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Effects of Nickel Doping on the Optical and Electrical Properties of MoS_2 Photodetectors

Zheng-Wen Chen[1], Tsung-Shine Ko[1], Der-Yuh Lin[1], Joonki Suh[2], Zheng-Sheng Chen[1]

[1] Department of Electronic Engineering, National Changhua University of Education,
No.2, Shi-Da Road, Changhua City, Changhua County 500, Taiwan
Phone: +886-4-723-2105-8337 E-mail: dylin@cc.ncue.edu.tw
[2] Department of Chemistry and Chemical Biology Cornell University

Abstract

Two-dimensional materials such as graphene and MoS_2 are emerging materials with a wide range of electrical and optical applications. In this study we present the optical and electrical properties of bilayer and bulk nickel doped MoS_2 metal-semiconductor-metal photodetectors (MSM PDs). The initial Ni-doped MoS_2 single crystals have been grown by chemical vapor transport (CVT) method and the bilayer MoS_2 has been prepared using a mechanical exfoliation technique. From the spectral response, we confirmed that the bilayer nickel doped MoS_2 has a direct band gap. We also found a significant increase of responsibility from 0.49 mA/W (for bulk MoS_2 detector) to 0.432 A/W (for bilayer MoS_2 detector) at wavelength of 652 nm. A time constant longer than one thousand seconds for bilayer nickel doped MoS_2 photodetector has been measured by persistent photoconductivity (PPC) measurement. Which may result from the existence of potential fluctuation due to nickel doping atoms. The Schottky barrier heights for gold and silver contacts to MoS_2 is determined to be 18 and 5 mV, respectively. We also found that the resistance of MoS_2 MSM PDs can be changed by environmental humidity. This fact makes it possible to be a multifunctional sensor.

1. Introduction

MoS2 is a layered semiconductor which belongs to the family of transition-metal dichalcogenides (TMDCs) [1]. A unit layer structure consists of two hexagonal plans of sulfur atoms and an intermediate hexagonal plan of molybdenum atoms, which are prismatically coordinated to the sulfur atoms. It is crystallized in a lattice with strong covalent bonds within a unit layer and weak interactions, usually of the van der Waals type, between the individual layers. Owing to the unique optical and electrical properties, the layered semiconductors have attracted considerable interest in basic studies and applications, such as photodetectors [1], solar cells, hydrogen fuel generation [2], hydrodesulfurization, water splitting [3], biosensors. Moreover, MoS2 has a direct band gap about 1.9 eV and high spectral responsivity for becoming phototransistors or photodetectors with good device mobility. The existence of band gap makes the devices much easier to being switch, which is an essential characteristic of phototransistors [4].

In this study, we studied the optical and electrical properties of bilayer and bulk Ni-doped MoS_2 MSM PDs. Since only weak van der Waals interactions between individual layers of MoS_2 crystals, usually thin MoS_2 flakes could be isolated by means of mechanical exfoliation technique. This technique has been developed by Konstantin Novoselov and Andre Geim, and provided a new method to separate two dimensional (2D) materials from three dimensional (3D) crystals [5]. As the number of layers decreases to several layers MoS_2 becomes a direct band gap semiconductor with high transparence and flexibility. Compared with the bulk MSM PD, the bilayer MSM PD has a significant increase of responsibility due to the change of band gap character. Doping may improve photoresponsivity by increasing photocurrent and maintaining dark current [6] and also may introduce acceptor states in the energy band gap, and thus increases the harvesting to long wavelength photons. In this paper we will discuss the effects on the optical and electrical properties of MoS_2 MSM PDs after doping nickel atoms.

