SnSe$_2$ Field-Effect Transistor with High On/Off Ratio and Polarity-Switchable Photoconductivity

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Abstract

SnSe$_2$ field-effect transistor was fabricated based on exfoliated few-layered SnSe$_2$ flake, and its electrical and photoelectric properties have been investigated in detail. With the help of a drop of de-ionized (DI) water, the SnSe$_2$ FET can achieve an on/off ratio as high as ~ $10^4$ within 1 V bias, which is ever extremely difficult for SnSe$_2$ due to its ultrahigh carrier density (10$^{18}$/cm$^3$). Moreover, the subthreshold swing and mobility are both improved to $\sim 62$ mV/decade and $\sim 127$ cm$^2$/V$^{-1}$s$^{-1}$ at 300 K, which results from the efficient screening by the liquid dielectric gate. Interestingly, the SnSe$_2$ FET exhibits a gate bias-dependent photoconductivity, in which a competition between the carrier concentration and the mobility under illumination plays a key role in determining the polarity of photoconductivity.

Keywords: Field-effect transistor, SnSe$_2$, Photoconductivity, On/off ratio

Introduction

Due to the quantum confinement effect, two-dimensional (2D) atomically layered materials (ALMs) behave very differently from their 3D bulk counterparts, exhibiting some unique and fascinating electronic, optical, chemical, magnetic, and thermal properties [1]. 2D ALMs provide an attracting platform for fundamental physical and chemical research at the limit of a single atom or few-layer thickness. Moreover, ALMs could be flexibly integrated with other devices, offering a bigger room or freedom to develop novel functions beyond the reach of the existing materials. Over the past decade, the 2D ALMs have been widely investigated and found potential applications in fields such as sensors, energy, and environment [2, 3].

Recently, as an important member of the IV-VI group, tin diselenide (SnSe$_2$) has drawn much attention. SnSe$_2$ has a hexagonal CdI$_2$-type crystal structure, in which the Sn atoms are sandwiched by two layers of hexagonally packed Se atoms with space group p$\overline{1}$2$_1$3m1 [4]. Unlike transitional metal dichalcogenides (TMDs), SnSe$_2$ possesses a narrower bandgap with indirect band gap characteristic within the entire thickness range from the bulk to the monolayer, resulting from outer p electrons of Sn involved in the structural bonding unlike d electrons of Mo or W in MoS$_2$ or WS$_2$ [5]. SnSe$_2$ has been investigated to have excellent properties in thermoelectrics, phase change memory, lithium-ion batteries, and various electronic logic devices [4, 6–9]. Especially, SnSe$_2$ has a higher electron affinity (5.2 eV) and therefore has a special application in fabricating tunneling field-effect transistors (FETs) [9–11]. Pan et al. systematically investigated FETs based on mechanically exfoliated SnS$_2$ – $x$Se$_x$ crystals with varying selenium content [12]. They found that the drain-source current ($I_d$) cannot be completely turned off with the Se content reaching $x = 1.2$ or above. Later Su et al. have fabricated a SnSe$_2$ MOSFET with high drive current (160 $\mu$A/ $\mu$m) at 300 K with the same result of no “OFF” state [13]. The main reason for the difficulty in obtaining “OFF” state of SnSe$_2$ FET device is the ultrahigh electron density (10$^{18}$ cm$^{-3}$ in bulk SnSe$_2$, compared with 10$^{16}$ cm$^{-3}$ in MoS$_2$) [14, 15]. Therefore, effective modulation of transport of carriers in SnSe$_2$ FETs is a challenging job. Bao et al. successfully turned off $I_d$ and obtained an on/off ratio of 10$^8$ at room temperature when using HfO$_2$ as a back gate combined with a top capping layer of polymer...
electrolyte. However, the performance of SnSe₂ cannot survive several screenings due to the irreversible structural transition caused by Li⁺ intercalation into the interlayer of SnSe₂ [16]. Guo et al. achieved a higher current on/off ratio of 10⁵ with a threshold voltage of ~100 V by thinning the SnSe₂ flake to 6.6 nm [17]. However, the working temperature is only 78 K, which is not convenient for practical application. An alternative way to enhance the modulation of the transport of carriers in FETs is to deposit a high-k dielectric layer as a top gate, such as HfO₂ and Al₂O₃ [18, 19]. However, the high deposition temperature will change the properties of SnSe₂ layer and further deteriorate the device performance. Employing a solid polymer electrolyte to modulate the carrier density is an attractive method owing to the highly efficient control of the electric double layer (EDL) formed at the interface between the electrolyte and the semiconductor [20–22]. But sluggish ionic migration process requires low-bias screening rates to match. So, a simple, efficient, and practical method to modulate the carriers of SnSe₂ is highly demanding.

