

RESEARCH ARTICLE | SEPTEMBER 21 2026

Metal-to-semiconductor transition and enhanced photoconductivity in PtSe₂ nanoflakes

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Appl. Phys. Lett. 129, 121602 (2026)

<https://doi.org/10.1063/5.0346024>



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Cite as: Appl. Phys. Lett. **129**, 121602 (2026); doi: [10.1063/5.0346024](https://doi.org/10.1063/5.0346024)

Submitted: 1 June 2026 · Accepted: 31 August 2026 ·

Published Online: 21 September 2026



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ABSTRACT

The electronic transport properties of two-dimensional (2D) platinum diselenide (PtSe₂) were systematically investigated. X-ray diffractometry, Raman spectroscopy, high-resolution transmission electron microscopy, and selected-area electron diffractometry were utilized to confirm the PtSe₂ with the single crystalline 1T-phase structure. The mechanically exfoliated PtSe₂ nanosheets exhibit semiconducting transport characteristic, which are different from their bulk counterparts with metallic nature. The room temperature conductivity at the range of 60–90 Ω⁻¹ cm⁻¹ is much lower than the values (2600 Ω⁻¹ cm⁻¹) of the metallic bulks. The exceptional photocurrent responses were also observed under different excitation wavelengths from 405 to 808 nm in the semiconducting PtSe₂ nanoflakes. The highest photocurrent responsivity of 1100 A/W and photoconductive gain of 3300 were achieved at the excitation wavelength of 405 nm. The presence of acceptor-like surface states resulting in metal-to-semiconductor transition and enhanced photoconduction in the 1T-PtSe₂ 2D nanostructures were proposed and discussed.

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Two-dimensional (2D) materials have become an important division in modern material research due to the exceptional physical properties that emerge when their thickness approaches the atomic scale. These unique characteristics distinct from those of their bulk counterparts have driven intense interest in exploring their potential for next-generation electronic and optoelectronic applications.^{1–4} Among the wide variety of 2D materials, transition-metal dichalcogenides (TMDCs) have attracted particular attention. Their naturally occurring van der Waals layered structure enables easy exfoliation into ultrathin sheets, although their intrinsic properties, such as sizable bandgap (1–2 eV), strong exciton binding energy, and high mechanical strength, make them highly suitable for nanoscale device integration.^{5–7} TMDCs exhibit diverse electrical behaviors depending on their transition-metal element, offering a rich platform for studying structure property interaction. Group-10 TMDCs with the formula MX₂ (M = Ni, Pd, Pt; X = Se) typically show metallic or semimetallic characteristics,^{8–10} which are distinct from the well-studied group 6B TMDCs (such as MoS₂, MoSe₂, WS₂, and WSe₂)

with semiconducting behavior. This contrast between TMDC families highlights the importance of electronic characteristics evolving with both composition and dimensionality.

Platinum diselenide (PtSe₂), a semimetallic TMDCs, exhibits interesting metal-to-semiconductor transition as its layer number decreases to a few layers or even a single layer.^{9–13} Theoretical studies indicate that monolayer PtSe₂ possesses a direct bandgap of approximately 1.2 eV, which is suitable for photodetectors and near-infrared absorbers.^{14–16} In addition, a high mobility at ~3000 cm² V⁻¹ s⁻¹ is predicted at room temperature revealing the potential of high-frequency and low-power consuming operations using PtSe₂.^{17,18} The exceptional optical and electrical properties and mechanically stable structure make PtSe₂ an attractive building block for flexible and high-performance electronic device applications.⁸ Despite these fascinating features, the fundamental electrical properties of 1T-phase PtSe₂ remains insufficiently explored. The studies of thickness-dependent and light-induced electronic transport are still limited.^{19,20}

In this report, we studied the metal-to-semiconductor transition in 1T-phase PtSe_2 . The PtSe_2 nanostructures exhibiting semiconducting behavior, which is different from the metallic nature of its bulk counterparts, were observed. Furthermore, photoresponse induced by different wavelengths in this semiconducting PtSe_2 nanoflakes was detected. The high photocurrent generation efficiency and its underneath mechanism were also discussed.

The high-quality PtSe_2 single crystals were grown by Flux technique using Cu–Se fluxes. In a quartz ampoule, Pt (slug), Cu (powder), and Se (slug) in 3N purity were combined in a molecular ratio of 1:8:8. The ampoule was sealed under high vacuum and heated to 900°C for 15 h. It is remained at that temperature for 24 h. The temperature of the furnace was gradually lowered to 650°C at a rate of 1°C per hour. Ultimately, the millimeter-sized single crystals were obtained at the ampoule's bottom after the PtSe_2 single crystals were isolated from the flux by centrifugation.

