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Fast Photoresponse from 1T Tin Diselenide Atomic Layers

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1. Introduction

Stimulated by the discovery of graphene and its fascinating electronic and physical properties,^[1-4] two-dimensional (2D) materials such as hexagonal boron nitride (h-BN),^[5-8] transitional metal chalcogenides (TMDs)^[9-15] and other 2D compounds,^[16-18] have received increasing interests because of their great potential in the field of catalysis, nanotribology, microelectronics, lithium batteries, hydrogen storage, medical and optoelectronics.^[19-22] However, their applications in nanoelectronic and optoelectronic devices are limited by the zero bandgap of graphene. The high leaking current in graphene based field-effect transistor (FET) make it difficult for realization of integrated circuits. For 2D compounds in a form of MX₂ (M = transitional and main group metal, X = S, Se and Te), it typically crystallizes in 2H and 1T types structure with D_{6h} and D_{3d} point-group symmetry respectively and the major difference between 2H and 1T is the coordination type of the metal atoms: the trigonal prismatic coordination for the former and the octahedral coordination, in addition, “2” and “1” in 2H and 1T represent the number of the layers in unit cell, shown in Figure S1. Substantial

efforts have been devoted to study 2H type MX_2 2D crystals (e.g. MoS_2 , WSe_2), because of their stable phase. Potential applications such as valleytronics, ultra-low-power consumption electronics and high performance catalyst were reported. For example, FETs fabricated using TMD MX_2 ($\text{M} = \text{Mo}$ and W , $\text{X} = \text{S}$ and Se) atomic layers exhibit excellent on/off current ratio (up to 10^8) and reasonably good carrier mobility,^{[22], [23]} and some MX_2 ($\text{M} = \text{Nb}$ and Ta , $\text{X} = \text{S}$ and Se) thin films show exciting superconductivity and charge density wave (CDW) behaviors.^{[22], [24], [25]}

However, it shed less light on the electronic and optoelectronic properties of 1T- MX_2 2D crystals simply due to the difficulties in synthesis. In addition, the metallic nature of some 1T phase 2D layers make them not suitable to the fabrications of FET and optoelectronic devices (such as, $\text{M} = \text{Mo}$, W , Nb and Ta , $\text{X} = \text{S}$, Se and Te).^[26] 1T- MX_2 2D crystals, however, show several advantages compared with their 2H phase counterparts, e.g., 1T monolayer WS_2 displays the better electrocatalytic and photocatalytic properties.^{[27], [28]} Therefore, the research of electronic and optoelectronic properties of atomically thin layers of 1T MX_2 2D materials is highly demanding.

Among 1T MX_2 2D crystals, SnSe_2 is a semiconductor with bulk band gap of about 1.0 eV. For a thick SnSe_2 film (84 nm) based device, it showed a mobility of $28 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ but a poor on/off ratio in single digit, and a high bulk electron affinity of 5.2 eV according to recent report.^[29] In addition, SnSe_2 films is also a good candidate for resistive memory and solar cells.^[30] However, most of the studies currently focused on thick or bulk SnSe_2 .^{[29], [31]} The properties of atomic layered SnSe_2 are still unknown.

In this paper, mono-layered and bi-layered SnSe_2 are firstly successfully exfoliated via mechanical exfoliation from the single-crystal SnSe_2 , which have been carefully examined their electronic and optoelectronic behaviors. Complementary characterizing tools such as atomic force microscope (AFM) and Raman microscopy have been employed to characterize the SnSe_2 atomic layers. The optoelectronic properties of the bilayer SnSe_2 devices were systematically studied, which show a mobility of $\sim 4 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ and on/off $\sim 10^3$. More interestingly, atomic layered SnSe_2 exhibits high photoresponsivity reaching 0.5 AW^{-1} and very fast response speed of $2.2 \pm 0.3 \text{ ms}$ (rise) and $3.2 \pm 0.2 \text{ ms}$ (fall), exceeding most of other 2D materials like MoS_2 and WSe_2 layers. These make few-layer SnSe_2 a promising active 2D material for electronic and optoelectronic applications.