In this work, we employed only a drop of de-ionized (DI) water as a solution top gate and successfully switched off the channel current at 300 K. Moreover the on/off ratio could reach ~ 4 orders controlled by a small gate voltage of less than 1 V. More strikingly, the SnSe₂ device exhibits an interesting bias-dependent negative and positive photoconductivity, in which the possible working mechanism has been analyzed.

**Experiments**

The SnSe₂ flake was obtained from high-quality bulk crystals by mechanical exfoliation. Then, it was transferred onto a Si wafer covered with 100 nm SiO₂. The detailed exfoliation and transfer method is described in Huang’s paper [23]. After the transfer, optical microscopy was used to identify selected flakes, and the accurate thickness was measured by atomic force microscopy. The SnSe₂ FETs were fabricated by a standard photolithography. Ti/Au (5/50 nm) contact was deposited by thermal evaporator, followed by in situ annealing at 200 °C in high vacuum (10⁻⁵ Pa) to improve the metallic contact. For DI water top-gated FETs, an additional polymer layer (polymethyl methacrylate (PMMA) type 950 A5) was deposited on the devices (spin coating at 3000 rpm, thickness ~400 nm), baked at 180 °C for 2 mins, and patterned by UV photolithography to open windows for contact between the water drop and the device channel.

Electrical characterization was performed by a Keithley sourcemeter 2634B on a four-probe station (Signatone). A laser diode with a wavelength of 532 nm was employed as a light source with a power density of 1 mW/mm² to examine the photoelectric performance of SnSe₂ FET. The time response was recorded by an oscilloscope MDO3000.

Optical images were obtained using an optical microscope (XTZ-2030JX with a CCD camera). Raman spectrum was performed in the Renishaw in Via Raman Microscope at room temperature with 532-nm laser excitation. AFM characterization was taken by a microscope of Bruker Multimode 8.

**Results and Discussion**

Figure 1a shows a schematic diagram of SnSe₂ FET device. The contacts are covered by a layer of PMMA (type 950 A5) to electrically isolate them from the top gate, which consists of a drop of DI water droplet from a pipette. The device can be gated by a top gate voltage (Vtg) applied to an electrode in contact with the DI water drop or by a back gate voltage (Vbg) applied via the SiO₂ support. The optical image of SnSe₂ flakes with patterned electrodes is shown in Fig. 1b. The source-drain gap is about 2 μm. Raman spectroscopy was used to characterize SnSe₂ material, as shown in Fig. 1c. The fingerprint peaks at 187 cm⁻¹ and 112 cm⁻¹ corresponds to the out-of-plane A₁g mode and in-plane E₁g mode, respectively, which agrees well with others’ reports. However, it is difficult to determine the thickness for SnSe₂ from the position of Raman peak. Unlike MoS₂, the thickness-dependent characteristic of Raman peak position is not clear [24–26]. So, we adopted atomic force microscopy (AFM) to measure the flake thickness directly. As shown in Fig. 1d, the thickness of SnSe₂ flake is about 34 nm.

The output curve of the FET device under different back gate voltages measured in the dark is shown in Fig. 2a. The linear and symmetric relationship of I_d–V_ds demonstrates an ohmic contact between the Ti/Au electrodes and the SnSe₂ channel. From Fig. 2a, we found that the modulation effect of the conductivity of SnSe₂ by back gate voltage is very slight. The ratio of I_d between gate voltage 30 and ~30 V is only 1.15 at V_ds of 50 mV. The current I_d at the back gate voltage of ~30 V is as large as ~1.47 μA at V_ds of 5 mV, which could not be turned off by back gate voltage. Even increasing the large gate voltage up to 100 V still did not bring the channel into its off state as a result of screening of gated potential by the ultrahigh carriers density in the SnSe₂, which has been reported in previous Pan’s and Su’s work [12, 13]. According to the semiconductor theory, we can make a rough estimation on the depletion width W of a metal-insulator-semiconductor (MIS) structure, which is determined by $W = \left(\frac{2eND\varepsilon_0V_{tg}}{\varepsilon_r\varphi_s}\right)^{1/2}$, where $\varphi_s$ is the surface potential, $N_D$ the donor impurity concentration, and $\varepsilon_0$ and $\varepsilon_r$ vacuum and relative permittivity, respectively. Taking $\varphi_s$, $\varepsilon_r$, $N_D$ of 1 V, 9.97, and $1 \times 10^{18}$/cm³ into the
equation as a conservative calculation, the depletion width $W$ is about 22 nm, which is much smaller than the thickness of our SnSe$_2$ flake (34 nm). So, it is easy to understand no depletion of the electrons by the back gate modulation.

