Research on photoresponse characteristics of bilayer molybdenum disulfide field effect transistors

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Abstract. The field-effect transistors (FETs) have attracted much attention because of the unique properties of the layered MoS$_2$ nanosheet as an ideal channel material. The phototransistors based on the MoS$_2$ FET have advantages of high photoresponsivity, rapid and stable response. This paper is concerned with the fabrication of bilayer MoS$_2$ based FET and the research on the photoelectric characteristics of the devices. The effect of the optical power and gate voltage on the photoelectric properties of the device was researched through the contrast experiments. It has been achieved that the photocurrent increases with the increase of optical power at the same gate voltage and drain voltage. The photoresponsivity also been enhanced with the gate voltage increased. And the photoresponsivity of bilayer MoS$_2$ FET was enhanced more than 100 folds by using MoS$_2$ / MoO$_3$ as the channel material. The results indicated that the MoS$_2$ / MoO$_3$ nanosheets can be a promising heterostructure material to offer a compelling case for application in enhancing the photoresponse characteristics of MoS$_2$ transistors. These unique properties make the bilayer MoS$_2$ based FET to be a great potential candidate of the next generation optoelectronic devices, which have the trend of miniaturization and integration.

1. Introduction

Two-dimensional (2D) semiconducting transition metal dichalcogenides (TMDs) materials, especially MoS$_2$, have attracted much attention for the past few years$^{[1-3]}$. Owing to the excellent semiconducting properties, MoS$_2$ has been used in electronic devices and circuits based on FETs$^{[4,5-8]}$. The layered MoS$_2$ nanosheet is an ideal channel material for FETs due to a small number of dangling bonds on the surface of MoS$_2$ and the stable structure$^{[9-12]}$. Due to the excellent gate voltage modulating action and the signal amplification of the FET, phototransistors based on FETs not only have a greater optical gain, higher photoresponsibility, exceedingly signal-to-interference ratio, but also easy integrated to the optoelectronic circuits. In previous studies, the layered MoS$_2$ have been recently developed and employed in various new devices because of its layer-dependent electrical properties$^{[13-18]}$. Li reported that the contact resistivity of devices slightly decreases with the reducing of MoS$_2$ thickness, which mainly governed by the quantum confinement effect$^{[19]}$. The density of states of bilayer MoS$_2$ nanosheet is three times higher than that of monolayer MoS$_2$, leading to considerably high drive currents in the ballistic limit$^{[20]}$. Moreover, Hall mobilities increase as the density of states increases, reaching 375 cm$^2$/(V·s) for the bilayer, in contrast to 250 cm$^2$/(V·s) for the monolayer$^{[21]}$. Therefore, the bilayer MoS$_2$ FET based phototransistors would exhibits the stable detection and high photoresponsivity to the strong impact of its structure and electrical properties. In our researches, a back-gate FET based on the bilayer MoS$_2$ nanosheet was fabricated successfully and
the outstanding photoresponse characteristics were demonstrated. We also researched the factors which affect the photoresponse characteristics of device. Our results indicated that the bilayer MoS₂-based FET would be a great potential candidate of the next generation optoelectronic devices.

2. Fabrication of bilayer MoS₂ phototransistor

The back-gate FET was adopted considering that the direction of laser irradiation is from top to bottom. The structure of the MoS₂ phototransistor was shown in figure 1a. The board of the UV photolithography was designed to prepare the source and drain electrodes of FET, as shown in figure 1b. The channel length of device which we designed is 2 to 5 μm. Subsequently, the source and drain electrodes (Au/Ni of 70nm/10nm) were prepared by the UV photolithography technique and the electron beam evaporation technique on a SiO₂/Si substrate. Then the bulk MoS₂ (spi SUPPLIES, 429MS-AB) was exfoliated into the channel regions, and the metallographic micrograph was shown in figure 1c. The length of MoS₂ channel which used in our research is 2 μm. The back-gate electrode was prepared by the quick-drying silver paste. The thickness of MoS₂ can be determined by measuring the Raman spectra according to the raman shift between in-plane vibration mode \( E_{2g} \) and the out-plane vibration mode \( A_{1g} \) (figure 1d inset). The results shown that the Raman shift of the MoS₂ film is 20.3 cm⁻¹ with the excitation of the 532 nm laser, as shown in figure 1d. According to previous studies[22-24], it can be inferred that the thickness of the MoS₂ is bilayer.

3. Results and discussion

3.1. Basic electrical characteristics of bilayer MoS₂ FET

The basic electrical properties of MoS₂FET without illumination were tested (figure 2). As the output characteristic \((I_{ds} - V_{ds})\) curve shown in figure2a, the \( I_{ds} \) increases with the increase of \( V_{ds} \) and \( V_{gs} \). This is the typical output characteristic of FET which based on n-type (MoS₂) channel material. Especially in low voltage region of \( V_{ds} \), it can be observed that the \( I_{ds} \) increases linearly with \( V_{ds} \) and the curve pass through the original point, indicating that the good ohmic contact was formed between the channel and electrodes, which is beneficial to the injection of electrons. Several important electrical parameters can be achieved from the transfer characteristic curve \((I_{ds} - V_{gs})\), as shown in figure 2b. According to calculation results: The field-effect mobility \((\mu)\) reached 25.4 cm²/(V·s), the transconductance \((g_m)\) was 1.7 and the switching current ratio \((I_{on}/I_{off})\) was as high as $10^7$.

