conduction band is formed with the downward bending of the valence band edge in the n-type side [35] (see figure 5(a)). Correspondingly, the positive polarization charges in the n-type semiconductor material will trap partially photogenerated electrons, suppressing the separation of the electron–hole pairs and further decreasing the photocurrent [50]. In contrast, the negative polarization charges could induce an expansion and shift the depletion region towards the n-type side. The corresponding valence band edge will bend upward in the n-type side (see figure 5(b)). Therefore, the separation of the electron–hole pairs is promoted correspondingly with a suppressed recombination rate, causing an increase in the photocurrent. The mechanisms of the piezo-phototronic effect could be well applied in photoelectric devices for improving their performance.

3. Piezoelectric semiconductor materials

Actually, piezoelectricity phenomena was observed in materials such as polymers, ceramics, and even biological media. The most well-known piezoelectric materials are quartz and

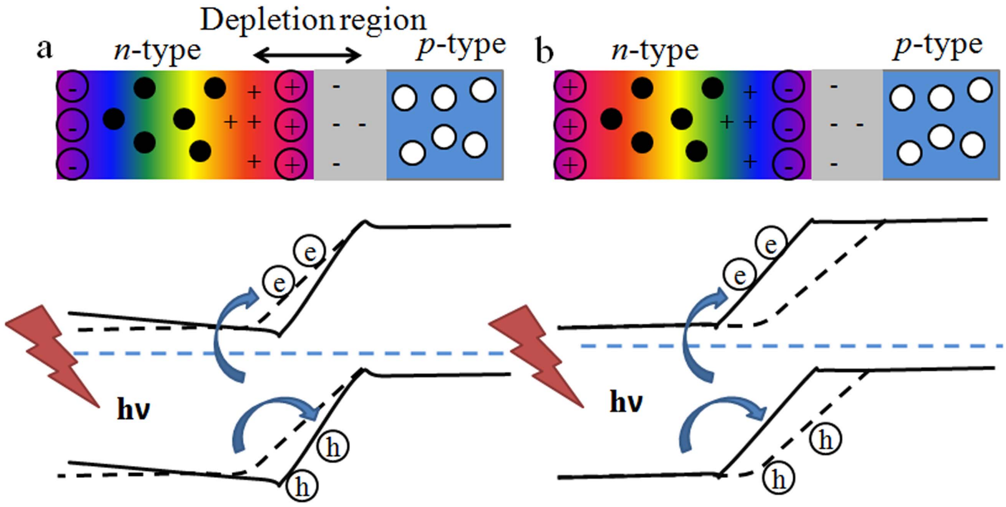

Figure 5. Schematic of an energy diagram showing carrier modulation of the piezotronic effect in a p–n junction. (a), (b) Carrier modulation under compressive or tensile strain with photoexcitation.

Table 1. The main parameters of materials.

Material	Group	Structure	Band gap	Piezoelectric coefficient
ZnO	II–VI	Wurtzite	Direct band gap of ~3.3 eV	$e_{11} = 266$ pc m^{-1}
CdS	II–VI	Wurtzite	Direct band gap of ~2.5 eV	—
CdSe	II–VI	Wurtzite	Direct band gap of ~1.74 eV	—
ZnS	II–VI	Wurtzite	Direct band gap of ~3.7 eV	—
CdTe	II–VI	Zinc blende	Direct band gap of ~1.44 eV	—
ZnSe	II–VI	Zinc blende	Direct band gap of ~2.7 eV	—
GaN	III–V	Wurtzite	Direct band gap of ~3.4 eV	$e_{11} = 148$ pc m^{-1}
InAs	III–V	Wurtzite	Direct band gap of ~0.4 eV	$e_{11} = 1.7$ pc m^{-1}
InN	III–V	Wurtzite	Direct band gap of ~0.7 eV	$e_{11} = 224$ pc m^{-1}
Monolayer MoS_2	TMDC	2H	Direct band gap of ~1.85 eV	$e_{11} = 362$ pc m^{-1}
Monolayer $MoSe_2$	TMDC	2H	Direct band gap of ~1.43 eV	$e_{11} = 383$ pc m^{-1}
Monolayer WS_2	TMDC	2H	Direct band gap of ~1.81 eV	$e_{11} = 243$ pc m^{-1}
Monolayer WSe_2	TMDC	2H	Direct band gap of ~1.53 eV	$e_{11} = 257$ pc m^{-1}

Pb(Zr, Ti)O_3 due to their non-semiconducting and insulating propertes, limiting their applications in photonic and electronic fields [1]. At present, researchers have studied many piezoelectric semiconductor materials in conjunction with carrier modulation by the piezoelectric effect, the main piezoelectric semiconductor materials that researchers have paid more and more attention to should be concluded. Theoretically, piezoelectric effects can be created by any semiconductor materials possessing a non-central symmetry. Many II–VI and III–V family materials such as ZnO, ZnSe, InN and GaN with wurtzite (the mainly studied piezotronic and piezo-phototronic materials are the wurtzite family at present, including but not limited to) or zinc blende non-symmetric structures in standard conditions have been studied for potential applications [51–53]. In general, wurtzite-structured ZnO is the most well-known II–VI family material in the study of the piezoelectric effect, as it both possesses a rich nanostructural morphology and exhibits a higher piezoelectric coefficient compared to other members, as shown in table 1. As building blocks for photonic and electronic devices, the main parameters of the typical piezoelectric semiconductor materials are briefly illustrated [54, 55].

