Device Performance of Multilayer $MoSe_2$ Field Effect Transistors

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Abstract. In this study, we report on the electrical and optoelectronic properties of field effect transistors based on multilayer $MoSe_2$. The multilayer $MoSe_2$ device showed a room-temperature mobility of 27.3 $cm^2\ V^{-1}\ s^{-1}$ and possessed a high gate modulation larger than 10^5. We obtained an ultrahigh photoresponsivity of 59.8 AW^{-1} under 405 nm laser beam excitation. These results showed that devices based on multilayer $MoSe_2$ are promising for applications in electronics and optoelectronics.

Introduction

In recent several years, two-dimensional (2D) layered materials such as graphene have attracted worldwide research interests [1-3]. These 2D crystals exhibit extraordinary properties. Thin transition metal dichalcogenides(TMDCs) such as MoS_2, WS_2, $MoSe_2$ and WSe_2 are a new class of 2D crystals with a variety of electrical and optoelectronic characteristics [4]. They have good prospects for device applications such as light emitting diodes(LEDs), photodetectors and field effect transistors (FETs).

Various TMDCs-based electronic devices have been demonstrated, with MoS_2 being investigated most extensively [5-7]. Properties of TMDCs are layer-dependent and monolayers of TMDCs show a sizable direct bandgap around 1～2 eV [8] [9]. The large bandgap can ensure a large I_{on}/I_{off} ratio. However, at present there are still many disadvantages in the use of monolayer TMDCs. On one hand, the fabrication process of monolayer TMDCs-based device is somewhat complex. On the other hand, the larger bandgap in thinner flakes is expected to give rise to larger schottky barrier, thereby increasing contact resistance [10]. Therefore, multilayered 2D material-based devices are more suitable for realistic fabrication processes.

Until now, few studies on TMDCs have concentrated on $MoSe_2$. $MoSe_2$ is an indirect-bandgap semiconductor in bulk state, but can turn into a direct-bandgap(1.6 eV) material when exfoliated into the monolayer state [11]. Larentis et al [12] fabricated the first back-gated FET based on few-layered $MoSe_2$, which showed a high I_{on}/I_{off} ratio. Xia et al [13] reported the realisation of a monolayer $MoSe_2$-based photodetector whose photoresponsivity was very small. Employing a transfer method, Abderrahmane et al [14] fabricated a multi-layer $MoSe_2$-based phototransistor.

In this paper, we report on the electrical and optoelectronic properties of field effect transistors based on multilayer $MoSe_2$. Our results showed that devices based on multilayer $MoSe_2$ are promising for applications in electronics and optoelectronics.

Experiment

Firstly, multilayer $MoSe_2$ flakes were mechanically exfoliated from natural $MoSe_2$(HQ graphene company）onto 300 nm SiO_2/Si substrates (doped p+, conductivity: 0.01-0.02 Ω•cm). After that, we fabricated two-terminal devices using 10 nm Ti /50 nm Au electrodes deposited by electron-beam evaporation at room temperature. The two-dimensional $MoSe_2$ flakes were characterized by Atomic Force Microscope(AFM) and Raman spectroscopy. Figure 1(a) shows the optical micrograph of a fabricated multilayer $MoSe_2$ FET. Figure 1(b) shows the topography of the dashed square in Figure 1(a) probed by AFM. As we can see, the thickness of $MoSe_2$ is approximately 20 nm. The measured channel length and width are 8.738 um and 13.264 um respectively. Figure 1(c) shows the Raman spectrum of the sample, which is consistent with earlier studies [15] [16]. We investigated the optoelectronic properties of the device using a 405 nm laser beam. Figure 1(d) illustrates the way we used to characterize optoelectronic properties of the back-gated multilayer $MoSe_2$ FET.

The output and transfer characteristics were measured by Keithley 4200 probe system (company: Cascade Microtech, model: Summit 11000B-M) in air and at room temperature (300K). We probed the optoelectronic properties of the device under different laser power density with 405 nm laser beam, the laser spot diameter of which was nearly 1 mm.

