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Few-Layer ReS_2 based Vertical *p-n* van der Waals Junction for Photosensing

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Abstract

We fabricated few-layer ReS_2 based on a vertical van der Waals *p-n* junction for photo-sensing application. Dry transfer of an *n*-ReS_2 flake to a patterned p^+Si substrate forms a photodiode and its performance under a different light wavelength and power has been studied. Our results show successful formation of *p-n* junction with its photosensing ability. This work demonstrates a possible application of ReS_2 based *p-n* junction, which can be further improved to enhance its efficiency.

1. Introduction

To realize optoelectrical device application, high quality *p-n* junction diode is important to build the structure. Two-dimensional (2D) layered transition metal dichalcogenides (TMDCs) and their interfaces are interesting for future optoelectronic device application [1-4]. Vertical geometry in *p-n* junction is extremely useful as it helps to apply high electric field strength in order to separate the generated excitons in the thin TMDC materials to contribute in current before recombination. Here we utilize a direct band gap *n*-type semiconducting thin ReS_2 material (band gap ~ 1.4-1.5 eV) on top of highly hole-doped Si substrate to make vertical *p-n* diode configuration. Most of the available TMDCs do not show direct band gap for few-layer thickness, whereas ReS_2 has direct band gap irrespective of thickness on other hand optical absorption increases for increasing thickness. Conventional technology in *p-n* junction based photodetector has serious issues in doping control, area selectivity, air stability and low damage, simultaneously. Further, from a technology perspective, most of these doping processes are incompatible with CMOS manufacturing technology. For overcoming these difficulties, *n*-ReS_2/*p*-Si is very promising because it has great advantages in device fabrication process, which is CMOS technology compatible. In this paper, for the first time, we report the realization of ReS_2/Si photodetector by overcoming the above difficulty by applying transfer process of large area electron doped ReS_2 flake directly on highly hole doped patterned Si wafer.

2. Results and Discussion

Few-layer thick ReS_2 flake is transferred on Si substrate using dry transfer method and the crystalline quality is confirmed using Raman spectroscopy (Fig. 1 (a,b)), which indicates 5-6 layer thickness and high chemical purity of the flake material as the Raman spectra matches with the high crystalline ReS_2 material [5].

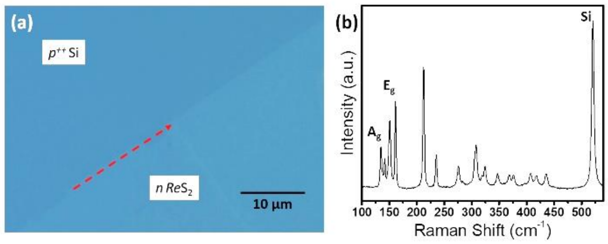

Fig. 1 (a) Optical image of Si-ReS_2 *p-n* junction formation. Red arrow shows the interface. (b) Raman spectra of the few-layer ReS_2 sample.

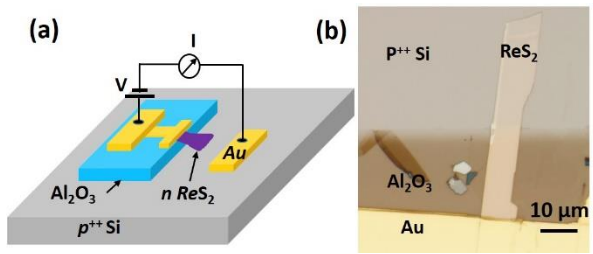

Fig. 2 (a) Schematic diagram of Si-ReS_2 *p-n* junction diode. (b) Optical image of the fabricated device.

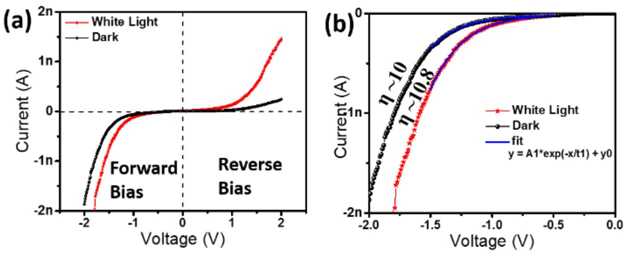

Fig. 3 (a) (c) *I-V* characteristics of the fabricated *p-n* junction with and without white light illumination. (b) Forward bias *I-V* characteristics are fitted with forward bias diode equation.

p^+-Si substrate was patterned using standard photolithography technique to open square shape (1 mm × 1 mm) windows in resist to deposit an Al_2O_3 layer of ~ 50 nm using sputtering techniques under high vacuum. Then, a thin layer of ReS_2 flake was transferred using dry transfer method on top of the Al_2O_3 and Si so that some part of the ReS_2 will directly contact with the Si surface. Next photolithography and e-beam evaporation of Cr/Au (3nm/60nm) were performed to make electrodes on top of ReS_2/Al_2O_3 and Si as shown in schematic diagram and optical image of the fabricated device (Fig. 2 (a,b)).

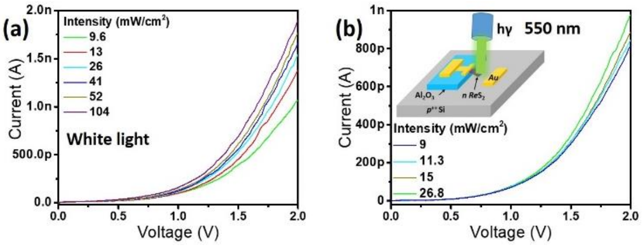

Fig. 4 (a,b) *I-V* characteristics of the *p-n* diode under different intensity of incident white light and 550 nm light illumination, respectively. Inset in Fig. 4(b) shows the schematic of photocurrent measurements during global irradiation of light without focusing through lens.