3.1. 1D piezoelectric semiconductor materials

Through the facile coupling of semiconducting and piezoelectric properties in nano/microwires of piezoelectric materials, 1D semiconductor materials are preferred as basic constructing blocks for building novel devices. Considering the confinement effect, carrier transport could be limited in a single channel by designing nanowire/microwire based devices; 1D semiconductor materials have attracted significant interest for constructing advanced photoelectric devices. At the same time, piezotronic and piezo-phototronic effects have been considered for tuning the performances of devices based on the II–VI or III–V family of 1D nanomaterials. For II–VI wurtzite materials, where each cation is surrounded by four anions at the corners of a tetrahedron (see figure 1(a)), ZnO is the most frequently used material due to its direct band gap (3.37 eV) and large exciton binding energy (60 meV) at room temperature [56]. A p–n junction can be formed by an n-type ZnO nanowire with an epitaxially grown p-type GaN film. When applying a compressive strain along the *a*-axis of the nanowire, a tensile strain is created along the *c*-axis. The generated piezopotential will cause band modification and the trapping of states by the local piezoelectric charges near the interface [14], which can be applied in piezoelectric energy harvesters, too low-powered energy harvesting may be realized using 1D ZnO nanorods [12, 57, 58]. Increased energy harvesting efficiency was realized from studies based on 1D n-type ZnO nanorod/p-type CuSCN owing to the decrease of surface conductivity by forming a depletion layer due to the piezotronic effect [58, 59]. In addition, the screening effect causes a piezopotential dependency on the free carriers in ZnO [60–62], the carrier concentration can be effectively tuned based on the ZnO/Au Schottky contact under ultraviolet (UV) light irradiation with changing intensities, which means the function of the modulation of the strain-induced piezopotential could be realized, these results demonstrate that the piezophototronic effect can be applied for optimizing the performance of piezoelectric devices combining with photoexcitation [61]. In further, the doping of 1D ZnO nanowires could also be considered for building high-efficiency piezotronic devices through a change in the Fermi level [13, 63, 64]. Through an overview of experimental research based on 1D non-centrosymmetric nanostructures, the piezotronic and piezo-phototronic effects can be applied for effectively modulating the charge carrier transport behavior in the designed photoelectric devices [9, 18–20, 38, 65]. Other 1D group II–VI piezoelectric semiconductor materials such as CdSe, CdTe, ZnSe, ZnS, and CdS have also been considered. For example, the efficiency of the piezotronic effect of CdS was enhanced over 550% due to the decrease in the density of mobile charge carriers in 1D CdS nanowires at low temperature [66]. It is well-known that 1D semiconductor nanowires possess such advantages as large surface-to-volume ratios [67], ideal charge carrier transport [68] and efficient light trapping for absorption [69, 70]. The electron–hole pair generation, transport, separation, and/or recombination of 1D n-CdS/p-Cu_2S core–shell nanowire photovoltaic devices could be well-controlled using the piezo-phototronic effect through surface modification [67]. By the application of the piezo-phototronic effect, the charge carrier generation, separation, and collection behaviors in the core or shell could be effectively tuned for enhancing the performance of the built photo-electric devices based on 1D CdSe–CdS, ZnO–CdS nanostructures. Carriers spatially confined in different conducting channels of type-II heterostructures, where one major type carrier is localized in the shell and the other in the core, result in a reduced recombination rate [71–74]. The efficiency of the piezotronic effect for charge carrier modulation can be effectively improved through the design of optimal device structures such as 1D type-II heterojunction core–shell nanowire arrays [75]. The concentration of the specific ions could be measured based on 1D ZnO–ZnS core–shell heterostructural nanoarrays by considering piezotronic effect [75, 76]. 1D CdSe nanowires have such advantages as a wurtzite structure, high aspect ratio [77, 78] , and a direct band gap of 1.74 eV [79, 80], which could be applied in energy harvesting fields. When Pt and CdSe form a metal–semiconductor contact, the Schottky barrier height is modulated under a strain, which gives rise to a current decrease from 84 to 17 pA at a 2 V bias [81]. ZnSe possesses a cubic zinc blende structure with a direct band gap of 2.7 eV and has become a very favorable material for building optoelectronic devices [82]. 1D ZnO–ZnSe nanowire arrays with type-II heterostructures could be applied to achieve an effective conversion of mechanical strain into electric power using the piezotronic effect [83]. In addition to such 1D compound piezoelectric materials as ZnO nanowire arrays grown on carbon fibers and used for optoelectronic devices, ZnO nanowires with CdTe nanomaterials could be applied for potential applications in the energy harvesting field. Non-centrosymmetric type III–V semiconductor materials such as GaN, InAs, InN, and GaN have been studied for building photo-electric devices based on direct band gap properties, which have attracted increasing interest for building green-, blue-, UV-, and white-light-emitting devices [56]. Hence, piezotronic and piezo-phototronic effects could be well applied for improving device efficiencies, especially in 1D nanomaterials. For example, high quality 1D GaN nanomaterials could be fabricated under strain-controlled cracking method [84] through carrier transport modulation using piezotronic effect [85], studies showed that the piezopotential of 1D GaN nanotubes was much higher than that of nanowires [86]. The effects of scale size may remarkably influence the piezopotential of 1D nanomaterials [86–90]. For 1D InN, the transport process of the charge carriers in the nanorods can be more effectively tuned by the piezotronic effect of the strain-induced piezopotential, considering the narrow band gap and unique characteristics of the surface properties [91]. Potential applications of the piezotronic and piezo-phototronic effects in other III–V family materials, 1D AlGaN/AlN/GaN heterojunctions, and group III–VII InAs with a small direct band gap of less than 1 eV, have also been studied [92, 93]. Besides group II–VI and III–V 1D nanomaterials, perovskite structures such as $ZnSnO_3$ with a non-central symmetry and a large piezopotential have attracted much attention [94, 95], due to a larger polarization value along the *c*-axis, with many efforts focused on the piezotronic strain sensor; when a small strain along the *c*-axis of the 1D nanomaterial is applied, the interface barrier of the metal–semiconductor contact can be modulated by the strain-induced piezopotential. It should be noted that the modulation of the piezotronic effect under higher stresses may cause larger displacements of the Zn atoms along the *c*-axis, increasing the occurrence of lattice defects [96].

3.2. 2D piezoelectric semiconductor materials

High-performance piezoelectricity efficiency is a constantly pursued target for building electronic and photonic devices such as sensors, transistors, LEDs, solar cells, and so on, based on 2D piezoelectric semiconductor materials considering technological compatibility by strain engineering, from which strain-induced in-plane devices could be easily built with large mechanical stretchability [40, 97].