2. Results and discussions

Figure 1 shows the optical images of the bilayer and bulk MoS_2 MSM PDs. The bilayer MSM PD consists of a field-effect transistor structure with two gold contacts and gated using a degenerately doped silicon substrate. Figure 2 presents the results of PC spectra of bilayer and bulk MoS_2 MSM PDs. It can be observed that the absorption edge of bilayer MSM PD starts at 1.8 eV corresponding to its direct band gap and the begging of the indirect band gap absorption of bulk MoS_2 PD is observed at 1.1 eV. This result demonstrates that the band gap of bilayer MoS_2 has been changed. The photoresponsivity of bilayer and bulk MoS_2 MSM PDs have been taken at different bias voltages as shown in Figure 3. We calculate the photoresponsivity using $R_\lambda = \Delta I_\lambda/(P_\lambda S)$, where ΔI_λ is the photocurrent, P_λ is the power density and S is the area of the incident light. We found that the photoresponsivities of bilayer and bulk MoS_2 MSM PDs are 0.432 A/W and 0.49 mA/W at 652 nm under 0.237 W/cm^2 photo-illumination.

We carried out the temperature-dependent I-V measurements at different temperatures to determine the Schottky barrier height Φ_B. The results are shown in Figure 4. In order to investigate the Schottky barrier height, it is common to use Arrhenius plot, i.e., $\ln(I_{ds}/T^{3/2})$ against 1000/T for various V_{ds}. By fitting the data to each V_{ds}, we obtained the slopes using $S = -\frac{q}{1000k_B}\left(\Phi_B - \frac{V_{ds}}{n}\right)$. Then by plotting the slopes as a function of V_{ds}, the SBH could be extracted from the y-intercept $S_0 = -\frac{q\Phi_B}{1000k_B}$. The calculated results of the SBH for gold and silver contacts to MoS_2 is determined to be 18 and 5 mV, respectively.

Figure 5 presents the PPC results for these two samples. These results show a fact that the photo-excited electrons and/or holes can exist in the conduction or valence band for a while, which may result from the existence of potential fluctuation due to nickel doping atoms. In the large lattice relaxation model, the PPC involves photoexcitation of electrons from deep-level-like traps (DX-like centers), which undergo a lattice relaxation to shallow effective-mass states. An electron-capture barrier may be created by doping atoms, preventing recapture of electrons by DX-like centers. The PPC decay curves shown in Figure 5 can be well described by the stretched-exponential" relaxation law,

$$I(t) = I(0)exp[-(t/\tau)^{\beta}],\ 0 < \beta < 1, \qquad (1)$$

Where I(t) is the current at the decay time t, I(0) is defined as the current immediately after the termination of the excitation source, τ is the decay time constant and β is the decay exponent. The time constants have been found to be 0.4 ms and 1849.54 s using equation 1 for bulk and bilayer MoS_2 MSM PDs, respectively. It is obvious that a pretty ling time constant has been found for the bilayer device. We believe that this result is responsible for the deep levels resulting from nickel atoms. A large potential barrier blocks the recapture of electrons, especially in 2D layer, because there is no interaction between inter layers.

(a) (b)

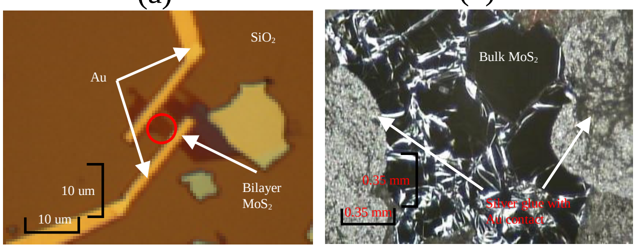

Fig. 1 Optical image of (a) bilayer and (b) bulk MoS_2 MSM PDs.

(a) (b)

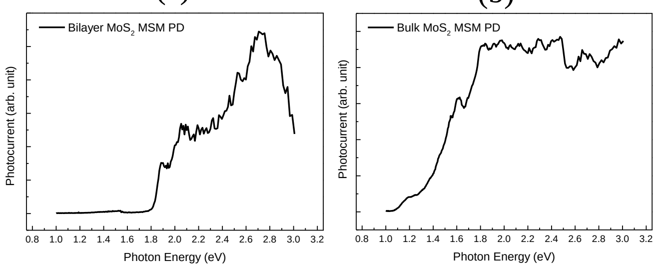

Fig. 2 PC spectra of (a) bilayer and (b) bulk MoS_2 MSM PDs.