PtSe_2 bulk crystals were mechanically exfoliated using dicing tape to produce nanoflakes. These nanoflakes were transferred onto insulating SiO_2 (300 nm)/ $\text{n}^+\text{-Si}$ substrates featuring a pre-patterned Cr/Au electrode layout, prepared in advance of contact electrode fabrication. The Cr/Au electrodes served as connectors between the millimeter-scale bonded wires and the microelectrodes formed via the focused ion beam (FIB, FEI Quanta 3D FEWG) technique. Subsequently, two Pt contacts were deposited onto the PtSe_2 nanoflakes using the FIB technique. For comparison, Ag paste was employed to fabricate two electrodes on PtSe_2 bulk crystals with a thickness of less than $10\ \mu\text{m}$. Raman measurements were performed in a backscattering geometry using a Renishaw inVia Raman microscope system with the light source of 532 nm laser. Transmission electron microscopy (TEM, JEOL JEM-2100F) was employed to acquire high-resolution lattice images and selected-area electron diffraction (SAED) pattern. The current vs voltage (I–V) characteristics of PtSe_2 nanoflake devices were measured using a two-probe configuration. The scanning electron microscope (SEM, Hitachi S3000H) was employed to capture the images of the devices. The thicknesses of the nanoflakes were determined by atomic force microscopy (AFM) using a Bruker Dimension Icon system. Temperature-dependent conductivity measurements were carried out in a cryogenic probe station with ultralow current leakage (Lakeshore Cryotronics TTP4). A Keithley 4200-SCS semiconductor characterization system was employed to apply DC voltage and record the resulting current.

Figure 1(a) presents the XRD analysis of PtSe_2 crystals, revealing four distinct diffraction peaks at 17.3° , 35.1° , 54.0° , and 74.5° , corresponding to the (001), (002), (003), and (004) planes, respectively, as identified by PDF No. 96-153-9199.^{20,21} These peaks confirm a strong out-of-plane orientation along the c-axis, the single crystalline quality, and hexagonal phase of the crystal. The inset of Fig. 1(a) shows the photo of PtSe_2 crystals grown using the flux method. Figure 1(b) depicts the Raman spectrum of the bulk PtSe_2 , displaying two peaks at 178 and $208\ \text{cm}^{-1}$ that are consistent with the E_g and A_{1g} vibrational modes in the previous reports for 1T phases of PtSe_2 .^{22,23} In addition, the narrow full width at half maximum (FWHM) values of 4.6 and $4.2\ \text{cm}^{-1}$ for the E_g and A_{1g} peaks, respectively, confirm the high crystalline quality of the PtSe_2 . To further confirm the 1T phase of PtSe_2 , high-resolution transmission electron microscopy (HRTEM) has been performed as illustrated in Fig. 1(c). The HRTEM image [Fig. 1(c)] shows well defined lattice fringes with a spacing of 0.32 nm,

