Research article

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Polarization-sensitive photodetectors based on three-dimensional molybdenum disulfide (MoS₂) field-effect transistors

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Abstract: The molybdenum disulfide (MoS₂)-based photodetectors are facing two challenges: the insensitivity to polarized light and the low photoresponsivity. Herein, three-dimensional (3D) field-effect transistors (FETs) based on monolayer MoS₂ were fabricated by applying a self-rolled-up technique. The unique microtubular structure makes 3D MoS₂ FETs become polarization sensitive. Moreover, the microtubular structure not only offers a natural resonant microcavity to enhance the optical field inside but also increases the light-MoS₂ interaction area, resulting in a higher photoresponsivity. Photoresponsivities as high as 23.8 and 2.9 A/W at 395 and 660 nm, respectively, and a comparable polarization ratio of 1.64 were obtained. The fabrication technique of the 3D MoS₂ FET could be transferred to other two-dimensional materials, which is very promising for high-performance polarization-sensitive optical and optoelectronic applications.

Keywords: 3D; FET; MoS₂; photodetector; polarization.

A light wave contains the basic information of amplitude, phase, frequency and polarization, among which people are always interested in amplitude, phase and frequency

information. In fact, the polarization is also a very important feature. After reflection at or transmission through an object, the polarization spectral information of the object would be extracted from the light. The polarization-sensitive photodetectors show good application prospects in remote sensing imaging [1], environmental monitoring [2, 3], medical detection [4] and military equipment [5, 6]. Nowadays, the photodetectors are developing towards miniaturized, modularized and highly integrated devices [7]. Owing to their unique structural characteristics, two-dimensional (2D) materials show great potential in such applications [8–11].

Molybdenum disulfide (MoS₂), a prototypical 2D layered semiconductor, is an appealing material for high-performance optical and optoelectronic applications, because of its excellent optical and electrical properties [12–16]. In contrast to graphene, monolayer MoS₂ exhibits a natural direct band gap and a higher light absorption coefficient [11, 15, 17]. Furthermore, unlike black phosphorous, high-quality, large-scale and air-stable MoS₂ can be grown maturely [18–20]. However, there are two factors limiting the development of MoS₂ in high-performance and polarization-sensitive photodetectors. Intrinsic MoS₂ is insensitive to polarized light because of its in-plane crystal symmetry [10, 21], and monolayer MoS₂ would absorb only 10% of the incident light, giving a relative low photoresponsivity. The photoresponsivity of the first reported monolayer MoS₂ photodetector was only 7.5 mA/W [22]. To increase the sensitivity to polarized light, in 2019, Tong et al. [21] transferred a metal-MoS₂-metal photodetector to a flexible polydimethylsiloxane (PDMS) substrate and demonstrated that the photodetector became polarization sensitive under uniaxial tensile strains (1–4%). For the second limitation, several approaches have been proposed to modestly enhance the photoresponsivity of MoS₂-based photodetectors, such as localized surface plasmon resonance [23–25], chemical doping [26, 27], Fabry–Pérot cavity [28] and heterojunctions [12, 29]. However, the strategies that solve the two limitations simultaneously using

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monolayer MoS₂ have not been reported, which are urgently desired in high-performance polarization-sensitive optical and optoelectronic applications.

Here, three-dimensional (3D) MoS₂ field-effect transistors (FETs) were fabricated using the self-rolled-up technique [30], which can be used as high-performance and polarization-sensitive photodetectors. The microtubular 3D MoS₂ FET provides a natural optical resonator microcavity to enhance the internal light field and increase the light-MoS₂ reaction area [31, 32], giving a high photoresponsivity of 23.8 A/W at the wavelength of 395 nm. Furthermore, the microtubular structure makes the 3D MoS₂ FET photodetectors become sensitive to linear-polarized light, and a polarization ratio of 1.64 is obtained. The fabrication technique for the 3D MoS₂ FETs is compatible with the existing integrated circuits (IC) planar processes and could be extended to other 2D materials.