In striking contrast, when using DI water as top gate, the $I_{d}-V_{ds}$ curve exhibits an efficient modulation even with a small gate bias, as shown in Fig. 2b. The current ratio between gate voltages of 0.4 V and $-0.8$ V is more than $10^3$, which is more clearly seen from Fig. 2c drawn in a semi-log scale. The transfer curves about SnSe$_2$ FET with top gate are shown in Fig. 2d, which shows a typical n-type conductive behavior. The voltage scans from the negative direction to the positive direction with a scanning rate of 10 mV/s. Electric double layer (EDL) in ionic liquid or solid electrolyte possesses a high capacitance and can be used to achieve a very efficient charge coupling in 2D and layered materials. However, slow charge transfer processes due to the large ions in size and mass require low-bias scan rates to maintain equilibrium at the gate-channel interface. In contrast, when using DI water as a dielectric layer, both the H$^+$ and OH$^-$ ions have smaller size and mass and water has a low viscosity. Therefore, DI water gating via the double layer at the water-semiconductor interface supports much higher voltage sweep rates and responds faster than ionic liquids gating or solid electrolyte gating. The inset is a linearly scaled plot of $I_{d}-V_{tg}$ characteristic. Notably, DI water as a top gate greatly enhances transconductance characteristics of the SnSe$_2$ FET. As $V_{tg}$ varies from $-0.8$ to 0.4 V, $I_d$ changes from $9.5 \times 10^{-11}$ to $7.6 \times 10^{-7}$ A with an on/off current ratio of $\sim 10^4$. The subthreshold swing calculated from the transfer characteristic is $\sim 62$ mV/decade. These values are good enough for practical, low-voltage operation of layered metal chalcogenide FETs devices. The mobility $\mu$ can be calculated using the following equation: $\mu = \frac{dI_d}{dV_g} \cdot \frac{L}{W \cdot C_{H_2O} V_{tg}}$, where $L$ and $W$ are the channel length and width ($L = 2 \mu m$, $W = 5 \mu m$), respectively, and $C_{H_2O}$ is the DI water gate-circuit capacitance per unit area. Here, the capacitance of $C_{H_2O}$ was measured to be $348 \text{ nF/cm}^2$, for which the detailed calculation is attached in the supplementary material.
The obtained electron mobility is 127 cm²/Vs, which is quite good compared with other few-layered 2D materials. The substantially improved modulation effect realized by top gate with DI water as a dielectric layer has ever been reported in Huang’s work [27]. They applied DI water gate on the SnS₂, MoS₂, and BP flake and achieved a high on/off ratio, ideal subthreshold swing and excellent mobility. They attributed these improvements to perfectly shield the flake from the ambient adsorbates and passivation of the interface states by the high-k dielectric (εᵣ(H₂O) = 80). The passivation and screening effect provided by DI water is similar to that by other conventional high dielectric materials, like HfO₂ or Al₂O₃ [18, 19]. In addition, the effective coupling between the DI water and the SnSe₂ through the flake edges seems to play an important role in achieving a high on/off ratio even for a thick flake. Compared with SiO₂ back gating, DI water gating can effectively reduce the electrical field distance (from few 100 nm to less than 1 nm), so the threshold gate voltage also decreased from several tens of volts to less than 1 V. From the inset image of Fig. 2d, the little current jump at about Vᵗ₉ = 0.4 V is possibly caused by the electrolysis of DI water due to its narrow electrochemical window, which has been reported in Huang’s work [27].