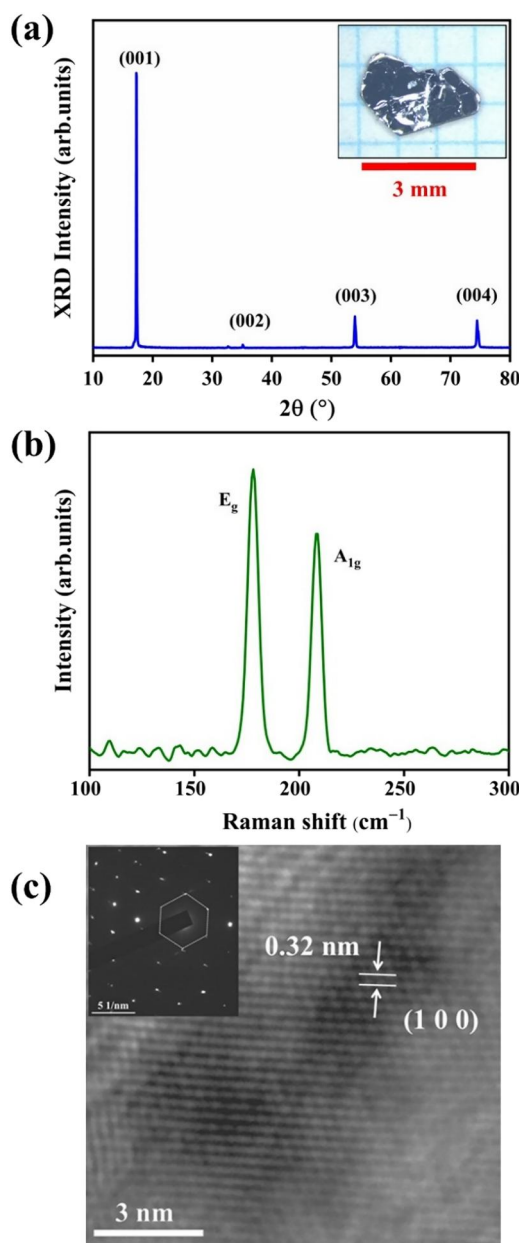


FIG. 1. (a) XRD pattern, (b) Raman spectrum, (c) HRTEM image, and SAED pattern (inset) of PtSe_2 single crystals.

which corresponds to the (100) plane of PtSe_2 with single crystallinity. The inset accompanying SAED pattern along [001] zone axis displays sixfold symmetry of 1T phase of PtSe_2 single crystal.^{24,25} SAED and XRD characterization confirm the crystal structure along the [001] out-of-plane orientation; meanwhile, HRTEM reveals the lattice fringes along the [100] in-plane orientation.

Figure 2(a) depicts the I–V measurements of PtSe_2 nanoflake devices with different thicknesses. The linear I–V characteristic indicates good Ohmic contact between FIB-fabricated Pt electrodes and

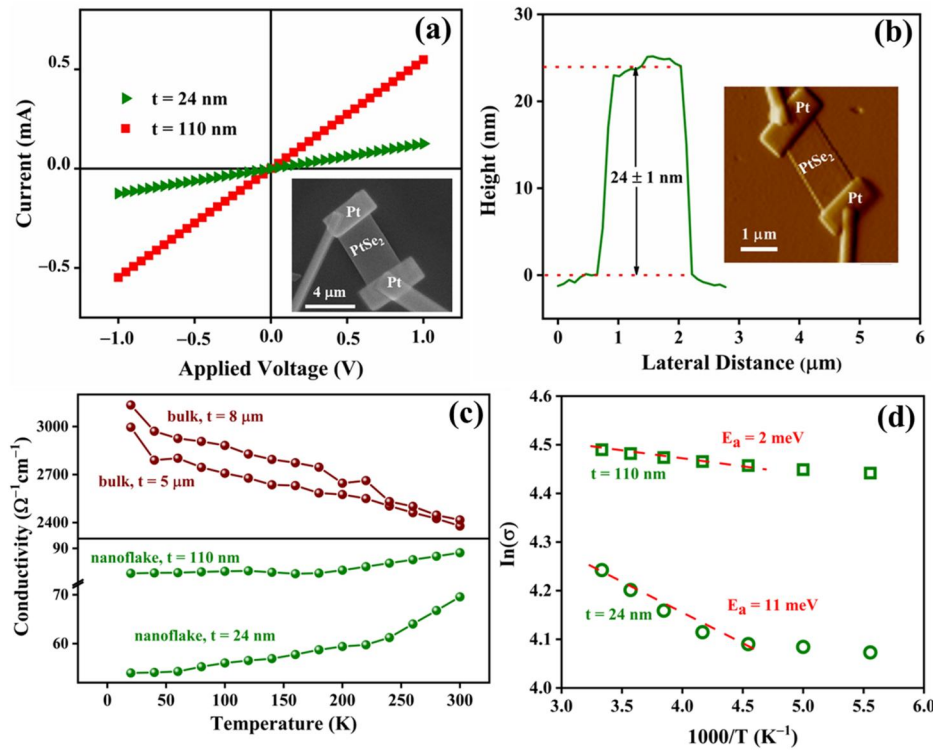


FIG. 2. (a) I–V curves of the PtSe₂ nanoflakes with different thicknesses of 24 and 110 nm. The inset shows a field-emission scanning electron microscopy (FESEM) image of a two-terminal device of PtSe₂ nanoflake fabricated by FIB. (b) AFM height profile and image (inset) of a PtSe₂ nanoflake with a thickness of 24 nm. (c) Temperature-dependent conductivity measurements and (d) their corresponding Arrhenius plots for the PtSe₂ bulks with different thicknesses (5 and 8 μm) and nanoflakes with different thicknesses (24 and 110 nm). The red dash lines show the linear fitting of data points.