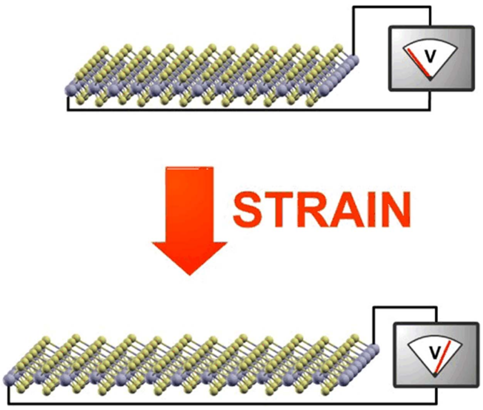

Figure 6. The enhancement of 2H–MoS_2 monolayer under strain. Reprinted with permission from [105]. Copyright (2012) American Chemical Society.

Two-dimensional (2D) piezoelectric semiconductor materials, TMDCs, and transition metal dioxides (TMDOs) such as MX_2 (M = Mo, W, Hf, Zr, or Ti; X = S, Se, or Te) have attracted significant interest [98–101]. TMDCs are materials of one or few atomic layers that usually possess 2T and 2H crystal structures [55, 102, 103]. Using first principles calculations, Duerloo *et al* investigated the piezoelectric properties of BN, MoS_2, $MoSe_2$, $MoTe_2$, WS_2, WSe_2, and WTe_2 monolayers [55]. Their research demonstrated that the piezoelectric properties of monolayer TMDCs with a 2H crystal structure were even better than those in bulk wurtzite structures. An enhanced piezopotential of a 2H–MoS_2 monolayer material was obtained under an applied strain, as shown in figure 6 [55]. Theoretical calculations showed comparable results with the experiments based on the TMDC and TMDO structures, which may have potential applications in nanogenerators [104].

Increasing attention has been focused on the studies of 2D monolayered MoS_2 materials, due to their possession of a large piezoelectric coefficient [41]. It was observed that the bulk and bilayer MoS_2 were not piezoelectric materials due to the existence of oppositely-oriented adjacent atomic layers. In addition, the piezoelectric effect can also be observed in odd-layered MoS_2 due to the stacking structure. Moreover, the band structure of the MoS_2 varied with the thickness [106]; this phenomenon was also observed in other materials such as WS_2 [107] and WSe_2 [108]. Theoretical studies demonstrated the transition mechanisms of the band structure [109]. Owing to the absence of defects and dislocations in 2D monolayered materials, the carrier transport behaviors could be more effectively modulated when compared with bulk materials. For example, the direct band structure of single-layer MoS_2 could be effectively tuned from a direct band gap to an indirect one under changing strain signs [110]. It was also observed that a transition from semiconductor to metal was realized for single-layer MoS_2 [111]. It should be noted that the strain-induced transition of the band structure also caused changes to the piezoresistive effect [112]. Strain-induced polarization can modulate carrier transport at the metal–semiconductor contact [113]. The carrier transport behavior can be tuned by polarization charges accumulated at the MoS_2/Pb–MoS_2 interface, with the piezoelectric potential caused by polarization charges further changing the interface barrier height, which can be tuned by the changing strain intensity. 2D monolayered MoS_2 fabricated using chemical vapor deposition or exfoliation techniques has a triangular shape with zigzagged edges using a seed-free method; the samples fabricated in this way possessed excellent optical and electrical properties [114]. It was observed that the polarization charges induced by the strain accumulating along the direction of the zigzag edges [55] and along the multiple conducting channels that were formed in the multilayered MoS_2 are absent in the single-layer [100]. By tuning the carrier transport through utilization of the piezotronic effect, the multilayer MoS_2 devices were built for improved device performance, such as in a p–n diode composed of p-type MoS_2 and n-type ZnO [106]. In 2D polycrystalline materials, double grain boundary barriers are created where electrons heavily accumulate due to the formation of positive-charge depletion layers [36] that cause a change in the semiconductor resistivity. The barrier height may be tuned by the piezotronic effect when applying a mechanical strain [115]. In addition, the current–voltage characteristic is highly nonlinear and naturally asymmetrical, which may be caused by the barrier of grain boundaries, the phenomenon of which can be strengthened or weakened by the piezotronic effect. The piezotronic effect is not the only reason for influencing the barrier height; the inhomogeneity of the grain boundaries should also be considered for the contribution of the changes [36].

4. Piezo-phototronic and piezotronic devices

Through coupling piezopotential in noncentral symmetry semiconductor materials without or with light interaction are called piezotronic and piezo-phototronic devices, respectively [51]. By applying effect of the piezoelectric potential, the charge carrier transport characteristics could be dynamically modulated for potential applications in mechanical electronic devices such as sensors, nanorobotics and human computing interfaces, and so on. By coupling the semiconducting and piezoelectric properties together, several important devices such as FETs, nanogenerators, and sensors related to the piezotronic effect could be included, while considering light interaction, by adjusting magnitude of strain and intensity of light, the charge carrier transport properties can be effectively tuned for devices such as LEDs, solar cells and photodetectors related to the piezo-phototronic effect have attracted significant interest due to their potential applications. The performance of photoelectric devices can be effectively improved based on fundamental structures such as the p–n junction and the metal–semiconductor contact through application of the piezo-phototronic effect. Optoelectronic device performance can be modified through the use of the effect and its influence on the mechanisms of carrier generation, transport, separation, and/or recombination behaviors [47, 116].

