Monolayer molybdenum disulfide (MoS$_2$) with a high predicted intrinsic mobility of ~410 cm$^2$/V at room temperature, shows great potential for application in sensors and optoelectronics as a result of good electrical performance and photoemission. Compared with the photoresponsive photodiodes, photoresponsive field-effect transistors exhibit higher sensitivity and lower noise. And, pentacene is a small molecule organic semiconductor and has high absorption in the visible region. Here, we reported on a high-performance photoresponsive field-effect transistor based on MoS$_2$/pentacene inorganic/organic planar heterojunction. The results showed that the device demonstrated superior performance. Under 655 nm light illumination, the device exhibited an ultrahigh photoresponsivity of $10^3$ A/W, a maximum photosensitivity of $1.8 \times 10^3$ and a high external quantum efficiency of around 195%, respectively.

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optoelectronics [11]. Among them, monolayer molybdenum disulfide (MoS2) with unusual physical properties, which is composed of S-Mo-S triple layers, has been paid more and more attention [12]. When the bulk MoS2 is thinned to few layer ranges, an indirect-to-direct bandgap transition occurs at the time that the bandgap range is in the range of from 1.2 to 1.8 eV [13,14]. For example, Radisavljevic et al. recently reported that single-layer MoS2 transistors had high mobility and ultralow standby power dissipation [15]. Besides, extensive efforts have been devoted to obtain thin-layer MoS2 including the chemical or mechanical exfoliation from bulk crystals (liquid exfoliation [16] and hydrothermal synthesis [17]) and the bottom-up growth method (physical vapor deposition [18] and chemical vapor deposition (CVD) [19]). In particular, most researches focus on obtaining large-area and high quality monolayer MoS2, and improving performance of inorganic electronic devices based on it, little research has been done on combining two-dimensional materials with organic semiconductor materials in application to the devices. In addition, pentacene is one of the most popular small-molecule organic semiconductors used in organic solar cells, organic thin-film transistors and organic light emitting diodes because of its excellent electrical properties and the ease with which it can be purified and processed [20]. It is noteworthy that pentacene with good absorption in ultraviolet and visible light has also been extensively researched [20]. Previous studies have been theoretically concentrated on researching the transporting characteristics of MoS2/pentacene heterojunction [21–27]. In particular, Jariwala et al. reported the gate-tunable, van der Waals p–n heterojunctions from pentacene and MoS2 [24]. After, Kim et al. and Homan et al. investigated the transport properties of pentacene/monolayer MoS2 p–n heterojunction, respectively [22,27]. However, to our best knowledge, it has not been practically used in photovoltaic device. So far, most of the MoS2/pentacene heterojunctions are fabricated by mechanical exfoliated transfer of monolayer MoS2 [21]. Generally, although this method could be suitable for fundamental research and proof-of-concept device fabrication, however, mechanical cleavage is not suitable for large-scale production due to the absence of layer number controllability, thus limiting actual production and application [28]. Consequently, CVD may be considered as a promising route for the mass production of large-area and high quality monolayer MoS2 with the ease of processing and synthesizing.

In this study, we reported on an ultrahigh photoresponsivity field-effect transistor based on MoS2/pentacene inorganic/organic planar heterojunction utilizing SiO2 as the bottom gate dielectric, which makes full use of the advantages of the high optical absorption coefficient of pentacene and the high mobility of monolayer MoS2. Under 655 nm illumination, the device exhibited an ultrahigh photoresponsivity of 103 A/W, a maximum photosensitivity of 1.8 × 104 and a high external quantum efficiency of around 195%, respectively.

2. Experimental details

2.1. Materials and device-preparation

Pentacene was purchased from Acros Co. Ltd and used as received. Monolayer MoS2 was fabricated on the mica using chemical vapor deposition (CVD) techniques via adopting the prescription of Ref. [29]. The illustrations of monolayer MoS2 is shown in Fig. 1a, as similar to the graphene, and covalent bonds are formed between Mo and S atoms in the crystal [12]. Furthermore, Fig. 1b shows the molecular structure and space filling model of pentacene, which is a polycyclic aromatic hydrocarbon consisting of five linearly-fused benzene rings [29].