A self-rolled-up technique was adopted to fabricate the 3D tubular MoS₂ FETs, which had been proposed in our previous work [31]. First, highly compressive and tensile strained silicon nitride (SiN_x) nanomembranes with thicknesses of 120 and 80 nm, respectively, were deposited on an aluminum (Al) sacrificial layer (50 nm). Second, a gate electrode (Cr/Au, 10 nm/30 nm) was sputtered on the SiN_x membranes, followed by covering of a SiO₂ dielectric layer (30 nm). Third, a single-layer chemical vapor deposition (CVD)-grown MoS₂ (6Carbon Technology, Shenzhen, LLC) was transferred onto the SiO₂ dielectric layer from the sapphire substrate using the wet-transfer potassium hydroxide (KOH) approach [33], followed by oxygen plasma etching for patterning the MoS₂ layer. Subsequently, the source and drain electrodes (Cr/Au, 10 nm/50 nm) were deposited on the MoS₂ layer, and the 2D buried-gate MoS₂ FET was obtained. Then, the strained SiN_x membranes rolled the 2D MoS₂ FET into a 3D tubular structure on selective etching of the underlying Al layer. Finally, after the washing and drying steps, the 3D MoS₂ FET was obtained (Figure 1a). Detailed information about the fabrication process can be found in Figure S1 in Supplementary material.

The 3D MoS₂ FETs were characterized by the environmental scanning electron microscope (FEI Quanta 200 ESEM FEG) and Raman spectroscopy (LabRam HR-800, Horiba Jobin Yvon). The electrical and optical measurements were carried out using a semiconductor parameter analyzer (B1500A, Keysight), a probe station (Summit 12000, Cascade) and a light-emitting diode (LED) light curing system. To explore the polarization characteristics of the 3D MoS₂ FETs, the fabricated 1.5 cm × 1.5 cm chip was diced into smaller chips with a size of 5 mm × 5 mm. Then the chip was bonded onto a printed circuit board with gold

(Au) wires using a multiprocess gold wire ball bonder (4522, K&S), as shown in Figure S2. A diode-pumped solid-state laser (class IIIB laser products) was used to provide the polarized light with a wavelength of 635 nm. A precision source/measure unit (B2911A, Agilent) was used to supply the source-drain bias voltage and monitor the source-drain current of the 3D MoS₂ FET simultaneously. All electrical and optical measurements were performed at room temperature in ambient conditions.

The scanning electron microscopy (SEM) image of high-ordered 3 × 4 array of 3D MoS₂ FET microtubes on the silicon substrate is displayed in Figure 1c. It is worth noting that the microtubes are almost homogeneous along the axial, proving a perfect and controllable self-rolled-up process. The fabrication process of the 3D MoS₂ FETs is compatible with the silicon-based integrated circuit process, enabling mass production and integration with low-cost and high-performance complementary metal oxide semiconductor read-out and postprocessing circuits. A zoomed-in view of the microtube containing five 3D MoS₂ FETs is shown in Figure 1d. Each 3D MoS₂ FET is rolled up from a planar 2D MoS₂ FET with dimensions of 30 μm × 200 μm (length × width). The ratio of the chip area occupied by the 3D MoS₂ FET to that of the 2D MoS₂ FET is about 1/3. With the increase in the rolled-up windings, the ratio can be further reduced significantly. It can be clearly seen from Figure 1e that the source, drain and gate electrodes were well constructed, with widths of 100, 100 and 10 μm, respectively, and the outer diameter of the 3D MoS₂ FET is 62 μm. From the side view of the 3D MoS₂ FET (Figure 1f), the microtube is hollow and the rolled-up winding number is about one. The diameter of the 3D MoS₂ FET is mainly determined by the parameters of the compressively and tensile strained SiN_x membranes, such as strain values and membrane thickness, whereas the rolled-up winding numbers can be easily and precisely controlled by changing the dimensions of the planar 2D device, as discussed in our previous work [31]. Recently, Saggau et al. demonstrated that the yield and quality of the rolled-up microtubes could be significantly improved by replacing the wet-release process of the rolled-up technique with a dry-release approach, and wafer-scale active optical microtube resonators with record high *Q*-factors up to 7800 were obtained [34].

Raman spectroscopy was used to characterize the 2D and 3D MoS₂ layers, where the MoS₂ thickness was investigated via the energy difference between *E*_{2g}¹ and *A*_{1g} Raman modes. Figure 1b shows the Raman spectra of the 2D and 3D tubular MoS₂ FETs under a 514-nm excitation laser. Two strong distinct peaks from MoS₂ in the 2D state were clearly observed from the spectra at 385 and 404 cm⁻¹,

Figure 1: The 3D tubular MoS₂ FETs.

