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Broadband UV-VIS-NIR Photodetection with High Responsivity MoS_2 Phototransistors Based on Light Reflection

Roda Nur, Kasidit Toprasertpong, Shinichi Takagi, and Mitsuru Takenaka

The University of Tokyo
Department of Electrical Engineering and Information Systems
7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8654, Japan
Phone: +81-3-5841-6733 | Email: nur@mosfet.t.u-tokyo.ac.jp

Abstract

We explored the integration of a back-plane mirror to enhance the optical absorption of light for multi-layered MoS_2 phototransistors. With the use of HfO_2 dielectrics and a mirror, we found the photogating effect to be more strongly enhanced. Its broadband photoresponse was evaluated at UV-VIS-NIR wavelengths and its time response was improved to the milliseconds time range by applying a reset pulse. As a result of this device structure, it offered high responsivities in the range of ~10^5 A/W at UV-VIS wavelengths.

1. Introduction

Atomically thin two-dimensional materials like transition metal dichalcogenides (TMDCs) have attracted interest for its unique optoelectronic properties such as direct bandgaps in the visible spectrum, layer dependent bandgap tuning for broader optical detection, and large responsivities. SiO_2-based MoS_2 phototransistors have been reported to show a varying range in responsivities from 10^{-3} to 10^5 A/W [9,3]. Typically to achieve large responsivities and high photogains, it requires the presence of trap sites near the interface of the semiconductor/dielectric layer. We have previously demonstrated the use of HfO_2-based dielectrics as a reliable charge-trapping layer to enhance the photoresponse in MoS_2 phototransistors [1]. Here, we explore the integration of a back-plane mirror to further enhance the light sensitivity in HfO_2-based MoS_2 phototransistors. In this device structure, the portion of light transmitted into the dielectric layer has a second chance for absorption via reflection at the back-gate surface.

2. Experimental Details

Fig. 1 shows the device structure and operation where a back-gate structure was selected to allow for easy access of light illumination onto the MoS_2 channel layer. The fabrication process starts with the pre-cleaning of heavily doped n^{++} -Si as the back-gate, where next a thin metal film of RF sputtered TiN (70 nm) was deposited. Next, 10 nm of ALD HfO_2 was deposited as the dielectric layer. MoS_2 was then mechanically exfoliated from a bulk crystal and transferred onto the dielectric layer. A 3 nm thick flake was then patterned by a lithography process. An image of the channel region and an AFM surface topography of the flake can be seen in Fig. 2(a) and (b) respectively. The source/drain contacts were deposited by e-beam evaporation of Ti (5nm)/Au (50 nm). Commercial LEDs of the following wavelengths were used to illuminate the MoS_2 channel region and to characterize its light response: UV (395 nm), blue (460 nm), green (525 nm), red (630 nm), and NIR (850 nm).

3. Results and Discussion

In Fig. 3(a) it shows the dark condition (no illumination) transfer characteristics of the MoS_2 mirror phototransistor with a channel length of 4.5 μm and channel width of 4.6 μm under different drain voltages: V_D = 50mV, 100 mV, and 500 mV. With V_D = 50 mV, the device showed an $I_{on}/I_{off} = 1.8\text{x}10^7$, V_{TH} = -0.1 V, and a field effect mobility of 4.5 cm^2/Vs. Its photoresponse for UV-VIS-NIR wavelengths under different optical power densities can be seen in Fig. 4 for UV, Fig. 5 for blue, Fig. 7 for green, Fig. 8 for red, and Fig. 9 for NIR (850 nm). As the light intensity increases, the illuminated I_D-V_G curves shift towards the left direction due to the enhancement of the photogating effect. In comparison, the HfO_2 device with no mirror can be seen in Fig. 6 where it also shows the photogating effect; however, its shifting is less than the mirror case. To evaluate the photogating effect, the change in the threshold voltage ΔV_{TH} (where $\Delta V_{TH} = V_{TH,LIGHT}$-$V_{TH,DARK}$) versus the optical power density for blue light was plotted in Fig. 10 where the negative sign indicates the presence of trapped hole charges. For the maximum optical power density of 1.5 mW/cm^2, the ΔV_{TH} for the mirror device was -1.16 V and the no-mirror HfO_2 was -0.72 V. Under the same light illumination, the mirror device showed more threshold voltage shifting indicating a more stronger photogating effect.