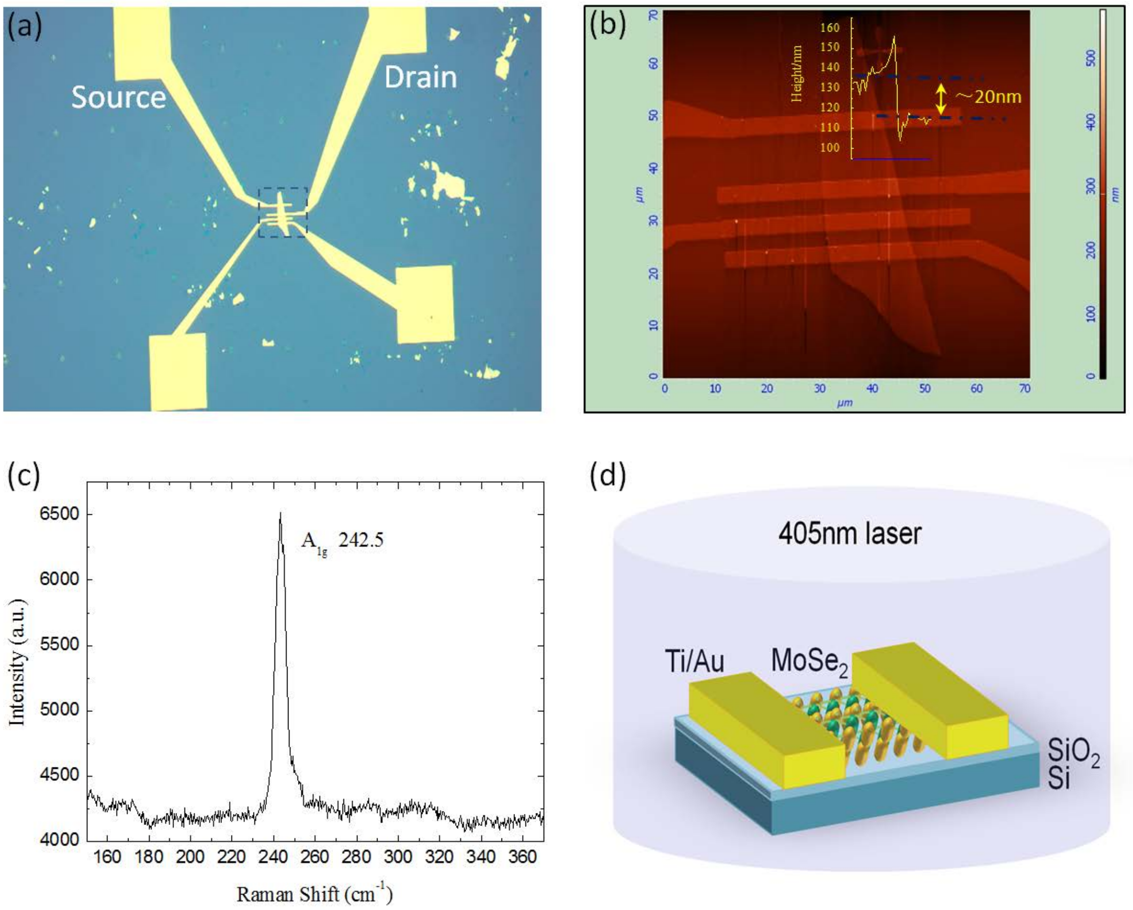

Figure 1. (a) Optical image of the fabricated multilayer $MoSe_2$ FET. (b) AFM image of the FET. (c) Raman spectrum of the multilayer $MoSe_2$. (d) Schematic diagram for characterization of optoelectronic properties.

Results and discussion

The output characteristics of the device under different gate voltage in dark is shown in Figure 2(a). As is shown, the I_D of the device could be modulated by the gate voltage. The I_D-V_{DS} dependence is linear, which implies the ohmic contact between the electrodes and the mulitilayer $MoSe_2$. Figure 2(b) shows transfer characteristics of the device at different drain-source voltage in dark. The device shows a bipolar behavior, which is a new phenomenon compared with the previous study [14]. In addition, the threshold voltage of the device appears to keep stable at different V_{DS}. The electron mobility could be obtained from the equation:

$$\mu = \frac{\partial I_D}{\partial V_G}\left(\frac{L}{WC_i V_{DS}}\right) \qquad (1)$$

