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Full Length Article

# High performance photodiode based on $MoS_2$/pentacene heterojunction

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ABSTRACT

Photodiodes based on monomolecular layer $MoS_2$/pentacene heterojunction were fabricated and characterized. Similar to other organic photodetectors, the device performances are strongly dependent on the incident optical power. The unoptimized device with Al top electrode, exhibited a fairly high photo responsivity of 0.27 A/W, external quantum efficiency (*EQE*) of 51.3% and specific detectivity ($D^*$) of $4.81 \times 10^{11}$ Jones for red light of 655 nm wavelength. These performances exceed not only the Schottky photodiode based on pentacene, and mono or few layer $MoS_2$ based photodiodes, but also the most organic photodiodes reported recently. More importantly, with Au as the top electrode, the device performances could be further improved, the photoresponsivity, *EQE* and $D^*$ reached 0.31 A/W, 58.1%, and $1.55 \times 10^{13}$ Jones, respectively at the same voltage biasing.

## 1. Introduction

Photodetectors are used in many electronic systems ranging from telecommunications, imaging and security fields. Due to light weight, being potentially flexible, organic photodiodes (OPDs) are the focus of much current research [1,2]. Pentacene is a well-known p-type organic small molecule semiconductor belong to a small number of with relatively high hole mobility in the range of 0.38–1.7 $cm^2$/Vs that suited for fabrication of organic field-effect transistors [3,4], organic light-emitting field-effect transistors [5], static induction transistor [6] and non-volatile organic transistor memories [7]. Having high optical absorption in visible wavelength region centered at around 650 nm, pentacene is also widely used to fabricate phototransistors [8,9], organic solar cells [10] and OPDs [11,12].

Monolayer $MoS_2$ is a direct-band gap semiconductor [13] with high charge carrier mobility. Effective electron mobility in the range of 1–480 $cm^2$/Vs [14–18] depending on device structure, dielectric environment and processing [17,19] were reported; Exploiting the high mobility of monolayer $MoS_2$, high performance field-effect transistors [20,21], with a high on/off ratio of $10^8$ was realized [20]. With a direct bandgap of 1.8 eV [22], monolayer $MoS_2$ exhibits strong optical absorption in the visible wavelengths [23]. High performance $MoS_2$ based PDs [24,25], and phototransistors [23,26,27] were constructed.

In this communication, we report on high performance photodiodes based on $MoS_2$/pentacene heterojunction. The PD with $MoO_3$/Al top electrode exhibited a high photoresponsivity of 0.27 A/W, external quantum efficiency of 51.3%, photo-to-dark current ratio of $1.6 \times 10^4$, and specific detectivity of $4.81 \times 10^{11}$ Jones. More importantly, by replacing Al with Au as the top electrode, the performance could be further improved, above parameters reached 0.31 A/W, 58.1%, $9.2 \times 10^5$, and $1.55 \times 10^{13}$ Jones respectively.

## 2. Experimental details

The device structure is schematically illustrated in Fig. 1. Indium Tin Oxides (ITO) glass with sheet resistance of 15 Ω/sq was patterned into strips of 2 mm width, and sequentially cleaned ultrasonically by acetone, ethanol and de-ionized water, and were dried with $N_2$ gas blowing and baked in an oven with a temperature of 60 °C for 30 min. Monolayer $MoS_2$ was fabricated on the mica by using chemical vapor deposition (CVD) [28]. A poly (methyl methacrylate) (PMMA) thin film was spin-coated on the $MoS_2$/ mica to peel-off $MoS_2$ thin layers from mica and transfer them onto ITO substrates using PMMA-mediated nanotransfer printing [29].

The ITO/$MoS_2$ sample was backed in a vacuum oven at a temperature of 60 °C. A Pentacene layer of 100 nm thick and $MoO_3$ layer of

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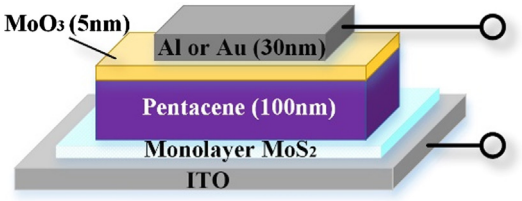


**Fig. 1.** Schematic structure of the photodiode based on $MoS_2$/pentacene heterojunction.

5 nm were vacuum deposited sequentially on $MoS_2$, respectively. The device fabrication was completed by vacuum deposition of 30 nm thick Al (denoted as Al-device) or Au (denoted as Au-device) film. During thermal evaporation, the vacuum was kept better than $2 \times 10^{-3}$ Pa.

TU-1901 spectrometer was used to measure the optical absorption of films. LabRam HR 800 Raman Spectrometer was used to measure Raman spectroscopy. And the surface morphology of thin films was characterized by Agilent 5500. A laser diode with a wavelength of 655 nm and power intensity of 170 mW/cm$^2$ was used as the light source. The variation of optical power was realized though utilizing neutral filters of various transmittances. By the measurement, the sample was positioned in a chamber with rotary pump vacuum (~10 Pa), and the current voltage characteristics was measured by using an automatic measure system.