(a) Schematic 3D view of the tubular MoS₂ FET; (b) Raman spectra of the 3D MoS₂ FET and 2D MoS₂ FET; (c) the array of 3D MoS₂ FET microtubes; (d) the SEM microimage of a 3D MoS₂ FETs microtube; (e) the zoomed-in image of the 3D MoS₂ FET; (f) the side view of a 3D MoS₂ FET with one rolled-up winding. 2D, two-dimensional; 3D, three-dimensional; FET, field-effect transistor; MoS₂, molybdenum disulfide.

respectively, corresponding to the in-plane E_{2g}^1 and the out of plane A_{1g} phonon modes [33, 35]. The wavenumber difference between E_{2g}^1 and A_{1g} Raman modes is 19 cm^{-1} , which is consistent with that of the previously reported single-layer MoS₂, indicating that the MoS₂ in our devices is single layer [25, 36]. Surprisingly, slight Raman redshifts of

E_{2g}^1 and A_{1g} modes were observed from the rolled-up MoS₂, where the redshifts of E_{2g}^1 and A_{1g} modes were up to -3 cm^{-1} (ΔE_{2g}^1 , from 385 to 382 cm^{-1}) and -2 cm^{-1} (ΔA_{1g} , from 404 to 402 cm^{-1}), respectively. More Raman spectra of the 2D and 3D MoS₂ FETs can be found in Figure S3. From the previous research works, it has been demonstrated that

strain can be introduced into the curved thin films because of the curvature effect [37, 38]. The redshifts of E_{2g}^1 and A_{1g} modes of our rolled-up MoS₂ are comparable to that of the wrinkled MoS₂ layers [39], which can be attributed to the strain in the rolled-up single-layer MoS₂ [21, 39].

The electrical properties of the MoS₂ FET before and after the rolled-up process were investigated by measuring the transfer characteristics of the 2D and 3D MoS₂ FETs, using a semiconductor parameter analyser. Counterparts of the 2D MoS₂ FET show an ideal transfer characteristic (I_{ds} vs. V_{gs}), as indicated in Figure 2a. At a source–drain voltage of 1 V, the source–drain current on–off ratio is as high as 10^4 , which is comparable with the early reported single-layer MoS₂ phototransistors [22]. The transfer characteristic of the 3D MoS₂ FET is shown in Figure 2b, where the current on–off ratio is ~30 within a small gate voltage range from –2 to 2 V. This

relative small gate voltage interval was chosen because the 30-nm-thick SiO₂ dielectric layer might be broken down at higher gate voltages. The source–drain current on–off ratio of the 3D MoS₂ FET can be further improved by thermal annealing treatment, which would remove the photoresist residue and improve the electrode contact [22].

To explore the photoelectrical properties of the 3D MoS₂ FETs, a 660-nm LED was used for irradiation, as presented in the schematic diagram of the experiment setup (Figure 3a). Because the spot size of the light is much larger than the effective area of the 3D MoS₂ FET, it is assumed that the light intensity illuminated on the device is evenly distributed. Figure 3b shows the temporal response of the 3D MoS₂ FET photodetector under the 660-nm LED illumination with an incident light intensity of 14.7 mW/cm², under the condition that the source–drain bias voltage (V_{ds}) and gate voltage (V_{gs}) are 1 and 0 V, respectively. When the light is switched on, the source–drain current (I_{ds}) of the 3D MoS₂ FET increases immediately and significantly and then saturates gradually. Once the light is switched off, I_{ds} decreases to its original level immediately. After several on–off cycles, the photoresponse of the 3D MoS₂ FET becomes stable. To explore the photoresponse speed, the rise time (τ_{rise}) is defined as the period for I_{ds} increasing from 10 to 90% of its steady state value, whereas the decay time (τ_{decay}) is defined as the period for I_{ds} decreasing from 90 to 10% of its steady state value. It can be seen from Figure 3c that the rise and decay times of the 3D MoS₂ FET photodetector are 690 and 110 ms, respectively. More experiments found that the photoresponse speed is related to the light wavelength and the rolled-up winding numbers of the 3D MoS₂ FET, as shown in Figure S4. Under the 395-nm LED illumination, a faster decay time of 40 ms was obtained by using a 3D MoS₂ FET with only one rolled-up winding. The photoresponse times of our devices are comparable with the previously reported MoS₂ phototransistors [40–42]. The photoresponse speed could be further improved by applying a high bias voltage or a short gate pulse [42]. We also fabricated control samples without the MoS₂ layer, with other parameters as same as the 3D MoS₂ FETs (Figure S5a). Under the same conditions, no photoresponse was observed with the control samples (Figure S5b). These results indicate that the photoresponse of the 3D MoS₂ FET was stem from the MoS₂ layer.

