Research progress of pressure-modulated photoelectric properties of materials*

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Abstract

The rapid development of optoelectronic technologies has raised increasing requirements for the photoelectric properties of semiconductor materials, thereby promoting the exploration of more efficient and controllable modulation strategies. High-pressure technology, as a clean and effective external tuning method, can accurately modulate the crystal structure and electronic states of materials. This modulation can induce novel phase transitions and physical effects, thereby significantly improving performance. In recent years, high-pressure techniques have emerged as powerful tools for optimizing photoelectric properties of semiconductor materials, providing new perspectives for enhancing performance and demonstrating significant research value and application potential.

This review paper comprehensively summarizes recent research progress in pressure-induced evolution of photoelectric properties in various material systems, such as two-dimensional transition metal dichalcogenides, metal and non-metal halides, perovskites, and other representative semiconductors. These materials exhibit a wide variety of pressure-induced structural transformations, accompanied by photocurrent enhancement, broadband spectral response, self-powered photoresponse, and polarity reversal. Furthermore, the intrinsic links between these structural evolutions and the corresponding photoelectric behaviors are systematically examined.

Scientific issues and development bottlenecks in this area are also discussed. Despite notable advances, there are still several challenges, including the insufficient understanding of

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* The paper is an English translated version of the original Chinese paper published in Acta Physica Sinica. Please cite the paper as: **CHENG Peng, YE Tingting, PAN Xiaomei, XUE Erqiao, YAO Deyuan, DING Junfeng, Research progress of pressure-modulated photoelectric properties of materials.** *Acta Phys. Sin.*, 2025, 74(20): 206201.
doi: 10.7498/aps.74.20250912

intrinsic correlations between structure and photoelectric properties and the lack of comprehensive evaluation criteria. Realizing pressure-enhanced photoelectric properties under ambient conditions remains a key challenge. Addressing these issues will be essential for advancing both fundamental understanding and practical applications.

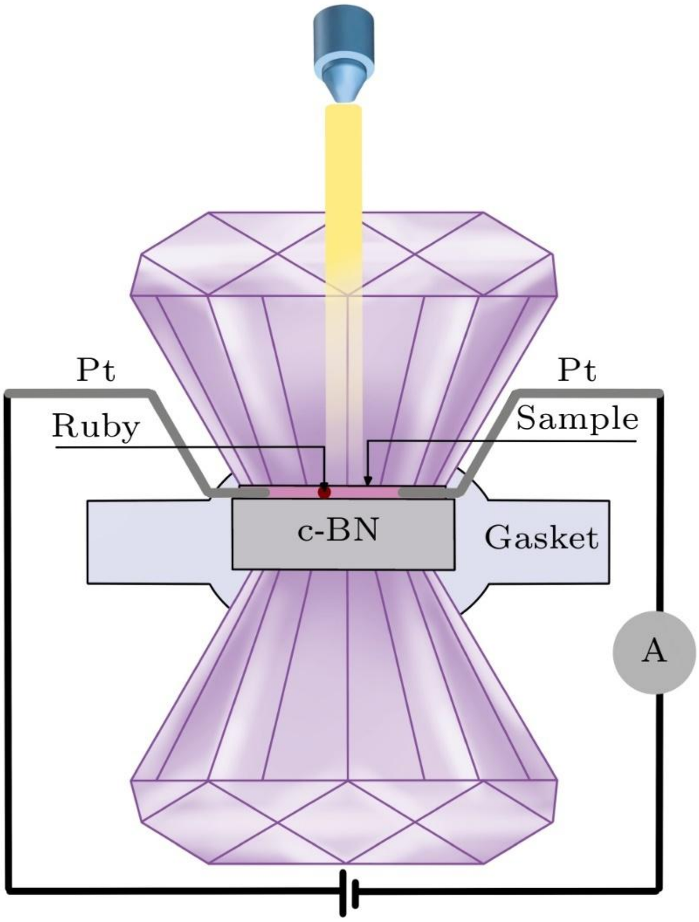
Overall, research on pressure-modulated photoelectric properties presents both significant challenges and exciting opportunities, providing valuable guidance for designing advanced optoelectronic materials and devices.

Keywords: high-pressure physics, photoresponse characteristics, structural phase transition, in situ high-pressure characterization

PACS: 62.50.–p, 78.56.–a, 61.50.Ks, 07.35.+k

doi: 10.7498/aps.74.20250912

cstr: 32037.14.aps.74.20250912



1. Introduction

As an important part of energy conversion, information processing and intelligent sensing, optoelectronic devices play an indispensable role in key applications such as information and communication technologies, quality inspection and analysis, biomedical and environmental monitoring[1–5]. The optoelectronic properties of materials determine the performance limits and application prospects of optoelectronic devices, and are the key to achieving technological breakthroughs in photovoltaic cells, photodetectors, light emitting diodes and other fields[6]. In recent years, with the rapid development of energy technology, information and communication, flexible electronic devices and other fields, increasing demands have been placed on optoelectronic materials in terms of detection efficiency, sensitivity, spectral response range and stability, and there is an urgent need to develop and optimize new optoelectronic functional materials. Precise tuning of optoelectronic properties of materials is not only the key to break through the bottleneck of existing optoelectronic devices, but also the strategic demand to support the development of emerging technologies such as information communication and intelligent sensing in the future.

The photoelectric properties of materials are usually affected by many factors, among which the crystal structure and energy band characteristics are the key factors. In addition, the carrier transport properties, the intrinsic defects of the material, and the interface effects also have a significant effect on the performance. In recent years, researchers worldwide have proposed a variety of effective control strategies to improve the photoelectric properties of materials, such as element doping, surface modification, and heterojunction construction[1,7–10]. These methods provide multiple strategies to adjust the band structure, improve optical absorption, and enhance carrier separation and transport efficiency, and promote the emergence of high-performance optoelectronic materials and devices. However, these means still face some difficulties and challenges in practical application. For example, when doping or surface modification is used to improve the performance, additional impurities or defects may be introduced, which increases the complexity of the internal structure of the material[5,11,12]. Although heterojunctions can significantly improve the photoelectric conversion efficiency and expand the absorption band, its device performance is often limited by complex fabrication processes and stability issues[9]. Therefore, it is an important research direction in this field to explore "clean", efficient and controllable external-field control strategies to optimize the photoelectric properties of materials.

As an important means to control the physical properties of materials, high-pressure technology has gained increasing attention in recent years and has rapidly shown great potential. As a clean external stimulus, pressure can effectively adjust the atomic spacing, interlayer interaction and orbital overlap of materials through lattice compression without introducing chemical impurities and defects, thus inducing many novel phenomena and effects, such as inducing crystal structure phase transitions, modifying the electronic structure and even inducing superconductivity[13–22]. With the rapid development of detection technology, a wealth of measurement systems have been constructed, which enable in situ characterization of the structural, optical, electrical, magnetic and photoelectric properties of materials under pressure, and provide valuable information for understanding the relationship between structure and physical properties[23,24].

Recently, high-pressure technology has made a lot of progress in the field of regulating the photoelectric properties of materials[25–33]. Under pressure, researchers have discovered a variety of intriguing phenomena in semiconductor materials, such as enhanced photocurrent, extended spectral response range, self-driven photoresponse, and negative photoconductivity effect, demonstrating their unique potential in improving the performance of optoelectronic devices. These results not only deepen the understanding of the intrinsic relationship between the structure and properties of materials, but also provide a theoretical and experimental basis for the development of new and efficient optoelectronic devices. This review summarizes recent studies on the photoresponse characteristics of materials under pressure. Section 2 systematically reviews the structural evolution and photoelectric response behavior of different types of materials under pressure, including transition metal dichalcogenides, metal and non-metal halides, perovskite materials, other van der Waals layered materials and three-dimensional semiconductor materials. Section 3 summarizes the response characteristics and the underlying physical mechanism of the photoelectric behavior of materials regulated by pressure. Finally, the challenges and bottlenecks in the current research on the photoresponse characteristics of pressure-regulated materials are summarized, and the future research directions are prospected, so as to provide a reference for the development and application of new photoelectric materials and devices. It should be pointed out that although a series of important achievements have been made in this field, the internal relationship between pressure-induced structural changes and the evolution of photoelectric properties is still in the preliminary stage of exploration, and the physical nature of many phenomena needs to be further explored. However, with the continuous progress of high-pressure experimental methods, in situ characterization techniques and theoretical calculation methods, high-pressure technology will play a more important role in the development of new optoelectronic functional materials and the design of advanced optoelectronic devices, and become an important frontier direction to promote the development of optoelectronic technology.

2. Photoelectric response of materials with different structures under high pressure

Under high pressure, the photoelectric response behavior of materials is highly dependent on the inherent crystal structure, electronic energy band and chemical composition of the materials. In recent years, studies worldwide have mainly focused on the semiconductor material systems with van der Waals layered structures. Due to the special layered structure, these materials show strong light-matter coupling and are excellent candidates for fabricating optoelectronic devices such as photodetectors[34–36]. In addition, some three-dimensional and ferroelectric, ferromagnetic functional semiconductor materials also show excellent photoelectric properties under pressure. The pressure response characteristics of the crystal and electronic structure of these materials endow them with promising prospects, which are also worthy of attention. According to the structural types and characteristics of the materials, these materials can be divided into five categories, namely, transition metal sulfides, metal/nonmetal halides, perovskite-type materials, other van der Waals layered materials, and other three-dimensional semiconductor materials, as shown in Fig. 1.

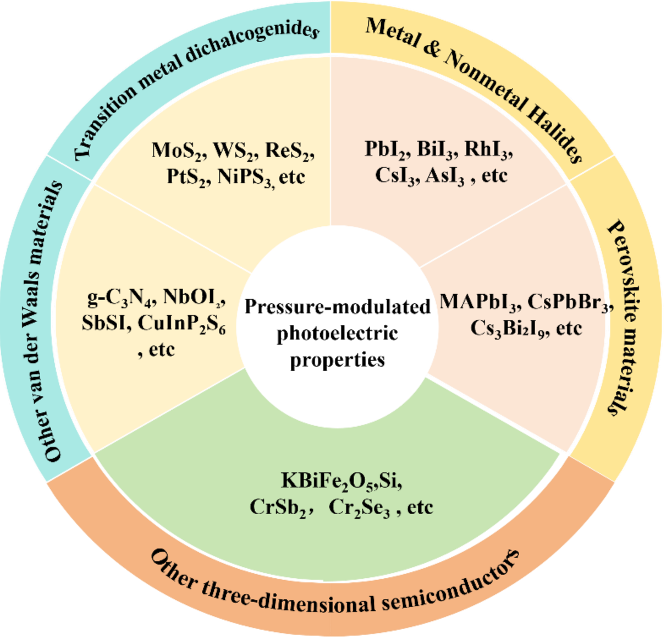


Figure 1. Schematic classification of representative material systems for high-pressure tuning of photoresponse properties.

2.1 Transition metal dichalcogenides

Transition metal dichalcogenides (TMDs) have a typical van der Waals layered structure with weak interlayer interaction and strong covalent bonding, which makes their electronic structure and optoelectronic properties extremely sensitive to external pressure, and are one of the earliest optoelectronic material systems that have attracted wide attention in the study of high pressure control[34,37–39]. In 2014, Nayak et al.[40] used diamond anvil cells to study the evolution of structural, electrical, vibrational and optoelectronic properties of multilayer MoS_2 under high pressure, and first verified the electronic phase transition process from semiconductor to metal. The pressure-dependent photocurrent response was further tested by using a 532 nm excitation laser, and it was found that the photocurrent gain decreased rapidly with increasing pressure and almost disappeared after about 10 GPa. This study revealed for the first time that high-pressure technology can be used to dynamically control the photoelectric response of materials, providing a new strategy for designing optoelectronic devices. Based on this finding, subsequent studies further extended the pressure regulation strategy to typical TMDs such as PtS_2, WS_2, ReS_2 and $ZrSe_2$, and found that they also showed rich photoelectric response regulation behavior under pressure.

