



Cite this: *J. Mater. Chem. C*, 2022,  
10, 13753

Received 4th April 2022,  
Accepted 15th June 2022

DOI: 10.1039/d2tc01340a

[rsc.li/materials-c](http://rsc.li/materials-c)

**Due to the intriguing optical and electronic properties, 2D materials are promising for next generation optoelectronic and electric device applications. Exploring new 2D materials with novel physical properties is rewarding for this area. In this work, we systematically investigated the optoelectronic properties of 2D metal thiophosphate  $\text{SnP}_2\text{S}_6$  with a unique nanoporous structure. The intermediate band-gap makes  $\text{SnP}_2\text{S}_6$  a good candidate for both the channel and gate dielectric materials in the transistor device.  $\text{SnP}_2\text{S}_6$  showed good photoresponse properties. In addition, the  $\text{MoS}_2$  transistor with  $\text{SnP}_2\text{S}_6$  as a dielectric layer showed a high dielectric constant ( $\approx 23$ ) and a low subthreshold slope down to  $69.4 \text{ mV dec}^{-1}$ , and it presented  $0.1 \text{ pA}$  scale leakage current, a threshold voltage as low as  $1.1 \text{ V}$ , an ON/OFF ratio reaching  $10^7$  and negligible hysteresis with high stability and reproducibility. This work could open up new avenues for the discovery of new metal thiophosphate systems for future device applications.**

## 2D semiconductor $\text{SnP}_2\text{S}_6$ as a new dielectric material for 2D electronics<sup>†</sup>

JIAYI HU,<sup>‡,ab</sup> ANQI ZHENG,<sup>‡,b</sup> ER PAN,<sup>b</sup> JIANGANG CHEN,<sup>b</sup> RENJI BIAN,<sup>b</sup> JINYAO LI,<sup>c</sup> QING LIU,<sup>\*,b</sup> GUIMING CAO,<sup>\*,b</sup> PENG MENG,<sup>b</sup> XIAN JIAN,<sup>ID,ac</sup> ALEXANDER MOLNAR,<sup>d</sup> YULIAN VYSOCHANSKII,<sup>ID,\*,d</sup> and FUCAI LIU,<sup>ID,\*,ab</sup>

on 2D materials are developed and studied, and this is still an active research field today.<sup>5–7</sup> The rapid development of 2D materials is beneficial for the discovery of novel 2D materials with exotic physical properties. For example, the discovery of 2D  $\text{CuInP}_2\text{S}_6$  brings 2D ferroelectricity and the related device application to the center of the ferroelectric transistor and memory device field. The isolation of layered  $\text{CrI}_3$  enables truly 2D ferromagnetic properties, attracting a lot of attention in the study of 2D magnetism. Layered ternary compounds such as  $\text{Ta}_2\text{PdS}_6$ ,<sup>8</sup>  $\text{In}_2\text{P}_3\text{S}_9$ ,<sup>9</sup> and  $\text{Bi}_2\text{O}_2\text{Se}$ <sup>10,11</sup> also provide new opportunities for the electronic and optoelectronic performance improvement for 2D material applications. There exist huge potential, opportunities and challenges for exploring new 2D material systems for application in future nanoelectronics and optoelectronics.<sup>12,13</sup>

For dielectric applications,  $\text{SiO}_2$  is used as a dielectric layer typically, but traditional silicon-based field effect transistors (FETs) face various challenges when the device scales down to nanometer regime, the most prominent ones of which are reduced mobility and increased short-channel effects.<sup>14</sup> In order to mitigate these problems, novel dielectrics with remarkable

## Introduction

The emergence of two-dimensional materials has brought new opportunities to the scientific and industrial fields. The quantum confinement effect in the thickness direction of two-dimensional materials is prominent, demonstrating the advantages of high carrier mobility, channel regulation capability and rich properties in force, heat, sound, light, electricity and magnetism.<sup>1–4</sup> As a result, novel electronic and optoelectronic devices based

<sup>a</sup> Yangtze Delta Region Institute (Huzhou), University of Electronic Science and Technology of China, Huzhou, 313099, China. E-mail: [fucailiu@uestc.edu.cn](mailto:fucailiu@uestc.edu.cn)

<sup>b</sup> School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China.

E-mail: [liuqing19@uestc.edu.cn](mailto:liuqing19@uestc.edu.cn), [guimingcao@163.com](mailto:guimingcao@163.com)

<sup>c</sup> School of Materials and Energy, University of Electronic Science and Technology of China, Chengdu, 611731, China

<sup>d</sup> Institute for Solid State Physics and Chemistry, Uzhhorod University, Uzhhorod, Ukraine

† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d2tc01340a>

‡ These authors contributed equally.



Fucai Liu

Dr Fucai Liu is a full professor at the University of Electronic Science and Technology China. He received his PhD degree and BSc degree from Nankai University China. After graduation, he worked as a postdoc at Tohoku University Japan, and Nanyang Technological University Singapore. His research interests focus on the study of electronic and optoelectronic properties of novel low-dimensional systems and their application in high performance information functional devices.

properties have begun to appear. Advanced functional materials based on eco-friendly cellulose and sputtered multicomponent dielectrics can be processed at low temperatures, and were reported to be implemented as high-capacitance gate dielectrics, bringing new insights into flexible and low-cost transistors and the need to meet the constraints for better band-offset matching.<sup>15,16</sup> Moreover, 2D insulators are regarded as the ultimate solution for dielectric miniaturization.<sup>17</sup> Hexagonal boron nitride (h-BN) has been deemed as the most promising 2D vdW dielectric layer, while novel 2D materials suitable for using as dielectric layers are rarely reported. However, the low dielectric constant ( $\approx 5.0$ ) and excessive leakage current make h-BN unsuitable for ultrascaled FETs with low power consumption.<sup>18,19</sup> Therefore, it is important to find new materials to serve as reliable gate dielectrics in FETs.

Among the various 2D material systems, the novel 2D metal thiophosphate  $MP_2X_6$  ( $M$  = metal,  $X$  = S or Se)<sup>20</sup> has received much attention due to its exceptional physical properties, including magnetic, electronic, ferroelectric, and optical characteristics.<sup>21-23</sup> Among the most extensively studied systems is the  $Sn_2P_2S_6$  crystal with a considerable piezo effect, appropriate ferroelectric and nonlinear optic properties,<sup>24,25</sup>  $MPS_3$  as a UV photodetector<sup>26</sup> which possesses magnetic order,<sup>27</sup> and  $CuInP_2S_6$  heterostructures for non-volatile ferroelectric switches, memory devices and field-effect transistors.<sup>28,29</sup> In addition,  $SnP_2S_6$ , a stable semiconductor material with a sizable indirect band gap of 2.23 eV,<sup>30</sup> is also of importance to be investigated as a member of this family.  $SnP_2S_6$  exhibits a unique nonporous structure as it lacks half of the metal ions compared to the

parent  $Sn_2P_2S_6$  structure. Due to the intrinsic 2D nanoporous structure, these days have witnessed more theoretical research studies on  $SnP_2S_6$ ,<sup>24,30-32</sup> despite the recent experimental study of a strong nonlinear optical response related to its inversion symmetry broken structure.<sup>33,34</sup> A recent theoretical study has predicted that  $SnP_2S_6$  could have high carrier mobility,<sup>20</sup> good switching stability, excellent insulation performance and gate-control ability. The measured dielectric constant is higher than that of the extensively used h-BN substrate.<sup>35</sup> Thus, it demonstrates great potential to be used as a channel or dielectric layer material in field effect transistors.

In this work,  $SnP_2S_6$  is proposed for the first time as a dielectric layer, the electronic and optoelectronic characteristics of which have been systematically investigated. Field effect transistors with excellent performance are successfully constructed, which verifies the feasibility of  $SnP_2S_6$  as a dielectric layer material and provides new reliable building blocks for 2D materials based electronic devices.