PtSe₂ nanoflakes. A typical SEM image of a PtSe₂ nanoflake device was depicted in the inset of Fig. 2(a). A typical AFM height profile and the corresponding AFM image (the inset) of the nanoflake device are shown in Fig. 2(b). The obtained thickness value of the PtSe₂ nanoflake is 24 nm. The electrical conductivity (σ) was calculated using the definition of conductance (G) as follows:²⁶

$$G = \frac{I}{V} = \sigma \frac{wt}{l}, \quad \sigma = G \frac{l}{wt}, \quad (1)$$

where w , t , and l denote the width, thickness, and length of the conducting channel, respectively. The calculated conductivity values for the nanoflakes with thicknesses ranging from 24 to 110 nm fall within the range of 60–90 $\Omega^{-1}\text{cm}^{-1}$. Interestingly, the conductivity values of nanoflakes are much lower than the bulk ($t = 5\text{--}8\ \mu\text{m}$) values obtained from our measurements (2200–2600 $\Omega^{-1}\text{cm}^{-1}$) and the previous report (6200 $\Omega^{-1}\text{cm}^{-1}$).²⁷

The temperature-dependent conductivity measurements in the range of 20–300 K were performed to further explore the transport characteristics of PtSe₂ bulk crystals and nanoflakes as shown in Fig. 2(c). The nanoflakes with thicknesses of 24 and 110 nm reveal semiconducting behavior, characterized by a decrease at conductivity with decreasing temperature. This behavior contrasts with the metallic behavior of bulk PtSe₂ crystals with the thickness of 5 and 8 μm . In metallic systems, conductivity typically increases as temperature decreases due to the reduced lattice scattering and temperature-insensitive electron concentration. The thermal activation energy (E_a) can be determined using the relation $\sigma(T) = \sigma_0 \exp(-E_a/kT)$,²⁶ where σ_0 represents the conductivity at infinite temperature (T) and k is Boltzmann's constant. The E_a values are extracted from the slope of

the Arrhenius plot ($\ln\sigma$ vs $1000/T$) derived from the σ – T data, as shown in Fig. 2(d). The calculated E_a values are 2 and 11 meV for the nanoflakes with the thickness of 110 and 24 nm, respectively.

Experimentally, the PtSe₂ bulks of the 1T phase show metallic characteristic.^{27,28} The metallic nature of 1T-PtSe₂ is due to the overlap of Pt 5d and Se p orbitals. The transition of metal-to-semiconductor in 1T-PtSe₂ has been observed and is attributed to quantum confinement and reduced interlayer coupling, leading to the opening of a bandgap.^{29–31} The critical thickness is roughly higher than 10 nm. The metallic 1T-PtSe₂ bulk is consistent with our observation. However, the thickness of our nanoflakes (≥ 24 nm) is much higher than 10 nm and is unlikely to be correlated with the quantum confinement effect.

The lower conductivity in nanoflakes implies the presence of the electron traps, which capture electron and reduce electron concentration. However, our PtSe₂ nanoflakes were exfoliated from the same batch of bulk crystals and expected to retain the metallic characteristics of the pristine bulks. This excludes the presence of electron traps in the inner bulk and suggests the defects could originate from the surface. If the surface states located below the conduction band minimum, free electrons can be captured by the surface states. In this case, thermal energy is required to release trapped electrons to the conduction band, which explain the thermal activation mechanism and semiconducting behavior in 1T-PtSe₂ flakes. Although PtSe₂, as a van der Waals material, does not have surface dangling bonds due to weak interlayer interactions,³² structural imperfections especially selenium vacancies are still expected to occur. Such surface defects may be introduced during the mechanical exfoliation process. Deselenization has also been reported to occur spontaneously when the ambient

molecules (such as O₂, H₂O, hydrocarbon, etc.) interact with the PtSe₂ surface in atmospheric environment.^{33,34} The nonstoichiometric characteristic of PtSe₂ could further enhance the generation of defect-induced surface states.³⁵ These surface states are typically located below the Fermi level and can act as acceptor-like traps facilitating electron capture, leading to carrier density decrease and the transition from metal-to-semiconductor in PtSe₂ nanoflakes.