The time-dependent photoelectric response of the SnSe₂ FET controlled by back or top gating is shown in Fig. 3. Interestingly, the SnSe₂ FET shows a positive photocurrent at a negative gating and a negative photocurrent at a positive gating regardless of gating from back gate via SiO₂ or from top gate through DI water. From Fig. 3a, we can see the magnitude of photocurrent increases with increasing the negative back gate voltage. When the back gate voltage is −80 V, the relative photocconductivity (defined as Δσ/σ₀, where σ₀ is the dark conductivity and Δσ is the difference between σ and σ₀) is 5%. When using DI water as a top gate, we get a similar law as shown in Fig. 3b. With the top gate voltage setting as −0.4 V, the relative photocconductivity could

**Fig. 2** Output and transfer characteristic of SnSe₂ FET measured in the dark. Iₜ versus Vₛḍ characteristic of SnSe₂ FET gated at different back gating voltages Vᵱᵣ (a), at different top gating voltages Vᵱₑ in a linear scale (b), and at different Vᵱₑ in a semi-log scale (c). Iₜ versus Vᵱₑ characteristic of SnSe₂ FET with Vₛḍ ranging from 2 mV to 10 mV in steps of 2 mV drawn in a semi-log scale, the inset is a linearly-scaled plot of Iₜ-Vᵱₑ characteristic (d).
reach 6%. However, it is easily to see that the response time between the two kinds of gating is quite different. For back gating with SiO$_2$ as dielectric, the response time for the rise edge is about 30 s. While for top gating with DI water as dielectric, the response time is only 1.7 s. Here, the 10–90% rise time (or 10–90% fall time) is defined as the response time. The much quicker response speed with DI water gating should be related to the higher carrier mobility (127 cm$^2$/Vs) due to the effective screening of impurity or adsorbates scattering.

Interestingly, when the gate voltage is positive, the SnSe$_2$ film exhibits a negative photoconductivity (NPC) as shown in Fig. 3c and d. It should be emphasized that the gate-dependent bipolar photoconductivity is not induced by the leakage current between the gate and the source. We measured the leakage current of $I_g$ when applying a positive or negative gate bias, as shown in Additional file 1: Figure S2. The sign of $I_g$ follows the direction of $V_{gs}$ and is just exactly contrary to the sign of drain-to-source photocurrent ($I_d$). Moreover, the magnitude of $I_g$ is much smaller than $I_d$, so its impact can be ignored. In NPC of SnSe$_2$ FET with H$_2$O as dielectric, there are two features which are distinct from positive photoconductivity (PPC). One is the absolute value of the relative photoconductivity gating at positive $V_{tg}$ (~20%) is eminently greater than that gating at negative $V_{tg}$ (6%). The other is the SnSe$_2$ FET exhibits a much longer response time (~30 s) at positive $V_{tg}$ than that at negative $V_{tg}$ (1.7 s).

The negative photoconductivity (NPC) phenomenon has been reported in several semiconductor nanostructures, such as carbon nanotube, InAs nanowire, and ZnSe nanowire [28–30]. Oxygen molecular adsorption and photo-desorption are usually suggested to be responsible for NPC effect. However, such an explanation does not apply to our SnSe$_2$ system, as oxygen desorption would only lead to higher electron concentration and conductivity. In order to understand NPC effect and the coexistence of NPC and PPC in SnSe$_2$, we measured the $I_d$-$V_{tg}$ curves of SnSe$_2$ FET under illumination, as shown in Fig. 4. For a clear comparison, the transfer curves in the dark are also added in. We can see the
device exhibits a bipolar photoconductivity, which can be switched by gate voltage. The transfer curves measured under illumination and in the dark intersect almost at a gate voltage of 0 V. Therefore, the device shows a positive photoconductivity at a minus gate bias and a negative photoconductivity at a plus gate bias, which is in agreement with the results shown in Fig. 3. As is well known, the conductivity \( \sigma \) is determined as \( \sigma = ne\mu \), where \( n \), \( e \), and \( \mu \) are carrier concentration, electron charge, and mobility, respectively. So, the conductivity is determined by the product of carrier concentration and mobility. In transfer curve under light, the change of transconductance \( g_m \) across the zero gate voltage implies an alteration of mobility. From the transfer curves, the mobility of illumination and dark can be calculated as shown in Tables 1 and 2. The mobility of SnSe_2 in the dark is about 70 cm^2/Vs, while the mobility under illumination has two values: about 60 cm^2/Vs at minus gate bias and ~ 4 cm^2/Vs at plus gate bias. At negative \( V_{tg} \), the mobility of the light and dark state is almost the same, while the carrier concentration under light excitation is larger than that of dark state. So, the device exhibits a positive photoconductivity. At positive \( V_{tg} \), the mobility is more than one order smaller than that in the case of negative \( V_{tg} \), and the decrease in mobility exceeds the increase in carrier concentration and dominates the photoconductivity evolution. Thus, a net negative photoconductivity occurs in replace of the positive photoconductivity.