### Materials characterization

Layered  $SnP_2S_6$  shows a rhombohedral layered structure (as shown in Fig. 1(a and b)), which belongs to the  $R\bar{3}$  space group (No. 146) with a rhombohedral symmetry,<sup>30,36</sup> and only contains one formula unit<sup>20</sup> of one metal cation  $Sn^{4+}$  and one anionic  $[P_2S_6]^{4-}$ . As depicted in Fig. 1(a and b), the ternary  $SnP_2S_6$  has a van der Waals layered structure and the interlayer spacing is about 0.65 nm, as reported in the literature.<sup>33</sup> Raman spectra were recorded using a 532 nm laser under ambient conditions. As shown in Fig. 1(c), three distinct peaks

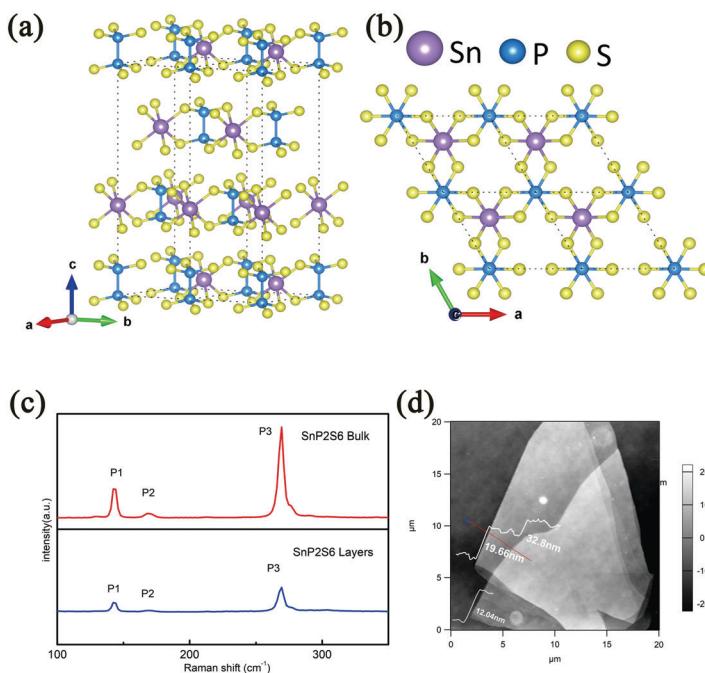
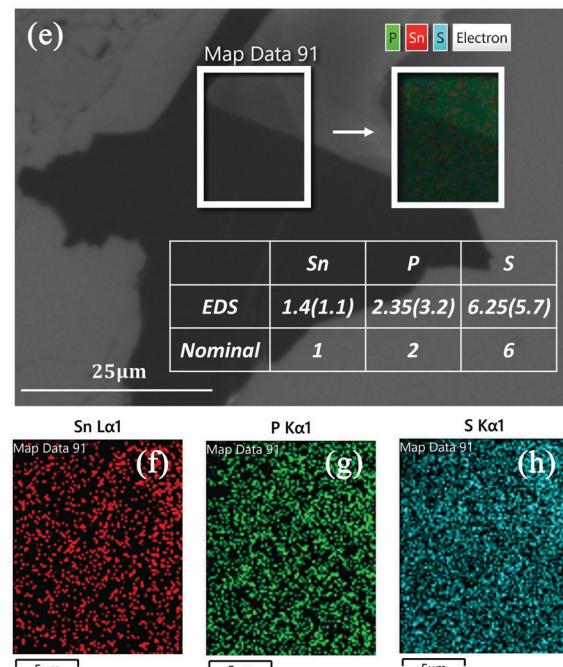


Fig. 1 Characterizations of the 2D material  $SnP_2S_6$ . (a and b) Crystal structure of layered  $SnP_2S_6$ . (a) Side and (b) top views. Purple, blue and yellow spheres represent Sn atoms, P atoms and S atoms, respectively. (c) Raman spectra of bulk and few-layer  $SnP_2S_6$ . (d) AFM topography of  $SnP_2S_6$  of different thicknesses. The thicknesses are around 12.04, 19.66 and 32.80 nm, respectively. (e) EDS results and elemental mappings of Sn (f), P (g) and S (h) for a typical  $SnP_2S_6$  crystal, which show a homogenous distribution of the three elements.



$P_1$  ( $\approx 142$   $\text{cm}^{-1}$ ),  $P_2$  ( $\approx 168$   $\text{cm}^{-1}$ ) and  $P_3$  ( $\approx 269$   $\text{cm}^{-1}$ ) can be identified in both bulk and layered  $\text{SnP}_2\text{S}_6$ . Specifically, the three peaks are related to the internal stretching vibrations of S-P-S bonds,<sup>9</sup> which are consistent with previous reports.<sup>33,37</sup> As the thickness increases, the intensity varies while the positions of all peaks hardly change, which might be due to the weak interlayer interaction. In addition, as shown in Fig. 1(e), it is noted that the atomic ratios of the  $\text{SnP}_2\text{S}_6$  sample are 14:23.5:62.5 and 11:32:57 (total 100), which are close to the stoichiometric ratio of 1:2:6, and the uniform distribution of elements Sn, P, and S is shown in Fig. 1(f-h), as confirmed by energy dispersive X-ray spectroscopy characterization (details in Fig. S1, ESI<sup>†</sup>).

### Optoelectronic properties of $\text{SnP}_2\text{S}_6$ thin flakes

The  $\text{SnP}_2\text{S}_6$  phototransistor is fabricated on the standard  $\text{SiO}_2/\text{Si}$  substrate (see the Methods section for details), and the schematic illustration of the device is shown in Fig. 2(a). The transfer and output curves of the  $\text{SnP}_2\text{S}_6$  based transistor are shown in Fig. 2(b and c). A linear relationship between  $I_{\text{ds}}$  and  $V_{\text{ds}}$  was observed. However, the transistor shows very low electron mobility, and the mobility ( $\mu = Ld/W\varepsilon_0\varepsilon_r V_{\text{ds}} \times dI_{\text{ds}}/dV_{\text{bg}}$ ) under a drain bias of 2 V was calculated to be  $2.17 \times 10^{-5}$   $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ . The electronic performance of the device with various thicknesses of  $\text{SnP}_2\text{S}_6$  was also studied (details in ESI<sup>†</sup> Fig. S2 and S3), demonstrating a similar insulating behaviour. The good insulating behaviour makes  $\text{SnP}_2\text{S}_6$  suitable for using as a dielectric layer, as discussed in detail in the next section.

The  $I_{\text{ds}}-V_{\text{ds}}$  curves shown in Fig. 3(a) are linear and symmetric while sweeping bias voltages, indicating an ohmic contact. The device shows an increase of drain current by several orders of magnitude once the device is illuminated. The typical optical image of the devices is shown in the inset of Fig. 3(a) and in Fig. S2 (ESI<sup>†</sup>). Furthermore, the power dependent photocurrent is plotted using a log-log scale method in Fig. 3(b). As the incident light power increases from 0.1 to 50 mW, the photocurrent  $I_{\text{ph}}$  increases monotonically from  $8.3 \times 10^{-12}$  to  $1.2 \times 10^{-10}$  A with a bias of 5 V, indicating that the photocurrent is linearly proportional to the incident light power following  $I_{\text{ph}}-P^{\beta}$ . Moreover, as the bias voltage shifts from 0.1 to 5 V, the value of  $\beta$  increases from 0.23 to 0.44. The great loss of photocurrent

represented by the non-unity exponent relationship and a low value of  $\beta$  suggests that the photocurrent is influenced by complex processes including the absorption of photons, generation of free carriers, recombination of the photogenerated free carriers, charge trapping by the defects and charge impurities in  $\text{SnP}_2\text{S}_6$  flakes, scarcely lateral photoeffect<sup>38</sup> and the adsorbed molecules at the  $\text{SnP}_2\text{S}_6/\text{SiO}_2$  interface.<sup>39-41</sup>