According to Zhao *et al.*, a critical thickness of approximately 11 nm was observed via temperature-dependent conductivity measurements.²⁷ Above the thickness (e.g., at 64 nm), a clear metallic transport behavior was still observed. Their simulations of the band structures confirmed that the semimetal-to-semiconductor transition of PtSe₂ is driven by the quantum confinement effect. However, in our study, the surface effect appears to be the dominant factor governing semiconducting behavior, rather than quantum confinement. The fact that nanoflakes with thicknesses up to 110 nm still behave as semiconductors indicates that they are far from the quantum confinement regime. The presence of the acceptor-like surface states (ALSS) was proposed to explain the semiconducting behavior of PtSe₂ flakes, which exhibits lower conductivity, thermal activation, and even photoconductivity. Figure 3 illustrates the power-dependent photocurrent response of the PtSe₂ nanoflakes with different thicknesses (24 and 110 nm) and bulk with a thickness of 5 μ m illuminated with a 405 nm wavelength (λ) at a bias of 1 V. A background dark current has been subtracted from these curves to extract the actual photocurrent values. Noted that the efficient photoresponse in nanoflakes is distinct from their bulk counterparts because the bulk does not show any detectable photocurrent. The difference could be correlated with the conductivity difference between semiconducting nanoflake and metallic bulk.

The metallic nature of PtSe₂ bulks has high electron concentration, and free electron absorption (FEA) takes place when the conductive material is illuminated. FEA reflects incident light and blocks materials from light absorption. However, FEA is weakened in nanoflakes with much higher surface-to-volume ratio if electron concentration is decreased due to the electron traps at the surface. This probably explains why the PtSe₂ nanoflakes have light absorption and exhibit photocurrent response. The photoconductivity result is

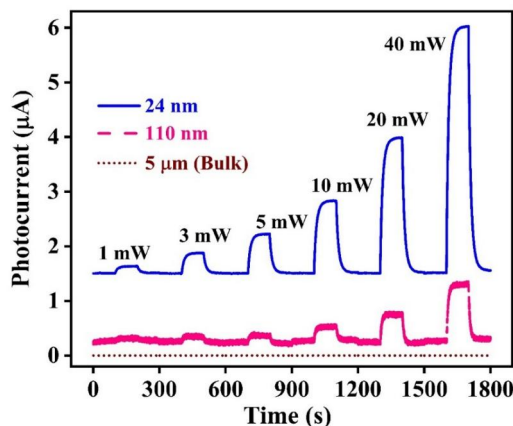


FIG. 3. Photocurrent response curves of the PtSe₂ nanoflakes with different thicknesses (24 and 110 nm) and the bulk with a thickness of 5 μ m recorded at a bias of 1 V and escalating optical power at the excitation wavelengths of 405 nm.

consistent with the dark conductivity observation and further supports the presence of acceptor-like surface states in PtSe₂.

The photocurrent response of the PtSe₂ nanoflake with a thickness of 24 nm was measured at different wavelengths of 532, 633, and 808 nm and included in [supplementary material](#) Fig. S1. The result shows that the PtSe₂ nanoflake also exhibits substantial photoresponses to the different wavelengths of light. The photocurrent value vs optical intensity (I) curves at different wavelengths are shown in Fig. 4(a). The photocurrent increases linearly with light intensity and the maximal photocurrent, which was observed at 405 nm wavelength.

To assess the device performance of the photoconductor-type PtSe₂ photodetector, two key parameters including photocurrent responsivity (R) and photoconductive gain (Γ) were calculated. R is defined as the photocurrent (i_p) produced by the optical power (P) incident on the photoconductor's effective area (A), and it is expressed as

$$R = i_p / P, \quad (2)$$

where $P = IA = Iwl$ and I is the incident optical intensity.³⁶ The calculated R values vs I at different excitation wavelengths were plotted in Fig. 4(b). The maximal R value of ~ 1100 A/W was obtained at $\lambda = 405$ nm. The optimal R value is over two orders of magnitude higher than the reported PtSe₂ based photodetectors, including the PtSe₂ monolayer ($R = 0.9$ A/W), the PtSe₂ bilayer ($R = 6.25$ A/W),³⁷ the PtSe₂ film (0.0014 A/W),³⁸ and the PtSe₂ layered film (0.4 A/W).²⁵ Also, the R of our PtSe₂ nanoflakes is much higher than those of several 2D photoconductors, such as reduced graphene oxide ($R = 0.004$ A/W),³⁹ graphene nanoribbon ($R = 1$ A/W),³⁹ MoS₂ multilayer films ($R = 0.71$ – 1.8 A/W),^{40–42} MoS₂ nanoflakes ($R = 20$ – 30 A/W),⁴³ GaS ($R = 4.2$ – 19.2 A/W),⁴⁴ GaSe nanosheets ($R \approx 2.8$ A/W),⁴⁵ and NbSe₂ nanoflake (3.8 A/W).⁴⁶ Only the 4 nm thick PtSe₂ with phototransistor configuration demonstrated by Yang *et al.* shows the maximal R reaching ~ 3500 A/W ($V_g = 0$ V), which is comparable with our photoconductor-type device.