For example, PtS_2, which is also a TMD material with van der Waals layered structure, shows a significant photocurrent enhancement in the range of 3-4 GPa, with an increase of about 6 times compared with that at ambient pressure (as shown in Fig. 2(a))[41]. X-ray diffraction and in situ Raman measurements show that the crystal structure of PtS_2 remains stable in this pressure range, and the band gap changes from indirect transition to quasi-direct transition, which leads to improved photoelectric performance without macroscopic phase transition. The core reason for the improvement of photoresponse is considered to be the band gap compression caused by high pressure and the enhancement of interlayer interaction. This stable and controllable photoresponse provides a new material candidate for shortwave infrared detection.

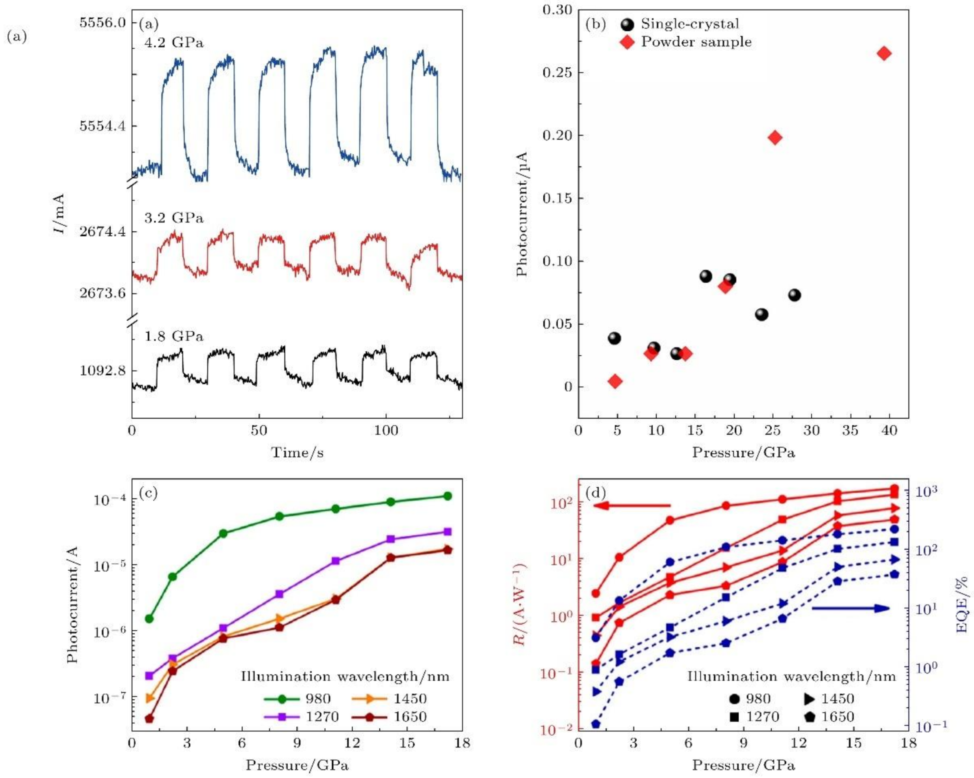


Figure 2. The photoelectric response behavior of TMD materials under pressure: (a) Photocurrent of PtS_2 at elevated pressures[41]; (b) photocurrent-pressure dependence of bulk and single-crystal ReS_2 samples[42]; (c) photocurrent-pressure dependence of layered WS_2 with 980, 1270, 1450, and 1650 nm NIR wavelengths[43]; (d) Responsivity (*R*) and *EQE* of WS_2 as a function of pressure under illumination of selected near-infrared wavelengths[43]. Reproduced with permission.

ReS_2 shows a unique structural and performance evolution path. It is found that as the pressure increases, the ReS_2 undergoes a structural transition from the 1*T* phase to the distorted 1*T′* phase at about 7.7 GPa, and a semiconductor-to-metal transition occurs around 38 GPa (as shown in Fig. 2(b))[42]. In this process, with the enhancement of interlayer S-S interaction, the visible photocurrent response of ReS_2 is continuously improved, showing good pressure response characteristics. This work not only reveals the details of the structural phase transition of ReS_2 under pressure, but also clarifies the variation of its photoresponse characteristics with structural adjustment, which provides a reference for the development of ReS_2 optoelectronic devices based on pressure regulation.

Under high pressure, WS_2 exhibits a significant enhancement of near-infrared response, the response wavelength is extended from the visible region to the near-infrared region (1650 nm), and the responsivity and external quantum efficiency are improved by about two orders of magnitude (as shown in Fig. 2(c) and Fig. 2(d))[43]. The enhancement mechanism is mainly due to the band gap compression and the red shift of optical absorption caused by the enhancement of interlayer S-S interaction. WS_2 can improve the infrared response without obvious phase transition, which reflects the effectiveness of pressure in broadening the spectral response range of TMD materials, and provides a new way for the design of wide-spectrum response and high-sensitivity infrared detectors.

$ZrSe_2$ exhibits an interesting high-pressure induced photoelectric polarity inversion[44]. Under pressure, the electronic band structure and crystal structure of $ZrSe_2$ change significantly, the band gap narrows from 1.13 eV to 0.83 eV, and the crystal structure changes from trigonal to monoclinic. The photocurrent reaches the maximum at 13.5 GPa, and the increase is about 3 orders of magnitude. Under further pressure, the metallization transition of $ZrSe_2$ occurs, accompanied by the inversion of positive photoconductivity and negative photoconductivity. This novel phenomenon is mainly due to the enhancement of carrier scattering caused by the thermal effect after metallization.

The above studies show that TMDs exhibit outstanding band gap control ability and excellent carrier transport properties under pressure, and the photoelectric response of most materials is significantly enhanced, accompanied by a broadening of the spectral response range. The application of pressure not only promotes the structural diversity of TMDs, but also significantly optimizes their photoresponse characteristics. These findings provide an experimental basis for the application of TMDs in the field of high sensitivity near-infrared light detection.

2.2 Metal and Nonmetal Halides

Metal and nonmetal halide materials show significant band gap narrowing, extended spectral response range and enhanced photoconductivity under high pressure due to their rich valence shell orbital composition, diverse crystal structures and unique ionic bond characteristics, which are important material systems for the regulation of photoresponse characteristics under pressure in recent years[45]. Among them, metal halides, such as PbI_2, BiI_3, SnI_4, RhI_3 and CsI_3, show good pressure tunability in structural stability, electronic band evolution and charge transport characteristics. In layered metal halides, the photoelectric properties of PbI_2 are significantly improved under high pressure. Under pressure, PbI_2 undergoes two structural phase transitions at about 0.58 and 2.6 GPa, respectively, resulting in a continuous narrowing of the band gap, an enhancement of Pb-I orbital overlap, and a significant decrease in resistivity[46,47]. When further pressurized to about 25 GPa, the crystal structure changes from orthorhombic $Pnma$ to tetragonal $I4/mmm$ symmetry again. At the same time, the spectral response range is extended from visible to infrared region, and the high-pressure absorption spectrum and first-principles calculations show that a semimetallic transition occurs at this time, and the photocurrent suddenly increases by more than two orders of magnitude.

Yue et al.[48] recently found that BiI_3 undergoes a structural phase transition from R-3 space group to $C2/m$ space group at pressures of about 5-7 GPa, accompanied by a reversible change of conduction type from p-type to n-type (as shown in Fig. 3). It is worth noting that a self-driven photocurrent is observed in the absence of an external bias, and the polarity reversal of the photocurrent is observed near the structural transition region. It is also found that the polarity reversal is related to the illumination position. At 24 GPa, when the laser irradiation position moves between the electrodes, the direction of the photocurrent switches accordingly, indicating that the regulation of the electronic structure by pressure can directly affect the type and migration behavior of carriers.

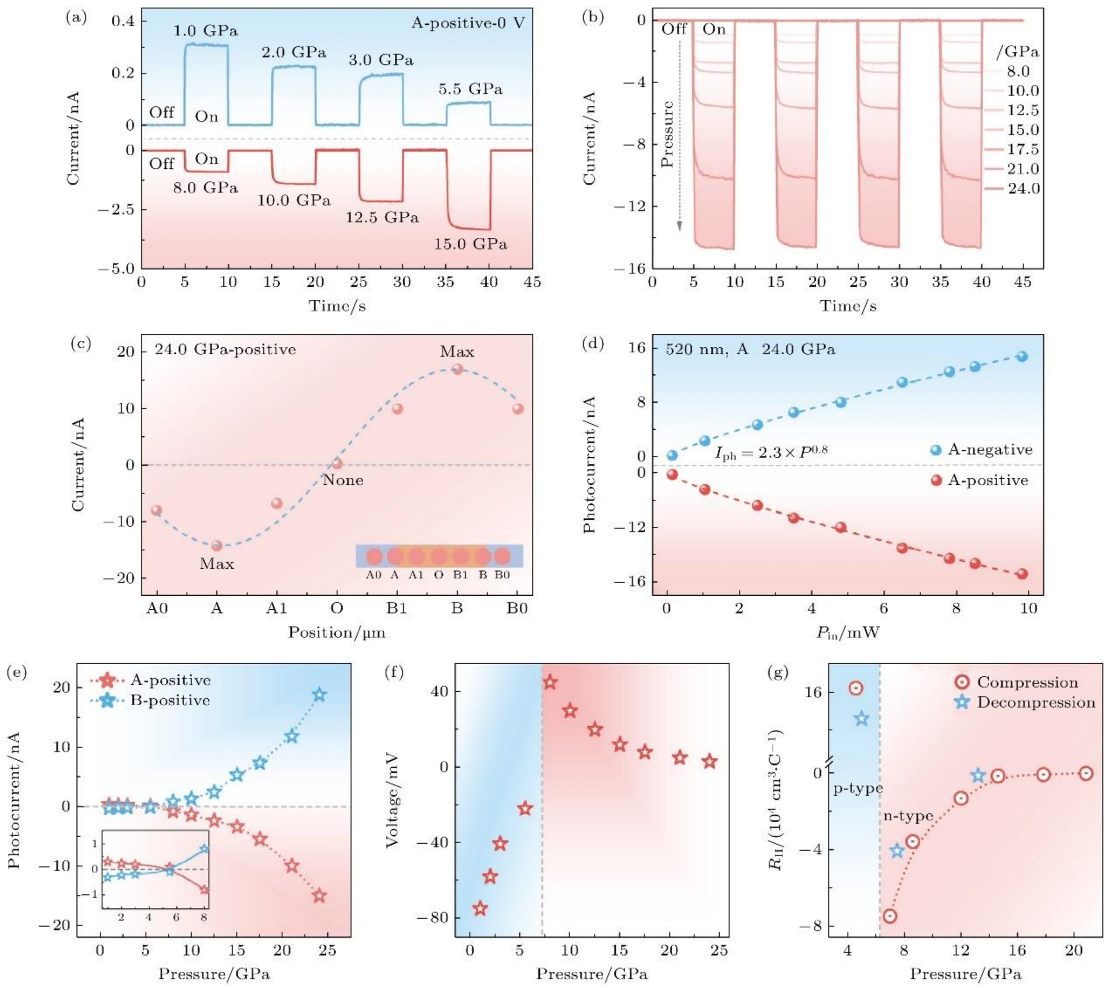


Figure 3. Pressure-induced polarity reversal of self-driven photocurrent in BiI_3: (a), (b) Photoresponse of BiI_3 under 520 nm laser illumination with zero bias under pressure[48]; (c) photocurrent distribution of BiI_3 at 24.0 GPa as the laser moves between the two electrodes[48]; (d) photocurrent of BiI_3 at 24.0 GPa with varying illumination intensity[48]; (e) variation in photocurrent with pressure at different illumination positions[48]; (f) changes in photothermoelectric voltage with pressure at illumination position A[48]; (g) pressure-dependent Hall coefficient of BiI_3[48]. Reproduced with permission.