Meanwhile, the photoresponsivity  $R$  and photo-gain  $G$  at a drain voltage of  $V_{\text{ds}} = 5$  V exhibit a strong dependence on the illumination power, as shown in Fig. 3(c). The photoresponsivity  $R$  is one of the most important features for a photodetector.<sup>42</sup>  $R = I_{\text{ph}}/PS$ , where  $P$  is the incident light power density and  $S$  is the effective illuminated area. As shown in Fig. 3(c), the photoresponsivity increases with the decrease of light power, which is possibly attributed to the less frequent carrier recombination and longer carrier lifetime under weaker illumination. This is consistent with the photoconductor-based photodetector previously reported.<sup>8,43</sup> Photogain ( $G$ ) is another parameter to evaluate the performance of a phototransistor, which can be calculated using the formula:  $G = (I_{\text{ph}}/q)/(PS/h\nu) = h\nu R/q$ ,<sup>44</sup> where  $I_{\text{ph}}$  is the photocurrent,  $q$  is the electron charge,  $h$  is Planck's constant,  $\nu$  is the light frequency, and  $R$  is the responsivity. The value of  $G$  was estimated to reach up to 3.74 at a power of 0.1 mW.

The gate voltage dependent photoresponse of  $\text{SnP}_2\text{S}_6$  is also investigated. The transfer curves under the light on and off conditions are shown in Fig. 3(d), where an incident illumination of 80 mW is applied. The curves show an increase of drain current by nearly two orders of magnitude once the device is illuminated, indicating that the photocurrent dominates in the entire operating range of the device. As can be seen from Fig. 3(d), the photocurrent shows an ambipolar behaviour with large gate-tunability.

In order to study the stability and photoresponse speed of the  $\text{SnP}_2\text{S}_6$  photodetector, the time-current curves with 532 nm laser switching on and off were measured. For three different bias voltages (1 V, 1.5 V and 2 V), as shown in Fig. 3(e), the time dependent photocurrent varies periodically with regular illumination, suggesting a stable and reversible photoresponse. The response speed is evaluated according to a typical rise time/decay time, which is defined as the time span over which

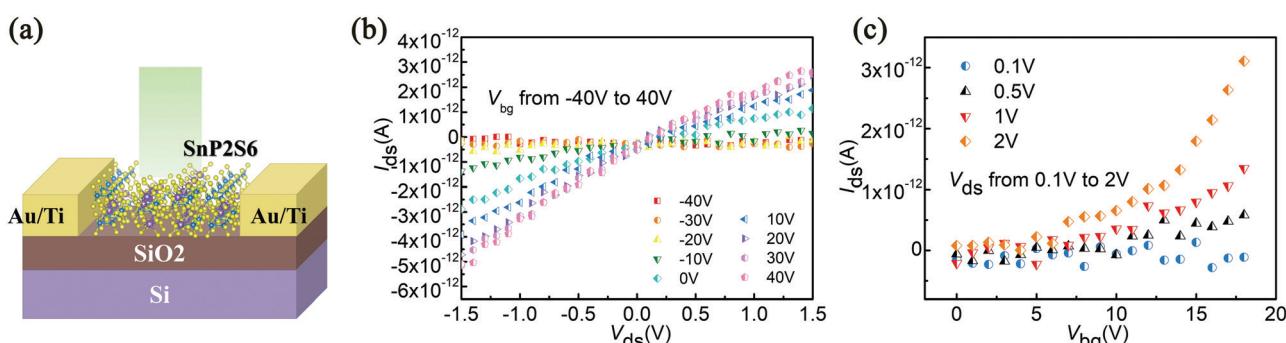


Fig. 2 Electronic properties of back-gated FETs using  $\text{SnP}_2\text{S}_6$  as the channel. (a) Schematic of the  $\text{SnP}_2\text{S}_6$  photodetector on the  $\text{SiO}_2/\text{Si}$  substrate, which provides the convenience of back gating. (b) Output curves ( $I_{\text{ds}}-V_{\text{ds}}$ ) under various  $V_{\text{bg}}$  ranging from  $-40$  V to  $40$  V. (c)  $I_{\text{ds}}-V_{\text{bg}}$  curves of  $\text{SnP}_2\text{S}_6$  with different  $V_{\text{ds}}$  bias ranging from  $0.1$  V to  $2$  V.

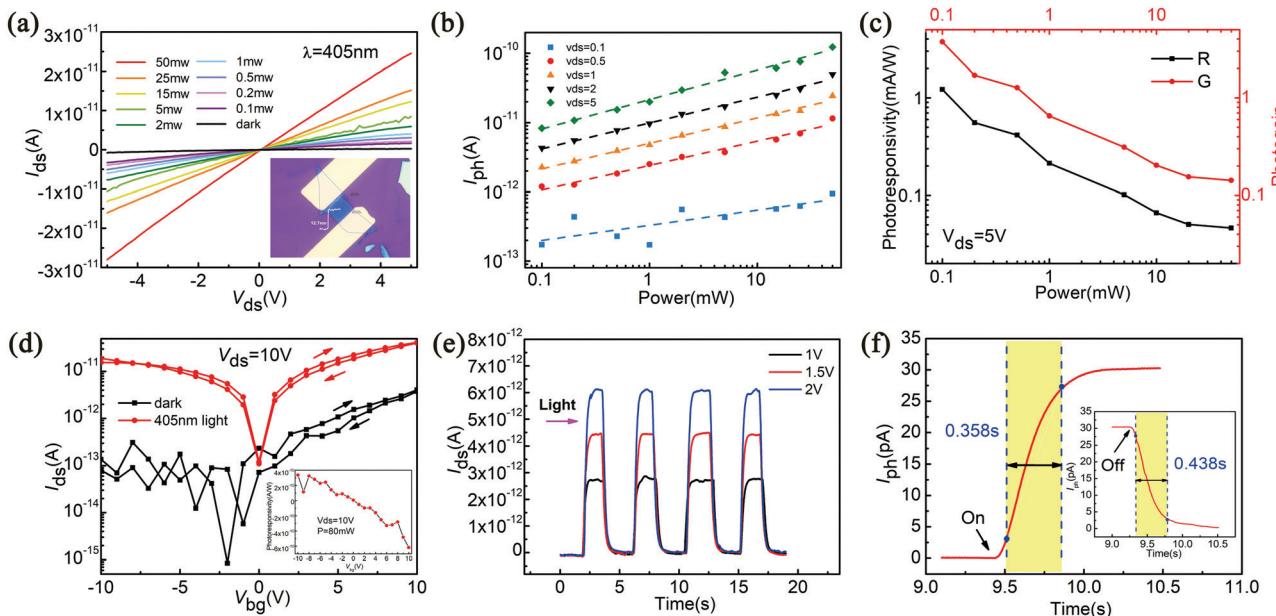


Fig. 3 Optical properties of the  $\text{SnP}_2\text{S}_6$  photodetector. (a)  $I_{ds}$ – $V_{ds}$  curves of  $\text{SnP}_2\text{S}_6$  at different light powers. Inset: The optical image of the device with a thickness of 12.7 nm. (b) Photocurrent ( $I_{ph}$ ) varies with light power and  $V_{ds}$ . (c) Photoresponsivity ( $R$ ) and photogain ( $G$ ) varying with light power.  $R_{\max} = 1.22 \text{ mA W}^{-1}$ ,  $G_{\max} = 3.74$ . (d)  $I_{ds}$ – $V_{bg}$  curves in the dark and under 405 nm light. The dark current could be reduced to the pA regime. Under light conditions, the current hysteresis box becomes small. Inset: Photoresponsivity varies with  $V_{bg}$ , under  $V_{ds} = 10$  V,  $P = 80$  mW. (e) The ON–OFF test of photocurrent under 532 nm light and a bias from 1 V to 2 V. The ON–OFF ratio  $>10^3$ . (f) The exponential fitting of the dynamic response of photocurrent for the rise and decay time. The deduced rise ( $\tau_{rise}$ ) and decay ( $\tau_{decay}$ ) time constants are about 0.358 s and 0.438 s.

the photocurrent increases from 10% to 90% (or decreases from 90 to 10% analogously) when the laser is switched on and off. Fig. 3(f) shows the results of the rise and decay times of  $\tau_{rise} = 0.358$  s and  $\tau_{decay} = 0.438$  s for  $V_{ds} = 2$  V, where the rising and falling parts of the curve can be fitted with an exponential function  $I = I_0 + Ae^{t/\tau_{rise \text{ or } decay}}$ , where  $\tau_{rise \text{ or } decay}$  is the rise or decay time constant.