Photoconductive gain serves as a critical figure of merit for evaluating photocarrier collection efficiency in photodetectors. Fundamentally, Γ represents the average number of charge carriers that transit through the photoconductive channel per absorbed photon before recombination occurs. This dimensionless parameter is defined as the ratio of the carrier lifetime (τ) to the transit time (τ_t) between electrodes, expressed as

$$\Gamma = \frac{\tau}{\tau_t} = \frac{V}{\mu E} \tau \mu, \quad (3)$$

where μ denotes carrier mobility.^{36,47} Experimentally, Γ can be determined through its linear relationship with the device responsivity and incident optical power, as described by the equation:

$$\Gamma = \frac{ER}{e\eta}, \quad (4)$$

where E corresponds to the photon energy, e is the elementary charge, and η is the quantum efficiency (assumed $\eta = 1$ to simplify the calculation).⁴⁷ Figure 4(c) illustrates the Γ vs I at different wavelengths. The highest value of ~ 3300 was obtained for the wavelength of 405 nm. The Γ value is also higher than the NbSe₂ nanoflake

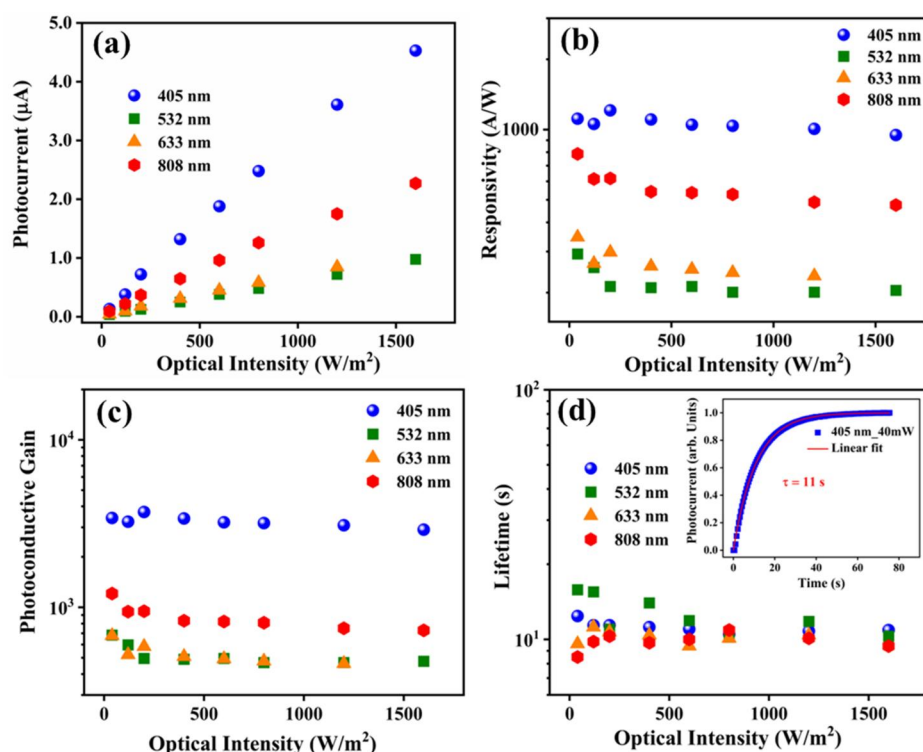


FIG. 4. (a) Photocurrent, (b) responsivity, (c) photoconductive gain, and (d) carrier lifetime vs light intensity at the wavelengths of 405, 532, 633, and 808 nm for the PtSe₂ nanoflake with 24 nm thickness. The inset in Fig. 4(d) is the curve fitting for a photocurrent rising curve measured at the power of 40 mW and the wavelength of 405 nm.