The photocurrent (I_{ph}) is defined as $I_{ph} = |I_{illumination} - I_{dark}|$, where $I_{illumination}$ and I_{dark} represent the state of I_{ds} under light illumination and in dark, respectively. Figure 4a shows I_{ph} of the 3D MoS₂ FETs with different rolled-up winding numbers, under different light intensities ranging from 2.6 to 219 mW/cm². For both 3D MoS₂ FETs with one winding and two windings, I_{ph} increases with the increase in light intensity because of more electron-hole pairs being

Figure 2: Electrical properties of MoS₂ FETs.

(a) Ideal transfer characteristic of 2D MoS₂ FET; (b) transfer characteristic of 3D MoS₂ FET. 2D, two-dimensional; 3D, three-dimensional; FET, field-effect transistor; MoS₂, molybdenum disulfide.

Figure 3: Photoresponse properties of the photodetector based on the 3D MoS₂ FET.

(a) Schematic diagram of the experiment setup; (b) the temporal response of the 3D MoS₂ FET photodetectors at $V_{ds} = 1$ V and $V_{gs} = 0$ V, under 660-nm LED illumination with the incident light intensity of 14.7 mW/cm²; (c) the time-resolved photoresponse of the 3D MoS₂ FET. 3D, three-dimensional; FET, field-effect transistor; MoS₂, molybdenum disulfide.

excited under higher light intensity. Under the same light intensity, I_{ph} of the 3D MoS₂ FET with two windings (insert in Figure 4a) is higher than that with one winding. The reasons for this phenomenon will be discussed in detail later. It can also be seen that the discrepancy in I_{ph} between two windings and one winding becomes significant with the increase in the light intensity. This is attributed to that light with higher intensity is easier to penetrate through the rolled-up SiN_x/SiO₂ windings. Hence, 3D MoS₂ FETs with two windings were measured in our following experiments to obtain a better performance. Photoresponsivity (R), defined as the ratio of photocurrent to effective incident light power, is a key indicator of photodetector performance. The photoresponsivity of our photodetectors is intensively explored by measuring the source-drain bias voltage-, gate voltage-, illumination intensity-dependent photoresponse (Figure S6). Unless otherwise specified, all the following measurements were performed under the light intensity of 2.6 mW/cm² and 5.5 mW/cm² at the wavelengths of 395 and 660 nm, respectively. Approximately linear scaling of the photoresponsivity with source-drain bias voltage (V_{ds}) for different incident light wavelengths is shown in Figure 4b. Within the interval for V_{ds} from 1 to 7 V, the photoresponsivities increase from 0.9 to 11.9 A/W and from 0.1 to 1.1 A/W at the wavelengths of 395 and 660 nm, respectively, because high source-drain bias voltage could promote the separation and suppress the recombination of photogenerated electron-hole pairs [19, 23, 43].

The gate voltage-dependent photoresponsivity of the 3D MoS₂ FET at different wavelengths is shown in Figure 4c, where the photoresponsivities decrease as the gate voltage increases above 0 V, whereas photoresponsivities increase as the voltage increases below 0 V. At the wavelength of 395 nm, a maximum photoresponsivity of 23.8 A/W is obtained when $V_{gs} = -4$ V and $V_{ds} = 5$ V, which is three orders of magnitude higher than that of a single-layer MoS₂ phototransistor (7.5 mA/W was obtained at $V_{gs} = 50$ V and $V_{ds} = 1$ V) [22]. Meanwhile, at the wavelength of 660 nm, the photoresponsivity is up to 2.9 A/W, which is much higher than that of the recently reported plasmon-enhanced MoS₂ photodetectors in the visible region [23–25] (a few mW/A obtained under the condition of V_{ds} up to 16 V [25]). The temporal photoresponses corresponding to the maximum photoresponsivities at 395 and 660 nm are shown in Figure S7. The external quantum efficiency (EQE) of a photodetector can be expressed as the following equation [11]:

$$EQE = \frac{hc}{e\lambda} \cdot R \quad (1)$$

where h is the Planck constant, c is the speed of light in vacuum, e is the electron charge, λ is the wavelength of the incidence light, and R is the photoresponsivity. Using the

Figure 4: Photoelectrical properties of the 3D MoS₂ FET photodetectors.