2. Result and Discussion

2.1. Synthesis and crystal structure of of SnSe_2 single crystals

SnSe₂ crystallizes with a hexagonal space group $P-3m_1$ of the CdI₂-type, which consists of the SnSe₆ octahedral layers bonded together by weak van der Waal's forces to form 1T structure but an anisotropic atomic structure shown in Figure 1a. The single crystals SnSe₂ bulk with the definite metallic sheen shown in Figure 1c have been synthesized by the direct transport method without the transport gas (Figure 1b and S2), which have been confirmed by the powder X-ray diffraction (XRD) (Figure S3) and the energy dispersive X-ray spectroscopy (EDX) with the formula of SnSe_{1.96(2)} (Figure 1d), consistent with the calculation formula SnSe₂. The atomic structure of our SnSe₂ is also confirmed by the atomically resolved annual dark-field (ADF) scanning transmission electron microscopy (STEM), as shown in Figure 2 and S4. SnSe₂ flakes have been mechanically exfoliated from bulk single crystals onto the SiO₂/Si (285 nm thick SiO₂) substrate using the scotch tape, and then transferred to TEM grids. Figure 2a displayed the film dominated by bi-layered SnSe₂. Inset is the Fast Fourier Transform (FFT) pattern which shows six-fold-symmetric spots, indicating the hexagonal structure of the samples. Monolayer SnSe₂ can be also observed at some locations, which is indicated by a white rectangle in Figure 2a. This same region is presented in Figure 2b, where we can clearly identify the sites of Sn and In atoms. The Sn–Sn bond length is estimated to be ~ 0.37 nm. This value fits to the simulation and model very well in Figure 2c and 2d.

2.2. AFM and Raman spectra of atomically thick SnSe₂ flakes

Figure 3a shows monolayer SnSe₂ with lateral dimensions exceeding 13 μm . Similar to other 2D atomic layers, the thickness of SnSe₂ layer can be roughly determined via the contrast of its optical images. In order to identify exactly the number of layers, AFM images are obtained from dashed-line region in Figure 3a. From the AFM images shown in Figure 3c, monolayer SnSe₂ is found along the edge with a thickness of ~ 0.87 nm. It is slightly more than the actual thickness of 0.62 nm (Figure 1a) likely due to the trapping of absorbed molecular (e.g., H₂O) between the flake and the substrate and the measuring error of AFM, similar to the thickness variations in monolayer SnS₂ (1.0 ± 0.2 nm VS 0.6 nm).³² In addition, the thickness of 2L, 3L, 4L and 5L SnSe₂ are 1.48, 2.13, 2.69 and 3.36 nm shown in Figure S5, respectively, which are also lightly more than the theoretical values, 1.24, 1.86, 2.48 and 3.1 nm. Therefore, the distances between 1L and 2L, 2L and 3L, 4L and 5L are 0.61, 0.65, 0.56 and 0.67 nm, which is basically in accordance with the thickness of monolayer, 0.67 nm.

Raman spectroscopy is a powerful nondestructive characterization tool to confirm the phase of 2D crystals. The Raman spectrum of bulk 1T SnSe₂ has been reported by the previous papers, indicated that there were two vibratory modes E_g (in-plane vibration) and A_{1g} (out-plane

vibration) with the values of 116.0 and 185.5 cm^{-1} in 300 K excited by the 488 nm laser,^[33] basically in accord with our experimental values of 110.6 and 183.5 cm^{-1} respectively under the 532 nm laser shown in Figure 3d and S6, in which there is an obvious red shift for A_{1g} with the reduce of the layer number but no change for E_g , compared to the change of Raman spectra of MoS_2 (blue and red shifts for E_{2g} and A_{1g} with reducing the layer number).^[34] Moreover, the Raman map of the blue line region of the optical microscopy image displays the monolayer SnSe_2 is easily identified from different layer sample, shown in Figure 3b. The A_{1g} mode shows low intensity in monolayer but is still detectable and can be clearly distinguished from bulk to monolayer SnSe_2 . (Figure 3d) A plot of the intensity ratio of $I(\text{Si})$ and $I(\text{SnSe}_2)$ for the A_{1g} and E_g modes respectively with the function of the number of the layers is shown in Figure 3e. For the A_{1g} mode, the $I(\text{Si})/I(\text{SnSe}_2)$ intensity ratio of monolayer and bilayer are basically the same, and then decreases approximately linearly with the thickness. But for the E_g mode, the $I(\text{Si})/I(\text{SnSe}_2)$ intensity ratio always decreases approximately linearly with increasing the thickness. Therefore, the variation of the $I(\text{Si})/I(\text{SnSe}_2)$ intensity ratio is basically normal.