($\Gamma \sim 300$),⁴⁶ MoS₂ ($\Gamma \sim 103$),⁴³ ZnS NBs ($\Gamma \sim 0.5$),⁴⁸ ZnSe NBs ($\Gamma \sim 0.4$),⁴⁹ ZnO nanospheres ($\Gamma \sim 5$),⁵⁰ and Nb₂O₅ NBs ($\Gamma \sim 6$).⁵¹

To further understand the PC mechanism, carrier lifetime (τ) was extracted by fitting the rise portion of the time-resolved photocurrent curve. According to the continuity equation, $i_p(t) \propto [1 - \exp(-t/\tau)]$,⁵² the curve fitting to the response curve measured at the power of 40 mW and the wavelength of 405 nm is illustrated in the inset of Fig. 4(d). The extracted τ values as a function of optical intensity for different excitation wavelengths are plotted in Fig. 4(d). The τ values are in the range of 8–16 s and insensitive to the light intensity for all excitation wavelengths. A comparison of our device and other reported 2D photodetectors is summarized in supplementary material Table S1.

According to Eq. (3), photoconductive gain is proportional to carrier lifetime. The carrier lifetime at the scale of seconds, which is several orders of magnitude higher than the nanoseconds in general semiconductors, indicates a long-lifetime mechanism in PtSe₂ flakes. To explore the underlying mechanism, photocurrent measurements were carried out under different environmental conditions (air and vacuum) using excitation wavelength of 405 nm at a bias voltage of 1 V, as shown in Fig. 5(a). The results reveal a significant enhancement in photocurrent and an increase in response time (indicative of prolonged carrier lifetime) when the environment is switched from ambient air to vacuum. The environment-sensitive photoconduction resembles the typical oxygen-sensitized photoconduction (OSPC) mechanism in the materials with semiconducting characteristic in which excess holes are required to involve in the reaction resulting in long carrier lifetime.^{53,54} However, photogenerated holes are unlikely to survive in metallic PtSe₂ with high electron concentration and so

PtSe₂ could follow a different mechanism. To explain the results, a modified model is proposed as follows.

According to our Hall effect measurements on the PtSe₂ bulk crystal, the resistivity, electron concentration, and mobility are $5 \times 10^{-5} \Omega \text{ cm}$, $8.2 \times 10^{19} \text{ cm}^{-3}$, and $1.2 \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, respectively. The obtained carrier concentration ($\sim 10^{20}$) is slightly lower than that of PtSe₂ thin films ($3.2 \times 10^{21} \text{ cm}^{-3}$)⁵⁵ and significantly lower than typical values for metals such as Cu and Au (10^{22} – 10^{23} cm^{-3}). If electrons are captured by the acceptor-like surface states (ALSSs), a built-in field and surface band bending (SBB) could still be generated in the region close to the surface of PtSe₂, though the electric field does not exist in general metals. Figure 5(b) illustrates a schematic band diagram in thermal equilibrium for PtSe₂.

Under illumination, excess electrons can be generated through band-to-band and surface states absorptions. The electron-hole pairs generated by the band-to-band absorption possessing very short carrier lifetime and low photocurrent are difficult to be detected due to the high electron concentration environment. Accordingly, electrons excited from the surface states (Step 1) could contribute photocurrent predominantly. The photogenerated electrons are subsequently swept into the inner bulk by the SBB (Step 2). Because there are no holes to recombine with the excess electrons, the electrons exhibit long carrier lifetime, as observed in Fig. 4(d). The only way for electrons to recombine is via oxygen adsorption. Oxygen molecules intend to capture electrons when adsorbing on the material surface (Step 3). Accordingly, electron lifetime is now decided by the oxygen adsorption rate. This explains the prolonged carrier lifetime (response time) and enhanced photocurrent in vacuum. The photoconduction mechanism for PtSe₂ is schematically shown in Fig. 5(c).