In addition, the photocurrent response intensity of BiI_3 is significantly improved by more than three orders of magnitude in the presence of an external bias. At the same time, the spectral response is extended to the near-infrared region of 1650 nm, showing excellent broad-spectrum detection capability. Based on first-principles calculations and transport analysis, the researchers pointed out that the pressure-induced electronic band transition and carrier concentration increase are the key to the enhancement of its photoelectric properties. Yue et al. further proposed a method to judge the carrier polarity based on the self-driven photocurrent dominated by the photothermoelectric effect, which not only provided direct evidence for the polarity switching mechanism under pressure control, but also provided a new idea for the subsequent design of related polar materials.

In the study of photoelectric behavior of SbI_3 under high pressure, Li et al. [49] have systematically revealed the phase transition process from molecular crystal to ionic crystal structure. The experimental results show that when the symmetrical Pt/Pt electrode configuration is used, responsivity of SbI_3 reaches the maximum value of 100 mA/W at about 4.4 GPa, which is nearly 10 times higher than that at ambient pressure, while the material maintains an ultra-low dark current. The results show that the improvement of the photoelectric properties is mainly attributed to the increase of the coordination number of SbI_3 and the enhancement of charge delocalization under pressure. The team also constructed SbI_3 devices based on Au/Pt asymmetric electrodes, and further explored their self-driven photoresponse behavior under pressure[50]. The device can continuously output a stable photocurrent at zero bias, and the response signal is enhanced by nearly two orders of magnitude at - 0.2 V bias. When the pressure is about 1.2 GPa, the short-circuit current reaches a peak value, and when the pressure is further increased, the performance gradually decays. It is pointed out that the performance degradation is mainly related to the change of band structure and work function induced by high pressure of SbI_3, which leads to the reduction of Schottky potential difference between metal electrodes, thus affecting the photoelectric conversion efficiency of the device.

The CsI_3 and SnI_4 also show good photoelectric control properties under high pressure. The photocurrent of CsI_3 increases by nearly 5 orders of magnitude during the transition from indirect band gap to direct band gap, and the responsivity can reach up to 245 A/W, and the wide spectrum detection function can be realized at low bias[51]. The extension of the spectral response from the visible region to the infrared band of 1650 nm is mainly attributed to the enhancement of carrier mobility caused by the enhancement of I-I bond interaction. SnI_4 transforms from a cubic phase to a triclinic phase and undergoes a semiconductor-to-metal transition, the conductivity jumps, the photocurrent increases by 5 orders of magnitude, and the spectral response extends from visible to near-infrared region[52].

The layer stacking reconstruction of RhI_3 occurs near 5 GPa, resulting in a rapid narrowing of the band gap and final metallization (about 21 GPa), and the light current at 7.8 GPa is about 5 orders of magnitude higher than that at ambient pressure[53]. The interlayer coupling is weak, the lattice still maintains good integrity under high pressure, and the carrier concentration increases by more than four orders of magnitude. RhI_3 has good physical property tunability and environmental stability, which provides a new candidate material and experimental basis for the design of two-dimensional optoelectronic devices based on high pressure control.

Compared with metal halides, which show significant photoelectric response enhancement under high pressure, the non-metallic halide AsI_3 shows a very limited regulatory increase under pressure[54]. Under pressure, AsI_3 undergoes a structural transition from a molecular crystal to an ionic crystal, accompanied by a continuous narrowing of the band gap, but its photocurrent is only about 2 times higher under 532 nm light irradiation, which is much lower than that of PbI_2, BiI_3 and other metal halides. The main reason is that AsI_3 has low band dispersion in the valence band and conduction band, and the movement of the top of the valence band and the bottom of the conduction band in the *k* space is disordered, which inhibits the effective excitation and transport of photogenerated carriers, thus hindering the further improvement of photoelectric properties.

The above studies show that most metal halide materials exhibit excellent photoresponse characteristics under high pressure, including photocurrent enhancement, self-driven response, polarity reversal, spectral response range expansion, etc. In contrast, the response amplitude of non-metallic halide AsI_3 under pressure is limited, indicating that although the shrinkage of band gap can broaden the range of optical absorption, it does not necessarily lead to the corresponding enhancement of photoelectric properties, and the factors affecting the photoelectric properties of materials under high pressure still need to be further explored. The difference of photoelectric behavior of different halide systems under high pressure also provides new research clues for further revealing the mechanism and law of their regulation.

2.3 Perovskite materials

Perovskite materials have been widely used in photoelectric detectors, solar cells and light-emitting devices due to their excellent light absorption, tunable band gap and high carrier mobility. In recent years, researchers have introduced high-pressure technology into perovskite material systems, which can significantly improve their photoelectric properties by adjusting the crystal structure and electronic band structure through pressure, showing a rich response behavior and regulation path.

Taking two-dimensional perovskite $(C_6H_5CH_2NH_3)_2CuBr_4$ as an example, the material shows good structural stability and property tunability under pressure[55]. In the pressure range of 10-40 GPa, with the increase of pressure, the band gap of $(C_6H_5CH_2NH_3)_2$ $CuBr_4$ shrinks from 1.8 eV to 1.47 eV, the absorption edge shifts significantly to red, and the photoconductivity increases continuously, reaching a peak value of 5×10^{-3} S/cm. This phenomenon is mainly attributed to $CuBr_6$ octahedral distortion and interlayer slippage, which provides a possibility for the application of two-dimensional hybrid perovskites in optoelectronic devices under high pressure. $Cs_2PbI_2Cl_2$, as another typical two-dimensional perovskite, also shows significant enhancement of photoelectric properties under pressure[24]. The results show that the exciton binding energy is reduced from 133 meV at atmospheric pressure to 78 meV at about 2 GPa, which significantly weakens the exciton binding, thus promoting the separation of photogenerated carriers and increasing the photoconductivity by more than three orders of magnitude. Structure analysis shows that $Cs_2PbI_2Cl_2$ transforms from a tetragonal to a monoclinic phase under high pressure. This study demonstrates the feasibility of enhancing the photoelectric response of two-dimensional perovskite by regulating the exciton behavior, which provides an important idea for the performance optimization of two-dimensional perovskite photoelectric devices.

Organic-inorganic three-dimensional perovskites also show significant performance optimization in the low pressure range. For example, the $CH_3NH_3PbBr_3$ reaches the maximum photocurrent at about 0.7 GPa and changes from ion-dominated to electron-dominated, which significantly improves the carrier mobility and response speed[56]. However, with the further increase of pressure, the lattice tends to be disordered, resulting in the gradual decline of photoresponse characteristics. $CH_3NH_3PbI_3$ nanosheets show excellent properties such as band gap reduction, photoluminescence enhancement and carrier lifetime extension at around 0.36 GPa[57]. It is worth mentioning that after decompression to normal pressure, the photocurrent of the material is still 4.5 times of the initial value, and the carrier lifetime is also prolonged by 1.5 times. This indicates that the material can partially retain the performance improvement obtained under pressure after pressure treatment and release to atmospheric pressure, which provides an effective way to achieve stable optimization of material performance under atmospheric pressure.

In the all-inorganic perovskite system, $CsPbBr_3$ and $CsPbCl_3$ show sensitive photoelectric response under pressure. The transition of $CsPbBr_3$ from an ionic-electronic mixed conductor to an electronic conductor is completed within 2.3 GPa, and the photocurrent is enhanced and reaches a maximum at about 1.4 GPa, followed by a rapid decline in performance due to structural and band gap broadening[58]. Eu^{3+} -doped $CsPbCl_3$, on the other hand, maintains strong luminescence and photoelectric response in the range of 22 GPa, and its photocurrent increases by nearly 2 times in the range of 1.1-20.5 GPa, while the responsivity and detectivity increase synchronously[59]. The improvement of these properties is due to the maintenance of short-range order structure under high pressure and the regulation of doping ions on the excited state.

In the high-pressure study of lead-free perovskite, $CH_3NH_3SnI_3$ undergoes an ordered transition to an amorphous phase at about 3 GPa. With the release of pressure, some regions recrystallize, and finally form the coexistence of amorphous and ordered structure[60]. After high pressure treatment, the material shows improved conductivity, enhanced photocurrent and reduced defect states, and part of the perovskite framework is retained. The unique advantages of pressure treatment in improving the structural stability and photoelectric response properties of tin-based perovskites open up a new path for the application of these environmentally friendly materials in optoelectronic devices.

In addition, the layered perovskite derivative $Cs_3Bi_2I_9$ also exhibits excellent photoelectric properties under pressure[61]. As shown in Fig. 4, the photocurrent of the material increases rapidly with the increase of pressure, and the peak value increases by nearly 5 orders of magnitude compared with the initial value, and the spectral response range covers the visible light from 520 nm to 1650 nm. Under the illumination of 1650 nm infrared light, the responsivity of $Cs_3Bi_2I_9$ is up to 6.81 mA/W, and the photoresponse time is 95/96 ms. The analysis shows that the improvement of performance is mainly due to the enhancement of Bi-I orbital interaction and the synergistic effect of photothermoelectric mechanism in $[BiI_6]^{3-}$ structure. In order to reveal the effect of photothermoelectric effect on the enhancement of $Cs_3Bi_2I_9$ photocurrent under high pressure, the research team compared the photoelectric response behavior of the center (*O* point) and the edge region (*A* point) of the sample. The results show that the edge region (*A* point) shows higher photoelectric response under different wavelength illumination. This is because it is close to the electrode interface, which is more likely to form a temperature gradient caused by local heating, thus significantly stimulating the photothermoelectric effect. In contrast, the *O* point is located at the center of the sample, the temperature distribution is symmetrical, and the contribution of the photothermoelectric effect is almost negligible. The pressure-induced amorphization further reduces the thermal conductivity of the material, thereby enhancing the photothermoelectric effect and carrier transport efficiency, which plays a key role in the improvement of the overall photoelectric properties.

