

Optical and Electrical Properties of Large-area MoS₂ Thin Film Photodetectors

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Abstract

In this study, large-area molybdenum disulfide (MoS₂) thin film was obtained by low pressure thermal sulfurized process. Scanning electron microscope image reveals continuous thin films on surface, meanwhile, the thickness is approximate 129 nm analyzed by secondary ion mass spectrometer. Raman scattering spectrum shows that the peaks at 374 cm⁻¹ and 403 cm⁻¹ are from MoS₂ thin film. X-ray diffraction reveals peaks at 33° and 58.5° indicating MoS₂ (100) and (110) crystal phase. Photoconductivity spectrum exhibits that the direct band-gaps are at 1.92 eV and 2.16 eV, and indirect band-gap is at about 1.20 eV. In addition, 512 mA W⁻¹ of photoresponsivity is obtained at V_{ds} = 20 V and 0.26 uW incident laser power. Photocurrent mapping explains that the MoS₂ devices have carrier diffusion lengths of ~235 um. Our results would be useful for development of large-area MoS₂ thin film photodetectors.

1. Introduction

Transition metal dichalcogenides (TMDs) are attracting intense research interest due to their appreciable band-gap in optical and electrical properties. While bulk molybdenum disulfide (MoS₂) is a n-type semiconductor with indirect band-gap of ~1.2 eV^[1] and direct band-gap of ~1.8 eV^[2] in monolayer MoS₂. Benefiting from the strong absorption in the visible band, MoS₂ has been widely used in photocatalysis^[3] and photodetection^[4] applications.

Devices such as transistors, memories, and photodetectors based on two-dimensional materials have been successfully fabricated.^[5] For example, Monolayer MoS₂ transistors have been demonstrated with current on/off ratios of 10⁸ and ultralow power dissipation.^[6] Photodetectors based on few-layered MoS₂ have some excellent properties of photodetection including a high broadband gain up to 24, a high detectivity up to 10¹⁰ cmHz^{1/2}W⁻¹, and a fast photoresponse time of 40 μs.^[7,8]

In this study, we observe the structural distribution of MoS₂ by scanning electron microscope (SEM) and secondary ion mass spectrometer (SIMS). Consequently, we analyze the lattice structures of MoS₂ by Raman scattering spectrum and X-ray diffraction. We measure the photoelectric properties of MoS₂ by photoconductivity spectrum, photogain measurement, and photocurrent

mapping. We also measure the photocurrent under different biases by photocurrent mapping, and fit the decayed photocurrent as the exponential function to calculate the diffusion lengths^[9,10] which explore the carrier transport characteristics.

2. Results and discussion

Figure 1(a) shows the large-area completely continuous MoS₂ thin films in SEM image, and the thickness is calculated approximate 129 nm in SIMS depth distribution (fig. 1b). As above, the 35 nm Mo film on 100 nm silicon dioxide/p⁺ silicon substrate has been totally reacted with sulfur atoms and the thickness increased from 35 nm to 129 nm, which the transform of thickness is about four times by low pressure thermal sulfurized process.

The Raman spectrum of MoS₂ thin film excited by 532 nm laser displayed in fig. 2(a) has two prominent peaks: an in-plane (E_{2g}^1) mode located at 374 cm⁻¹ and an out-of-plane (A_{1g}) mode located at 403 cm⁻¹. The in-plane mode corresponds to the S atoms vibrating in one direction and the Mo atom in the other, while the out-of-plane mode is a mode of just the S atoms vibrating out-of-plane. Figure 2(b) expresses two X-ray diffraction peaks at 2θ = 33° and 58.5° which are assigned to (100) and (110) reflection plane, respectively.

Figure 3(a) represents the I-V characteristic curve of MoS₂ thin film illuminated by solar simulator. Under illumination, the resistance of MoS₂ thin film is decreased from 59.8 MΩ to 35.7 MΩ significantly. It is also illustrated the great photoresponsivity with MoS₂ direct band-gap of 1.92 eV and 2.16 eV, and indirect band-gap of ~1.2 eV for photoconductivity spectrum shown in fig. 3(b).

In photogain measurements, we can obtain that the photocurrent of MoS₂ thin film is enhanced along with the different incident laser power (fig. 4a), and calculate the photoresponsivity achieved to 512 mA W⁻¹ with 0.26 uW laser power (fig. 4b).

For photocurrent mapping, a semiconductor laser provided 652 nm optical excitation, which is modulated at 2 kHz, and the photocurrent is recorded by lock-in amplifier at V_{sd} = 0 - 30 V. The collected current decays exponentially away from the junction, and the exponential decay rate of the photocurrent does not change as different biases in fig. 5(a). In this situation, the decayed

photocurrent is fitting with the exponential function:

$$I = I_0 \times \exp(-x/L_D)$$

Here, I_0 is the value of maximum current, and L_D is the diffusion length.