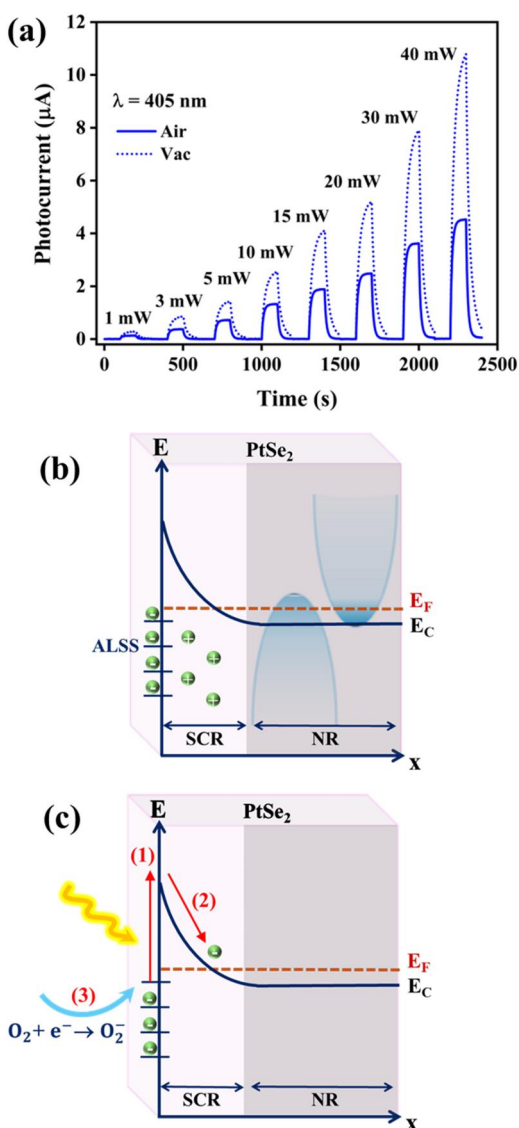


FIG. 5. (a) Photocurrent responses measured at the wavelength of 405 nm in air and vacuum ambiances for the PtSe₂ nanoflake with a thickness of 24 nm. (b) Schematic showing free electrons captured by the acceptor-like surface states (ALSSs) resulting in the space charge region (SCR) in thermal equilibrium. (c) Schematic showing ALSS-captured electrons being excited and subsequently transferring into neutral region (NR) under light illumination.

The intensity-insensitive carrier lifetime is consistent with the surface-dominant PC mechanism because the lifetime is determined by the oxygen adsorption rate rather than free carrier recombination. In addition, Fig. 4(d) shows that the carrier lifetime is almost independent of the wavelength. However, PC gain shows substantial wavelength-dependent, of which the gain at the wavelength 405 nm is the highest. This indicates that the wavelength-dependent photoresponse is attributed to the different quantum efficiency. The energy dispersion of the density of surface states is random and difficult to

predict. However, the shortest wavelength at 405 nm exhibiting substantially higher photoresponse could be correlated with the shallower penetration depth of light, which generates more effective carriers near the surface area and results in higher quantum efficiency and photocurrent in PtSe₂ nanoflakes.

In addition to photoconductivity, the mentioned model also explains the metal-to-semiconductor transition in PtSe₂ nanostructures. Thermal electron concentration decreases due to the presence of ALSS as the surface-to-volume ratio substantially increases from bulk to nanostructure, which results in lower conductivity in nanoflakes. In addition, thermal electrons can be released by the DLSS, which makes the temperature-dependent conductivity follows the thermal activation mechanism like semiconductors as our observation in Fig. 2(c).

In summary, we have investigated the electronic transport properties in 1T-PtSe₂. The conductivity of nanoflakes was two orders of magnitude lower than their bulk counterparts. Temperature-dependent measurements revealed the semiconducting behavior in PtSe₂ nanoflakes, which is different from their metallic bulks. The exceptional photocurrent responses were observed under different excitation wavelengths from 405 to 808 nm in the semiconducting PtSe₂ nanoflakes. The highest responsivity of 1100 A W⁻¹ and photoconductive gain of 3300 were achieved at the excitation wavelength of 405 nm. This study provides new insights into the electrical and optoelectronic properties of the 1T-PtSe₂ nanostructures and highlights its potential for optoelectronic device applications.

See the [supplementary material](#) for additional photocurrent response measurements of PtSe₂ nanoflakes at different excitation wavelengths and a comparison of the performance of 2D photodetectors with previously reported devices.

R.-S.C. acknowledges the support of the National Science and Technology Council (NSTC) of Taiwan (Grant Nos. NSTC 114-2112-M-011-001, MOST 111-2112-M-011-004-MY3, NSTC 113-2622-E-011-025, and NSTC 114-2823-8-011-001). R.S. acknowledges the financial support provided by the Ministry of Science and Technology in Taiwan under Projects Nos. 114-2124-M001-009 and NSTC-114-2112M001-045-MY3 as well as support from the Academia Sinica for the budget of ASiMATE115-14.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Pushpa Selvarasu: Conceptualization (lead); Formal analysis (lead); Methodology (lead); Writing – original draft (lead). **Hemanth Kumar Bangolla:** Investigation (lead). **Raman Sankar:** Investigation (equal). **Rajeshkumar Ulaganathan:** Investigation (supporting). **Kalaivanan Raju:** Investigation (supporting). **Yu-Chiang Lin:** Investigation (supporting). **Kuei-Yi Lee:** Investigation (equal). **Ruei-San Chen:** Conceptualization (lead); Resources (lead); Supervision (lead); Validation (lead); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available within the article and its [supplementary material](#).

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