4.1. Piezo-phototronic effect on LEDs

The piezo-phototronic effect couples piezoelectricity, photonic excitation, and semiconductor properties together. By applying the piezo-phototronic effect to control the electron-optical processes in optoelectronic devices such as photodetectors, solar cells, and LEDs, the performance could be improved under strain-induced piezopotential dynamically [31, 117]. The basic structure of a LED is the p–n junction, in which minority carriers are injected from their counterparts under a forward bias, and the carrier recombination occurs for light emission. Utilizing the piezo-phototronic effect, light intensity modulated LEDs can be built, in which one type of conductive structure may be a piezoelectric material used for improving the performance, and the properties of the device can be effectively tuned through carrier injection, recombination, or extraction modulation by the piezo-phototronic effect. For example, considering the coupled effects, the external efficiency of a hybridized inorganic/organic LED made of a ZnO nanowire/p-polymer structure was further enhanced by modulating the carrier injection, recombination, and extraction [9]. Due to the high flexibility of the polymers and the chemical stability of the inorganic nanostructures, a higher light extraction efficiency was realized; the efficiency of this hybrid LED was doubled by the piezo-phototronic effect. The emission intensity of LEDs could be enhanced by applying an external strain, which may have potential applications in building efficient light-emission devices [4]. The barrier height for hole transport can be modulated for promoting recombination, which leads to the enhancement of the emission intensity of LEDs based on the reported LEDs with a poly (3,4-ethylenedioxythiophene) polystyrene sulfonate/ZnO nanowire array heterojunction. It is also reported that, due to the improvement of the injection current (which increased by a factor of 4) under a compressive strain, the corresponding emission intensity of the LEDs based on ZnO microwires was boosted by a factor of 17 [14]. By applying an appropriate strain, the performance of LEDs can be greatly influenced by the piezo-phototronic effect. From another point of view, the distribution of pressure could be detected by designing micro/nano LED arrays. A pressure sensor based on an n-ZnO nanowire array/p-GaN heterojunction was explored using the piezo-phototronic effect [39]; mechanical strains could be detected at the micro/nanoscale based on the designed LED by recording electroluminescence light intensities, and the LED device could map the distribution of the strain with a spatial resolution of several micrometers [118]. A spatial resolution of 7 μm for mapping pressure distributions was realized with a pressure range from 40 to 100 MPa. Recent research demonstrates that a higher spatial resolution of 2.7 μm could be realized based on a piezoelectric nanowire LED array (see figures 7(a) and (b)) [39], and the designed LED had a fast response and recovery speed to detect the distribution of pressure (see figure 7(c)). The output signal intensity emerged with a trend of enhancement with increasing strain (see figure 7(d)). Coupling effects, such as magnetics-mechanics-electrics-optics combinations, can be used for next-generation LED design [119]. The piezoelectric polarization and optical properties of devices could be effectively tuned when considering multi-fields; as an example, the piezoelectric polarization could be caused by a strain based on the magnetomechanical property of the Terfenol-D material. Therefore, the optical properties of LED devices could be modulated by polarization charges by the applied magnetic field with improved performance.

4.2. Piezo-phototronic effect on solar cells

The basic structure of solar cells is either a metal–semiconductor contact or a p–n junction, in which the separation of the electron–hole pairs could be realized under an electric field, and the collected charge carriers will contribute to the photocurrent. When considering the piezo-phototronic effect for band structure modification, the performance of solar cells based on piezoelectric materials can be greatly modulated for carrier generation, separation, and transport in the devices. A theoretical model of the piezoelectric solar cell based on the p–n junction and metal–semiconductor contact was investigated in detail by Zhonglin Wang [121]. The band structure can be modified by the piezoelectric potential applying for enhancing charge carrier separation. As an example, the output voltage of the P3HT/ZnO micro/nanowire heterojunction solar cell could be modulated by the mechanical strain shown in figures 8(a) and (b) [122]. The open-circuit voltage, V_{oc}, of the device, exhibited changes depending on the applied strains (see figure 8(c)). The band structure of the heterojunction was tuned, and then was followed with the creation of a piezoelectric potential under an external strain. It was reported that the energy conversion efficiency of a solar cell based on an all-inorganic type-II ZnO/ZnSe core/shell nanowire heterojunction was enhanced by applying the piezo-phototronic effect [73]. The piezoelectric potential of a Cu_2S/CdS coaxial nanowire solar cell is created in the core by applying a strain, which significantly influences the carrier transport at the interface of the core/shell, and the performance of the device was enhanced by a factor of 70%, owing to the function of the coupled effects.

4.3. Piezo-phototronic effect on photodetectors

The basic structure of a photodetector is similar to that of a solar cell; they both turn light signals into electrical signals [123]. Usually, the designed structure is composed of photoactive layers and carrier-collection electrodes. The main factors for photodetectors include surface functionalization for carrier trapping or transport, doping for band structure modification, and interface contact. However, the piezophototronic effect can be applied to dynamically modulate the band structure and carrier transport behavior in the photodetectors. The performance of photodetectors could be applied to influence photodetection by piezopotential induced by polar charges [124], which may have potential applications for metal–semiconductor contact or p–n junctions with non-centrosymmetric materials. It would seem contrary to logic that the light emission intensity of the LEDs and the energy conversion efficiency of solar cells could both be improved using the piezo-phototronic effect due