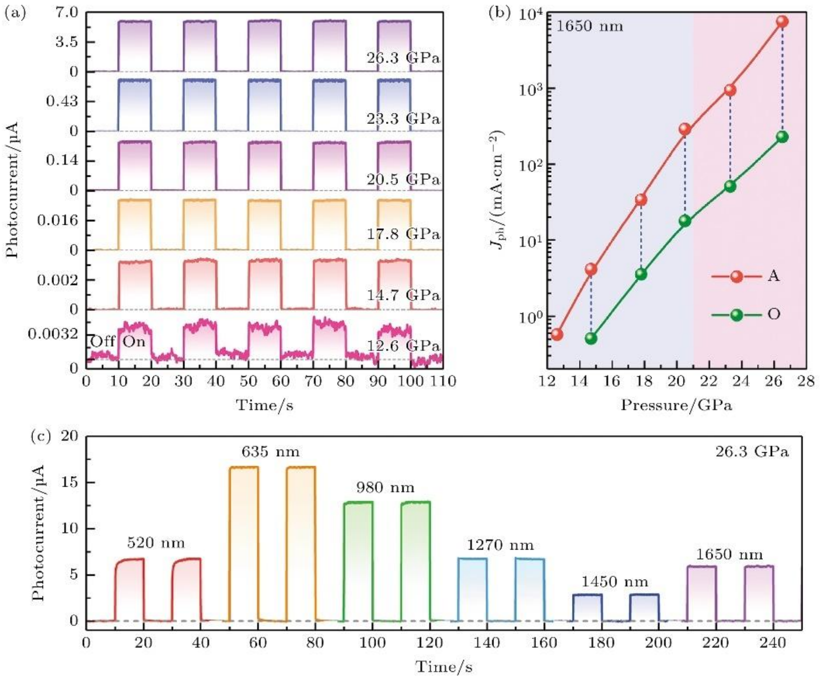


Figure 4. Photoresponse properties of $Cs_3Bi_2I_9$ under laser illumination of different wavelengths[61]: (a) Photocurrent evolution of $Cs_3Bi_2I_9$ during compression with 1650 nm laser illumination and 10 V bias at position *A*; (b) pressure-dependent photocurrent density J_{ph} of $Cs_3Bi_2I_9$ under 1650 nm laser illumination at different positions; (c) photocurrent of $Cs_3Bi_2I_9$ under laser illumination of different wavelengths at position *A* under a 10 V bias at 26.3 GPa. Reproduced with permission.

The above studies show that although the photoelectric behavior of perovskite materials under high pressure is different, they all show good tunability and potential application prospects, especially in broad spectrum detection, self-driven response and performance retention under ambient conditions.

2.4 Other van der Waals layered materials

In addition to the typical two-dimensional or van der Waals material systems mentioned above, some functional materials with van der Waals layered or low-dimensional structures also show unique high-pressure response characteristics. The structural stability and electronic state of these materials are particularly sensitive to external fields because the layers are only connected by weak van der Waals forces. When pressure is applied, the interlayer coupling can be effectively adjusted, resulting in significant changes in the crystal structure and electronic energy bands. This behavior not only leads to the optimization of photoelectric properties, but also induces new photoelectric response phenomena in some materials.

$NbOI_2$ is a typical two-dimensional van der Waals ferroelectric semiconductor material. Recently, $NbOI_2$ has been found to exhibit a reversible switching of the n-p conduction type under high pressure, accompanied by a significant enhancement of the photoelectric response[62]. As shown in Fig. 5, the $NbOI_2$ undergoes a semiconductor-semiconductor structural transition from the $C2$ phase to the $C2/m$ phase when pressurized to 11.5 GPa. This process hinders the off-center displacement of Nb atoms along the b axis, thus inducing the transition of carriers from n-type to p-type. At the same time, pressure weakens the interaction between Nb-Nb dimers within the $NbOI_2$ plane, resulting in the increase of charge delocalization, which improves the photocurrent response. At 21.0 GPa, the photocurrent of $NbOI_2$ is increased by more than three orders of magnitude compared with that at ambient pressure, and the spectral response range is extended to the near-infrared band of 1450 nm. This is the first time that pressure-induced n-p polarity reversible switching has been observed in a semiconductor with a large band gap, which broadens the application potential of $NbOI_2$ in photoelectric detection and related fields.

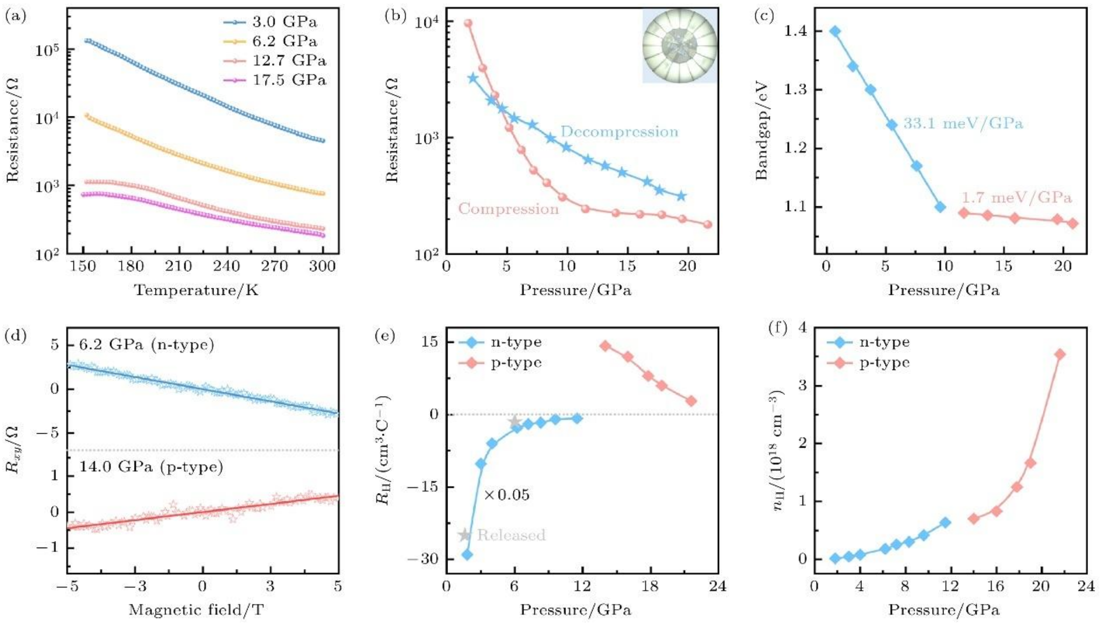


Figure 5. Pressure-induced n-p conduction type switching in semiconductor-to-semiconductor transition of $NbOI_2$[62]: (a) Representative temperature-dependent resistance curves of $NbOI_2$ during compression; (b) pressure-dependent resistance of $NbOI_2$ measured at 300 K, inset: the optical photo of the sample and electrodes in diamond anvil cell; (c) optical band gap as a function of pressure; (d) Hall resistance of $NbOI_2$ as a function of the magnetic field at 300 K under pressures of 6.2 and 14.0 GPa; (e) derived Hall coefficient as a function of pressure; (f) carrier density of $NbOI_2$ as a function of pressure. Reproduced with permission.

Liu et al.[63] systematically studied the effects of lone electron pairs (LPEs) on the polarization and photoelectric properties of SbSI crystals under pressure by combining experimental and theoretical methods. The results show that the zero-dimensional SbSI undergoes a phase transition from nonpolar to polar structure at about 2.9 GPa, and the spontaneous polarization of the material is significantly enhanced. With the increase of pressure, the stereochemical effect of LPEs is further enhanced, which effectively promotes the separation and migration of photogenerated carriers. The photocurrent response of the material reaches the maximum at about 14 GPa, and the material shows obvious self-driven output without bias (as shown in Fig. 6). This work clarifies the key role of stereochemical effect of LPEs in pressure-regulated ferroelectric and photovoltaic properties, and provides a new path for the design of high-performance ferroelectric photovoltaic materials.

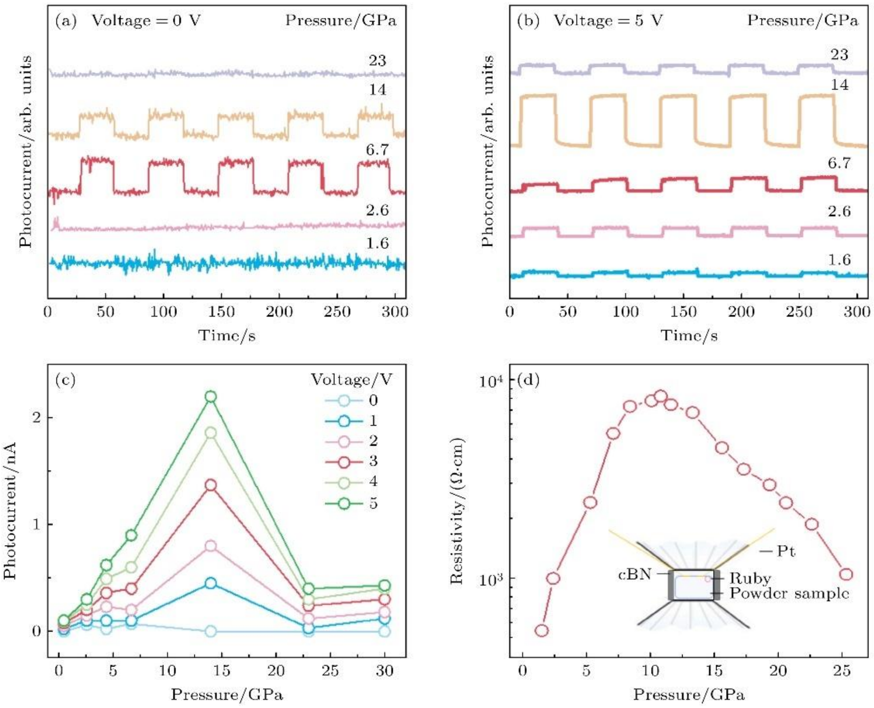


Figure 6. (a), (b) Pressure-dependent photocurrent of SbSI at 0 and 5 V bias voltages[63]; (c) photocurrent as a function of pressure at different bias voltages[63]; (d) the resistivity of SbSI under high pressures[63]. Reproduced with permission.

Graphite carbon nitride (g-C_3N_4) has attracted much attention due to its outstanding performance in the field of photocatalysis, but its wide band gap limits its further application[64,65]. Recently, by introducing nitrogen vacancies and applying high pressure, researchers have achieved a wide range of continuous control of the band gap and optimization of the photoresponse characteristics of g-C_3N_4[66,67]. The band gap of g-C_3N_4 is reduced from 2.70 eV to 2.40 eV due to the introduction of nitrogen vacancies. When further pressurized to 46 GPa, the band gap of the material is significantly narrowed to 1.70 eV, and the photocurrent is increased by nearly 50% compared with the initial value (as shown in Fig. 7). It is worth noting that the pressure-induced band gap narrowing and enhancement of photoelectric properties are still retained after pressure release, which is closely related to the pressure-induced irreversible amorphization transition. The results also provide a reference for the performance optimization of g-C_3N_4 under environmental pressure.

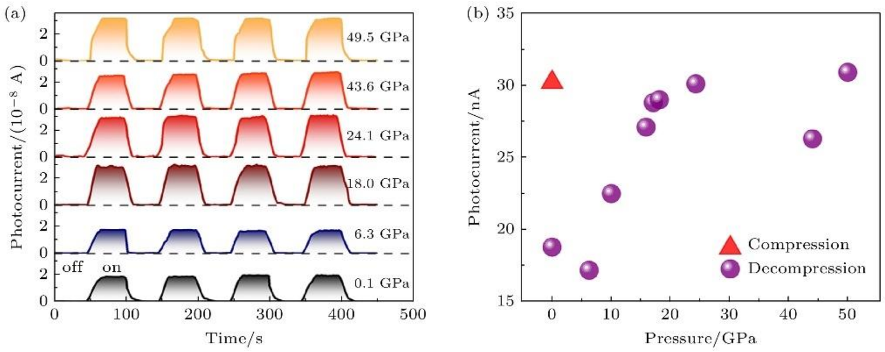


Figure 7. (a), (b) Photocurrent of g-C_3N_4 under visible light illumination at a 15 V bias voltage under pressure[66]. Reproduced with permission.