2.3. Theoretical Calculations

The electronic band structures of bulk (Figure 4b), 4L (Figure S7b), 3L (Figure S7a), 2L (Figure 4c) and 1L (Figure 4d) have been obtained by the first principle calculation based on density functional theory (DFT) respectively. Figure 4b shows bulk SnSe_2 are a semiconductor with an indirect band gap of 0.710 eV, which is lower than the experimental value of 1.0 eV due to the insufficient cancellation of the self-interaction error by the approximate GGA functionals.^[35] Of particular interest of our finding from the band structure is that the band gap is insensitive on the number of layers compared with the observations in MoS_2 and black phosphorus.^{[18], [36]} In addition, the calculated results show SnSe_2 from bulk to monolayer always have the indirect band gaps, which have been confirmed by the photoluminescent measurement with no PL phenomenon from bulk to monolayer, which is different from MoS_2 which has an indirect bandgap for bulk but direct band gap for monolayer.^[18]

2.4. The electronic properties of bilayered SnSe_2 FET

The electrical contacts made of Ti/Au films have been deposited by an e-beam evaporator after photolithography, shown in Figure 5a. The substrate and the electrode are attached to chip carrier fixtures for electrical testing. The current–voltage (I_d – V_d) curve and the transfer characteristics (I_d – V_g) of the fabricated SnSe_2 transistor in the absence of laser irradiation is shown in Figure 5b and 5c. It can be depicted that the bilayer SnSe_2 FET exhibited n-type

semiconducting behavior, which is consistent with theoretical results and previous literatures.^[29] On the other hand, we also observe a clear hysteresis loop in the electrical characteristics, resulting from surrounding conditions or the charge transfer from neighboring adsorbates or trapping states on the substrate.^[37] The mobility of the carriers can be calculated by $\mu = \frac{L}{W \times (\epsilon_0 \epsilon_r / d)} \times \frac{dI_{ds}}{dV_g} \times \frac{1}{V_{ds}}$, where L, W and d denote the channel length, width and the thickness of SiO₂ layer (285 nm in our devices), respectively. V_{ds} , I_{ds} and V_b denote the source–drain bias, current, and bottom gate voltage in the linear region in the I_d – V_g curve. ϵ_0 and ϵ_r are the vacuum dielectric constant and the dielectric constant of SiO₂ ($\epsilon_r = 3.9$), respectively. The calculated mobility of our device is about $4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, which is at least one order higher than that of other similar compounds such as GaS, GaSe, GaTe and WS₂,^{[16], [38]} even though it is much lower than these of MoS₂ and WSe₂.^{[39], [40]} Furthermore, the mobility can be improved by optimizing crystal quality, contact resistance and the dielectric environment similar to MoS₂ transistors, the mobility of which is increased from $0.1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ to nearly $200 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ by employing high- k gating of HfO₂ layer.^[41] The relatively high mobility of the SnSe₂ transistor could be applied in optoelectronic and photonic applications. Figures 5c and 5d display the on/off ratio of FET fabricated by bilayer SnSe₂ is up to 10^3 , compared with single digit ratio reported 84 nm-thick SnSe₂ based FET^[29] In the dark state, our device shows a typical behavior of n-type transistor and a threshold voltage of $V_t = 5 \text{ V}$. When we illuminated the biased device using a focused 633 nm laser, the dark current increased in the range of 10 nA. As a result, the photocurrent dominates over the tunneling currents and thermionic currents in the operating working range, indicating that the SnSe₂ FET is suitable for photodetector device.

2.5. The optoelectronic properties of bilayered SnSe₂ photodetector

We probed the bilayer SnSe₂ FET devices (Figure 6a and 6b) and their time-dependent photoresponse to laser excitation using a focused laser beam ($\lambda = 633 \text{ nm}$) and an illumination power of 4 mW. A parabolic mirror and micromechanical stage were used to localize the device. The spot size has a typical diameter of $\sim 0.5 \text{ mm}$, resulting in an estimated maximum illumination intensity of $\sim 0.64 \text{ W/cm}^2$. The time-dependent photocurrent measurement results are shown in Figure 6c and 6d. The photocurrent I_{ph} ($I_{ph} = I_{\text{illuminated}} - I_{\text{dark}}$) of SnSe₂ FET is about 10^5 nA corresponding to a photoresponsivity of $\sim 0.5 \text{ A/W}$ under a source–drain bias of 100 mV. The photocurrent can be further increased by applying a higher source–drain voltage, as shown in Figure 6d. The decay time can be fitted by the following equation:

$I_{rise} = I_0 - A \exp(-(t - t_1) / \tau_1)$ and $I_{decay} = I_0 + B \exp(-(t - t_2) / \tau_2)$,^[42] where τ is the time constant and t is the time when laser is switched on or off. I_{dark} is the dark current, and A is the scaling constant. The fitted characteristic photoresponse time coefficients, τ_1 and τ_2 , are 2.2 ± 0.3 ms (rise) and 3.2 ± 0.2 ms (fall), respectively, which is one of the fastest response times among all types of 2D photodetectors, e.g., 600 ms for 1L MoS₂,^[43] 5.3 ms for few layered WS₂,^[44] 6 ms for multilayer GaTe,^[16] 20 ms for multilayer GaSe,^[45] etc. On the other hand, the rise time and fall time can also be calculated by the time period between the 10% and 90% of the current in the arising and falling curves, as shown in Figure 6c. The rise time ($\tau_1 = 2.1$ ms) and fall time ($\tau_2 = 3.2$ ms) are consistent with the former fitted values. Further improvement of the mobility by dielectric engineering or decreasing the thickness of the SnSe₂ layer may further boost the response time. More importantly, due to the phase changing property of SnSe₂, the performance of the SnSe₂ photodetector can be improved by phase engineering analogous to MoS₂.^[46]

On the other hand, with the increasing of laser power, the photoresponse can be expressed by a power law $I_{PC} = CP^\gamma$ (C is a constant and P is the illumination power) as shown in Figure 6e. For the laser with the wavelength of 532 nm and 633 nm, γ is 0.90 and 0.82, respectively, indicating that the recombination kinetics of photocarriers involves both traps states and interactions between photogenerated carriers. The decrease of the photocurrent with the incident laser power can be attributed to the reduction of the numbers of photogenerated carriers available for extraction under high photon flux due to the Auger process or the saturation of recombination/trap states that influence the lifetime of the generated carriers.^{[47],[48]} **The Schottky junction formed at the metal–SnS₂ interfaces is also important to the photocurrent generation, which can be inferred from Figure 6f that a nonlinear effect is observed in the photocurrent generation with various bias voltage.** Considering the trade-off between response time and responsivity for typical materials used in photodetectors, our SnSe₂ based photodetector shows a relatively faster response time compared to other two-dimensional metal chalcogenides, but slower than that of graphene photodetector which has an ultrahigh mobility. The responsivity of SnSe₂ based photodetector is higher than these of graphene,^[49] WS₂^[44] and WSe₂,^[50] but still lower than these of MoS₂^{[43], [51]} and GaTe,^[16] which might be attributed to the lower light absorption efficiency and higher carriers scattering in SnSe₂ in the semiconductor channel.

3. Conclusion

The properties of few-layer and monolayer SnSe₂, a new 2D material whose components are both cheap and earth-abundant, have been firstly investigated systematically in this paper

using comprehensive characterization, device fabrication and measurement of electronic and optoelectronic device. We unambiguously identify monolayer and few-layer SnSe₂ by optical and atomic force microscope, whose monolayer thickness is ~0.87 nm. Moreover, combined with atomic force microscope, Raman spectra of monolayer and few-layer SnSe₂ have been studied, which show an obvious red shift for A_{1g} with the reduce of the layer number but no change for E_g. Electronic structure calculations indicate the bandgap is indirect from bulk to monolayer, consistent with the behavior observed in SnS₂ and contrast with MoS₂. We have successfully fabricated back-gated electronic and optoelectronic device based on bilayer SnSe₂ with thermal evaporated SiO₂ as dielectric layer, which exhibit a mobility up to 4 cm²V⁻¹s⁻¹ and on/off ratio of 10³ at room temperature and the dark state. Moreover, the bilayer SnSe₂ photodetector upon illumination of 633 nm laser displays a good responsivity of 0.5 AW⁻¹ and a very fast time response of 2.2 ± 0.3 ms (rise) and 3.2 ± 0.2 ms (fall), which make it also a promising 2D material for photodetection in the visible region.