Where L is the channel length, W is the channel width, and C_i is the gate capacitance which can be given by the equation $C_i = \varepsilon_0 \varepsilon_r / d$. ε_0 is vacuum dielectric constant. ε_r and d are dielectric constant and thickness of SiO_2 respectively. Here, ε_0 is 8.85×10^{-12} F/m, ε_r is 3.9 and d is 300 nm. Employing equation (1), we calculated electron mobility of the FET to be 27.3 $cm^2\ V^{-1}\ s^{-1}$ when drain-source voltage was 3V and the gate voltage was 40V. From Figure 2(b), we can also observe a high I_{on}/I_{off} ratio larger than 10^5.

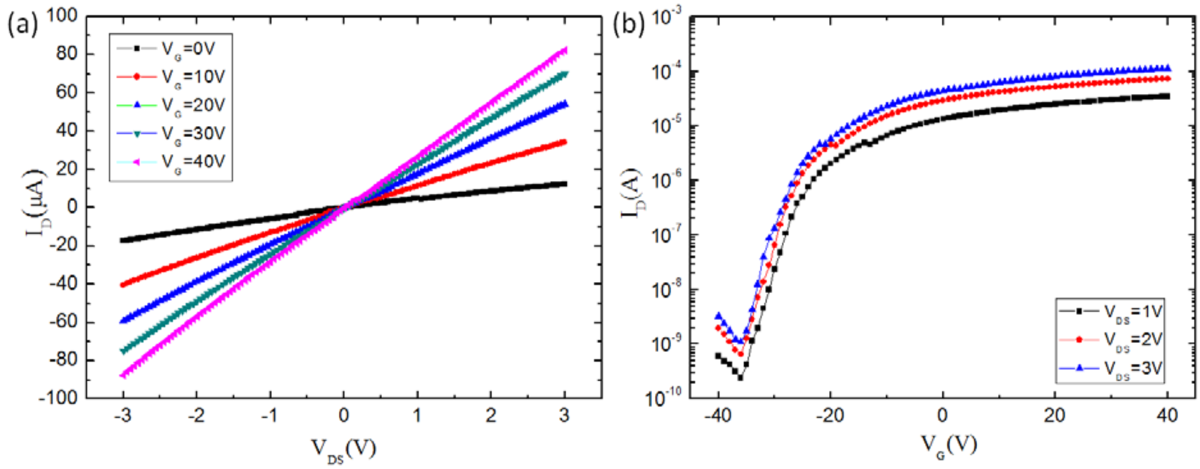

Figure 2. (a) Output characteristics of the multilayer $MoSe_2$ FET under different gate voltage in dark. (b) Transfer characteristics of the device at different drain-source voltage in dark.