$CuInP2S_6$ (CIPS) belongs to a family of van der Waals layered materials with both ferroelectric and optoelectronic properties. Under high pressure, the photoelectric characteristics of CIPS show obvious periodic changes[68]. As shown in Fig. 8, the photoresponse is basically stable in the low pressure range of 0.6-4.2 GPa. When the pressure is further increased to 7.6 GPa, the photocurrent increases significantly, which is mainly attributed to the narrowing of the band gap and the improvement of the carrier transport ability caused by the transformation of the crystal structure from monoclinic to trigonal. However, when the pressure continues to increase to 15.1 GPa, the photoresponse shows a downward trend. At higher pressures, the photocurrent of CIPS is significantly enhanced again due to the gradual metallization, the rapid increase of carrier concentration and mobility. The results show that the structural phase transition induced by pressure and its control on the band structure and carrier behavior are the key factors affecting the optoelectronic properties of CIPS.

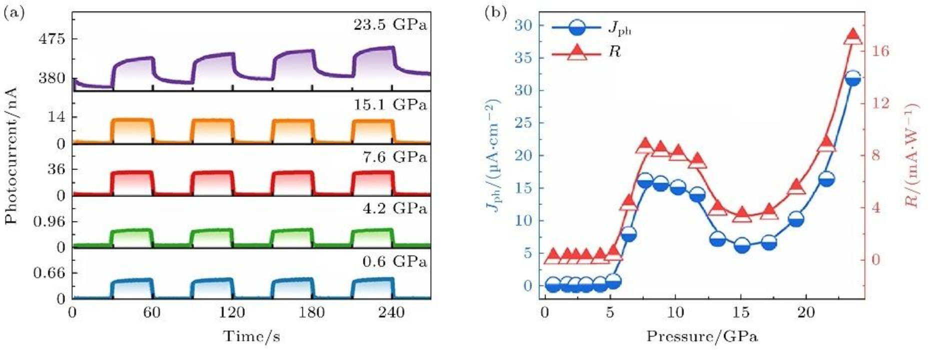


Figure 8. (a), (b) Pressure-dependent photocurrent, current density (J_{ph}) and responsivity (R) of $CuInP_2S_6$ at a voltage of 20 V[68]. Reproduced with permission.

$NiPS_3$ is a kind of TMD derivative material with both magnetism and layered structure[69]. As shown in Fig. 9, the photocurrent is enhanced by about 5 orders of magnitude under pressure, and maintains an enhancement of 2 orders of magnitude after decompression, and the spectral response range is extended to the near-infrared region (1650 nm), and the stability is maintained for more than 120 h at room temperature. The structure analysis shows that the $NiPS_3$ exhibits an obvious multiphase evolution process within 14 GPa, accompanied by the formation of new bonds and the sudden change of vibration modes, which significantly improves the carrier mobility. The results reveal good performance improvement and performance retention after decompression, which expands the potential application of TMD materials in infrared detection devices, and also provides a reference for the design of high-performance devices under ambient pressure.

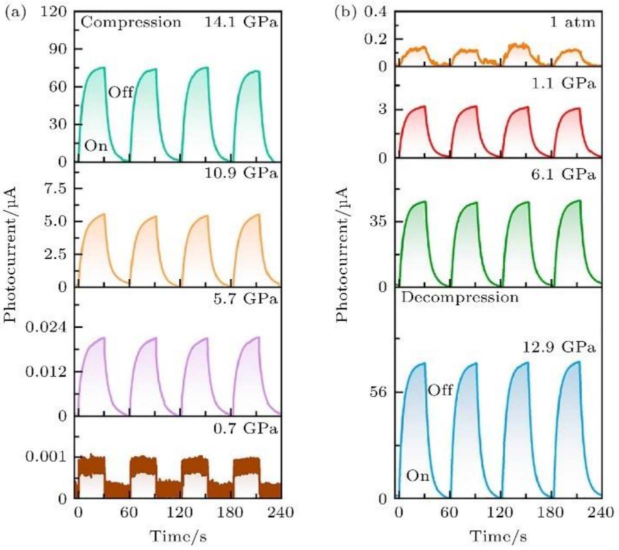


Figure 9. Photocurrent of $NiPS_3$ during (a) compression and (b) decompression under illumination by Xe lamp at 1 V[69] (1 atm = 1.013×10^5 Pa). Reproduced with permission.

Among the typical two-dimensional Bi-based chalcogenides, $Bi_9O_{7.5}S_6$ and BiOBr show significant enhancement of optoelectronic properties under high pressure. $Bi_9O_{7.5}S_6$ undergoes a structural transformation from a layered stacking structure to a three-dimensional network under pressure[70]. The reconstruction of Bi-S bonds greatly improves the degree of orbital coupling, resulting in a gradual compression of the band gap from 1.34 eV to 0.45 eV, accompanied by 6 orders of magnitude increase in conductivity and a 4 order of magnitude enhancement in photocurrent. In contrast, the photocurrent density and responsivity of BiOBr are increased by more than one order of magnitude in the pressure range of 3.8 GPa, and the response speed is also increased by nearly 10 times[71]. First-principles calculations show that pressure effectively reduces the effective mass of carriers and promotes the charge transfer between Bi-O atoms, thus greatly improving the photoresponsiveness and response speed. The evolution of structural dimensions and the enhancement of optoelectronic properties of the above materials under high pressure verify the effectiveness of high-pressure technology in regulating the optoelectronic properties of low-dimensional functional oxygen group materials, which provides an important reference for the design of high-performance and fast-response photodetectors.

2.5 Other three-dimensional semiconductors

In addition to the above typical material systems, some three-dimensional semiconductors, such as ferroelectric, ferromagnetic and some bulk materials, also show excellent photoelectric properties under high pressure. These materials are often accompanied by structural phase transitions, electronic band reconstruction or carrier type changes, and some of them also show unconventional phenomena such as photoconductive polarity reversal.

Taking the multiiron oxide $KBiFe_2O_5$ as an example, the material undergoes a reversible structural phase transition at 10 GPa, the polarization is significantly enhanced, and the band gap is narrowed, which shows that the conductivity is increased by two orders of magnitude, and the photocurrent and external quantum efficiency are simultaneously improved[72]. The experimental results show that the structural evolution of $KBiFe_2O_5$ under pressure has a synergistic effect on the polarization characteristics and carrier transport ability of the material, which makes it have the potential to become a highly efficient polarization optoelectronic material.

In addition, structural coupling materials such as WO_3/CuO, $CrSb_2$ and Cr_2Se_3 also show unique photoelectric response properties under pressure, such as photoconductive polarity reversal and spectral response range expansion. In the WO_3/CuO heterojunction, the photoconductivity changes from positive to negative with the increase of pressure, which may be related to the pressure-induced lattice distortion and electron-hole recombination process[73]. Similarly, $CrSb_2$ and Cr_2Se_3 also switch from n-type to p-type under high pressure, accompanied by the appearance of negative photoconductivity effect[74,75].

Bulk semiconductor materials play an important role in the traditional optoelectronic field because of their excellent structural stability and wide application. Although these materials do not have layered structures like two-dimensional materials, recent studies have found that their electronic bands and crystal structures can also be significantly regulated by pressure, thereby improving their photoresponse characteristics. For example, bulk Si undergoes a semiconductor-metal transition under pressure[76]. In this process, there is not only an obvious increase in the photoconductivity intensity, but also a reversible switching of the photocurrent polarity. The negative photoconductivity effect of Si at high pressure is considered to be due to the photothermal effect. For $CuInS_2$ nanocrystals, pressure treatment also brings significant improvement in photoelectric properties[77]. With the increase of pressure, the band gap widens gradually and reaches an optimal value of 1.5 eV at about 5.9 GPa, while the photocurrent density reaches a maximum value, which is nearly 4 times that at normal pressure. First-principles calculations show that the broadening of the band gap is mainly due to the enhancement of the interatomic charge density and ionic polarization of In-S. This work verifies the effectiveness of pressure means to optimize the photoelectric properties of bulk semiconductors such as $CuInS_2$, and expands their application potential in photovoltaic devices.

The structural phase transition, carrier transport evolution and negative photoconductivity effect of the above three-dimensional semiconductor materials under pressure reflect the effectiveness of pressure on the control of material optoelectronic properties, which provides an effective reference for the development of new multi-functional optoelectronic devices.

3. Characteristics and Physical Mechanism of Photoelectric Response Evolution under High pressure Control

As a special external control means, high pressure has a direct impact on the structure and electronic structure of materials. Despite the rich material systems and different structures, by systematically reviewing the research results of TMDs, metal and non-metal halides, perovskite materials, other van der Waals layered materials and other three-dimensional semiconductor materials under high pressure in recent years, it can be found that the regulation of photoelectric properties of different types of materials shows some obvious common rules and unique physical effects, which are mainly reflected in the following aspects.

3.1 Band structure control and band gap evolution

High pressure can effectively control the electronic band structure of materials by compressing the atomic spacing and lattice constant. The band structure of materials, especially the band gap, is one of the key parameters that determine their photoelectric properties. The change of band gap directly affects the optical absorption ability and carrier behavior of the material. When pressure is applied, the overlap between atomic orbitals is enhanced, which usually leads to a decrease in the energy level spacing between the bottom of the conduction band and the top of the valence band, showing a continuous contraction of the band gap, and even a band gap closing phenomenon in some materials. Taking TMDs as an example, the band gaps of MoS_2, WS_2, PtS_2, ReS_2 decrease significantly under pressure, and the interlayer coupling is enhanced, which leads to the gradual reduction of the band gap, thereby changing the photoresponse characteristics[40–43]. In metal halide systems, PbI_2, BiI_3, RhI_3, CsI_3 and so on will transform from semiconductor to semimetal or even metal under pressure, which is usually accompanied by a significant improvement in photoelectric properties[46–48,51,53].

The band gap evolution mechanism of perovskite materials is more complex, such as

$CH_3NH_3PbI_3$, $CH_3NH_3PbBr_3$, $CH_3NH_3SnI_3$ and other materials. The band gap usually decreases with the increase of pressure in the low pressure range, which effectively enhances the carrier excitation efficiency. However, when the pressure exceeds a certain value, the crystal may tend to be disordered or even amorphous, resulting in the uncertainty of band gap change or even reverse increase[56,57,60]. These band gap evolution behaviors are essentially due to the coordinated control of bond length, bond angle and octahedral distortion in the perovskite structure under high pressure[78–83]. In the initial pressure stage, with the increase of pressure, the bond length of Pb-*X* (I, Br, Cl, etc.) shortens, and the orbital overlap of Pb-*X*-Pb increases, thus changing the valence band and conduction band energy levels, and the band gap usually shows a trend of narrowing. When the pressure continues to increase, the Pb-*X*-Pb bond angle deviates from 180 °, the degree of octahedral distortion increases, and the band gap of the material appears non-monotonic behavior (for example, first decreases and then increases).

The band gap control of BiOBr and $CuInS_2$ under high pressure shows more complex behavior. The band gap of BiOBr increases with the increase of pressure in the low pressure range (0-15.2 GPa), and the band gap changes reversely when the pressure continues to increase (15.2-27.6 GPa), which is mainly related to the pressure-induced lattice distortion[71]. The band gap of $CuInS_2$ widens under pressure, which may be due to the enhancement of interatomic charge density distribution and ionic polarization under pressure[77]. It can be seen that although the band gap of most semiconductors is narrowed due to the enhancement of orbital overlap under pressure, the specific evolution of the band gap is significantly different for different materials due to the differences in structure and bonding characteristics, which cannot be generalized.