4. Experimental Section

Synthesis and mechanical exfoliation of of SnSe₂ single crystals: Polycrystalline SnSe₂ was prepared by melting stoichiometric amounts of Sn powder (99.99 %, Sigma-Aldrich) and Se powder (99.995 %, Sigma-Aldrich), which were sealed in an evacuated quartz ampoule under vacuum at 10⁻⁶ Torr and then placed in one-zone tube furnace with the heating procedure: heated to 600 °C in 10 h, dwelt for 24 h, then naturally cooled to room temperature. The obtained sample, which is in the form of a shining polycrystalline mass, is the pure phase of SnSe₂ confirmed by powder X-ray diffraction (Figure S2). In order to obtain the high quality single crystals of SnSe₂, a direct transport method without the transport gas is applied due to the good volatility of SnSe₂ in vacuum. Prior to the growth of the single crystals, the SnSe₂ polycrystalline sample is grinded to the powder in a mortar and then sealed in a 23 cm-long quartz tube under vacuum 10⁻⁶ Torr. The quartz tube is placed in a two-zone furnace with the reaction zone at higher temperature 800 °C and the growth zone at a lower temperature 620 °C for three days. In this method, the shining black opaque single crystals of SnSe₂ is obtained in the growth zone (Figure 1c). Monolayer and few-layer SnSe₂ flakes were mechanically exfoliated from bulk SnSe₂ single crystals and transferred to a silicon substrate

with a 285 nm thick silica layer using the scotch tape-based mechanical exfoliation method, which was widely employed for preparation of monolayer graphene and transitional metal dichalcogenides (TMD).

Elemental Analysis: Semi-quantitative microprobe analyses on the single crystals of SnSe₂ were performed with the aid of a field emission scanning electron microscope (JSM-5410) equipped with an energy dispersive X-ray spectroscope (EDX, Oxford INCA). The energy dispersive spectra (EDS) taken on visibly clean surfaces of the sample proved the presence of Sn and Se with the formula SnSe_{1.96(2)} shown in Figure 1d.

Powder X-ray Diffraction: The powder XRD patterns were collected using a Rigaku DMAX 2500 diffractometer with monochromatized Cu-K α radiation at room temperature in the 2θ range of 10–85° with a scan step width of 0.05°. The measured X-ray powder diffraction patterns were in accordance with the calculated ones simulated from the single crystal data as shown in Figure S1.

TEM sample preparations and AD-STEM imaging and image simulations: The TEM sample was prepared by transferring the SnSe₂ flakes onto lacey-carbon grid after evaporating a drop of IPA solvent and etching away the underneath SiO₂ layer with potassium hydroxide solution. The as-prepared TEM membranes were briefly irradiated in TEM mode before ADF-STEM characterization. The ADF-STEM were done with a FEI Titan ChemiSTEM equipped with a probe corrector. This microscope was operated with an acceleration voltage of 80 kV. The convergent angle for illumination is about 22 mrad with a probe current of 70 pA, and the collection angle is about 43.4 to 200 mrad. ADF-STEM image simulations of pristine SnSe₂ were done with software STEMSIM.⁵¹ The input parameters were set according to the experiment conditions: collection angle is about 45 to 200 mrad, acceleration voltage and C3 is 80 kV and 1.5 μ m respectively. A Wiener and average background subtracted filter is applied to Figure 2a and 2d, based on R. Kilaas's work and developed by David Mitchell.

Thickness measurements: The thickness measurements of monolayer and few-layer were carried out in atomic force microscopy (DI-3100), which shows the thickness of monolayer SnSe₂ is 0.87 nm shown in Figure 3c.

Raman spectra: Analysis of atomically thin SnSe₂ flakes and bulk sample by Raman spectroscopy was carried out on a WITec CRM200 confocal Raman microscopy system with the excitation line of 532 nm and an air-cooling charge-coupled device (CCD) as the detector (WITec Instruments Corp, Germany).

Calculations of band structure of SnSe₂ from bulk to monolayer: The first-principles calculations are based on the generalized gradient approximation (GGA)^[53] using the projector augmented wave method^{[54], [55]} as implemented in the VASP package.^{[56], [57]} The kinetic energy cutoff of 500 eV was used, and the spin-orbit coupling was included in all the calculations. A vacuum layer of 15 Å was adopted to avoid interactions between neighboring layers for slab calculations. The numerical integration of the Brillouin zone was performed based on a $8 \times 8 \times 6$ k-point mesh-grid for 3D bulk SnSe₂ and a $8 \times 8 \times 1$ k-point mesh-grid for 2D SnSe₂.