(a) Dependence of photocurrent on light power density with different rolled-up winding numbers at $V_{ds} = 8$ V and $V_{gs} = 0$ V under 395-nm illumination. The inset shows the side view of the SEM microimage for the 3D MoS₂ FET with two rolled-up windings; (b) photoresponsivities of the device with two windings at different source–drain voltages, in which V_{gs} is 0 V; (c) the relationship between gate voltage and photoresponsivity, in which V_{ds} is 5 V; (d) the normalized photoresponsivities of 2D and 3D MoS₂ FET photodetectors at different light power densities, where R_0 is the photoresponsivity of the 2D MoS₂ FET at $V_{ds} = 6$ V, $V_{gs} = 0$ V and light power density of 219 mW/cm². The dimension of the conductive channel for the 2D MoS₂ FET is 30 μm × 200 μm (length × width). 2D, two-dimensional; 3D, three-dimensional; FET, field-effect transistor; MoS₂, molybdenum disulfide.

above equation, the EQEs at 395 and 660 nm of the 3D MoS₂ FETs with two rolled-up windings can be calculated as 7486 and 569%, respectively. The high photoresponsivities and EQEs stem from the photogating and photoconducting effects in MoS₂ photodetectors [44, 45], and the unique 3D structure of our devices. Lopez-Sanchez et al. demonstrated that the photoresponsivity and EQE of MoS₂ photodetectors increase approximately linearly with the decreasing of the illumination power intensity and realized a photoresponsivity of 880 A/W and an EQE of $2 \times 10^5\%$ at a wavelength of 561 nm, under an illumination power intensity of 24 μW/cm² [42]. Recently, Kumar et al. fabricated UV photodetectors based on multilayer MoS₂ grown by the pulsed-laser deposition technique and obtained a photoresponsivity of 3×10^4 A/W and an EQE of $1 \times 10^7\%$ at a wavelength of 365 nm, under an illumination power

intensity of ~80 nW/cm² [46]. Considering that the illumination power intensity used in our photoelectrical experiments (≥ 2.6 mW/cm²) is 2–5 orders of magnitude higher than that used in their experiments (80 nW/cm²–24 μW/cm²), the photoresponsivity and EQE of our devices can be further improved under lower illumination power intensities.

Further experiments demonstrate that the normalized photoresponsivity of the 2D MoS₂ FET with a conductive channel dimension of 30 μm × 200 μm (length × width) is significantly lower than that of the one-winding 3D MoS₂ FET with the same conductive channel dimension and much lower than that of the two-winding 3D MoS₂ FET with a conductive channel dimension of 30 μm × 400 μm, as shown in Figure 4d. The mechanism for the photoresponsivity enhancement will be discussed in the next section. In addition, for all of the 2D and 3D MoS₂ FET

photodetectors, the photoresponsivity decreases with the increase of light intensity. This phenomenon can be explained in terms of trap states present either in MoS₂ or at the interface between the MoS₂ and the underlying SiO₂ layer [47]. Under high light intensities, the density of available states is reduced, resulting in a saturation in photoresponse. This result also indicates that the photoresponsivity of the 3D MoS₂ FET photodetectors can be further improved under lower light intensities [13, 25, 28, 42].