3.2 Crystal structure evolution and phase transformation induction

The crystal structure and stability of materials are the important basis of their photoelectric properties. The application of pressure can trigger a series of crystal structure evolution and even phase transition processes, which plays a key role in regulating the photoelectric properties of materials. Many materials, such as MoS_2, BiI_3, CsI_3, $CuInP_2S_6$, $NbOI_2$, $ZrSe_2$ and so on, undergo definite structural phase transitions, which are mostly accompanied by changes in the electronic structure, carrier concentration and mobility of the materials, and then lead to abrupt changes in the optical and electrical properties[40,44,48,51,62,68]. Taking metal halides as an example, the lattice of CsI_3 also undergoes a phase transition process under pressure, and the band gap changes from indirect to direct transition. The rearrangement of the lattice effectively improves the carrier mobility, and the photoelectric properties are significantly enhanced. BiI_3 undergoes a significant space group transition (from *R*-3 to *C*2/*m*) at 5-7 GPa, which is accompanied by a conduction mechanism switch from p-type to n-type and induces a significant photoelectric response enhancement. $NbOI_2$ also shows a similar conduction type conversion during the structural transition, indicating that the change of physical properties caused by the pressure-induced structural phase transition has a certain common rule in different material systems.

It is worth noting that some materials tend to be amorphized under pressure. For example, $CH_3NH_3SnI_3$ shows a tendency of lattice disordering at about 3 GPa, accompanied by partial framework reconstruction and conduction behavior to enhance[60]; g-C_3N_4 undergoes an irreversible amorphization transition at about 17 GPa under pressure, accompanied by a continuous compression of the band gap and an increase in photocurrent[66].

Although some materials do not show obvious crystal symmetry mutation under pressure, they can still achieve significant improvement in photoelectric properties through the formation of new bonds and the expansion of structural connections. For example, $Bi_9O_{7.5}S_6$ and BiOBr materials show a gradual change from layered to three-dimensional network structure under pressure, which realizes the smooth improvement of photoelectric properties[71,72]. The results show that both the structural phase transition and the non-phase transition structural evolution under pressure can effectively control the photoelectric properties, but the control effects are significantly different.

3.3 Pressure-induced photoelectric response feature

The regulation of photoelectric properties of materials under pressure is diverse. In addition to the common increase of photocurrent intensity, it also induces novel physical effects such as spectral response expansion, self-driven photoresponse, and negative photoconductivity effect. The discovery of these phenomena not only expands the application scenarios of materials in extreme environments, but also reveals the fundamental changes in the photoelectric response mechanism of materials under pressure.

3.3.1 Spectral Response Range Expansion

The phenomenon of pressure-induced spectral response range expansion is usually closely related to the gradual decrease of material band gap with pressure. With the increase of pressure, the lattice spacing of the material is compressed, and the interaction between atomic orbitals is enhanced, resulting in the conduction band and valence band energy levels of the material gradually approaching, thus extending the absorption band of the material from the initial ultraviolet or visible region to the near-infrared or even infrared region. Taking WS_2 as an example, under pressure, the band gap of WS_2 is broadened at the top of the valence band and the bottom of the conduction band due to the enhanced coupling between W 5*d* and Se 3*p* orbitals, and the *S*-*S* interlayer interaction is enhanced, resulting in a continuous decrease of the band gap[43]. Similar band gap evolution has been observed in MoS_2 and ReS_2[40,42]. Thanks to the effective control of the band gap, the spectral response range of WS_2 is extended to the near-infrared band of 1650 nm, which significantly enhances its ability to detect broadband optical signals. In addition, CsI_3, PbI_2, $NiPS_3$ and $NbOI_2$ also show the phenomenon that the spectral response range extends to the infrared region under pressure[46,47,51,62]. For example, in the range of 0.6-17 GPa, the high-pressure absorption spectrum shows that the absorption edge of PbI_2 is continuously red-shifted, and the band gap is continuously reduced from about 2.25 eV to 1.36 eV. The band gap is further reduced to about 0.8 eV at 24 GPa. The results of first-principles calculations are in good agreement with the experimental phenomena. At 20 GPa, the density of states of Pb and I hybridize near the Fermi level, and the band gap is 0.74 eV, which is an indirect band gap semiconductor. When the pressure reaches 30 GPa, the band structure of PbI_2 shows that the band gap closes, the valence band along the Γ-X direction and the conduction band along the X direction cross the Fermi level at the same time, and the overall density of states is low but not zero. The band overlap feature corresponding to the finite Fermi density of states is a typical manifestation of topological semimetals, and the pressure-induced semiconductor-semimetal transition is further verified by femtosecond time-resolved spectroscopy experiments. With the continuous shrinkage of the band gap, the spectral response band of PbI_2 is also extended to the infrared region. These phenomena demonstrate the effectiveness of high-pressure technology in regulating the broadband photoelectric response of materials, and provide an effective theoretical and experimental basis for the design of new broadband detection devices.

3.3.2 Self-driven photoresponse

In materials with ferroelectric or multiferroic properties (such as CIPS and SbSI), pressure can enhance the internal polarization of the material, thus inducing a strong built-in electric field, so that the material can achieve stable photocurrent output without external bias. Taking CIPS as an example, under pressure, its crystal structure changes and its polarization increases significantly, thus showing obvious self-driven photoresponse characteristics without external bias[68]. In addition, PbI_2 and BiI_3 also show strong self-driven photocurrent under pressure, which may be related to the pressure-induced crystal polarization and the synergistic effect of photothermoelectric effect[47,48]. These results show that pressure technology has unique advantages for the development of autonomous photodetectors without external bias driving.

3.3.3 Negative photoconductivity effect

Generally, semiconductor materials show a typical positive photoconductivity effect under illumination, which is due to the transition of electrons from the valence band to the conduction band under the excitation of incident light, resulting in more free carriers, thus improving the conductivity of the material, which is manifested by a significant increase in the current of the material under illumination. This phenomenon widely exists in semiconductor material systems and is the basis for the preparation of photodetectors. However, in some specific materials or under specific pressure conditions, there will be abnormal negative photoconductivity/photocurrent effect, that is, illumination leads to the decrease of material conductivity or even the reversal of current polarity, which is diametrically opposed to the conventional photoresponse behavior. This phenomenon of pressure-induced negative photoconductivity or photocurrent polarity reversal has the following explanations: one is the thermal effect caused by the pressure-induced metallization transition. In the process of metallization, the material absorbs light energy and dissipates it mainly in the form of heat, rather than exciting carriers. The thermal effect leads to the enhancement of carrier scattering and the decrease of carrier mobility, which suppresses the conductivity of the material and leads to the negative photoconductivity. This effect has been demonstrated in bulk Si, Bi_2S_3 and $ZrSe_2$ under pressure[44,76,84]. Another possible explanation involves carrier type switching. Under the action of pressure, the dominant carrier type of the material changes from electron (n) type to hole (p) type, and the material shows a special phenomenon that the photoconductivity changes from positive to negative with the change of the dominant carrier type. For example, similar carrier type switching behavior has recently been observed in WO_3/CuO heterojunction materials, $CrSb_2$, Cr_2 Se_3 and other materials[73–75]. However, there is still some controversy about the explanation of this phenomenon. In essence, the phenomenon of negative photoconductivity originates from the decrease of free carrier concentration after illumination, which leads to the increase of material resistance, while the change of carrier type itself does not directly determine the polarity of photocurrent. Although the simultaneous occurrence of carrier type switching and negative photoconductivity has been observed in some experiments, the correlation between the two phenomena may also be caused by the change of carrier concentration and mobility. Therefore, the specific explanation of this effect remains to be clarified by further experimental verification and theoretical analysis.

3.4 Pressure-induced "memory effect"

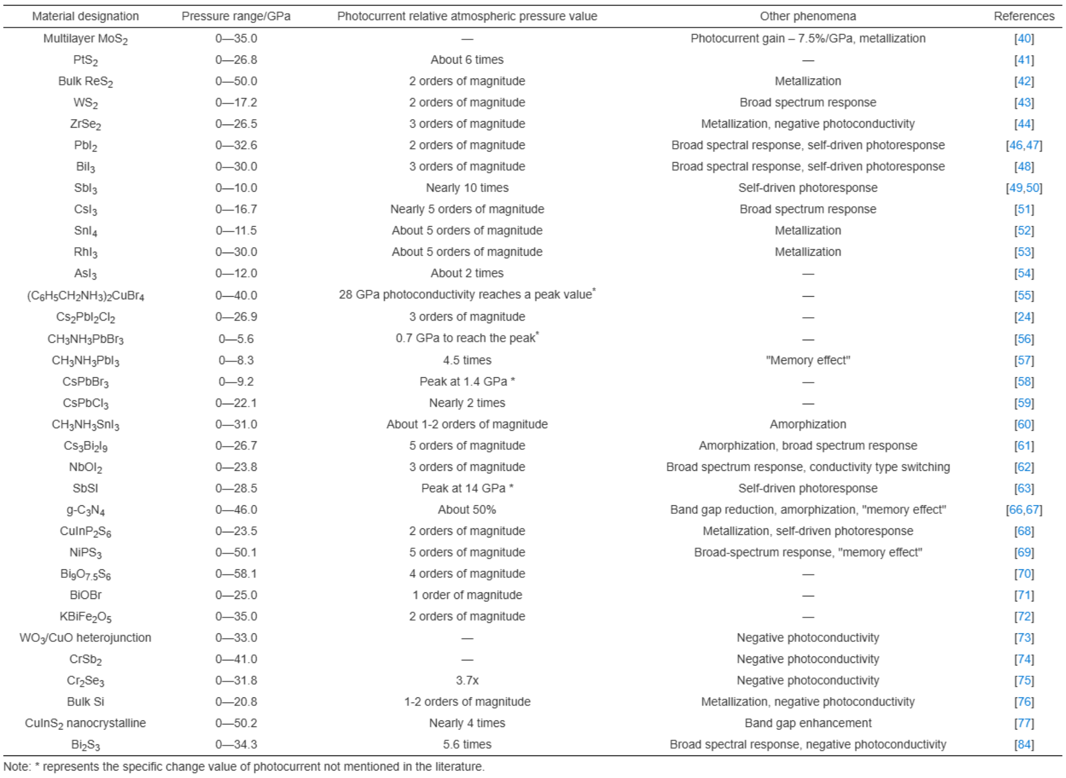
In addition, some materials show obvious photoelectric response and enhanced "memory effect" under high pressure, that is, they can still maintain the performance optimization characteristics induced by pressure after decompression. For example, in the lead-free perovskite $CH_3NH_3SnI_3$, pressure induces its amorphization, and the material still maintains excellent photoconductivity after decompression, showing obvious performance retention ability[60]. The "memory effect" after decompression has also been observed in g-C_3N_4, $NiPS_3$ and other materials, which is mainly due to the stable defect state or amorphous state formed under pressure[66,69]. This phenomenon shows that pressure can not only be used as a means of dynamic regulation, but also has the potential to achieve long-term stable physical property regulation, which provides a new idea for the application of pressure regulation effect at atmospheric pressure.

To sum up, high-pressure technology has induced a series of novel effects in many semiconductor materials, including photocurrent enhancement, broad spectral response, polarity reversal, self-driven response and performance retention, by controlling the crystal structure and electronic energy band of materials. These effects are different in different materials, and their formation mechanism is often not caused by a single action, and the physical mechanism behind them has not yet been clarified, which also provides a direction for follow-up research.