### Dielectric properties of the $\text{SnP}_2\text{S}_6$ film

We first studied the temperature dependent dielectric permittivity at different frequencies. For this, bulk samples of  $\text{SnP}_2\text{S}_6$  with a size of  $5 \times 5 \times 0.05$  mm<sup>3</sup> were obtained from the gas phase. Silver paste deposited on opposite planes of the test sample was used as the electrodes. The measurements were carried out at the frequency range of 10 Hz to 50 kHz and the temperature range of 80 to 400 K. Meanwhile, a GW INSTEK LCR-819 meter and an immersed liquid nitrogen cryostat with a temperature measurement accuracy of 0.001 K were adopted. The cooling rate was 0.1 K min<sup>-1</sup> at a measuring field strength of 1 V cm<sup>-1</sup>. As can be seen in Fig. 4(a and b), when the  $\text{SnP}_2\text{S}_6$  crystals are cooled, a monotonic decrease trend in the permittivity (a) and dielectric losses (b) is observed. At high temperatures, low frequency  $\epsilon'$  and  $\epsilon''$  increase strongly, which is most likely caused by an increase in the conductivity of the sample. The dielectric value of  $\text{SnP}_2\text{S}_6$  ( $\approx 23$ ) is much higher than that of h-BN ( $\approx 5.0$ ), which is comparable with or higher than those of traditional high- $k$  oxide dielectrics such as  $\text{Al}_2\text{O}_3$ ,<sup>45</sup>  $\text{HfO}_2$ ,<sup>46</sup> and  $\text{ZrO}_2$ .<sup>47</sup>

Considering that the  $\text{SnP}_2\text{S}_6$  film has excellent insulating property, good chemical stability and a high dielectric constant,

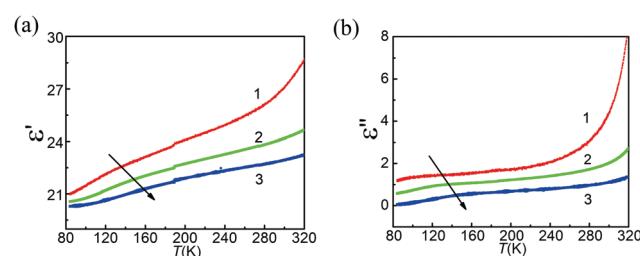


Fig. 4 Temperature dependence of the  $\text{SnP}_2\text{S}_6$  crystal dielectric permittivity of the real (a) and imaginary (b) parts at frequencies 1(1 kHz), 2(10 kHz), and 3(40 kHz).

it shows great potential for integrating into 2D FETs as a dielectric layer to modulate the carrier density of semiconducting channel. To demonstrate its advantages in this regard, we fabricate 2D FETs and evaluate the gating effect of  $\text{SnP}_2\text{S}_6$  as top-gate dielectrics.

The well-studied 2D semiconductor  $\text{MoS}_2$  was chosen as a representative channel material. Initially, we build  $\text{MoS}_2$ / $\text{SnP}_2\text{S}_6$  FETs on  $\text{SiO}_2$ /Si substrate (the corresponding schematic is provided in ESI† Fig. S5A), but the result shows that the hysteresis window of the devices is too big (ESI† Fig. S5C). Here, in order to reduce the hysteresis window, we use h-BN as the substrate, which can be prepared with a very uniform thickness and an atomically flat surface,<sup>48</sup> and this method is proven to be effective in improving the performance of  $\text{MoS}_2$  FETs.<sup>49,50</sup> The schematic illustration of our device is shown in Fig. 5(a) (optical image in ESI† Fig. S6 and S7D).

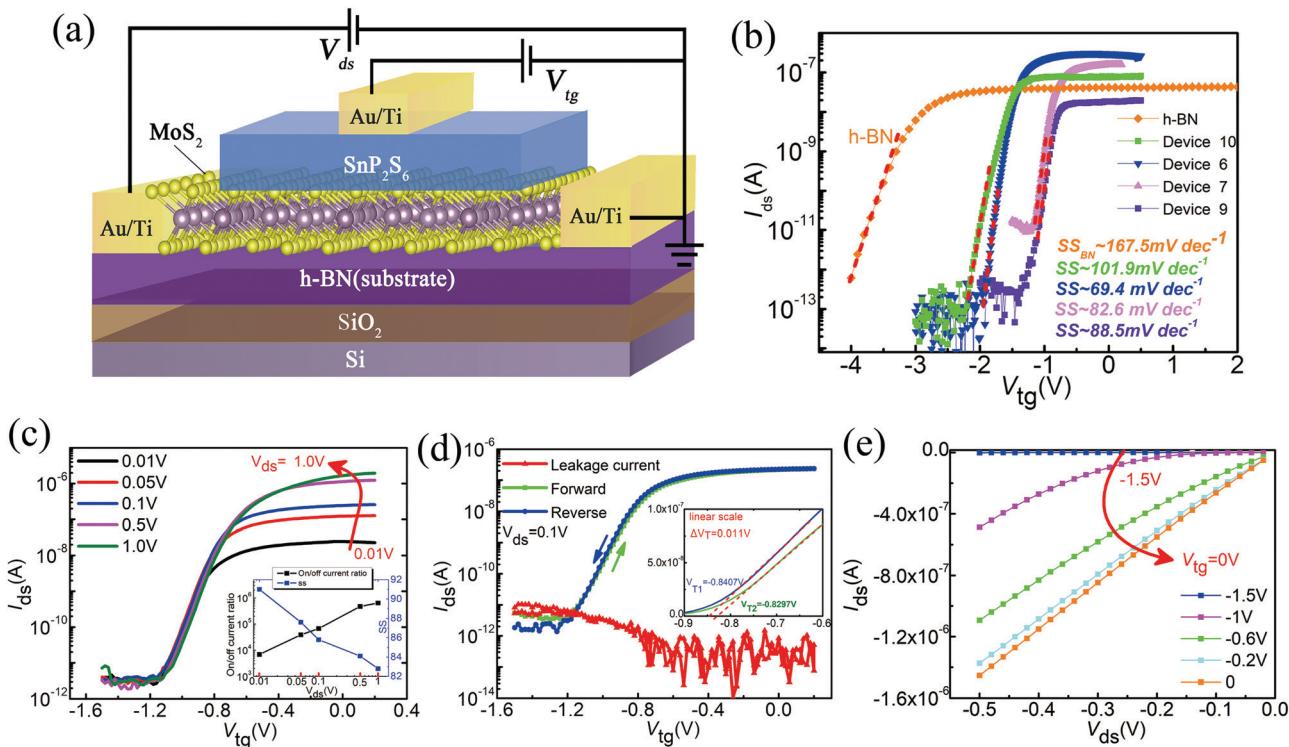


Fig. 5 Electronic properties of top-gated MoS<sub>2</sub> FETs using SnP<sub>2</sub>S<sub>6</sub> as a gate dielectric. (a) Schematic of SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> FETs using h-BN as a substrate. (b)  $I_{ds}$ – $V_{tg}$  curves of MoS<sub>2</sub> FETs at 300 K. The orange points represent the  $I_{ds}$ – $V_{tg}$  curve of h-BN/MoS<sub>2</sub> FET as a contrasting device, in which h-BN is thinner than SnP<sub>2</sub>S<sub>6</sub>. Others are the  $I_{ds}$ – $V_{tg}$  curves of SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> FETs which exhibit a subthreshold slope (SS) down to 69.4 mV dec<sup>-1</sup>. (c–e) The best performance of the SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> FET (Device 7). (c)  $I_{ds}$ – $V_{tg}$  characteristics measured at a drain bias ranging from 0.01 V to 1 V, and the inset shows the ON/OFF current ratio and SS extracted at different  $V_{ds}$  values. (d) Double-sweep  $I_{ds}$ – $V_{tg}$  curves with a small hysteresis and leakage current, and the inset exhibiting the current on a linear scale (hysteresis gap  $\Delta V_T \approx 0.011$  V). (e)  $I_{ds}$ – $V_{ds}$  characteristics measured at different  $V_{tg}$  values.