(a) (b)

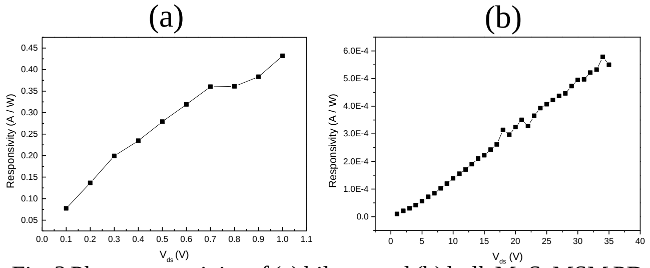

Fig. 3 Photoresponsivity of (a) bilayer and (b) bulk MoS_2 MSM PDs at different V_{ds}.

(a) (b)

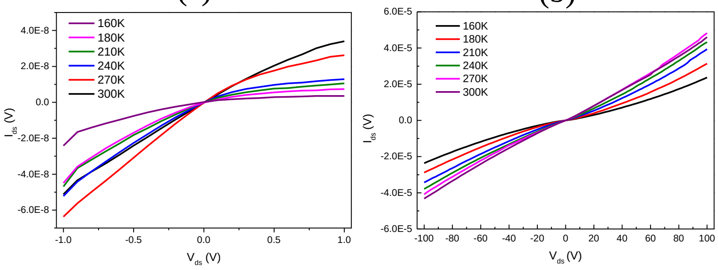

Fig. 4 I-V curves of (a) bilayer and (b) bulk MoS_2 MSM PDs at several temperatures.

(a) (b)

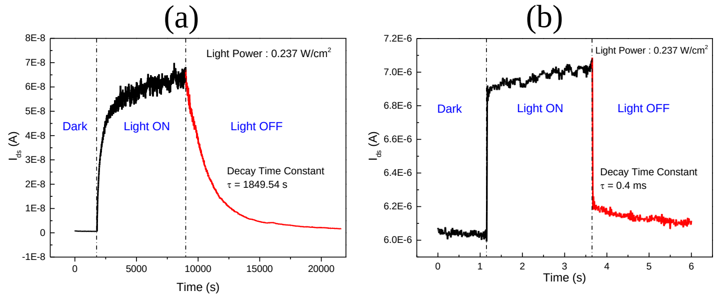

Fig. 5 PPC curves for (a) bilayer and (b) bulk MoS_2 MSM PDs.

3. Conclusion

In this study we present two MSM PDs made of bulk and bilayer MoS_2 crystals grown by CVT method. It is found that the responsivity of the bilayer MoS_2 MSM PD has been increased about one thousand times compared with the bulk one. A low Schottky contact barrier is performed in the nickel doped MoS_2 using gold or silver. In the PPC results, a pretty long time constant has been observed. This result can be understood by the deep potential fluctuation induced by doping atoms.

References

[1] W. Zhang, C. P. Chuu, J. K. Huang, C. H. Chen, M. L. Tsai, Y. H. Chang, J. H. He, Scientific reports, **4** (2014).

[2] J. V. Lauritsen, M. Nyberg, J. K. Nørskov, B. S. Clausen, H. Topsøe, E. Lægsgaard, and F. Besenbacher, J. Catal., **224** (2004) 94.

[3] J. Liao, B. Sa, J. Zhou, R. Ahuja, and Z. Sun, The Journal of Physical Chemistry C, **118** (2014) 17594.

[4] H. S. Lee, S.W. Min, Y.G. Chang, M. K. Park, T. Nam, H. Kim, J. H. Kim, S. Ryu, and S. Im, Nano Lett. **12** (2012) 3695.

[5] K. S. A. Novoselov, A. K. Geim, S. Morozov, D. Jiang, M. Katsnelson, I. Grigorieva, & A. Firsov, "Two-dimensional gas of massless Dirac fermions in graphene," Nature. 2005 Nov 10, 438(7065):197-200.

[6] Perumal Packiyaraj, et al. "Ultra‐Thin Layered Ternary Single Crystals [Sn (SxSe1− x) 2] with Bandgap Engineering for High Performance Phototransistors on Versatile Substrates." ADV FUNCT M. (2016). DOI: 10.1002/adfm.201600081.