Next, a time response measurement was performed at UV, green, and red wavelengths in Fig. 11. HfO_2-based dielectrics show the behavior of persistent photocurrent (PPC) effect where the current slowly decays after light exposure due the slow de-trapping times of deep-level traps [2]. Here, the light exposure duration was for 20 seconds and a 2 ms positive gate reset pulse was performed after light exposure to improve the fall time to ~870 ms by releasing the trapped charges. The responsivity of the mirror device was benchmarked with other MoS_2 phototransistors in Fig. 12. This device showed a high responsivity at UV of 3.68x10^5 A/W, green was 6.47x10^5 A/W, red was 7.85x10^5 A/W, and NIR (850 nm) was 54.4 A/W.

4. Conclusion

In summary, the exploration of a back-plane mirror integrated into a back-gated MoS_2 phototransistor has been investigated. Due to the intrinsic property of charge-trapping with HfO_2 dielectrics, the photogating effect becomes a dominant photocurrent generation mechanism. The introduction of a back-plane mirror offers a second opportunity to reflect the portion of light that is transmitted through the dielectric layer. As a result, the photogating effect is more strongly enhanced providing a high responsivity and detection of low light signals.

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References:[1] R. Nur *et al.*, Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials (2019) 925. [2]A. Di Bartolomeo *et al.*, Nanotechnology. **28** (2017) 214002. [3] J.-Y. Wu *et al.*, Adv. Mater. **30** (2018) 1705880. [4] W. Choi *et al.*, Adv. Mater. **24** (2012) 5832. [5] O. Lopez-Sanchez *et al.*, Nat. Nanotechnol. **8** (2013) 497. [6] M. M. Furchi et al., Nano Lett. 14 (2014) 6165. [7] Z. Yin et al., ACS Nano. 6 (2012) 74. [8] W. Zhang et al., Adv. Mater. 25 (2013) 3456. [9] N. Perea-Lopez et al., 2D Mater. 1 (2014) 011004.

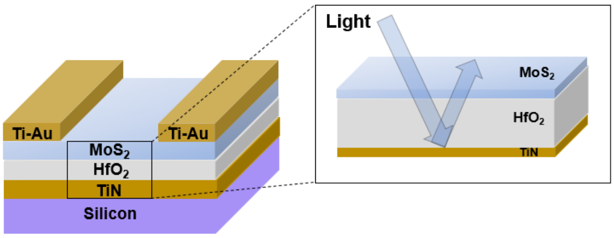
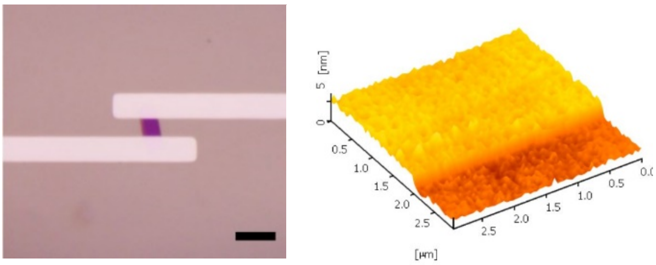


Fig. 1 Device structure and operation of back-gated Mirror HfO_2-based MoS_2 phototransistor.



(a) (b)

Fig. 2 (a) Optical image of channel region. Scale bar 10 µm. (b) AFM surface topography MoS_2 flake. Flake thickness 3 nm.