The thin-film 2D materials are obtained through a mechanical exfoliation process (see ESI† Fig. S7A–C). Through the process described in the methods, 7 devices based on SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> flakes with various thicknesses were fabricated. The optimal electric performance was observed in the devices with the thickness of SnP<sub>2</sub>S<sub>6</sub> about 49.7 nm (details in ESI† Fig. S6 and S8). Meanwhile, a top-gate h-BN/MoS<sub>2</sub> FET was also fabricated for comparison according to the schematic in ESI† Fig. S9C, in which h-BN (with a thickness of about 23.44 nm) is thinner than SnP<sub>2</sub>S<sub>6</sub> (optical and AFM images in ESI† Fig. S6). Fig. 5(b) shows the top-gate transfer ( $I_{ds}$ – $V_{tg}$ ) characteristics of the h-BN/MoS<sub>2</sub> FET (the orange points) and four SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> FETs on the insulating h-BN substrate (see ESI† Fig. S7D). For the former one, a subthreshold slope (SS) value of 167.5 mV dec<sup>-1</sup> and an ON/OFF ratio of  $10^5$  were obtained. While for the latter, SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> FETs, a small subthreshold slope (SS) value as low as 69.4 mV dec<sup>-1</sup> of device 6 (blue points) was achieved at a drain bias of 0.1 V, which is close to the limit value<sup>51</sup> of 60 mV dec<sup>-1</sup>. The device could even reach a high ON/OFF ratio of  $10^7$  and a high carrier mobility of 28.498 cm<sup>2</sup> V<sup>-1</sup> s<sup>-1</sup> at a higher drain bias (ESI† Fig. S10(A)). The threshold voltage ( $V_t$ ) is a useful parameter to describe how much voltage is needed to initiate the channel conduction. Here,  $V_t$  of the fabricated device is as low as  $-1.1$  V (ESI† Fig. S10(B)). Thus, the FETs with a smaller SS value, low on voltage and low threshold voltage can achieve effective switching at a low  $V_{ds}$ , thereby reducing the

leakage current and power consumption of FET devices. It is remarkable for our SnP<sub>2</sub>S<sub>6</sub> based FET to have such an excellent SS. In order to unravel the underlying mechanisms, we have carried out the following discussions. The contrast above indicates that thicker SnP<sub>2</sub>S<sub>6</sub> films with thickness from 47.7 nm to 49.7 nm show the best performance and they have stronger gate control capability and low leakage current compared with 23.44 nm-thick h-BN. Thus, it means SnP<sub>2</sub>S<sub>6</sub> owns a larger capacitance value than h-BN in MoS<sub>2</sub> FETs ( $C_{SnP_2S_6} > C_{h-BN}$ ), though SnP<sub>2</sub>S<sub>6</sub> is thicker than h-BN ( $d_{SnP_2S_6} > d_{h-BN}$ ). According to the equation

$$C = \epsilon_0 \epsilon_r / d$$

where  $C$  is the capacitance value per unit area of the gate dielectric,  $\epsilon_0$  is the permittivity of vacuum and  $\epsilon_r$  is the relative dielectric constant. This confirms the high dielectric constant of SnP<sub>2</sub>S<sub>6</sub> and the advantages of integrating an SnP<sub>2</sub>S<sub>6</sub> nanosheet with semiconductor crystals to design FETs compared with h-BN, demonstrating the potential of 2D SnP<sub>2</sub>S<sub>6</sub> as a high- $k$  dielectric for low-power-consumption and miniaturized electronics.

As shown in Fig. 5(c and d), the typical SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> device exhibits a high ON/OFF ratio and steep SS simultaneously. The effect of the increasing drain bias, resulting in an augmented drive current and steeper SS value, is displayed in (Fig. 5(c)).

It can be seen that the best transistor performance is achieved at  $V_{ds} = 1$  V, with a maximum measured on-state current of  $\sim 1$   $\mu$ A, ON/OFF current ratio close to  $10^6$ , SS value as small as 82.6 mV dec $^{-1}$  (inset of Fig. 5(c)) and the leakage current as low as  $\sim 10^{11}$  A (Fig. 5(d)). The corresponding hysteresis stability of the device is demonstrated in Fig. 5(d). To describe the hysteresis stability, we introduce the hysteresis window ( $\Delta V_T$ ), which is defined as the difference between the forward and reverse sweep threshold voltage.<sup>52</sup> As obtained on a linear scale in the inset of Fig. 5(d),  $\Delta V_T = |V_{T1} - V_{T2}|$  was determined as low as 0.011 V, which is a fairly small value in FETs. However, the hysteresis window became larger after two days in a glove box (ESI† Fig. S11D–F) and different hysteresis behaviours were observed in some of our devices (ESI† Fig. S11A–C). The hysteresis variation may be associated with flake quality or fabrication process in a laboratory environment, which can lead to charge trapping at the interface, adsorption/desorption of ambient molecules or atmospheric moisture in the exposed active layers.<sup>50,53</sup> The small hysteresis could indicate that the fabricated SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> device shows an atomic flat and sharp interface. The corresponding output ( $I_{ds}$ – $V_{ds}$ ) characteristics measured in the case of different  $V_{tg}$  values (Fig. 5(e)) show linear  $I_{ds}$ – $V_{ds}$  characteristics at low drain bias and saturated current at a high drain bias.

The breakdown electric field ( $V_{bd}$ ) is another important parameter to evaluate the strength of the insulating layer. To test the current leakage and breakdown threshold, SnP<sub>2</sub>S<sub>6</sub> is sandwiched between two electrodes to build a vertical device as shown in the inset of Fig. S12 (ESI†). At room temperature,

$V_{bg}$  is fixed at 0 V, and  $V_{ds}$  is swept.<sup>54</sup> The  $I_{ds}$ – $V_{ds}$  curve is plotted in Fig. S12 (ESI†), where the initial low current increases slowly as the  $V_{ds}$  value increases. The current increases dramatically once  $V_{ds}$  approaches  $V_{bd}$ . After the breakdown, the device is permanently destroyed as a large current flows across SnP<sub>2</sub>S<sub>6</sub>.  $V_{bd}$  is estimated to be about 5 V (with a thickness of 26.5 nm), and the corresponding breakdown electric field  $F_{bd}$  could reach as high as 1.9 MV cm $^{-1}$ .