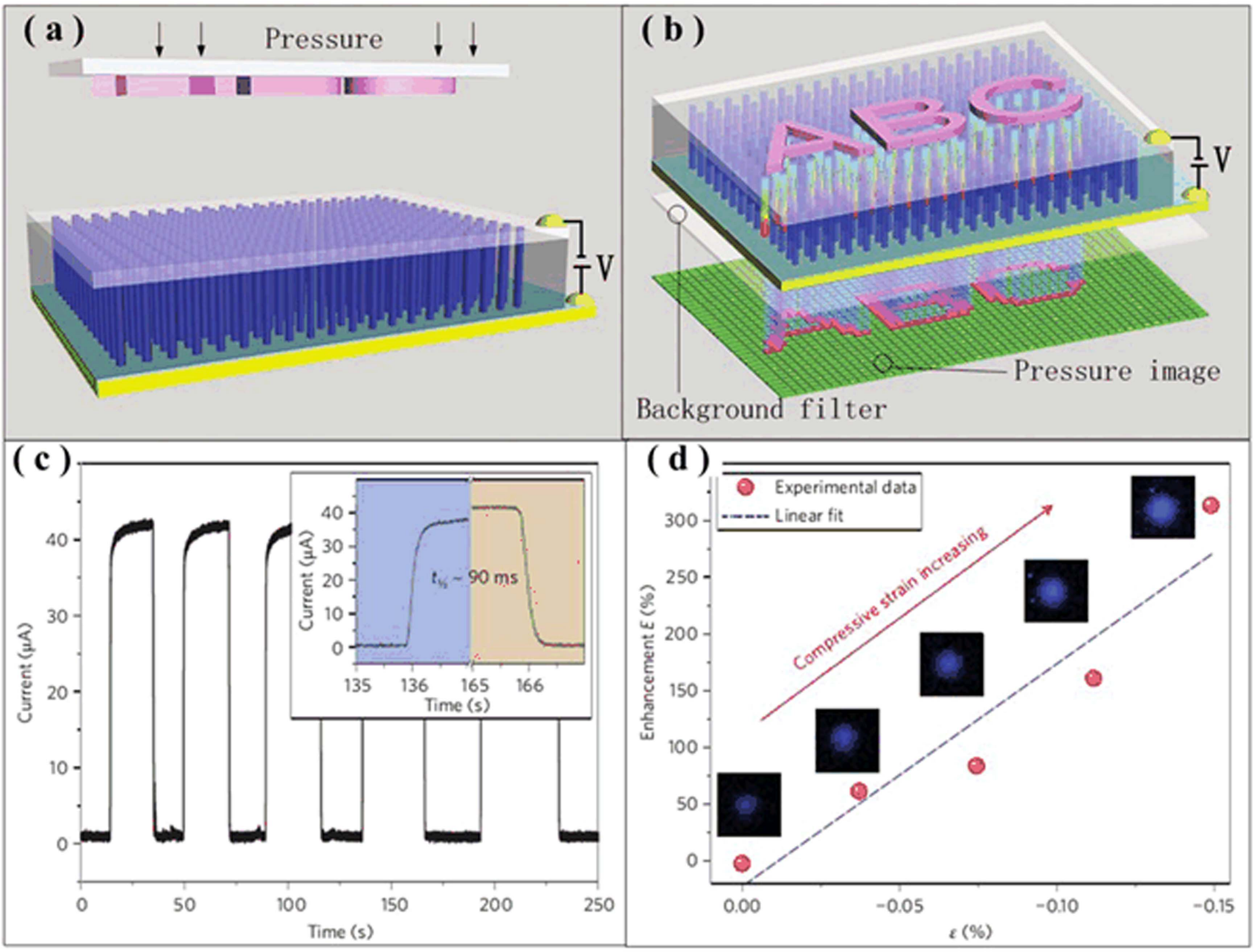

Figure 7. (a) Schematic illustration of a nanowire LED array for imaging pressure distribution before applying a compressive strain. (b) Schematic illustration of a nanowire LED array for imaging pressure distribution after applying a compressive strain. (c) Fast response and recovery of a nanowire LED array. (d) Enhancement of a nanowire LED under increasing compressive strain, with the corresponding emitting light image. Reprinted by permission from Macmillan Publishers Ltd: [Nature Photonics] [120], copyright (2013).

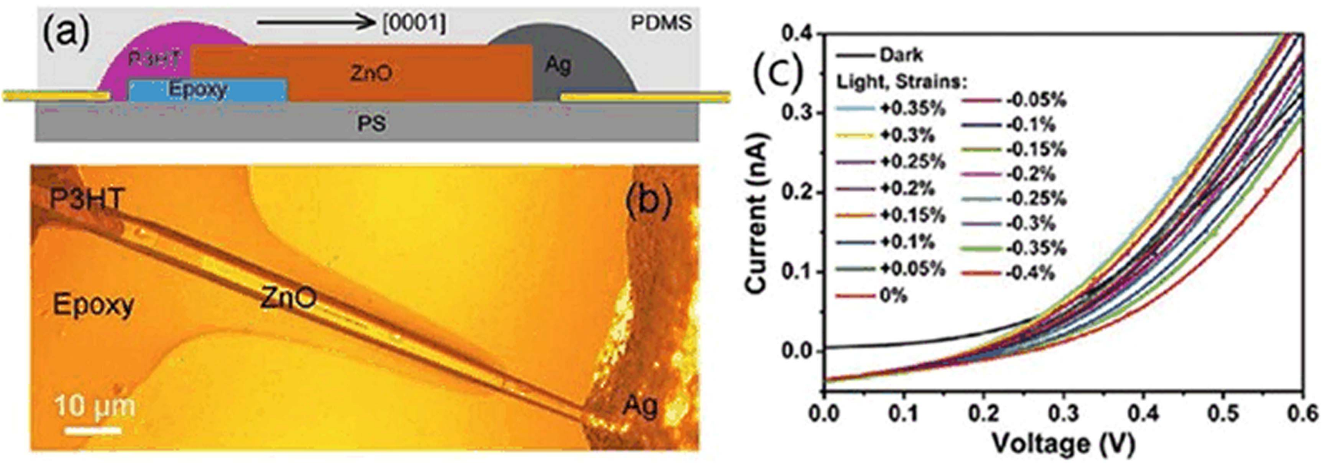

Figure 8. (a) Schematic of a device fabricatedby [0001] ZnO. (b) Optical image of the fabricated device. (c) $I–V$ characteristics of the device under different strain. Reprinted with permission from [122]. Copyright (2011) American Chemical Society.

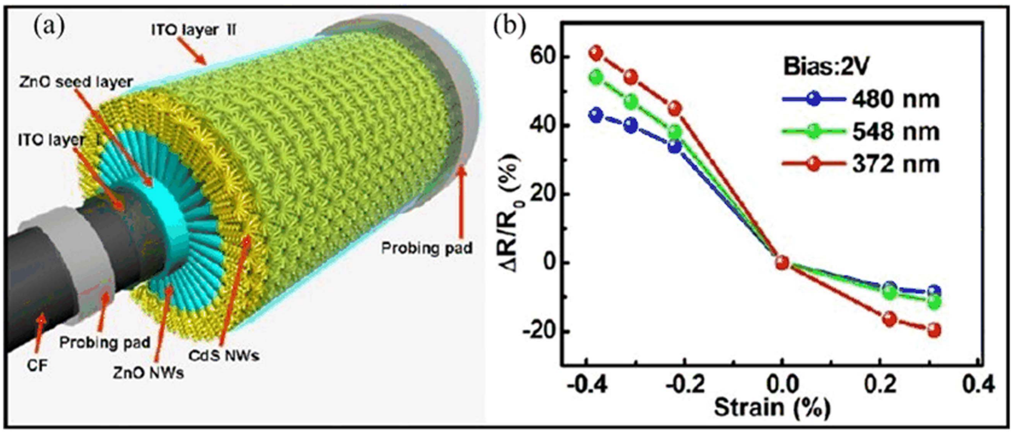

Figure 9. (a) Schematic structure illustrating carbon-fiber/ZnO–CdS double-shell. (b) Change of responsivity under different excitation; R_0 is set as responsivity under unstrain. Reprinted with permission from [127]. Copyright (2013) American Chemical Society.