To investigate the mechanism of the photoresponsivity enhancement for the 3D MoS₂ FETs, the optical field (the electromagnetic field) near the 3D MoS₂ FETs has been simulated by the finite element method using the commercial COMSOL Multiphysics® software. Under illumination by normally incident light at a wavelength of 395 nm and an electric field magnitude of $E_0 = 1$ V/m, the electric field magnitude distribution near a 3D MoS₂ FET with one rolled-up winding is shown in Figure 5a. The incident light resonates close to the interior and exterior surfaces of the 3D MoS₂ FET using an evanescent mode, that is, the electric field magnitude decreases exponentially with increasing distance away from the surfaces because of the ingenious microcavity provided by the tubular geometry. Similar phenomenon was also observed in rolled-up 3D graphene FETs, as demonstrated in our previous work [31]. The average relative electric field magnitude (E_{3D}/E_0) at the interior surface of the 3D MoS₂ FET approaches a value of 282. Because higher electric field magnitude at the 3D MoS₂ surface allowed more energy to be absorbed, higher photoresponsivities were obtained with the 3D MoS₂ FET photodetectors. Furthermore, the average E_{3D}/E_0 increases with the increase in rolled-up winding number (Figure 5b), when the other structural parameters such as the diameter and thickness of the SiN_x layer remain the same. The average E_{3D}/E_0 for the 3D MoS₂ FET with one rolled-up winding (282) is about one-fifth of that with two rolled-up windings (1255). The MoS₂-light reaction area of the one-winding 3D MoS₂ FET is only half of that for the two-winding 3D MoS₂ FET. The MoS₂ photoresponse is based on the photogating and photoconducting effects [44, 45]; the two-winding device with a larger surface area would trap more charges than the one-winding device. Thus, the photoresponsivity of the one-winding device is much lower than that of the two-winding device (Figure 4d). Böttner et al. demonstrated that the resonator quality much depended and was very sensitive on the structural properties of the rolled-up microtubes [48]. So, the influences of the diameter and the SiN_x thickness of the 3D MoS₂ FETs on the optical field enhancement have also been simulated, as shown in Figure S8. The results indicate that the average E_{3D}/E_0 remains nearly constant when the diameter of the

Figure 5: Simulation of the optical field of the 3D MoS₂ FETs.

(a) The distribution of the electric field magnitude close to a 3D MoS₂ FET with one rolled-up winding, under the illumination by a surface light source with an operating wavelength of 395 nm and an electric field magnitude of $E_0 = 1$ V/m; (b) the average relative electric field magnitude (E_{3D}/E_0) at the surface of the 3D MoS₂ layer varies with the number of rolled-up windings of the 3D MoS₂ FETs. 3D, three-dimensional; FET, field-effect transistor; MoS₂, molybdenum disulfide.

3D MoS₂ FET increases from 40 to 70 μm, with a fixed SiN_x layer thickness, and when the thickness of the SiN_x layer varies from 150 to 300 nm with a fixed diameter. Detailed information about the simulations can be found in Section 8 of Supplementary material.

To our surprise, an unexpected linear-polarized photoelectrical feature was achieved by our 3D MoS₂ FETs. Figure 6a schematically presents the experimental setup of the polarization sensitivity measurement. A polarized light was obtained after a 635-nm laser passing through a polarizer, where the light polarization direction can be adjusted by rotating the polarizer. The angle between the

Figure 6: The polarized light-dependent photoresponse of the 3D MoS₂ FETs.

(a) The schematic diagram of the polarization detection; the polarization angle (θ) is defined as the angle between the incident light polarized direction and the axis direction of MoS₂ roll. (b) Polarization dependence of the photocurrent for the 3D MoS₂ FET

light polarization direction and the 3D MoS₂ FET microtube axis direction is defined as the polarization angle (θ), as shown in Figure 6a. Figure 6b shows the polarization angle versus the normalized photocurrent of the 3D MoS₂ FET at different source–drain bias voltages. It can be obviously seen that the photocurrent is highly sensitive to the polarization angle. When the polarization angle varies from 0° to 360°, the photocurrent exhibits a periodical behavior. The relationship between the polarization angle and photocurrent could be well fitted by a sinusoidal function. The photocurrent peaks locate at 90° and 270°, whereas the valleys locate at 0° and 180°. When the source–drain bias voltage increases from 0.5 to 0.8 V, the positions of the photocurrent peak and valley values retain unchanged, although the photocurrent increases significantly. The increase in photocurrent can be explained by that a higher source–drain bias can facilitate the separation of photo-generated carriers and reduce the recombination probability of photogenerated carriers [43]. The polarization ratio is defined as $I_{ph,peak}/I_{ph,valley}$, where $I_{ph,peak}$ and $I_{ph,valley}$ are the photocurrent peak and valley values, respectively. From Figure 6b, the polarization ratios for both $V_{ds} = 0.5$ V and $V_{ds} = 0.8$ V are 1.64. This polarization ratio is comparable with that of a polarization-sensitive photodetector based on high-anisotropy rhenium diselenide (ReSe₂) nanosheets (polarization ratio of 2) [49], whereas the photoresponsivity of the ReSe₂ device is 1.5 mA/W at 633 nm [49], which is three orders of magnitude lower than that of our device (2.9 A/W). The polarization-sensitive optical properties of the devices can also be investigated using other approaches such as polarized Raman and absorption [50, 51].