I_{DS}-V_{DS} characteristic at dark condition shows highly asymmetric, where negative bias at *n*-ReS_2 region corresponds to forward bias. Reverse bias condition at positive bias produce less current as compared with forward bias. Under white light illumination, it has been found that the reverse bias region produces high photocurrent (I_{photo}-I_{dark}) as compared with the forward bias configuration due to the band alignment between ReS_2 and Si interface of forming depletion region and its sensing ability (Fig. 3(a)). I_{photo} and I_{dark} represent total current with and without light illumination, respectively. The forward bias characteristics under dark and light illumination are fitted with standard *p-n* diode forward bias equation,

$$I_{DS} = I_0\left(e^{qV_{DS}/\eta k_B T} - 1\right). \qquad (1)$$

Non-ideal parameter, η, which provides a very high value indicates the poor interface between ReS_2 and Si (Fig. 3(b)). This result the presence of high density interface defect states and trap states. Both Si and ReS_2 act as active optical absorb layer and we observe defects trap states dominated photoresponse, which discussed in Fig. 5.

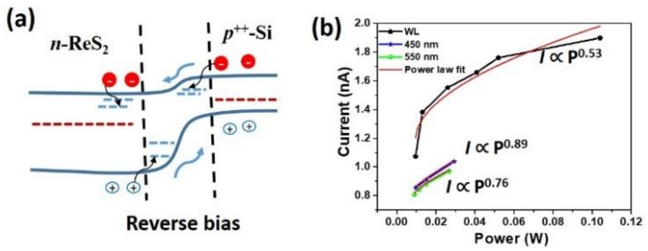

Fig. 5 (a) Schematic band diagram of Si-ReS_2 *p-n* junction diode under reverse bias operation. Bulk trap states, interface trap states and defects levels are shown by dashed lines. (b) Power dependence current at reverse bias of 2 V under different light power and wavelength of illumination.

Photo-sensing ability of the device is shown in Fig. 4 (a,b), which indicates white light illumination produce higher photocurrent as compared with 550 nm and 450 nm light illumination, which can be further discussed in a schematic band diagram and power law plots (Fig. 5 (a,b)). Under photo-sensing configuration at reverse bias, the interface will have high defect and trap states as shown in Fig. 5(a). Those defect and trap states have important role under specific wavelength excitation (i.e. 550 and 450 nm) as compared with wide band excitation, which is the reason of getting high power law coefficient (0.89 and 0.76) as compared with coefficient under white light illumination (0.53). Including bulk traps states in ReS_2, the interface states and defect traps states have high influence with high effective trap density under white light illumination. This produce high photocurrent and low value in power-law coefficient. We have also observed large hysteresis in *I-V* sweep, which further support the existence of high-density interface and defect trap states.

Table I Comparison of our work with reported *p-n* photodiode.

Device Photodiode	Wavelength and bias	Photoresponsivity (mA/W)	Reference
ZnO/Si	365 nm, 2 V	75	[6]
Graphene/Si	500 nm, 2 V	~120	[7]
MoS_2/Si	365 nm, 4 V	~700	[8]
ReS_2/Si	550 nm, 2 V	3.1	Our work

We have calculated photo-responsivity, R(λ) value of the device using formula,

$$R(\lambda) = \frac{I_{photo} - I_{dark}}{i_{in}(\lambda)\ \times S} \qquad (2)$$

and compare the value with the reported *p-n* photodiode (Table 1). Here, $i_{in}(\lambda)$ and S are the incident light intensity at wavelength λ and effective active area of the flake, respectively. At the present stage, the photoresponsivity of the ReS_2/Si devices is not so ideal. However, through our detailed experiments, we have clearly figured out the cause of the low photoresponsivity, which is due to the high density of interface defects and traps at the ReS_2 and Si interface.

3. Conclusions

We have first demonstrated vertical *p-n* Si-ReS_2 van der Waal junction diode for photosensing application. The device performance was studied under broad illumination of different wavelength of light with varying intensity. The device performance was found a bit lower than the reported TMDCs materials based *p-n* diodes, however we found that it will be overcome by improving the quality of the ReS_2/Si interface. Through this work, we have a guiding principle of how we can improve the performance of ReS_2/Si photodetectors.

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References

[1] C. H. Lee *et al.*, Nature Nanotechnology. **9** (2014) 676.
[2] O. Lopez-Sanchez *et al.*, ACS Nano. **8(3)** (2014) 3042.
[3] C. Yim *et al.*, Nano Letters. **18(3)** (2018) 1794.
[4] V. Dhyani & S. Das, Scientific Reports. **7** (2017) 44243.
[5] Y. Feng *et al.* Phys. Rev. B. **92** (2015) 054110.
[6] P. Hazra *et al.*, J. Semicond. Technol. Sci. **14** (2014), 117.
[7] S. Riazimehr *et al.*, ACS Photonics, **4 (6)** (2017), 1506.
[8] Y. Li *et al.*, Scientific Reports, **4**(2014), 7186.