Furthermore, to investigate the optoelectronic properties of our FETs, we put one of our SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> FETs (Device 9, its optical image in the inset of Fig. 6(b)) under 405 nm laser irradiation of 80 mW. The output and transfer characteristics in the dark (black), under 405 nm irradiation (blue) and after irradiation (red) are separately depicted in Fig. 6(b and c). Under illumination, the output characteristic of the device remains linear while the reduced electrical resistance of the semiconductor was observed due to the photoconductive effect (PC effect), where the extra free carriers are generated by the photon absorption (Fig. 6(b)). Meanwhile, as shown in Fig. 6(c), a significant change in the threshold voltage was also observed when illuminated by 405 nm light. The shifting of the threshold voltage to the negative  $V_{tg}$  side is known as the photogating effect (PG effect). The PG effect is a phenomenon in which photogenerated holes get trapped and then attract more electrons, thus gradually increasing the channel conductivity.<sup>55,56</sup>

In Fig. 6(c), compared with the initial device in the dark, the off-state current after irradiation is dramatically increased by more than five orders of magnitude at the same  $V_{tg}$ , implying a long-time decay of the photoconductive state. As shown in

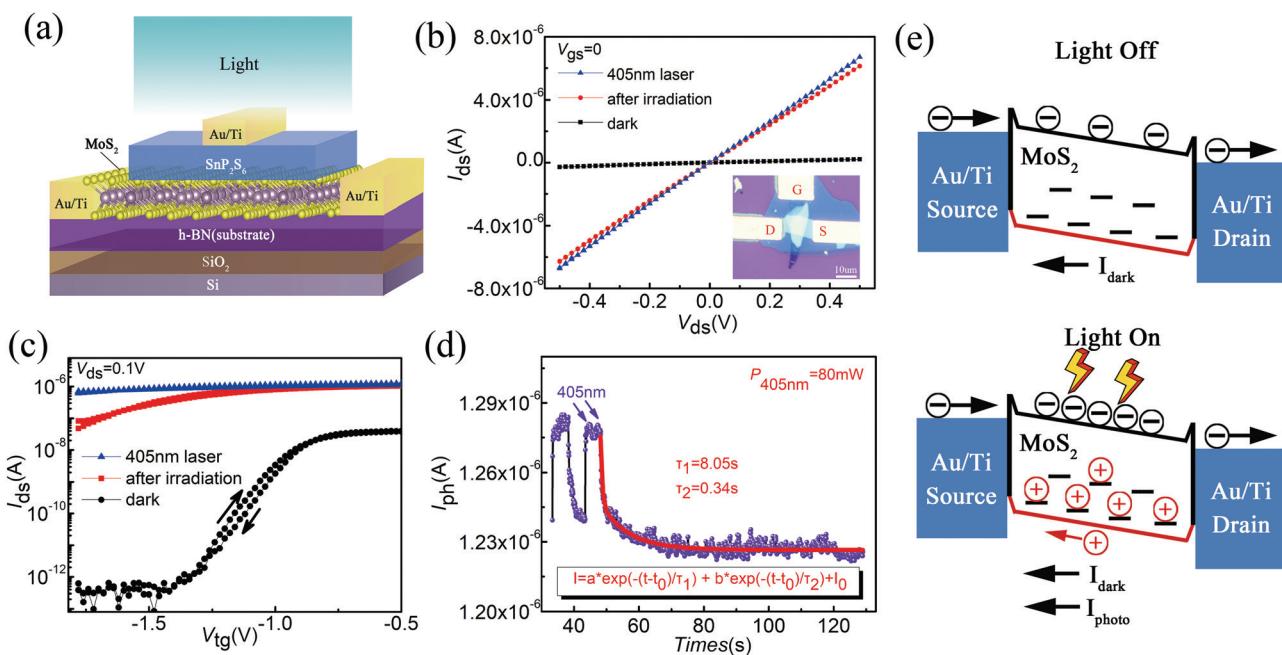


Fig. 6 Optical properties of top-gated SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> FETs. (a) Schematic diagram of photogating dominated SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> FETs (Device 9). (b) Typical  $I_{ds}$ – $V_{ds}$  characteristics of Device 9 in the dark (black), under illumination (blue) and after irradiation (red), and the inset showing the optical image of the FET. (c)  $I_{ds}$ – $V_{tg}$  characteristics showing transfer curve shifts in the negative  $V_{tg}$  direction under and after irradiation. (d) Photocurrent decay after a longer light pulse with longer ( $\tau_1 \sim 8.05$  s) and shorter ( $\tau_2 \sim 0.34$  s) time constants, which corresponds to (b) and (c). (e) Band diagram of the device without (top panel) and with light (bottom panel), showing hole trapping in shallower and deeper trap states close to the valence band.

**Table 1** Comparison of SnP<sub>2</sub>S<sub>6</sub> performance with other new 2D dielectrics

Materials	Dielectric constant	SS value [mV dec <sup>-1</sup> ]	ON/OFF ratio	Ref.
Ta <sub>2</sub> O <sub>5</sub>	15.5	61	10 <sup>6</sup>	58
Bi <sub>2</sub> SeO <sub>5</sub>	21	75	10 <sup>5</sup>	59
CaF <sub>2</sub>	8.43	90	10 <sup>7</sup>	53
In <sub>2</sub> P <sub>3</sub> S <sub>9</sub>	24	88	10 <sup>5</sup>	9
Sb <sub>2</sub> O <sub>3</sub>	11.5	64	10 <sup>8</sup>	60
SnP <sub>2</sub> S <sub>6</sub>	23	69.4	10 <sup>7</sup>	This work

Fig. S13 (ESI<sup>†</sup>), SnP<sub>2</sub>S<sub>6</sub> has little effect on the optical response and persistent photocurrent of the device. Therefore, to explore the photocurrent decay of the device, we then check the transient characteristics by measuring the source-drain current at a fixed  $V_{tg} = 0$  V in Fig. 6(d). An abrupt increase in  $I_{ds}$  was observed under 405 nm laser illumination, as a result of photoexcitation, followed by a much slower current increase. A very slow decay of the current can be observed when the light was switched off. This is because the trapped charges in the PG effect cause long sustained conductivity.<sup>56</sup> In order to quantify the trapping time constant, transient data were fitted with a biexponential equation<sup>57</sup>

$$I = I_0 + Ae^{(t-t_0)/\tau_1} + Be^{(t-t_0)/\tau_2}$$

where  $\tau_1$  and  $\tau_2$  are the two relaxation time constants, possibly corresponding to two different photoresponse mechanisms. The fast part is potentially due to the photoconductivity effect. The slow part could be regarded with the defect trapping or photogating effect.  $I_{ds}$  decays exponentially from  $\sim 1.27$   $\mu$ A and saturates after 35 s with a longer time constant  $\tau_1 \sim 8.05$  s and a shorter time constant  $\tau_2 \sim 0.34$  s. (See the detailed parameter values in the ESI<sup>†</sup> Table S2 and time constants for different wavelengths in the ESI<sup>†</sup> Fig. S14). The shorter decay component could be attributed to the PC effect and shallower traps, while the longer decay component due to the PG effect might be caused by deeper (middle gap) traps in Fig. 6(e), as elucidated by Furchi *et al.*<sup>55</sup> Simultaneously, the longer time constants of the devices on SiO<sub>2</sub>/Si FETs are  $\sim 6.814$  s and  $\sim 13.39$  s, which are close to 5.05 s in the FETs on h-BN (see details in the ESI<sup>†</sup> Fig. S15). Consequently, we infer that the long persistent photocurrent measured in our devices is not likely due to the traps at the MoS<sub>2</sub>/SiO<sub>2</sub> or MoS<sub>2</sub>/h-BN interface since our SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> FETs fabricated on h-BN which have rare charge trapping.<sup>50</sup> Thus, it is conjectured that the defect trapping might have mainly originated from photo charge trapping associated with MoS<sub>2</sub> defects and the MoS<sub>2</sub>/SnP<sub>2</sub>S<sub>6</sub> interface. Therefore, improving the quality of MoS<sub>2</sub> and optimizing the MoS<sub>2</sub>/SnP<sub>2</sub>S<sub>6</sub> interface can be a reasonable approach to decrease this phenomenon.

Finally, the good stability, reliability and reproducibility of the devices are summarized as shown in Fig. S16–S19 (ESI<sup>†</sup>).