4. Conclusion and prospect

Key information on the photoelectric response of the semiconductor materials mentioned in this paper under pressure is collated in Tab. 1. Throughout the previous studies, pressure has shown wide applicability and remarkable effectiveness in regulating the photoresponse characteristics of materials, and has become an important way to optimize the properties and explore the mechanism of semiconductor materials. In this review, we summarize the structural phase transitions, electronic band evolution, and optoelectronic response behaviors of TMDs, metal and nonmetal halides, perovskites, other van der Waals layered materials, and other three-dimensional semiconductors under pressure, and summarize the underlying physical mechanisms behind their regulatory features and performance improvements. Although there are differences in the structure and bonding properties of different types of semiconductor materials, there are still some common rules under pressure. For example, most materials show a significant increase in photocurrent intensity to varying degrees under pressure. Under pressure, the overlap of atomic orbitals in most materials is enhanced and the band gap is narrowed, which leads to the obvious expansion of the light absorption range to the infrared region, thus enhancing the light response ability of the material to a wider wavelength band. At the same time, pressure can enhance the response speed and carrier mobility, induce phenomena such as negative photoconductivity, self-driven photocurrent response and "memory effect". These phenomena expand the understanding and boundary of the regulation of photoelectric physical properties of materials. It can be seen that pressure, a technical means independent of chemical modification, can be widely applied to materials with different structures and bonding types, demonstrating the effectiveness of crystal structure and electronic band control, conductivity type conversion, and spectral response expansion, further expanding its application scope in the field of materials science.

Table 1. Optoelectronic response characteristics of selected materials under high pressure.



Material designation	Pressure range/GPa	Photocurrent relative atmospheric pressure value	Other phenomena	References
Multilayer MoS_2	0—35.0	—	Photocurrent gain – 7.5%/GPa, metallization	[40]
PtS_2	0—26.8	About 6 times	—	[41]
Bulk ReS_2	0—50.0	2 orders of magnitude	Metallization	[42]
WS_2	0—17.2	2 orders of magnitude	Broad spectrum response	[43]
$ZrSe_2$	0—26.5	3 orders of magnitude	Metallization, negative photoconductivity	[44]
PbI_2	0—32.6	2 orders of magnitude	Broad spectral response, self-driven photoresponse	[46,47]
BiI_3	0—30.0	3 orders of magnitude	Broad spectral response, self-driven photoresponse	[48]
SbI_3	0—10.0	Nearly 10 times	Self-driven photoresponse	[49,50]
CsI_3	0—16.7	Nearly 5 orders of magnitude	Broad spectrum response	[51]
SnI_4	0—11.5	About 5 orders of magnitude	Metallization	[52]
RhI_3	0—30.0	About 5 orders of magnitude	Metallization	[53]
AsI_3	0—12.0	About 2 times	—	[54]
$(C_6H_5CH_2NH_3)_2CuBr_4$	0—40.0	28 GPa photoconductivity reaches a peak value*	—	[55]
$Cs_2PbI_2Cl_2$	0—26.9	3 orders of magnitude	—	[24]
$CH_3NH_3PbBr_3$	0—5.6	0.7 GPa to reach the peak*	—	[56]
$CH_3NH_3PbI_3$	0—8.3	4.5 times	"Memory effect"	[57]
$CsPbBr_3$	0—9.2	Peak at 1.4 GPa *	—	[58]
$CsPbCl_3$	0—22.1	Nearly 2 times	—	[59]
$CH_3NH_3SnI_3$	0—31.0	About 1-2 orders of magnitude	Amorphization	[60]
$Cs_3Bi_2I_9$	0—26.7	5 orders of magnitude	Amorphization, broad spectrum response	[61]
$NbOI_2$	0—23.8	3 orders of magnitude	Broad spectrum response, conductivity type switching	[62]
SbSI	0—28.5	Peak at 14 GPa *	Self-driven photoresponse	[63]
g-C_3N_4	0—46.0	About 50%	Band gap reduction, amorphization, "memory effect"	[66,67]
$CuInP_2S_6$	0—23.5	2 orders of magnitude	Metallization, self-driven photoresponse	[68]
$NiPS_3$	0—50.1	5 orders of magnitude	Broad-spectrum response, "memory effect"	[69]
$Bi_9O_{7.5}S_6$	0—58.1	4 orders of magnitude	—	[70]
BiOBr	0—25.0	1 order of magnitude	—	[71]
$KBiFe_2O_5$	0—35.0	2 orders of magnitude	—	[72]
WO_3/CuO heterojunction	0—33.0	—	Negative photoconductivity	[73]
$CrSb_2$	0—41.0	—	Negative photoconductivity	[74]
Cr_2Se_3	0—31.8	3.7x	Negative photoconductivity	[75]
Bulk Si	0—20.8	1-2 orders of magnitude	Metallization, negative photoconductivity	[76]
$CuInS_2$ nanocrystalline	0—50.2	Nearly 4 times	Band gap enhancement	[77]
Bi_2S_3	0—34.3	5.6 times	Broad spectral response, negative photoconductivity	[84]

Note: * represents the specific change value of photocurrent not mentioned in the literature.

Although important progress has been made in the regulation of photoelectric properties of high-pressure materials, there are still some scientific problems and technical bottlenecks to be solved urgently. First of all, there is still a lack of clear mechanism to explain the intrinsic relationship between the structural phase transition, electronic structure evolution and photoelectric properties of materials under pressure, especially how the pressure-induced structural phase transition and band gap control precisely affect the photoelectric properties, which shows obvious differences in different material systems. In addition, most of the current studies focus on the basic photoelectric characteristic parameters such as photocurrent change and spectral response range expansion, while the kinetic parameters such as photogenerated carrier lifetime, carrier mobility and diffusion length, which are more relevant to applications, are relatively scarce, resulting in the one-sidedness of the existing results in evaluating the actual photoelectric application potential of materials. On the other hand, due to the great differences in light intensity, wavelength range, external field bias and other test conditions used in different experiments, the comparability of data between different experimental systems is limited, which makes the cross-comparison between different studies uncertain. In addition, most of the current work focuses on the pressure-induced photoconductive effect when clarifying the enhancement mechanism of photoelectric properties. Although the combined effect of photothermoelectric effect has been observed in individual materials, the contribution proportion of each mechanism has not been effectively distinguished, and the synergistic relationship between different mechanisms needs to be further explored. Finally, although a large number of materials show excellent improvement of photoelectric properties under pressure, most materials have rapid photoelectric properties degradation after decompression. How to effectively maintain or partially retain these pressure-induced enhancement characteristics, so that the material still has stable optoelectronic properties under ambient pressure, is the key problem to realize the transformation of high-pressure technology to practical optoelectronic device applications. In order to overcome the application bottleneck under extreme conditions, it is combined with other regulatory means to achieve the stable retention of pressure-induced performance under normal pressure. For example, internal stress is introduced by chemical pressure strategy (ion replacement, element doping, etc.) To simulate the regulation of pressure on lattice constant, bond length and local structure; Strain engineering (epitaxial growth, strain applied by flexible substrate) is used to maintain part of the lattice distortion or phase transition structure formed under pressure without external pressure; In addition, the structure formed under pressure can be stabilized by the cooperation of multiple fields (such as light, temperature gradient, electric field or magnetic field). The above strategies are helpful to maintain the performance improvement of pressure regulation at atmospheric pressure, thus improving the application potential of materials in practical devices such as photoelectric detection.

To sum up, high-pressure technology provides a "clean" and efficient physical strategy for the further development of optoelectronic properties of materials. This method not only shows significant advantages in the precise control of structure and electronic state, but also helps to reveal novel photoelectric phenomena that are difficult to discover by conventional means, and provides a new way to break through the limits of photoelectric characteristics of materials. With the continuous progress of pressure in situ characterization methods and theoretical calculation methods, as well as the breakthrough of key technologies such as the maintenance of high-pressure induced properties at ambient pressure, people will have a deeper and systematic understanding of the relationship between structural changes and photoelectric properties of materials under extreme conditions. In the future, high-pressure technology is expected to play a more important role in optimizing the performance of optoelectronic devices and expanding the application scenarios of materials, laying a solid foundation for the development of new optoelectronic materials and devices with high efficiency, stability and wide application.

References

[1] Wang X M, Cheng Z Z, Xu K, Tsang H K, Xu J B 2013 Nat. Photonics 7 888

[2] Youngblood N, Chen C, Koester S J, Li M 2015 Nat. Photonics 9 247

[3] Koepfli S M, Baumann M, Koyaz Y, Gadola R, Güngör A, Keller K, Horst Y, Nashashibi S, Schwanninger R, Doderer M, Passerini E, Fedoryshyn Y, Leuthold J 2023 Science 380

1169

[4] Chetia A, Bera J, Betal A, Sahu S 2022 Mater. Today Commun. 30 103224

[5] Wang H Y, Li Z X, Li D Y, Chen P, Pi L J, Zhou X, Zhai T Y 2021 Adv. Funct. Mater. 31 2103106

[6] Liu C Y, Guo J S, Yu L W, Li J, Zhang M, Li H, Shi Y C, Dai D X 2021 Light Sci. Appl. 10 123

[7] Li C Y, Li W J, Cheng M M, Yang W Y, Tan Q H, Wang Q J, Liu Y K 2021 Adv. Opt. Mater. 9 2100927

[8] Liu J, Xia F N, Xiao D, Garcia de Abajo F J, Sun D 2020 Nat. Mater. 19 830

[9] Rao G F, Wang X P, Wang Y, Wangyang P H, Yan C Y, Chu J W, Xue L X, Gong C H, Huang J W, Xiong J, Li Y R 2019 InfoMat 1 272

[10] Tian W, Liu D, Cao F R, Li L 2017 Adv. Opt. Mater. 5 1600468

[11] Ezhilmaran B, Patra A, Benny S, M. R S, V. V A, Bhat S V, Rout C S 2021 J. Mater. Chem. C 9 6122

[12] Allain A, Kang J, Banerjee K, Kis A 2015 Nat. Mater. 14 1195

[13] Cheng P, Wang Y F, Ye T T, Chu L Q, Yang J, Zeng H, Yao D Y, Pan X M, Zhang J, Jiang H C, Su F H, Ding J F 2022 Appl. Phys. Lett. 120 212104

[14] Pan X M, Xin B J, Zeng H, Cheng P, Ye T T, Yao D Y, Xue E Q, Ding J F, Wang W H 2023 J. Phys. Chem. Lett. 14 3320

[15] Pan X M, Xue E Q, Li W G, Pan W J, Yao D Y, Zhang X, Yin Y W, Cheng P, Liu Q J, Ding J F 2025 Phys. Rev. B 111 115104

[16] Mao H K, Chen X J, Ding Y, Li B, Wang L 2018 Rev. Mod. Phys. 90 015007

[17] Jiang S Q, Holtgrewe N, Lobanov S S, Su F H, Mahmood M F, McWilliams R S, Goncharov A F 2018 Nat. Commun. 9 2624

[18] Cheng P, Ye T T, Zeng H, Ding J F 2020 AIP Adv. 10 045110

[19] You Y, Li S S, Su T C, Hu M H, Hu Q, Wang J Z, Gao G J, Guo M M, Nie Y 2020 Acta Phys. Sin. 69 238101

[20] Qin X L, Zhu X L, Cao J W, Wang H C, Zhang P 2021 Acta Phys. Sin. 70 146301

[21] Li Q, Zhang Y J, Xiang Z N, Zhang Y H, Zhu X Y, Wen H H 2024 Chin. Phys. Lett. 41 017401

[22] Hou J, Yang P T, Liu Z Y, Li J Y, Shan P F, Ma L, Wang G, Wang N N, Guo H Z, Sun J P, Uwatoko Y, Wang M, Zhang G M, Wang B S, Cheng J G 2023 Chin. Phys. Lett. 40 117302