Pai-Chun Wei et al. found NPC effect in a small band gap and degenerate InN film and ascribed it to the depression of the mobility caused by severe scattering from the charged recombination centers [31], which may be applied to our SnSe_2 system. But why the mobility decreases when the gating bias scans from the negative to the positive voltage is not clear. We believe this phenomenon originates from some in-gap states. The in-gap states can be caused by some point defects, such as Se vacancies. Under illumination, the in-gap states below \( E_f \) will trap some photogenerated holes and become positively charged scattering centers. With \( V_{tg} \) scanning from the negative to the positive bias, more in-gap states dropping below \( E_f \) become charged scattering centers, leading to a decline of mobility. Further work is needed to fully understand the mechanism of NPC.

**Conclusions**

In summary, SnSe_2 field-effect transistor (FET) has been fabricated based on SnSe_2 flake exfoliated from single crystal. With a drop of water as a top dielectric gate, we successfully turned off the device with a high current rejection ratio of \( \sim 10^4 \). Compared with SiO_2 dielectric gate, the DI water can eminently improve the transport behavior of SnSe_2 FET with an ideal subthreshold swing of \( \sim 62 \text{ mV/decade} \) and an excellent electron mobility of \( \sim 127 \text{ cm}^2/\text{Vs} \) at 300 K. Especially, the SnSe_2 FET exhibits bipolar photoconductivity when the top gate bias scans from \(-0.4 \) to \(+0.4 \) V. The polarity could be switched by the sign of gate voltage. At a negative gate bias, the positive photoconductivity is dominated by the increase in carrier concentration. While at a positive bias, the negative photoconductivity is caused by a sharp drop of mobility. A competition between the carrier concentration and the mobility determines the evolution of photoconductivity. With a facile solution gate method presented in this work, the SnSe_2 FET demonstrates excellent electric properties and at the same time presents an interesting polarity-switchable photoconductivity, which will open up a new modulate way for high-performance optoelectronic devices.

**Table 1** The mobility of SnSe_2 FET with top gating measured in the dark

| \( V_{tg} \) (V) | \( g_m \) (S) | \( \mu \) (cm^2/Vs) |
|------------------|--------------|-----------------|
| 0.005            | 2.98E−07     | 68.56           |
| 0.01             | 5.84E−07     | 67.08           |
| 0.015            | 8.81E−07     | 67.48           |
| 0.02             | 1.15E−06     | 65.93           |

**Table 2** The mobility of SnSe_2 FET with top gating measured under illumination

| \( V_{tg} \) (V) | \( g_m \) (S) | \( \mu \) (cm^2/Vs) |
|------------------|--------------|-----------------|
| \( V_{sd} \) (V) | \( g_m \) (S) | \( \mu \) (cm^2/Vs) |
| 0.005            | 2.26E−07     | 52.02           |
| 0.01             | 4.76E−07     | 54.74           |
| 0.015            | 7.32E−07     | 56.09           |
| 0.02             | 9.88E−07     | 56.78           |

negative photoconductivity occurs in replace of the positive photoconductivity.
Additional file

**Additional file 1**: Supplementary material for details about calculation of capacitance with DI water as dielectric material and experimental results of leakage current measurements. Figure S1 (a) \( V_g \) versus \( V_{GS} \) of SnSe\(_2\) FET biased at different \( V_{DS} \) (b) \( V_{GS} \) versus \( V_{DS} \) derived from \( I_D = 240 \) nA. The red line is a linear fit to the data. Figure S2 Leakage current \( I_L \) of SnSe\(_2\) FET gated at \(+V_{GS}\) (a) and at \(-V_{GS}\) (b). (DOCK 249 kb)

**Abbreviations**

2D: Two-dimensional; AFM: Atomic force microscopy; ALWs: Atomically layered materials; DI: De-ionized; FETs: Field-effect transistors; MIS: Metal-insulator- semiconductor; NPC: Negative photoconductivity; PMMA: Polymethyl methacrylate; PPC: Positive photoconductivity; TMDs: Transitional metal dichalcogenides

**Funding**

This work has been supported by the National Natural Science Foundation of China (Grant Nos. 11104255 and 11874405) and Fundamental Research Funds for the Central Universities.