3.2. Photoresponse characteristics of device with different optical power

According to the photoconductive effect, the extra free carriers is generated by the absorption of photon, reducing the electrical resistance[25,26], and then the current of the device is added. Without
illumination, a small $I_{ds}$ can flow. Under illumination, the absorption of photons with energy higher than the bandgap ($E_{ph}>E_{bg}$) generates $e-h$ pairs which are separated by the $V_{ds}$. The photogenerated free electrons and holes drift in opposite directions towards the metal leads, resulting in a net increase in the current ($I_{ph}$, $I_{ph} = I_{ds} - I_{dark}$). As shown in Fig 3a, the $I_{ds}$ increases with the increase of optical power ($P_{inc}$) with the same $V_{ds}$. The obvious $I_{ph}$ is produced with the illumination. Then, the curve about the relationship between the $I_{ph}$ and $P_{inc}$ was fitted as $y = y_0 + Ae^{-x/t}$, as shown in figure 3b, which $x$ is the $P_{inc}$, $y$ is the $I_{ph}$, $A$ is the amplitude, $t$ is the attenuation constant and $y_0$ is the compensation constant. Photoreponsivity ($R$) of the MoS$_2$ phototransistor can be calculated by $R = \frac{I_{ph}}{P_{inc}}$. By calculating, the relationship between $R$ and $P_{inc}$ was shown in figure 3b inset. It was observed that the $R$ of the device increases linearly with the increase of $P_{inc}$ with the $V_{ds}$ of 40V.

![Figure 3](image1.png)  
![Figure 4](image2.png)

**Figure 3.** Photoresponse characteristics of device with different optical power at $V_{gs}$ of 0 V.  
**Figure 4.** Photoresponse characteristics of device with different $V_{gs}$ at optical power of 1 mW.

3.3. **Photoresponse characteristics of device with different gate voltage**

The photogenerated electrons and holes which only exist on the surface of the semiconductor are easily combined without the $V_{gs}$. And the effective current which formed between the source and the drain is small. But the photogenerated $e-h$ pairs can be separated quickly with the effect of $V_{gs}$. Figure 4a shown the variation of output characteristic curves with different $V_{gs}$ at $P_{inc}$ of 1 mW. The $R$ would be calculated and the relationship between the $R$ and $V_{gs}$ was shown in figure 4b. Furthermore, the photoswitching behavior of MoS$_2$ phototransistor at $P_{inc}$ of 1mW, $V_{ds}$ of 5V, $V_{gs}$ of 10V was shown in figure 4c,d. Photoswitching rate test shown the switching of 0.35s duration for the photocurrent rise or decay process. Photoswitching stability test of more than ten cycles indicated that the bilayer MoS$_2$ phototransistor has a great stability of the photoelectric switch properties with the $V_{gs}$ adjustment.

3.4. **Photoresponse characteristics of device with heterojunction as the channel material**

The output characteristics of MoS$_2$/MoO$_3$ phototransistor at different $P_{inc}$ was tested, and the $R$ of MoS$_2$/MoO$_3$ transistor was calculated and compared with the MoS$_2$ transistor, which was shown in figure 5a and 5b. It is obvious that the $R$ increased about 100 times after the deposition of MoO$_3$ layer. Then, the Figure 5c shown the threshold voltage ($V_{th}$) changes from -18.5V to -2.6V before and after the deposition of MoO$_3$ layer. As the energy band diagram shown in figure 5d, a significant electron charges transfer happened due to the energy level position of MoS$_2$ and MoO$_3$. Therefore, the $V_{th}$ shift toward positive direction [27]. Moreover, the interfacial charge transfer induced the band-bending of MoS$_2$ and MoO$_3$ layer. Then, an induced built in electric field can effectively seperate the photogenerated $e-h$ pairs in MoS$_2$ layer and contribute to the holes to be trapped at the interface trap.
sites. Therefore, the $R$ could be enhanced by 100 times after the deposition process.

![Figure 5. Photoresponse characteristics of device with MoS$_2$/MoO$_3$ heterojunction as the channel material.](image)

In the process of depositing MoO$_3$ layer, the MoS$_2$ phototransistor was placed in the high temperature tube furnace. In order to eliminate the influence of high temperature on the photoresponse characteristics, we compared the photoelectric properties of the same device before and after annealing, the result was shown in figure 5e and 5f. It indicated that the temperature in the tube furnace has no effect on the photoresponse characteristics of the bilayer MoS$_2$ phototransistor. Finally, the morphology of electrodes (a,b), channel regions (c,d) and channel material (e,f) of the device which before and after annealing was tested by scanning electron microscope (SEM), as shown in figure 6. These test results shown that the annealing process did not destroy the structure of the transistor. These researches shown that the MoS$_2$/MoO$_3$ heterojunction can effectively improve the photoresponse characteristics of the bilayer MoS$_2$ phototransistor.

4. Conclusions

In our researches, the bilayer MoS$_2$ FET was fabricated and the photoelectric properties of our devices were studied. We also researched the factors which affect the photoresponse characteristics of device through the contrast experiments. We indicated that the photocurrent and photoresponsivity increased gradually with the increase of optical power and gate voltage. Moreover, we discovered that the photoresponsivity would be enhanced 100 times with the process of depositing MoO$_3$ layer which has high work function. The change of photocurrent and photoresponsivity was explained by the band theory in our research. Finally, the effect of ambient temperature on the photoelectric properties of the device was eliminated by the comparison test before and after the annealing process. Our researches indicated that bilayer MoS$_2$-based FET would be the best potential candidate in order to adapt to the trend of "miniaturization" and "integration" for the next generation optoelectronic devices.

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