to the differing mechanisms [14]. However, the piezo-phototronic effect may be applied in different ways in a designed structure [67]. For instance, the performance of Schottky-contacted photodetectors can be enhanced by tuning the interfacial barrier height with the piezo-phototronic effect, which could be applied to improve the sensitivity of photodetectors by as much as 18% under a compressive strain [2]. The piezo-phototronic effect can also be applied to tune the dark current of photodetectors; an increase by a factor of 530% was realized under a compressive strain in a ZnO micro-/nanowire photodetector [125]. The optoelectronic properties of non-piezoelectric semiconductor materials may also be enhanced through interaction with conjugated materials possessing the piezoelectric effect [50]. Utilizing the piezo-phototronic effect for modulating carrier generation, separation, and recombination behaviors, the performance of photodetectors based on a p-Si/ZnO nanowire hybridized structure can be modulated for enhancing detection capabilities. Through barrier height adjustment under the coupled effect for the carrier transport, the UV/visible photodetector based on ZnO–ZnS core–shell nanowire array was effectively enhanced over a large spectral range [75], which demonstrated that the limited photon detection capability in a large range could be improved by considering the effect based on a type-II heterojunction structure. In addition, the photon responsivity based on a ZnO–CdS core–shell structure showed a significant enhancement through the applied piezo-phototronic effect [80]. At present, a more than 10-times enhancement was observed by introducing the effect when a compressive strain was applied to the device. Additionally, a flexible photodetector based on a carbon-fiber/ZnO–CdS double-shell showed ultrahigh responsivity; owing to the strain-induced piezoelectric potential, an enhancement factor of 60% was realized under a compressive strain (see figures 9(a) and (b)) [126].

4.4. Piezoelectric FETs

A typical piezoelectric transistor could be a M–S–M structure with Ohmic or Schottky contacts. A FET is a semiconducting transistor that can be controlled by voltage, and the conductivity of the device is determined by the major carrier. The carrier density influences the conductivity between the source and the drain. Therefore, the performance of FETs can be modified considerably through the modulation of the major carriers. By inserting piezoelectric materials into the FETs, the on/off states can be tuned by applying a mechanical force in piezopotential-gated devices [18]. A piezoelectric FET composed of a single ZnO nanowire bridging two ohmic contacts acts as a source for draining current, which could be controlled by changing the bending state of the nanowire. When the piezoelectric FET is applied as a force sensor, an almost linear relationship between the bending force and the conductance is realized, which demonstrates that a single nanowire-based sensor with a source–drain could be used for nanonewton force measurements. The piezotronic effect was created when the external force was applied, which caused a piezoelectric potential drop across the wire. Using a freestanding ZnO wire, a lateral piezopotential-gated FET of a single ZnO nanowire could be realized [19]. It should be noted that the polarization potential direction of a piezoelectric nanowire occurs along its axis, so the states of the device can be effectively controlled. For carrier transport in 2D piezoelectric semiconductor transistors, using the confinement transport in single-layer MoS_2 as an example [128], the modulation of piezo-charges in carrier transport confined in a 2D location could be performed. According to theoretical principles, the piezotronic effect could be applied to effectively tune the carrier behaviors based on MoS_2/Pd–MoS_2 piezoelectric transistors [113]. The carrier mobility could be considered as an important parameter in designing FETs, which demonstrates the response speed of the FET. Early studies showed low mobilities on the order of several or tens in the monolayered MoS_2 FETs [129, 130], which greatly affects the potential applications of 2D-based FETs. However, based on first-principles calculations, the piezotronic effect could be well utilized for building 2D MoS_2 piezotronic transistors [131]. The corresponding studies also provide a better understanding of the 2D piezoelectric semiconductor devices.

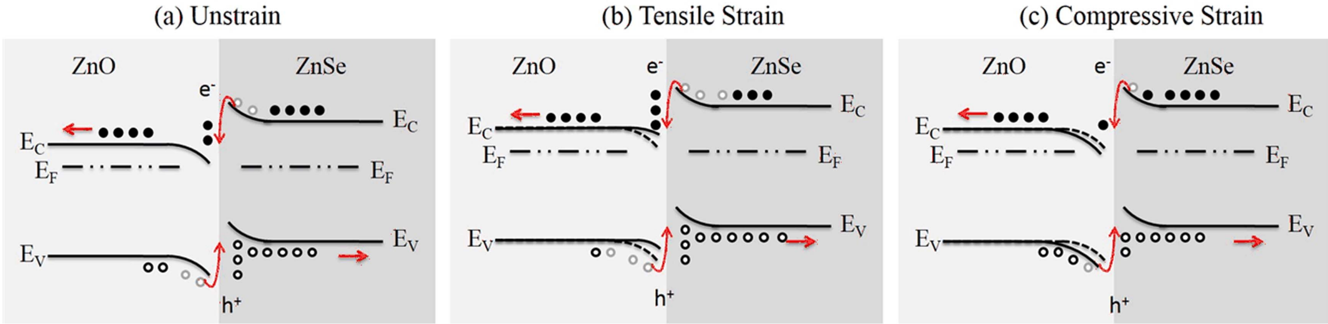

Figure 10. (a) Energy band diagram of an unstrained device. (b) Energy band diagram of a device under tensile strain. (c) Energy band diagram of a device under compressive strain. Reprinted from [138], Copyright (2014), with permission from Elsevier.