**Availability of Data and Materials**

The datasets used in the current study are available from the corresponding author on reasonable request.

**Authors’ Contributions**

XJ, HY, and XH initiated the research and analyzed the experimental data. XH, HY, HX, and DJY worked on the exfoliation, device fabrication, and characterization. XJ, HY, and XH initiated the research and analyzed the experimental data. XJ, HY, HC, HHY, DJJ, and LH discussed the experimental results. XJ wrote the manuscript. All authors read and approved the final manuscript.

**Competing Interests**

The authors declare that they have no competing interests.

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Received: 8 November 2018 Accepted: 2 January 2019
Published online: 09 January 2019

**References**

1. Tan CL, Cao XH, Wu XJ, He QY, Yang J, Zhang X, Chen JZ, Zhao W, Han SK, Nam GH, Sindoro M, Zhang H (2017) Recent advances in ultrathin two- dimensional nanomaterials. Chem Rev 117:6225–6331.

2. Jariwala D, Sangwan VK, Lauhon LJ, Marks TJ, Hersam MC (2014) Emerging dimensional nanomaterials. Chem Rev 117:6225–6263.

3. Tan P, Chen X, Wu L, Shang YY, Liu WW, Pan J, Xiong X (2017) Hierarchical flower-like SnSe\(_2\) supported Ag\(_2\)PO\(_4\) nanoparticles: towards visible light driven photocatalyst with enhanced performance. Appl Catal B-Environ 202:326–334.

4. Sun BZ, Ma Z, He C, Wu KC (2015) Anisotropic thermoelectric properties of layered compounds in Sn\(_x\)Te\(_{1-x}\) (X = S, Se): a promising thermoelectric material. Phys Chem Chem Phys 17:29844–29853.

5. Huang Y, Sutter E, Sadowski JT, Cotlet M, Monti OLA, Racke DA, Neupane MR, Wickramaratne D, Lake RK, Parkinson BA, Sutter P (2014) Thin disulfide-an emerging layered metal dichalcogenide semiconductor: materials properties and device characteristics. ACS Nano 8:10743–10753.

6. Wang RY, Caldwell MA, Jeyasinge RG, Aloni S, Sheby RM, Wong HSP, Milliron DJ (2011) Electronic and optical switching of solution-phase deposited SnSe\(_2\), phase change memory material. J Appl Phys 109:240.

7. Lee L, Chen CW, Manikanad A, Lee SH, Wang ZM, Chueh YL (2018) Phase-engineered SnSe\(_2\) toward SnSe\(_2\)/SnSe\(_2\) heterostructure with improved thermal conductance by a low-temperature plasma-assisted chemical vapor reaction. Nano Energy 44:419–429.

8. Zhang F, Xia C, Zhu J, Ahmed B, Liang H, Velusamy DB, Schwingenschlogl U, Alshareef HN (2016) SnSe\(_2\): 2D anodes for advanced sodium ion batteries. Adv Energy Mater 6:16001188.

9. Yan X, Liu C, Li C, Bao WZ, Ding SJ, Zhang DW, Zhou P (2017) Tunable SnSe\(_2\)/WSe\(_2\) heterostructure tunneling field-effect transistor. Nano Lett 17:3348–3354.

10. Roy T, Tosum M, Heitck M, Ahn GH, Hu C, Lavey A (2016) 2D–2D tunneling field-effect transistors using WSe\(_2\)/SnSe\(_2\) heterostructures. Appl Phys Lett 108:437–439.

11. Yan R, Fathipour S, Han Y, Song B, Xiao S, Li M, Ma N, Protasenko V, Muller DA, Jena D, Xing HG (2015) Elaki diodes in van der waals heterojunctions with broken-gap energy band alignment. Nano Lett 15:5791–5796.

12. Pan TS, De D, Marrongodo J, Guloy AH, Hadjiev YG, Lin Y, Peng HB (2013) Field effect transistors with layered two-dimensional Sn\(_2\)Se\(_2\) conduction channels: effects of selenium substitution. Appl Phys Lett 103:666–666.

13. Su Y, Ebris MA, Olson EJ, Koester SJ (2013) SnSe\(_2\) field-effect transistors with high drive current. Appl Phys Lett 103:8983.