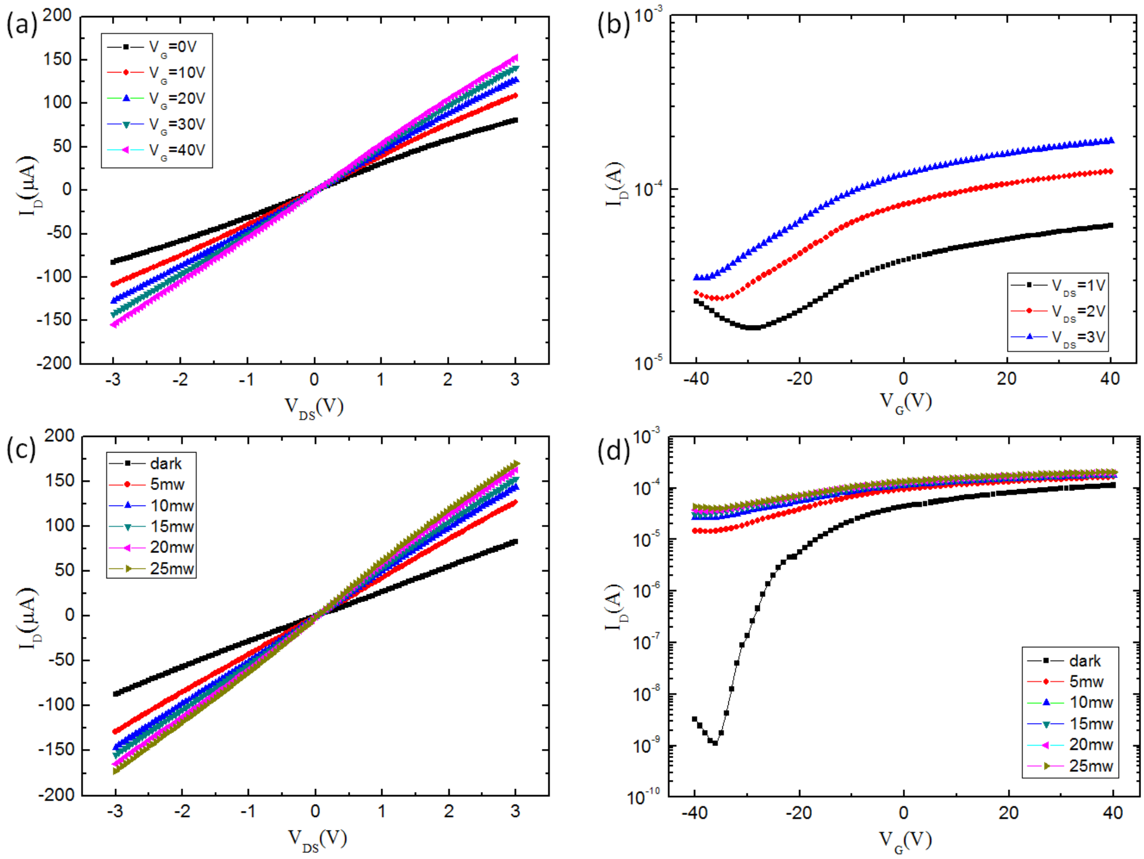

Figure 3. (a) Output characteristics of the FET measured at different gate voltage in air under illumination of 15 mw laser power intensity. (b) Transfer characteristics of the device measured at different drain-source voltage in air under illumination of 15 mw laser power intensity. (c) Output characteristics of the FET measured at different laser power intensity with the gate voltage being 40V. (d) Transfer characteristics of the FET measured at different laser power intensity with the drain-source voltage being 3V.

Figure 3(a) shows output characteristics of the FET measured at different gate voltage in air under illumination of 15 mw laser power intensity. The I_D-V_{DS} dependence is similar to that of Figure 2(a) measured in dark. Figure 3(b) demonstrates the transfer characteristics of the device measured at different drain-source voltage under the same conditions as Figure 3(a). It is obvious that the device can hardly turn to the off state under laser beam excitation. Figure 3(c) shows the output characteristics of the FET measured at different laser power intensity with the gate voltage being 40V. As seen in the figure, the current increases with the incident power intensity, but it does not increase proportionally with power intensity and seems to exhibit a saturation behavior. Figure 3(d) demonstrates the transfer characteristics of the FET measured at different laser power intensity with the drain-source voltage fixed at 3V.

Here, the actual incident laser intensity P_{act} can be calculated from the equation:

$$P_{\mathrm{act}} = P_{laser} \bullet (S_{dev} / S_{laser}) \tag{2}$$

Where P_{laser} is the total power intensity of laser beam, S_{laser} is area of the laser beam, and S_{dev} is area of the device. Photoresponsivity R_λ can be obtained by the equation:

$$R_\lambda = \left(I_{illumination} - I_{dark}\right) / P_{act} \tag{3}$$

Where $I_{illumination}$ and I_{dark} represent photo current and dark current respectively. We obtained an ultrahigh photoresponsivity of 59.8 AW^{-1} under 5 mw laser excitation with drain-source voltage being 3V and gate voltage being 40V.

Conclusion

The electrical and optoelectronic properties of field effect transistors based on multilayer $MoSe_2$ were investigated. The device showed a room-temperature mobility of 27.3 $cm^2V^{-1}s^{-1}$ and possessed a high gate modulation larger than 10^5. Under 405 nm laser beam excitation, an ultrahigh photoresponsivity of 59.8 AW^{-1} was obtained. These results showed that devices based on multilayer $MoSe_2$ are promising for applications in electronics and optoelectronics.

Acknowledgement

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