4.5. Nanogenerators (NGs)

The proposed nanogenerators can be charged up by mechanical energy from the environment, which supplies a novel approach as a power source for self powered devices and systems. The nanogenerators based on the piezopotential-driven charge carrier are devices that convert mechanical or thermal energy into electrical power at a small scale. In general, there are three types: piezoelectric, triboelectric, and pyroelectric. Both the piezoelectric and triboelectric nanogenerators can convert mechanical energy into electrical power, while the pyroelectric nanogenerator creates electrical power by harvesting thermal energy. Using ZnO nanowire material, Zhonglin Wang *et al* (2006) had a significant breakthrough when they built the first nanogenerator [132]. Since then, nanogenerators have been heavily studied. For the ZnO-based flexible nanogenerator [133], the lattice strain along the polar *c*-axis direction of the ZnO was modulated by doping with a halogen element, and thus the performance of the nanogenerator was enhanced by tuning the lattice strain. The performance enhancement of the generator occurred through the coupling of the effects of piezoelectricity and band structure modification by doping. Through the coupling of piezoelectric, semiconducting, and optoelectric properties, the output signal of a single CdS nanowire nanogenerator was effectively tuned under the excitation of visible light [134]. Considering the inner resistance and the screening effect, the piezoelectric potential of a single-nanowire nanogenerator was related to the carrier concentration. It was observed that the maximum output current was 50 nA when the carrier concentration was $5.63 \times 10^{18}\ \mathrm{cm}^{-3}$. Based on GaN nanowire array piezoelectric nanogenerators, decreased output current was observed with an increase in carrier concentration [135]. The interfacial barrier height greatly influenced the output signal of the nanogenerator, and by introducing the piezotronic effect, the barrier height could be modulated for efficient charge carrier collection. Due to the modulation for interfacial barrier height under the external strain-induced piezoelectric potential, the average output current of a nanogenerator based on an InN nanowire array reached 205.6 nA [136]. Passivation can suppress the screening effect and improve the output signal of nanogenerators based on the CuSCN p–n junction [58], and the depletion width of the p–n junction could be tuned via proper surface modification. It was realized that piezoelectric nanogenerators with high output signals could be actualized by coating P3HT polymer on ZnO surfaces. As a result, a signal improvement several times higher than that from ZnO nanowire-based nanogenerators was obtained [137]. It should be noted that the length of the vertically aligned nanowire generator does not have a remarkable relation with the output piezoelectric potential [11]. Fundamentally, due to the modification of the band structure, the improved performance of the nanogenerator devices can be realized. Here, the schematic diagram of the ZnO–ZnSe heterostructure is proposed to illustrate the band structure of the nanogenerator as shown in figure 10 [83], where a compressive strain is applied to the ZnO nanowire. A negative piezopotential is created, followed by changes of the conductive and valence bands, and the barrier height of the interface is decreased (see figure 10(b)); similarly, when a positive piezopotential is generated, the barrier height of the interface is increased (see figure 10(c)).

4.6. Piezoelectric sensors

Through bending curvature of the piezoelectric material, the mechanical force can be retrieved by recording the electrical signal, which could be applied for measuring forces in the nanonewton range or smaller [18]. Through a combination of piezoelectricity and semiconductivity properties, strain sensors can be built. As an example, by modulating the interfacial barrier height of the $ZnSnO_3$ single microbelt with the piezotronic effect, a self-powered piezoelectric strain sensor can be fabricated [29]. Through modification of the interfacial barrier height, the sensitivity of the strain sensors can be significantly enhanced [139]. A strain/force sensor with a high gauge factor of about 1160 based on a triangular single-layer MoS_2 was fabricated [40], demonstrating a higher gauge factor; the applied triangular MoS_2 is also beneficial for multi-directional nanoforce detection. A higher gauge factor of 1250 of the strain sensor was achieved based on an individual ZnO fine wire [45]. Based on investigation of the *I*–*V* characteristics, a strain sensor with high sensitivity was realized. It was observed that the sensitivity of the $ZnSnO_3$ nanowires/microwires sensor was significantly affected by the interfacial barrier height when a force was applied along the *c*-axis (see figure 11(a)) [28]. The sensor demonstrated a higher gauge factor of 3740 (see figures 11(b) and (c)). When the barrier

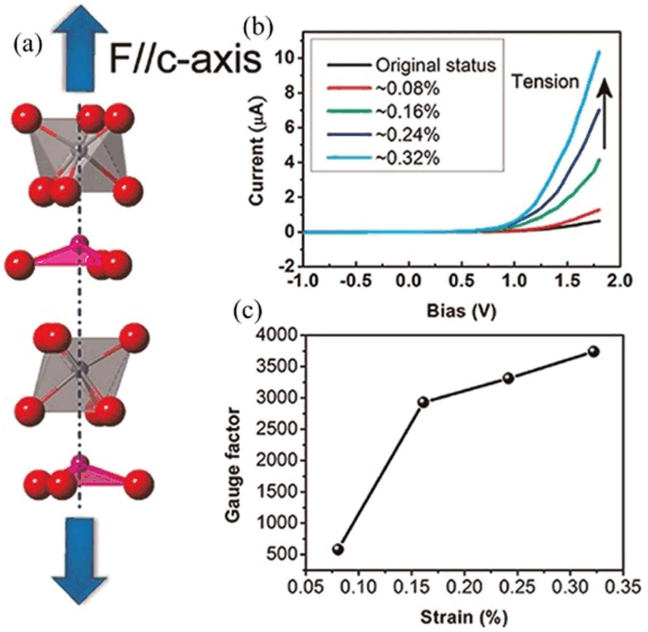

Figure 11. (a) Crystal structure of $ZnSnO_3$ and the direction of force. (b) *I–V* characteristic of sensor under different strains. (c) Gauge factors under different strains. Reprinted with permission from [145]. Copyright (2012) American Chemical Society.

height is tuned, the charge carrier transport also changes dramatically. When used as a ZnO piezoelectric strain sensor, the screening effect caused by the increased carrier density influenced the modulation of the polarization charge, under a higher illumination density, the performance of device showed unexpected results [140]. A temperature sensor based on the ZnO nanowire and utilizing the piezotronic effect with a modulated sensitivity can be fabricated [141]. Under a compressive strain, a humidity sensor with a large responsivity of 1240% was demonstrated based on the piezotronic effect [142]. The piezoelectric pressure sensors based on a LED array could be applied for the mapping of spatial pressure distributions as mentioned above [118], and a switch ratio of 353% with a sensitivity of 445% could be obtained [143]; this kind of pressure sensor can be applied to modulate the photoluminescence intensity [144]. In all, it is expected that the piezotronic effect could be applied for more and more promising sensor applications.

Besides the above-mentioned LEDs, solar cells, nanogenerators and so on, piezotronic resistive switching, logic nanodevices, electromechanical memories, actuators, diodes and resonators adjusted by strain-induced polarization via electromechanical modulation could also be well constructed with dynamically modulated performance by considering piezotronic and piezo-phototronic effects. By exploring strain induced polarization, charge carriers created at a p–n junction and/or semiconductor–metal interfaces under externally applied forces, the on/off characteristics of the resistive switching devices can be modulated, and these designed devices have potential applications for integrating and self powered multidimensional operations, and the designed piezotronic and piezo-phototronic devices in small scale size may have potential applications for ultrahigh density memory storage, logic computing, etc with characteristics such as high density, low cost. By applying the piezopotential for carrier transport modulation under externally strain, piezoelectric nanodevices together with photoexcitation processes can be coupled for the exploration of physical mechanisms and realization of unprecedented applications [1, 146, 147].