## 3. Results and discussions

Fig. 2(a) shows the UV–Vis absorption of monolayer $MoS_2$, pentacene (50 nm) and mono-layer $MoS_2$/pentacene (50 nm) films on quartz substrates. It is seen that the onset wavelength of absorption of monolayer $MoS_2$ is 690 nm, corresponding to a band width of 1.8 eV, which is near that reported in literatures [22]. The absorption dominates in the blue light wavelength region of 400–500 nm, while that of monolayer $MoS_2$/pentcene is nearly the linear sum absorption of $MoS_2$ and pentacene, and having absorption maximums at the wavelength of 590 and 655 nm. Fig. 2(b) is the Raman spectra of the $MoS_2$ monolayer film grown on mica substrates. It is worth noting that two characteristic peaks at 386.4 and 406.4 cm$^{-1}$ are caused by in-plane vibration of Mo and S atoms ($E^1_{2g}$) and out-of-plane vibration of S atoms ($A_{1g}$), respectively. The value of difference between $A_{1g}$ and $E^1_{2g}$ modes (20 cm$^{-1}$) verifies the existence of monolayer $MoS_2$ film as reported by previous literature [30,31]. As shown in Fig. 2(c)(d), we demonstrated that the thickness of $MoS_2$ is about 6–8 Å by AFM, consistent with the theoretical thickness of 6.15 Å [32]. In summary, we confirm that the synthesized $MoS_2$ film is monolayer by absorption spectra, Raman spectra and AFM, respectively. The $MoS_2$ monolayer film with high-quality is one of the keys to fabricate $MoS_2$/pentacene heterojunction devices.

### 3.1. Characterization of the OPD with Al top electrode

Fig. 3 shows the *I-V* characteristics of the OPD with Al top electrode (Al-device) at reverse bias (ITO electrode being negatively biased) both in the dark and under illumination. It is seen that the currents under illumination are much larger than that in the dark. For example, at $V_d = -15$ V, the dark current, $I_{dark}$ = 39.4 nA, while that under illumination of 0.015 mW/cm$^2$ is 209 nA, 5.2 times as large as the dark current. For a given reverse bias voltage, the current under

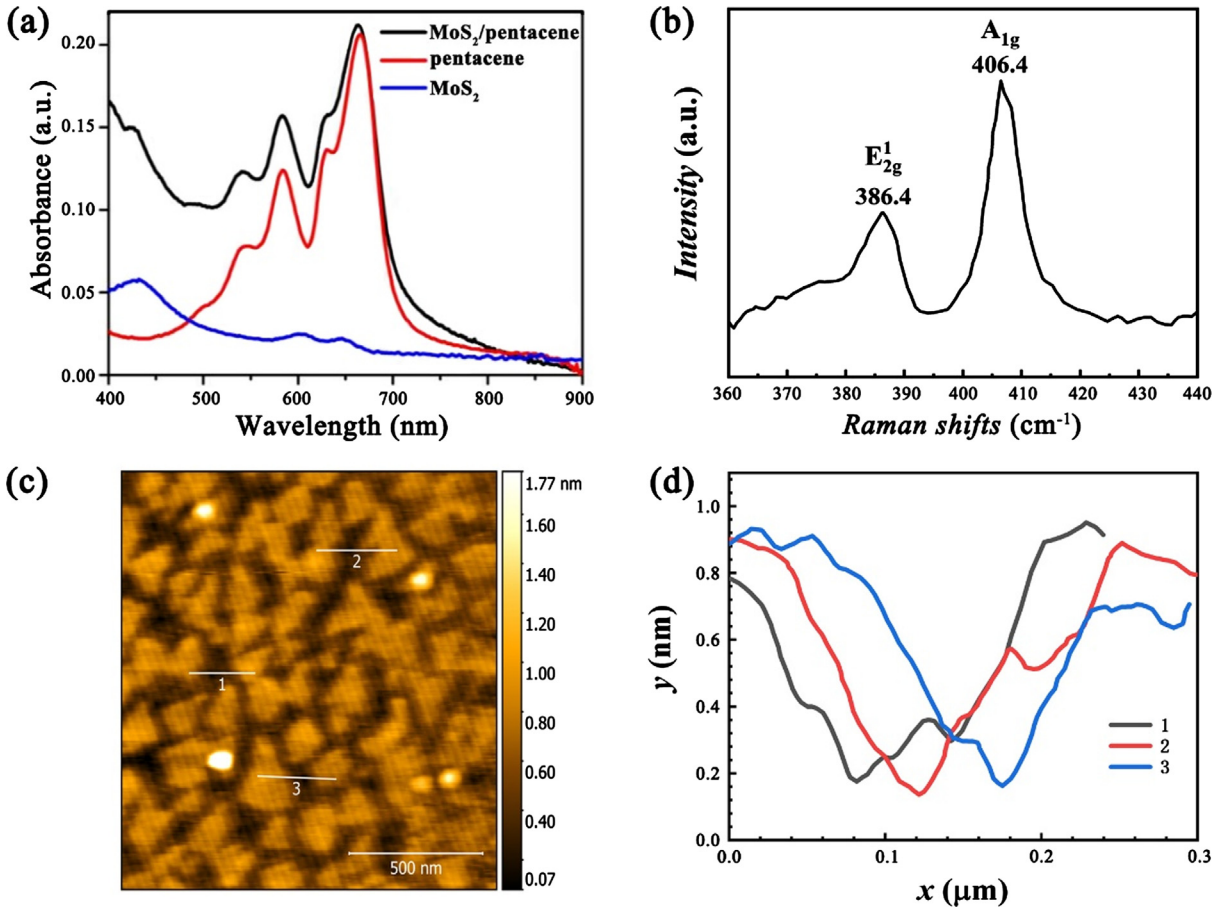


**Fig. 2.** Analysis of thin films. (a) The optical absorption of monolayer $MoS_2$, pentacene (50 nm), and $MoS_2$/pentacene (50 nm) thin films on quartz substrates; (b) Raman spectra of monolayer $MoS_2$ grown on mica substrates; (c) The AFM surface image of monolayer $MoS_2$ grown on mica substrates; (d) Analysis of film thickness according to (c), where the same number in two figures represents the corresponding measurement range.