The fabrication and measurements of the devices: The devices were fabricated by standard optical lithography and deposited Ti/Au (20 nm/80 nm) as contact electrodes using electron-beam evaporation. The final devices were annealed at 400 K for 2 h with the protection of nitrogen in order to remove resist residues and enhance the metallic contacts. Electrical characterization was performed by current–voltage measurements on a probe station using a semiconductor characterization system (Agilent, B1500A). Furthermore, the phototransistor performance were measured using a 633 nm laser.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Figure 1. Synthesis and morphologies of SnSe₂ bulk single crystals. (a) The structure of SnSe₂ with 0.62 nm of the thickness of monolayer, inset: SnSe₆ octahedron. (b) The synthesis process of SnSe₂ polycrystalline powder (up) and the growth process of SnSe₂ single crystals using vapor mass transport (VMT) technique without transport gas (down). (c) The optical image of SnSe₂ single crystals with the size of several millimeters. (d) EDX result of SnSe₂ single crystal.

Figure 2. Atomically resolved imaging of few layered SnSe₂. (a) SnSe₂ film dominated by Bi-layered SnSe₂. A small area of monolayer SnSe₂ is highlighted by the white rectangle. Inset is the corresponding Fast Fourier Transform (FFT) pattern. (b) A close-up of the monolayer area. The Sn-Sn bond with 0.37 nm, which fits to the crystal model in (c) and (d) very well.

Figure 3. The characterization of few-layer and monolayer SnSe₂. (a) Optical image of SnSe₂ flake placed on the surface of a silicon wafer capped by 285-nm-thick silicon dioxide. (b) Raman mapping image of the blue region in (a), which clearly displays the monolayer. (c) The thickness of monolayer SnSe₂, inset: AFM image of the different thick sample. (d) Normalized Raman spectra of SnSe₂ from monolayer to bulk. The intensity of Si peak is set as constant. (e) The Raman intensity ratio of Si/A_{1g} and Si/E_g with the dependence of the various thick layers. The inset in Figure 3d and 3e is the schematics of displacement of atom for Raman active A_{1g} and E_g modes in SnSe₂.

Figure 4. The calculated electronic band structures of SnSe₂ with the spin-orbit couple (SOC) from bulk to monolayer. (a) The Brillouin zone of SnSe₂. (b)–(d) The band structures of bulk (b), bilayer (c) and monolayer (d). The indirect band gaps of bulk and, bilayer, and monolayer SnSe₂ are 0.710, 0.759 and 0.969 eV, respectively.

Figure 5. The electrical property of the fabricated SnSe₂ bilayer FET. (a) Optical microscopy image of a bilayer SnSe₂ FET device with Ti/Au as the electrodes on Si/SiO₂ substrate. The scale bar is 20 μm. The white-color dashed line indicates the sample area. (b) Current–voltage (I_d – V_d) curve acquired with different gate voltages (without light illumination). (c) Gating response (I_d – V_g) of the SnSe₂ FET acquired for a backgate voltage V_g between –80 V and 80 V with a source–drain voltage (V_{S-D}) of 0.1 V (without light illumination). (d) Gating response (I_d – V_g) of the SnSe₂ transistor in dark and illuminated states. The illumination intensity is 500 W/cm².

Figure 6. The optoelectronic properties of the fabricated SnSe₂ bilayer device. (a) Schematic representation of the photodetector device consisting of a bi-layered SnSe₂ on SiO₂/Si wafer with laser illumination. (b) Time-resolved photoresponse of the device recorded for a bias voltage of 0.1 V and zero gate voltage. (c) Photocurrent dynamics of one period of the time-resolved photoresponse. The laser used in Figure 6b and 6c is 633 nm laser with a power of 4 mW. (d) Time-resolved photoresponse of the device recorded for different source-drain voltages varying from 0.1 V to 0.7 V at a step of 0.2 V with 633 nm laser illumination (4 mW). (e) Power dependences of the photocurrent with 532 nm and 633 nm laser illumination recorded at $V_{SD} = 0.1$ V. (f) Photocurrent response-bias characteristic of the device under 632 nm laser illumination with power of 4 mW.

ToC figure