5. Conclusions

In brief, carrier modulation can be well tuned by using piezotronic and piezo-phototronic effects for building or enhancing the performances of related semiconductor devices which couple external force induced polarization, semiconductor properties and/or light interaction in piezoelectric materials, and factors such as the junction/contact properties should also be considered by the designed devices. The reviewed effects can be applied for building effective devices using basic structures such as p–n junctions, metal–semiconductor contacts, core–shell heterojunctions, and so on, when considering the coupled effects based on non-centrosymmetric materials. When a strain is applied, the piezopotential is created for dynamically modulating the charge carrier behaviors based on the piezoelectric materials, which is key to the piezotronic effect. The essence of the piezo-phototronic effect that combines semiconducting properties, photoexcitation and piezoelectricity, and the modulation of the carrier generation, transport, separation, and/or recombination can be well realized.

Through this review, the main piezoelectric semiconductor materials in families such as II–VI and III–V were investigated. 1D ZnO with a wurtzite structure is the most-studied semiconductor material, and can be applied for building LEDs, photodetectors, FETs, nanogenarators, and the like. Other II–VI family piezoelectric semiconductor materials such as 1D CdS, CdSe, ZnS with wurtzite structure, and CdTe and ZnSe with zinc blende structures are also investigated. The III–V family materials such as GaN, InAs, and InN have been included based on piezoelectric properties for potential applications. 2D piezoelectric semiconductor materials such as MoS_2, WS_2, and WSe_2 have also been studied. Due to its higher piezoelectric coefficient, 2D monolayer MoS_2 has attracted significant attention. The performance of electronic and phototronic devices can be enhanced by modulating the carrier transport behavior by the coupled effects. For the potential applications, the light emission intensity of LEDs and the energy conversion efficiency of solar cells could be efficiently improved when considering the piezo-phototronic effect; and the piezopotential gated FETs can be turned on/off by applying mechanical force, which may be applied as strain sensors. The output signal of nanogenerators could be significantly enhanced by the modulation of carrier transport by designing proper structures when considering the piezotronic effect. In addition, the performance of sensors modified by the piezotronic effect can also be enhanced for potential applications. In recent years, research in the literature has reported the advantages of the piezotronic and piezo-phototronic effects in modulating the charge carrier behaviors of materials in the II–VI/II–V and TMDC families. In the literature, several conclusions have been made: (1) piezotronic and piezo-phototronic effects could be applied for modifying the energy band structure by external strain, the carrier transport behaviors thus could be effectively modulated, (2) the overall performance of the designed device also depends on factors such as the p–n junction or metal–semiconductor interfaces when considering the piezotronic or piezo-phototronic effects; (3) charge carrier behaviors such as generation, transport, separation/recombination could be dramatically modulated for improving the performance of devices such as LEDs, photodetectors, solar cells, nanogenerators, FETs and sensors by piezotronic and piezo-phototronic effects.

6. Perspective

The fundamental theories of piezotronics and piezo-phototronics have been largely investigated, which provides a novel solution to modulate the performances of devices based on piezoelectric semiconductor materials. The materials that have non-central symmetry can be applied for coupling piezoelectricity, semiconductivity, and photoexcitation, and in the next generation properties such as ferroelectricity, thermoelectricity, and superconducting effects may also be conjugated for newly emerging devices. At present, tribotronics, a combination of triboelectricity and semiconductivity, has emerged with promising applications [148], and energy harvesting efficiency could be further enhanced by considering piezotronics based on semiconductor materials. When considering the design factors for building generators such as charge polarization created due to the piezotronic effect and the interface contact barrier, conversion from mechanical energy to electric power could be further increased for energy storage [132]. Until now, it was anticipated that the carrier transport modulation could be effectively realized for energy harvesting based on the piezotronic effect. Self-powered devices could be built based on the piezotronic effect [149], which are promising candidates for next generation products. Through the combination of the piezotronic effect and small size effect [150], the band structure and charge carrier transport behavior of semiconducting materials can be modulated for building tunneling devices. It is anticipated that the performance of devices such as memory devices can be enhanced by tuning their structures based on the piezotronic effect. Therefore, the coupled effects can be well applied for modulating carrier transport behaviors of the designed devices for improving their performance. Furthermore, newly emerging devices could be realized for potential applications by combing the piezotronic effect and other properties. Besides piezotronic and piezo-phototronic effects in modulating charge carrier behaviors, other factors such as piezoresistance effect and contact properties in the interface could also affect the performances of the constructed devices. Nowadays, more and more research efforts have been devoted to integrated systems with multifunctions, which are able to processing multi-tasks such as sensing, communicating and responding via micro/nano technologies based on piezoelectric materials. Charge carrier generation, transport, separation/recombination modulation is at the core of these research and applications for constructing electronic and photonic devices through piezotronic and piezo-photoronic effects for improving performance of the corresponding devices. Moreover, due to several reasons such as low cost, facile preparation process, well crystal quality at low temperature, large scale fabrication on any substrate and high elasticity, low dimension piezoelectric semiconductors are much prefered for constructing photonic and electronic devices. Considering future design/implementation of piezotronic/piezo-phototronic devices, several corresponding factors could be included: (1) well orientated nanostructures with a smaller size could be considered for their designs with large degrees of mechanical strain without formation of any fracture, (2) piezoelectric nanostructures with smaller size highly increases the toughness and density distribution of the function units, so the designed devices could be fatigue-free, (3) piezoelectric devices with high sensitivity could be built under a smaller force for triggering mechanical strain, (4) the contact properties such as the basic p–n junction and/or semiconductor–metal interfaces which influence charge carrier behaviors should be considered for device design. Finally, we anticipate that research in piezotronic and piezo-phototronic devices such as LEDs, solar cells, nanogenerators, and so on, will make further progress, and new electronic and photonic devices could be invented by continuous efforts.

Acknowledgments

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