The carrier diffusion lengths are extracted from the measurements showed in fig. 5(b) and determined to be in the range between 190 and 280 μm , which do not change so much for the device.

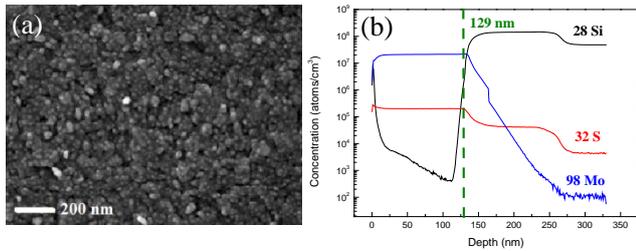


Fig. 1 (a) SEM image of MoS₂ thin film, and (b) SIMS depth distribution of Mo, S, and Si.

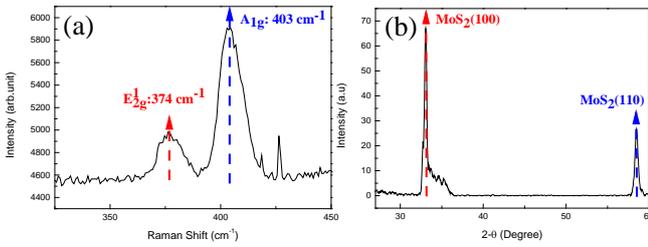


Fig. 2 MoS₂ thin film (a) Raman scattering spectrum excited by 532 nm laser, and (b) X-ray diffraction.

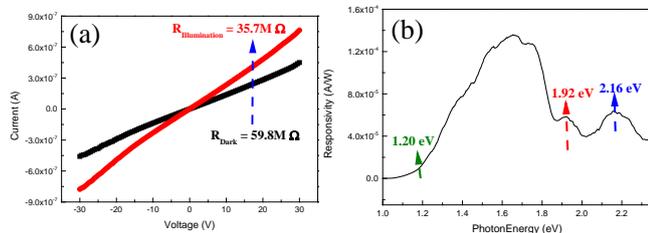


Fig. 3 (a) I-V characteristic curve of MoS₂ thin film device measured at $V_{sd} = -30 - 30$ V, and (b) photoconductivity spectrum modulated at 9 Hz and $V_{sd} = 20$ V.

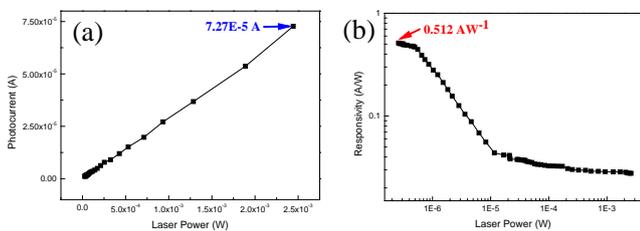


Fig. 4 Photoresponse of MoS₂ thin film (a) photocurrent measurement, and (b) photoresponsivity profiles for 652 nm laser power at $V_{sd} = 20$ V.

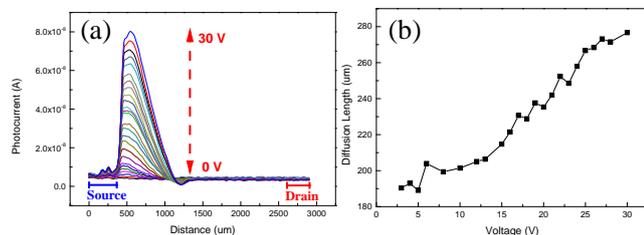


Fig. 5 (a) Photocurrent mapping of MoS₂ thin film modulated at 2 kHz by 652 nm laser, current received by lock-in amplifier at $V_{sd} = 0 - 30$ V, and (b) diffusion lengths fitted by exponential function.

3. Conclusions

In conclusion, we have obtained the good quality and continuous large-area MoS₂ thin film by low pressure thermal sulfurized process. As the decreasing photon intensity, we can obtain the photoresponsivity up to 512 mA W^{-1} . In the photocurrent mapping, an obvious photoresponse is observed when the laser is focused at the heterjunction, which the photo-generated electrons and holes are separated. We also find that the diffusion lengths of photocurrent (~ 235 μm) do not increase solely under increasing biases. This behavior which results in finite carrier flowing due to the carrier diffusion-limited in carrier transport process with the negligible drift current. Our results can be useful for MoS₂ photodetectors development.

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