The device was fabricated with bottom-gate and top contact geometry, as shown in Fig. 1c (3D model) and Fig. 1d (cross-sectional structure). Before fabrication, the SiO2 (300 nm)/Si substrate was cleaned by ultrasonication using acetone, ethanol and deionized water for 10 min at each step. Afterwards, the substrates were dried with nitrogen gas flowing and then baked in a vacuum chamber with a temperature of 60 °C for 20 min. Next, the single-layer MoS2 was transferred to the SiO2 substrate which were transferred to the vacuum chamber. Then, 50-nm-thick pentacene film was vacuum-deposited on the single-layer MoS2 under a vacuum of 2 × 10−2 Pa at a deposition rate of 0.01 nm/s. Finally, the source/drain electrodes were also vacuum-deposited through a shadow mask which defined a channel length (L)/width (W) of 50 μm/2 mm, respectively. At the same time, a single layer device with monolayer MoS2 as the active layer on top of the SiO2 gate-insulator with Au top source–drain contacts was fabricated for comparison.

2.2. Measurements and characterizations

All the measurements were carried out immediately after the devices were fabricated. The prepared samples were systematically characterized using X-ray photoelectron spectroscopy (Kratos Axis Ultra DLD), SEM (Hitachi, S-4800) and Raman spectroscopy (HORIBA Jobin Yvon, LabRAM HR800), respectively. The illumination light source was a commercial laser diode with 655 nm wavelength. The variation of optical power was realized through utilizing different neutral filters. For optical absorption measurements, monolayer MoS2 was transferred to cleaned quartz substrate and 50-nm-thick pentacene film was vacuum-deposited on cleaned quartz substrates. MoS2/pentacene bilayer films were prepared as 50-nm-thick pentacene vacuum-deposited on monolayer MoS2 transferred to cleaned quartz substrates. And TU-1901 spectrometer was used to measure the optical absorption of these films. Finally, I–V characteristics of the devices were measured by an organic semiconductor measuring system in a vacuum chamber (vacuum level, ~10−2 Pa).

3. Results and discussion

To confirm the monolayer MoS2 formed by using chemical vapor deposition (CVD), we measured XPS (X-ray photoelectron spectroscopy) spectrum of the sample, as shown in Fig. 2. It can be seen from Fig. 2a, the spectrum of Mo 3d orbit shows two peaks at 232.6 and 229.4 eV, respectively, which can be the doublet of Mo 3d3/2 and Mo 3d5/2. For each doublet, the peak positions of the 3d5/2 and 3d3/2 orbit are characteristic for molybdenum (Mo) in a formal oxidation state [29]. Finally, Fig. 2b shows that the binding energy for S 2p1/2 and S 2p3/2 are respective 163.3 and 162.1 eV, consistent with the S2+ type ligands [28]. All the measured binding energies are consistent with the reported values for MoS2 [29]. An area of the MoS2 sample was further identified to explore MoS2 layer thickness. It is notable that the peak frequency difference between A2g and E1g modes (Δ) can be used to identify the layer number of MoS2 sample in Fig. 2c. The value of Δ (20 cm−1) confirms the existence of monolayer MoS2 film as reported by previous works on account of exfoliated samples [18,30,31]. Then, Fig. 2d shows the absorption spectrum of the MoS2 sample transferred on quartz, the result of which is in reasonable agreement with the characteristic of monolayer MoS2 transferred on quartz [32]. The direct band gap energy (Eg) of the MoS2 sample can be estimated by its absorption spectra according to the simplified formula of $a \nu h = A (\nu h − E_g)^{1/2}$, where $\alpha$, $\nu$, $E_g$ and $A$ are the absorption coefficient, photon energy with frequency $\nu$, band gap and constant, respectively. As can be seen in the inset of Fig. 2d, $E_g$ is calculated to be 1.79 eV, which further proves that this sample is
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