To highlight the performance of the SnP<sub>2</sub>S<sub>6</sub> dielectric, the main set of achievements of the present study, such as the dielectric constant, SS value and ON/OFF ratio, are presented in Table 1. Compared with other new 2D dielectric materials, the

excellent performance of SnP<sub>2</sub>S<sub>6</sub> is comparable to or even better than those of these materials.

## Conclusion

In this paper, we have systematically investigated the photoelectric and electrical properties of a novel 2D SnP<sub>2</sub>S<sub>6</sub> crystal. Moreover, it was integrated into MoS<sub>2</sub> based FETs to serve as a top gate dielectric. The results demonstrate its excellent properties including a large dielectric constant ( $\approx 23$ , compared with h-BN), a fairly small SS value (as low as 69.4 mV dec<sup>-1</sup>), a high ON/OFF ratio (reaching 10<sup>7</sup>), a negligible hysteresis, and a considerable breakdown voltage ( $\approx 1.9$  MV cm<sup>-1</sup>). Due to its good photoelectric properties, good reliability and reproducibility (0.5 standard deviation of threshold voltage), SnP<sub>2</sub>S<sub>6</sub> could become a potential candidate for the construction of advanced optoelectronic and electronic devices.

## Methods

### Material characterization

Raman spectra are recorded using a Horiba confocal Raman system with an excitation laser of 532 nm. The morphology characterization and thickness calibration of the SnP<sub>2</sub>S<sub>6</sub> film as well as thickness measurement of h-BN and MoS<sub>2</sub> are carried out with an optical microscope and AFM instruments.

### Fabrication of an SnP<sub>2</sub>S<sub>6</sub> phototransistor and SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> FET devices

An SnP<sub>2</sub>S<sub>6</sub> phototransistor was fabricated by exfoliating thin flakes onto heavily doped silicon substrates. The top electrodes are defined using a standard photolithography process followed by thermal evaporation of the Ti/Au metal, and a lift-off process. We have built three batches of SnP<sub>2</sub>S<sub>6</sub>/MoS<sub>2</sub> devices on a SiO<sub>2</sub>/Si substrate and an h-BN substrate, respectively. Thin-film 2D materials are obtained through a mechanical exfoliation process first. Then, the 2D nanosheets of top-gate FETs are stacked up by a polydimethylsiloxane (PDMS) assisted transfer technique onto an h-BN nanosheet to develop heterostructures. The source-drain and gate electrodes Ti/Au of each device were patterned and deposited by photolithography and a lift-off process. Preparation methods for other devices including back-gate FETs and top-gate FETs on different substrates adjust according to their schematic.

### Electrical and optical characterization measurements

We tested the device directly after fabrication. Electrical and photoelectrical characterization of devices including  $I_D$ – $V_G$ ,  $I_D$ – $V_D$  and  $I_{ph}$ – $t$  involved measurements were performed under vacuum condition at room temperature (300 K) using a probe station.

## Author contributions

J. H. and A. Z. carried out the electrical and optoelectronic measurements. E. P., J. C. and R. B. assisted in the device fabrication and electrical measurement. E. P. carried out the

AFM measurement. J. L. and X. J. carried out the Raman characterization. A. M. and Y. V. conducted dielectric measurement and crystal growth. Q. L., G. C. and P. M. analyzed the data. J. H., A. Z. and F. L. wrote the manuscript. Q. L. and G. C. revised the manuscript. F. L. supervised the project. All the authors commented on the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

F. L. acknowledges the support from the National Natural Science Foundation of China (62074025,12161141015), the National Key Research & Development Program (2021YFE0194200, 2020YFA0309200), the Applied Basic Research Program of Sichuan Province (2021JDGD0026), and the Sichuan Province Key Laboratory of Display Science and Technology.

## References

- Y. Liu, N. O. Weiss, X. Duan, H.-C. Cheng, Y. Huang and X. Duan, *Nat. Rev. Mater.*, 2016, **1**, 16042.
- A. K. Geim and I. V. Grigorieva, *Nature*, 2013, **499**, 419–425.
- G. B. Liu, D. Xiao, Y. Yao, X. Xu and W. Yao, *Chem. Soc. Rev.*, 2015, **44**, 2643–2663.
- L. Mennel, J. Symonowicz, S. Wachter, D. K. Polyushkin, A. J. Molina-Mendoza and T. Mueller, *Nature*, 2020, **579**, 62–66.
- F. Schwierz and M. Ziegler, *Presented in part at the 2021 IEEE Latin America Electron Devices Conference (LAEDC)*, 2021.
- T. Tan, X. Jiang, C. Wang, B. Yao and H. Zhang, *Adv. Sci.*, 2020, **7**, 2000058.
- J. Chen, G. Cao, Q. Liu, P. Meng, Z. Liu and F. Liu, *Rare Met.*, 2022, **41**, 325–332.
- P. Yu, Q. Zeng, C. Zhu, L. Zhou, W. Zhao, J. Tong, Z. Liu and G. Yang, *Adv. Mater.*, 2021, **33**, e2005607.
- C. Y. Zhu, J. K. Qin, P. Y. Huang, H. L. Sun, N. F. Sun, Y. L. Shi, L. Zhen and C. Y. Xu, *Small*, 2022, **18**, e2104401.
- Y. Chen, W. Ma, C. Tan, M. Luo, W. Zhou, N. Yao, H. Wang, L. Zhang, T. Xu, T. Tong, Y. Zhou, Y. Xu, C. Yu, C. Shan, H. Peng, F. Yue, P. Wang, Z. Huang and W. Hu, *Adv. Funct. Mater.*, 2021, **31**, 2009554.
- T. Tong, Y. Chen, S. Qin, W. Li, J. Zhang, C. Zhu, C. Zhang, X. Yuan, X. Chen, Z. Nie, X. Wang, W. Hu, F. Wang, W. Liu, P. Wang, X. Wang, R. Zhang and Y. Xu, *Adv. Funct. Mater.*, 2019, **29**, 1905806.
- X. Zou, Y. Xu and W. Duan, *Innovation*, 2021, **2**, 100115.
- G. Cao, P. Meng, J. Chen, H. Liu, R. Bian, C. Zhu, F. Liu and Z. Liu, *Adv. Funct. Mater.*, 2021, **31**, 2005443.
- I. Ferain, C. A. Colinge and J. P. Colinge, *Nature*, 2011, **479**, 310–316.
- I. Cunha, R. Barra, P. Grey, D. Gaspar, E. Fortunato, R. Martins and L. Pereira, *Adv. Funct. Mater.*, 2017, **27**, 1606755.
- P. Barquinha, L. Pereira, G. Goncalves, R. Martins, D. Kuščer, M. Kosec and E. Fortunato, *J. Electrochem. Soc.*, 2009, **156**, H824.
- Y. Y. Illarionov, T. Knobloch, M. Jech, M. Lanza, D. Akinwande, M. I. Vexler, T. Mueller, M. C. Lemme, G. Fiori, F. Schwierz and T. Grasser, *Nat. Commun.*, 2020, **11**, 3385.
- F. Hui, C. Pan, Y. Shi, Y. Ji, E. Grustan-Gutierrez and M. Lanza, *Microelectron. Eng.*, 2016, **163**, 119–133.
- T. Knobloch, Y. Y. Illarionov, F. Ducry, C. Schleich, S. Wachter, K. Watanabe, T. Taniguchi, T. Mueller, M. Waltl, M. Lanza, M. I. Vexler, M. Luisier and T. Grasser, *Nat. Electron.*, 2021, **4**, 98–108.
- M. Lin, P. Liu, M. Wu, Y. Cheng, H. Liu, K. Cho, W.-H. Wang and F. Lu, *Appl. Surf. Sci.*, 2019, **493**, 1334–1339.
- I. P. Studenyak, V. V. Mitrovcij, G. S. Kovacs, M. I. Gurzan, O. A. Mykajlo, Y. M. Vysochanskii and V. B. Cajipe, *Phys. Status Solidi B*, 2003, **236**, 678–686.
- I. P. Studenyak, O. A. Mykajlo, V. O. Stephanovich, M. I. Gurzan, Y. M. Vysochanskii and V. B. Cajipe, *Phys. Status Solidi A*, 2003, **198**, 487–494.
- I. Studenyak, O. Mykajlo, Y. M. Vysochanskii and V. Cajipe, *J. Phys.: Condens. Matter*, 2003, **15**, 6773.
- K. Z. Rushchanskii, Y. M. Vysochanskii, V. B. Cajipe and X. Bourdon, *Phys. Rev. B*, 2006, **73**, 115115.
- Y. M. Vysochanskii, D. Baltrunas, A. A. Grabar, K. Mazeika, K. Fedyo and A. Sudavicius, *Phys. Status Solidi B*, 2009, **246**, 1110–1117.
- Y. Gao, S. Lei, T. Kang, L. Fei, C. L. Mak, J. Yuan, M. Zhang, S. Li, Q. Bao, Z. Zeng, Z. Wang, H. Gu and K. Zhang, *Nanotechnology*, 2018, **29**, 244001.
- B. L. Chittari, Y. Park, D. Lee, M. Han, A. H. MacDonald, E. Hwang and J. Jung, *Phys. Rev. B*, 2016, **94**, 184428.
- Z. Zhu, X. Chen, W. Li and J. Qi, *Appl. Phys. Lett.*, 2019, **114**, 223102.
- W. Huang, F. Wang, L. Yin, R. Cheng, Z. Wang, M. G. Sendeku, J. Wang, N. Li, Y. Yao and J. He, *Adv. Mater.*, 2020, **32**, e1908040.
- Y. Jing, Z. Zhou, J. Zhang, C. Huang, Y. Li and F. Wang, *Phys. Chem. Chem. Phys.*, 2019, **21**, 21064–21069.
- Z. Wang, R. D. Willett, R. A. Laitinen and D. A. Cleary, *Chem. Mater.*, 1995, **7**, 856–858.
- V. Haborets, K. Glukhov, J. Banys and Y. Vysochanskii, *Integr. Ferroelectr.*, 2021, **220**, 90–99.
- Y. Zhang, F. Wang, X. Feng, Z. Sun, J. Su, M. Zhao, S. Wang, X. Hu and T. Zhai, *Nano Res.*, 2021, **15**, 2391–2398.
- I. P. Studenyak, V. V. Mitrovcij, G. S. Kovacs, O. A. Mykajlo, M. I. Gurzan and Y. M. Vysochanskii, *Ferroelectrics*, 2001, **254**, 295–310.
- Y. Hattori, T. Taniguchi, K. Watanabe and K. Nagashio, *ACS Nano*, 2015, **9**, 916–921.
- Z. Wang, R. D. Willett, R. A. Laitinen and D. A. Cleary, *Chem. Mater.*, 1995, **7**, 856–858.
- Y. M. Vysochanskii, V. Stephanovich, A. Molnar, V. Cajipe and X. Bourdon, *Phys. Rev. B*, 1998, **58**, 9119.
- R. Martins and E. Fortunato, *Rev. Sci. Instrum.*, 1995, **66**, 2927–2934.
- W. Zhang, J. K. Huang, C. H. Chen, Y. H. Chang, Y. J. Cheng and L. J. Li, *Adv. Mater.*, 2013, **25**, 3456–3461.
- F. Gonzalez-Posada, R. Songmuang, M. Den Hertog and E. Monroy, *Nano Lett.*, 2012, **12**, 172–176.