14. Likhiter AI, Pel EG, Pryazhnyuk SI (1972) Electrical properties of tin diselenide under pressure. Phys Stat Sol 1(a):1426–5270.

15. D’Ambra DM, Marzil IV, Kershaw R, Baglio T, Dwight K, Wold A (1985) Preparation and electronic properties of MoS\(_2\) and WS\(_2\): single crystals grown in the presence of cobalt. J Solid State Chem 57:351–356.

16. Pei TF, Bao LH, Wang GC, Ma RS, Yang HF, Li JJ, Gu CZ, Pantelides S, Du SX, Gao HJ (2016) Few-layer SnSe\(_2\) transistors with high on/off ratios. Appl Phys Lett 108:10451.

17. Guo CL, Tan Z, Xiao YJ, Mi QX, Yue JH (2016) Field-effect transistors of high-mobility few-layer SnSe\(_2\). Appl Phys Lett 109:9202.

18. Radisavljevic B, Radenovic A, Brivio J, Giacometti V, Kis A (2010) Single-layer MoS\(_2\) transistors. Nat Nanotechnol 6:147–150.

19. Kim S, Konar A, Hwang W, Lee JH, Lee J, Yang J, Jung C, Kim H, Yoo J, Choi J, Jin YW, Lee SY, Jena D, Choi W, Kim K (2012) High-mobility and low-power thin-film transistors based on multilayer MoS\(_2\) crystals. Nat Commun 3:1011.

20. Eferov DK, Kim P (2010) Controlling electron-photon interactions in graphene at ultra high carrier densities. Phys Rev Lett 105:256805.

21. Xu HL, Fathipour S, Kinder EW, Seabaugh AC, Fullerton-Shirey SK (2015) Reconfigurable ion gating of 2H-Mo\(_2\)Te\(_2\) field-effect transistors using poly (ethylene oxide)-CsClO\(_4\) solid polymer electrolyte. ACS Nano 5:4900–4901.

22. Xu K, Lu H, Kinder EW, Seabaugh A, Fullerton-Shirey SK (2017) Monolayer solid-state electrolyte for double layer gating of graphene field-effect transistors. ACS Nano 11:5453–5464.

23. Huang Y, Sutter E, Shi NN, Zheng J, Yang T, Englund D, Gao H, Sutter P (2015) Reliable exfoliation of large-area high-quality flakes of graphene and other two-dimensional materials. ACS Nano 9:10612–10620.

24. Li H, Zhang Q, Yap CCR, Edwin THT, Olivier A, Baillargeat D (2012) From bulk to monolayer MoS\(_2\) evolution of Raman scattering. Adv Funct Mater 22:1385–1390.

25. Gonzalez JM, Oleynik II (2016) Layer-dependent properties of SnSe\(_2\) and SnSe\(_2\) novel two-dimensional materials. Phys Rev B 94:125443.

26. Zhou W, Yu ZH, Song H, Fang RY, Wu ZT, Li L, N ZH, Ren W, Wang L, Ruan SC (2017) Lattice dynamics in monolayer and few-layer SnSe\(_2\). Phys Rev B 96:035401.

27. Huang Y, Sutter E, Wu LM, Xu H, Bao LH, Gao HJ, Zhou XJ, Sutter P (2018) Thick layered semiconductor devices with water top-gates: high on-off ratio field-effect transistors and aqueous sensors. ACS Appl Mater Interfaces 10:23198–23207.

28. Zhu JL, Zhang G, Wei J, Sun J (2012) Negative and positive photoconductivity modulated by light wavelengths in carbon nanotube film. Appl Phys Lett 101:46.

29. Han YX, Zheng X, Fu MQ, Pan D, Li X, Guo Y, Zhao JH, Chen Q (2016) Negative photoconductivity of InAs nanowires. Phys Chem Chem Phys 18:818–826.

30. Zhang XW, Jie JS, Wang Z, Wu CY, Wang L, Peng Q, Yu YQ, Jiang P, Xie C (2011) Surface induced negative photodconductivity in n-type ZnSeBi nanowires and their nano-optoelectronic applications. J Mater Chem 21:6736–6741.

31. Wei PC, Chattopadhyay S, Yang MD, Tong SC, Shen JL, Lu CY, Shih HC, Chen LC, Chen KH (2010) Room-temperature negative photoconductivity in degenerate In thin films with a supergap excitation. Phys Rev B 81:1718–1720.