[23] Zhang L J, Wang Y C, Lv J, Ma Y M 2017 Nat. Rev. Mater. 2 17005

[24] Guo S H, Bu K J, Li J W, Hu Q Y, Luo H, He Y H, Wu Y H, Zhang D Z, Zhao Y S, Yang W G, Kanatzidis M G, Lü X J 2021 J. Am. Chem. Soc. 143 2545

[25] Shi Y, Zhou Y, Ma Z W, Xiao G J, Wang K, Zou B 2020 J. Mater. Chem. C 8 12755

[26] Attique S, Ali N, Imran T, Rauf S, Khesro A, Ali S, Wang W J, Khatoon R, Abbas A, Ullah khan E, Yang S K, Wu H Z 2022 Sol. Energy 239 198

[27] Wang L R, Yao P P, Wang F, Li S F, Chen Y P, Xia T Y, Guo E J, Wang K, Zou B, Guo H Z 2020 Adv. Sci. 7 1902900

[28] An C, Du X L, Chen X L, Zhou Y, Zhang M, Zhou Y H, Zhou J, Yang Z R 2023 Phys. Rev. B 107 134501

[29] Qi M Y, Ye M Y, Ma S L, Feng J M, Du M Y, Huang H Y, Song H, Cui T 2024 J. Mater. Chem. C 12 12372

[30] Shen Z W, Wu Z Y, Wang S J, Wang H C, Li H K, Song J, Gao G Y, Wang L, Tian Y J 2024 Chin. Phys. Lett. 41 117101

[31] Shi Y Y, Wu M, Yue L, Wang K, Li Q J, Wu Y, Ye G L, Huang H J 2024 Appl. Phys. Lett. 124 094103

[32] Wang N, Zhang G Z, Wang G Y, Feng Z B, Li Q, Zhang H W, Li Y W, Liu C L 2024 Small 20 e2400216

[33] Feng J M, Qi M Y, Song H, Ye M Y, Runowski M, Hu Z Y, Huang L K, Lian M, Zhao X B, Dan Y Q, Ma S L, Cui T 2025 Chem. Eng. J. 515 163611

[34] Mak K F, Lee C, Hone J, Shan J, Heinz T F 2010 Phys. Rev. Lett. 105 136805

[35] Wang Q H, Kalantar-Zadeh K, Kis A, Coleman J N, Strano M S 2012 Nat. Nanotechnol. 7 699

[36] Song X F, Guo Z X, Zhang Q C, Zhou P, Bao W Z, Zhang D W 2017 Small 13 1700098

[37] Khan K, Tareen A K, Aslam M, Wang R H, Zhang Y P, Mahmood A, Ouyang Z B, Zhang H, Guo Z Y 2020 J. Mater. Chem. C 8 387

[38] Liu Y, Duan X D, Huang Y, Duan X F 2018 Chem. Soc. Rev. 47 6388

[39] Choi W, Choudhary N, Han G H, Park J, Akinwande D, Lee Y H 2017 Mater. Today 20 116

[40] Nayak A P, Bhattacharyya S, Zhu J, Liu J, Wu X, Pandey T, Jin C Q, Singh A K, Akinwande D, Lin J F 2014 Nat. Commun. 5 3731

[41] Yuan Y F, Zhang Z T, Wang W K, Zhou Y H, Chen X L, An C, Zhang R R, Zhou Y, Gu C C, Li L, Li X J, Yang Z R 2018 Chin. Phys. B 27 066201

[42] Wang P, Wang Y G, Qu J Y, Zhu Q, Yang W G, Zhu J L, Wang L P, Zhang W W, He D W, Zhao Y S 2018 Phys. Rev. B 97 235202

[43] Zhang X T, Dong Q, Li Z L, Jing X L, Liu R, Liu B, Zhao T T, Lin T, Li Q J, Liu B B 2022 Mater. Res. Lett. 10 547

[44] Wang N, Moutaabbid H, Feng Z B, Wang G Y, Zhang H W, Zhang G Z, Cao Z Y, Li Y W, Liu C L 2024 Appl. Phys. Lett. 125 093904

[45] Aji Suleiman A, Zhou X, Zhai T Y 2021 J. Phys. D: Appl. Phys. 54 013002

[46] Cheng P, Ye T T, Yan J W, Zhang K, Yao D Y, Pan X M, Wang Y F, Xue E, Su F H, Zhang J, Ding J F 2023 Adv. Opt. Mater. 11 2300316

[47] Li Z, Li Q, Li H, Tian F, Du M, Fang S, Liu R, Zhang L, Liu B 2022 Small Methods 6 2201044

[48] Yue L, Tian F Y, Liu R, Li Z L, Li R X, Li C Y, Li Y C, Yang D L, Li X D, Li Q J, Zhang L J, Liu B B 2025 Natl. Sci. Rev. 12 nwae419

[49] Li Z L, Chen S X, Tian F Y, Fang S X, Li Q J, Du M Y, Yuan B, Kang L, Zhang L J, Liu B B 2024 Acta Mater. 278 120263

[50]Xing S Y, Chen S X, Fang S X, Tian F Y, Li Z L, Jin X L, Li Q J, Liu B B 2024 Adv. Opt. Mater. 12 202401433

[51] Li Z L, Li Q J, Li H Y, Yue L, Zhao D L, Tian F Y, Dong Q, Zhang X T, Jin X L, Zhang L J, Liu R, Liu B B 2021 Adv. Funct. Mater. 32 2108636

[52] Lu R H, Li Z L, Yue L, Song L Y, Fang S X, Liu T Y, Shen P F, Li Q J, Jin X L, Liu B B 2024 Mater. Today Phys. 42 101381

[53] Fang Y Q, Kong L P, Wang R Q, Zhang Z, Li Z Y, Wu Y H, Bu K J, Liu X Q, Yan S, Hattori T, Li N N, Li K, Liu G, Huang F Q 2023 Mater. Today Phys. 34 101083

[54] Li Z L, Gao D X, Chen S X, Yue L, Yuan B, Shen X D, Kang L, Li Q J, Liu B B 2025 J. Mater. Chem. A 13 9801

[55]Zhan X H, Jiang X M, Lv P, Xu J, Li F J, Chen Z L, Liu X B 2022 Angew. Chem. Int. Ed. 61 e202205491

[56] Yan H C, Ou T J, Jiao H, Wang T Y, Wang Q L, Liu C L, Liu X Z, Han Y H, Ma Y Z, Gao C X 2017 J. Phys. Chem. Lett. 8 2944

[57] Zhang H F, Yang J Z, Li Q J, You W W, Mao Y L 2023 Appl. Phys. Lett. 123 021107

[58] Ou T J, Liu C L, Yan H C, Han Y H, Wang Q L, Liu X Z, Ma Y Z, Gao C X 2019 Appl. Phys. Lett. 114 062105

[59] Jing X L, Zhou D L, Sun R, Zhang Y, Li Y C, Li X D, Li Q J, Song H W, Liu B B 2021 Adv. Funct. Mater. 31 2100930

[60] Lü X J, Wang Y G, Stoumpos C C, Hu Q Y, Guo X F, Chen H J, Yang L X, Smith J S, Yang W G, Zhao Y S, Xu H W, Kanatzidis M G, Jia Q X 2016 Adv. Mater. 28 8663

[61] Li Z L, Jia B X, Fang S X, Li Q J, Tian F Y, Li H Y, Liu R, Liu Y C, Zhang L J, Liu S Z, Liu B B 2022 Adv. Sci. 10 2205837

[62] Yue L, Li Z L, Yu L C, Xu K B, Liu R, Li C Y, Li Y C, Yang D L, Li X D, Li Q J, Liu B B 2024 J. Am. Chem. Soc. 146 25245

[63] Liu T B, Bu K J, Zhang Q, Zhang P J, Guo S H, Liang J Y, Wang B H, Zheng H Y, Wang Y G, Yang W G, Lü X J 2022 Materials 15 3845

[64] Yu H, Shi R, Zhao Y, Bian T, Zhao Y, Zhou C, Waterhouse G I N, Wu L Z, Tung C H, Zhang T 2017 Adv. Mater. 29 1605148

[65] Cheng P, Ye T, Yi M, Cheng W, Zhang L, Hong P, Sun C, Xie Y, Yao D, Pan X, Xue E, Zhang X, Shen C, Ding J 2025 Appl. Phys. Lett. 126 251902

[66] Cheng P, Yao D Y, Yan J W, Ye T T, Liu H H, Zeng H, Pan X M, Zhang G Q, Ding J F 2023 Phys. Rev. Appl. 19 024048

[67] Li Y Z, Yang X G, Lü C F, Qin J X, Zhang C, Zhang Z F, Chen X X, Zang J H, Lou Q, Dong L, Shan C X 2022 Carbon 199 453

[68] Fang S X, Dong Q, Li Z L, Tian H, Liu T Y, Li R X, Jing X L, Yue L, Li C Y, Liu R, Li Q J, Liu B B 2023 J. Phys. Chem. C 127 8383

[69] Fang S X, Li Q J, Li Z L, Dong Q, Jing X L, Li C Y, Li H Y, Liu B, Liu R, Liu B B 2022 Mater. Res. Lett. 11 134

[70] Zhang G H, Zhang Q, Hu Q Y, Wang B H, Yang W G 2019 J. Mater. Chem. A 7 4019

[71]Yue L, Cui D D, Tian F B, Liu S, Li Z L, Liu R, Yao Z, Li Y C, Yang D L, Li X D, Li Q J, Du Y, Liu B B 2024 Acta Mater. 263 119529

[72] Zhang G H, Liu F L, Gu T T, Zhao Y S, Li N N, Yang W G, Feng S H 2017 Adv.

Electron. Mater. 3 600498

[73] Rahman S, Samanta S, Kuzmin A, Errandonea D, Saqib H, Brewe D L, Kim J, Lu J L, Wang L 2019 Adv. Sci. 6 1901132

[74] Li C, Liu K, Peng S, Feng Q, Jiang D Q, Wen T, Xiao H, Yue B B, Wang Y G 2023 Chem. Mater. 35 1449

[75] Li C, Liu K, Jiang D Q, Wen T, Chen E, Ma Y Y, Yue B B, Chu S Q, Wang Y G 2023 Chem. Mater. 35 4821

[76] Li C Y, Liu R, Zhao T T, Li Z L, Yue L, Lin T, Zhang X T, Li Q J, Liu B B 2022 Appl. Phys. Lett. 121 042102

[77] Ye M Y, Li Y, Tang R L, Liu S Y, Ma S L, Liu H Z, Tao Q, Yang B, Wang X, Yue H J, Zhu P W 2022 Nanoscale 14 2668

[78] Wang L R, Wang K, Xiao G J, Zeng Q S, Zou B 2016 J. Phys. Chem. Lett. 7 5273

[79] Wang L, Wang K, Zou B 2016 J. Phys. Chem. Lett. 7 2556

[80] Wang F, Tan M P, Li C, Niu C Y, Zhao X 2019 Org. Electron. 67 89

[81] Morana M, Malavasi L 2021 Sol. RRL 5 2100550

[82] Zhang W W, Tang G, Sahoo M P K, Liang Y T, Zhang Y J 2022 Phys. Rev. B 105 075150

[83] Mączka M, Dybała F, Herman A P, Paraguassu W, Barros dos Santos A J, Kudrawiec R 2024 RSC Adv. 14 38514

[84]Feng H C, Zhang G Z, Feng Z B, Li Q, Wang G Y, Li Y W, Fang Y Y, Liu C L 2024 Appl. Phys. Lett. 124 043902