41 X. Zhou, L. Gan, W. Tian, Q. Zhang, S. Jin, H. Li, Y. Bando, D. Golberg and T. Zhai, *Adv. Mater.*, 2015, **27**, 8035–8041.

42 O. Lopez-Sanchez, D. Lembke, M. Kayci, A. Radenovic and A. Kis, *Nat. Nanotechnol.*, 2013, **8**, 497–501.

43 G. Konstantatos, M. Badioli, L. Gaudreau, J. Osmond, M. Bernechea, F. P. Garcia de Arquer, F. Gatti and F. H. Koppens, *Nat. Nanotechnol.*, 2012, **7**, 363–368.

44 X. Xie, S. Y. Kwok, Z. Lu, Y. Liu, Y. Cao, L. Luo, J. A. Zapien, I. Bello, C. S. Lee, S. T. Lee and W. Zhang, *Nanoscale*, 2012, **4**, 2914–2919.

45 J. Robertson, *Rep. Prog. Phys.*, 2005, **69**, 327.

46 Y.-S. Lin, R. Puthenkovilakam and J. Chang, *Appl. Phys. Lett.*, 2002, **81**, 2041–2043.

47 Y.-S. Lin, R. Puthenkovilakam, J. Chang, C. Bouldin, I. Levin, N. V. Nguyen, J. Ehrstein, Y. Sun, P. Pianetta and T. Conard, *J. Appl. Phys.*, 2003, **93**, 5945–5952.

48 K. Zhang, Y. Feng, F. Wang, Z. Yang and J. Wang, *J. Mater. Chem. C*, 2017, **5**, 11992–12022.

49 Y. Ji, C. Pan, M. Zhang, S. Long, X. Lian, F. Miao, F. Hui, Y. Shi, L. Larcher, E. Wu and M. Lanza, *Appl. Phys. Lett.*, 2016, **108**, 012905.

50 C. Lee, S. Rathi, M. A. Khan, D. Lim, Y. Kim, S. J. Yun, D. H. Youn, K. Watanabe, T. Taniguchi and G. H. Kim, *Nanotechnology*, 2018, **29**, 335202.

51 R. K. Jana, G. L. Snider and D. Jena, *Phys. Status Solidi C*, 2013, **10**, 1469–1472.

52 D. Estrada, S. Dutta, A. Liao and E. Pop, *Nanotechnology*, 2010, **21**, 85702.

53 Y. Y. Illarionov, A. G. Banshchikov, D. K. Polyushkin, S. Wachter, T. Knobloch, M. Thesberg, L. Mennel, M. Paur, M. Stöger-Pollach, A. Steiger-Thirsfeld, M. I. Vexler, M. Waltl, N. S. Sokolov, T. Mueller and T. Grasser, *Nat. Electron.*, 2019, **2**, 230–235.

54 X. Yan, I. S. Esqueda, J. Ma, J. Tice and H. Wang, *Appl. Phys. Lett.*, 2018, **112**, 032101.

55 A. Di Bartolomeo, L. Genovese, T. Foller, F. Giubileo, G. Luongo, L. Croin, S. J. Liang, L. K. Ang and M. Schleberger, *Nanotechnology*, 2017, **28**, 214002.

56 M. Buscema, J. O. Island, D. J. Groenendijk, S. I. Blanter, G. A. Steele, H. S. van der Zant and A. Castellanos-Gomez, *Chem. Soc. Rev.*, 2015, **44**, 3691–3718.

57 D. J. Late, B. Liu, H. S. Matte, V. P. Dravid and C. N. Rao, *ACS Nano*, 2012, **6**, 5635–5641.

58 B. Chamlagain, Q. Cui, S. Paudel, M. M.-C. Cheng, P.-Y. Chen and Z. Zhou, 2018, arXiv:1808.08303, DOI: [10.48550/arXiv.1808.08303](https://doi.org/10.48550/arXiv.1808.08303).

59 T. Li, T. Tu and Y. Sun, *Nat. Electron.*, 2020, **3**, 473–478.

60 K. Liu, B. Jin, W. Han, X. Chen, P. Gong, L. Huang, Y. Zhao, L. Li, S. Yang, X. Hu, J. Duan, L. Liu, F. Wang, F. Zhuge and T. Zhai, *Nat. Electron.*, 2021, **4**, 906–913.