Figure 6c shows the polarization angle-dependent normalized photoresponsivities of two randomly chosen 3D MoS₂ FETs. For both device 1 and device 2, the photoresponsivity peaks locate at ~90° and ~270°, whereas the valleys locate at ~0° and ~180°, and the polarization ratios are 1.64 and 1.63, respectively, indicating that the polarization measurements for the 3D MoS₂ FETs are repeatable. As the 3D MoS₂ FET microtube acts as an optical resonator and the resonant light modes in rolled-up microtubular cavities are highly polarized [52], the polarization-sensitive optoelectronic property of the 3D MoS₂ FET photodetectors can be attributed to the symmetry of the microtubular cavity.

under different source–drain bias voltages, where $I_{ph,0}$ represents the photocurrent measured at the polarization angle of 0°. (c) The relationship between the polarization angle and normalized photoresponsivity of the 3D MoS₂ FET photodetector in polar coordinates. 3D, three-dimensional; FET, field-effect transistor; MoS₂, molybdenum disulfide.

Recently, Tong et al. demonstrated that uniaxial tensile strain can break the crystal symmetries of 2D monolayer MoS₂ by stretching the underlying PDMS substrate and make the MoS₂/PDMS photodetector sensitive to the polarized light [21]. Although the rolled-up process inevitably introduces strain in the MoS₂ layer, the strain in the 3D MoS₂ layer of our devices is very small ($1.54 \times 10^{-6}\%$, Figure S9), which is about six orders of magnitude lower than that (1–4%) in the 2D MoS₂ layer of the MoS₂/PDMS photodetectors. Thus, the effect of strain in the 3D MoS₂ layer on the polarization-sensitive optoelectronic property of the 3D MoS₂ FET photodetectors is negligible. The microtubular structure of the 3D MoS₂ FET photodetectors provides not only an effective way to enhance the photoresponsivity but also a new idea to realize the detection of polarized light. This device structure can also be transferred to other isotropic 2D materials, which is very attractive for high-performance polarization-sensitive optical and optoelectronic applications.

In summary, a polarization-sensitive and high-sensitivity photodetector based on 3D MoS₂ FETs was demonstrated for the first time in this article. A polarization ratio of 1.64 was obtained for our 3D MoS₂ FET with two rolled-up windings. The photoresponsivities of the photodetectors were measured up to 23.8 and 2.9 A/W at the wavelengths of 395 and 660 nm, respectively, which are much higher than that of planar monolayer MoS₂-based photodetectors. The 3D MoS₂ FET photodetectors also exhibit a fast response speed of ~40 ms. These results indicate that the unique tubular structure can not only introduce the polarization-sensitive property to monolayer MoS₂-based photodetectors but also significantly improve its photoresponsivity. The integration of MoS₂ with 3D tubular structure provides a new idea for developing miniaturized and high-performance photodetectors, especially polarization-sensitive photodetectors.

Supporting information

See Supplementary material for the detailed fabrication process of the 3D MoS₂ FETs, 3D MoS₂ FET sample preparation for the polarization experiments, Raman spectra of MoS₂ before and after the rolled-up process, response times of 3D MoS₂ FETs with different rolled-up winding numbers, photoresponse of the 3D rolled-up microtubes without the MoS₂ layer, the source–drain bias voltage– and gate voltage–dependent photoresponse under different incident light intensities, temporal photocurrent response of the 3D MoS₂ FET at a gate voltage of –4 V, simulation of the optical field of the 3D MoS₂ FETs, and calculation of the strain in the rolled-up 3D MoS₂ layer.

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