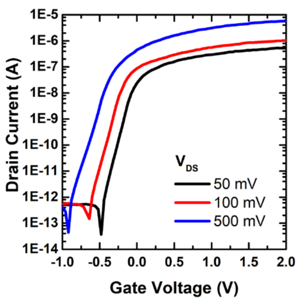


Fig. 3 Dark Condition Transfer Characteristics of Mirror-HfO_2 device under different drain voltages.

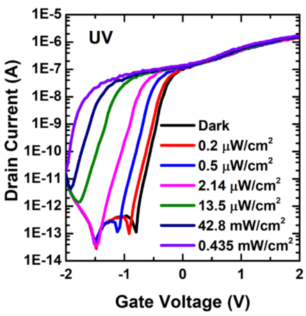


Fig. 4 Illumination with UV light at V_D=150mV.

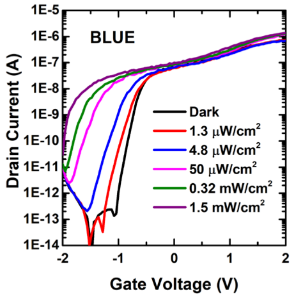


Fig. 5 Illumination with blue light (mirror device) at V_D=150mV.

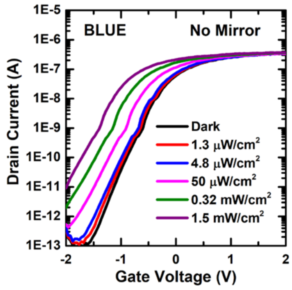


Fig. 6 Illumination with blue light (no-mirror device) at V_D=150mV.

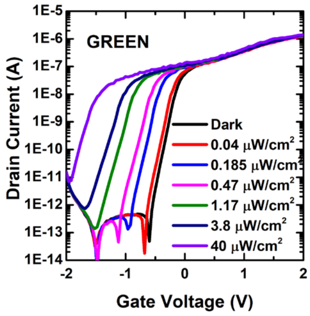


Fig. 7 Illumination with green light at V_D=150mV.

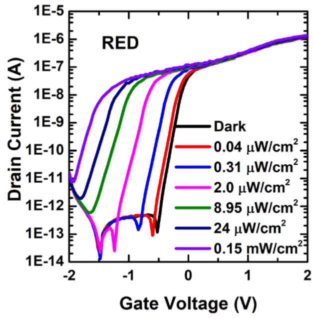


Fig. 8 Illumination with red light at V_D=150mV.

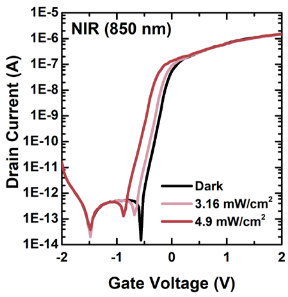


Fig. 9 Illumination with NIR (850nm) light at V_D=150mV.

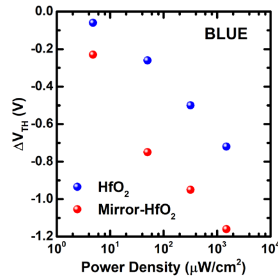


Fig. 10 Comparison of mirror and no mirror device threshold voltage shift (ΔV_{TH}) vs. optical power density at V_D=150mV.

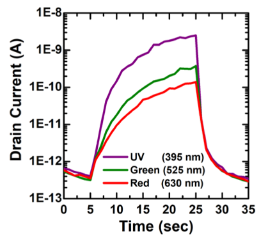


Fig. 11 Time response under UV, green, and red light at V_D=500mV.

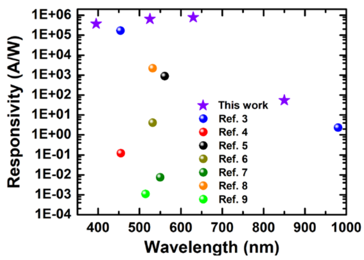


Fig. 12 Benchmark of responsivity of monolayer and multi-layered MoS_2 phototransistors.