

Photoresponse Enhancement in MoS₂ Phototransistors by the Photogating Effect

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Abstract

We investigated the effect of dielectric selection and its influence on the photoresponse of MoS₂ phototransistors. Out of the two dominant photoresponse mechanisms for MoS₂, we found SiO₂ showed the photoconductive effect and high-k HfO₂ showed the photogating effect. As a result of the photogating effect for HfO₂, we obtained simultaneously a very high responsivity of 1.7×10^5 A/W and a record high detectivity of 1.0×10^{15} Jones under low power operation and low light detection. Whereas the SiO₂ device had a responsivity of 1030 A/W with a detectivity of 1.0×10^{13} Jones.

1. Introduction

Recently, 2D transition metal dichalcogenides such as MoS₂ has attracted great interest for its unique electrical and optical properties. Phototransistors are a photodetection element that converts light into an electrical signal of current or voltage. MoS₂ phototransistors have been previously reported to offer high responsivities in visible light of 880 A/W [1] and 10,000 A/W [2] using $t \sim 300$ nm SiO₂ as a dielectric layer. Here, we explore for the first time HfO₂-based MoS₂ phototransistors.

The overall light detection process is explained. Incident light whose energy satisfies the condition $E_{\text{photon}} \geq E_{g, \text{MoS}_2}$ will be absorbed by the photoactive channel and will generate e^-/h^+ pairs. Since phototransistors share a similar structure to photoconductors, the photogenerated e^-/h^+ pairs are separated by an electric field generated from V_{DS} [3]. MoS₂ has been demonstrated to exhibit two types of photocurrent generation mechanisms: the photoconductive effect and the photogating effect. The photoconductive effect is where generated free electrons and holes are collected by the electrodes and results in an additional photocurrent that adds to the dark current [4]. The photogating effect is where the photogenerated holes are trapped in states near the valence band that generates a local electric field. This electric field shifts the Fermi level and results in inducing more electrons and a shift in the V_{TH} [4].

2. Experimental Details

A bottom-gate top-contact structure was utilized in order to expose the MoS₂ channel region for light illumination (Fig.1). Heavily doped n++ silicon was used a back-gate where ~ 10 nm of thermally oxidized SiO₂ or ALD HfO₂ was deposited. Next, mechanically exfoliated few layered MoS₂ was transferred onto the dielectric layer and was followed by depositing source/drain top contacts [Ti(5nm)/Au(50nm)]. A commercial blue LED ($\lambda = 460$ nm) was used as a light source and the distance between the sample and LED was 6.5 cm. In

order to obtain a steady state condition for light measurements, the LED is turned on for 1 minute before the measurement is taken. The LED is turned off for 3-5 minutes before subsequent measurements are made. All measurements were made at room temperature and under ambient conditions.

3. Results and Discussion

Fig. 2(a,b) shows the typical dark condition (no illumination) transfer characteristics of the SiO₂ and HfO₂ phototransistors with a channel length of 5 μm at different drain voltages ($V_{\text{D}} = 150\text{mV}, 250\text{mV}, \text{ and } 500\text{mV}$). At $V_{\text{D}} = 150\text{mV}$, the SiO₂ device displayed an $I_{\text{on}}/I_{\text{off}} = 2 \times 10^6$, $V_{\text{TH}} = -0.12\text{V}$, and a field effect mobility of $2.19\text{ cm}^2/\text{V}\cdot\text{s}$. The HfO₂ device had $I_{\text{on}}/I_{\text{off}} = 1 \times 10^6$, $V_{\text{TH}} = -0.91\text{V}$, and a field effect mobility of $3.5\text{ cm}^2/\text{V}\cdot\text{s}$. The effects of light illumination on both of the MoS₂ phototransistors can be seen in Fig. 3(a,b). As expected, there is an increase in I_{D} as the light intensity is increased. Both devices showed one of the photo-mechanisms as dominating its photoresponse: SiO₂ showed the photoconductive effect and HfO₂ showed the photogating effect.

The photocurrent vs. V_{G} is shown in Fig. 4. Under the same biasing and illumination conditions, the HfO₂ device provided a 55 times higher photocurrent generation compared to the SiO₂ device. The peak photocurrents (I_{PH}) were 804 nA for HfO₂ and 14.6 nA for SiO₂. The change in V_{TH} vs. incident optical power density can be seen in Fig. 5 where $\Delta V_{\text{TH}} = V_{\text{TH, LIGHT}} - V_{\text{TH, DARK}}$. The HfO₂ device displayed a larger shift in V_{TH} as the optical power was increased. This result shows that the HfO₂ device is more sensitive to the photogating effect than the SiO₂ device. Next, we measured the time response of both devices under the same biasing and illumination conditions ($V_{\text{G}} = -1\text{V}$, $V_{\text{DS}} = 150\text{mV}, 500\text{mV}$, and $P_{\text{opt}} = 1.5\text{mW}/\text{cm}^2$) in Fig.6(a,b). The light source was turned on for a duration of 30 seconds. The "ON" state is the generated photocurrent under illumination and the "OFF" state is under the dark condition (no illumination). Under the same optical power, both devices showed the trend of increasing photocurrent with larger V_{DS} . For the SiO₂ device, it displayed a faster response to light where its rise and fall times were in the millisecond range. On the other hand, the HfO₂ device showed the behavior of persistent photocurrent (PPC) effect where after illumination the I_{D} slowly decays due the slow de-trapping times of deep traps [5]. The decay current can be modelled by a stretched exponential decay where β is the decay exponential and τ is the relaxation time constant [6].

$$I_{\text{PPC}}(t) = I_0 e^{-\left(\frac{t}{\tau}\right)^\beta} \quad (1)$$

The fitting of the PPC model to the experimental results

can be found in Fig. 7 and the fitting parameters in Table I. Table II summarizes the performance metrics of both phototransistors. Due to the photogating effect, we achieved a record high detectivity with the HfO₂ phototransistor.

4. Conclusion

The effect of dielectric selection and its influence on the photoresponse of MoS₂ phototransistors has been investigated. We found that the photogating effect strongly influenced the HfO₂ phototransistor's photoresponse and as a result offered simultaneously a very large responsivity and detectivity.

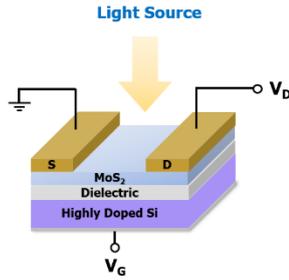


Fig. 1 Device structure and operation of back-gated MoS₂ phototransistor.

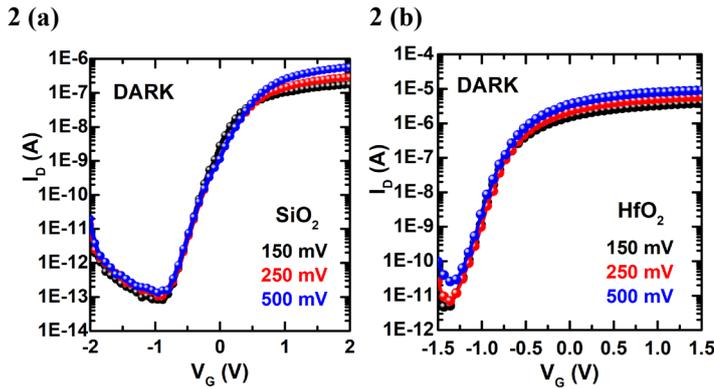


Fig. 2 Dark Condition Transfer Characteristics of MoS₂ Phototransistor at different drain voltages (a) SiO₂ (b) HfO₂.

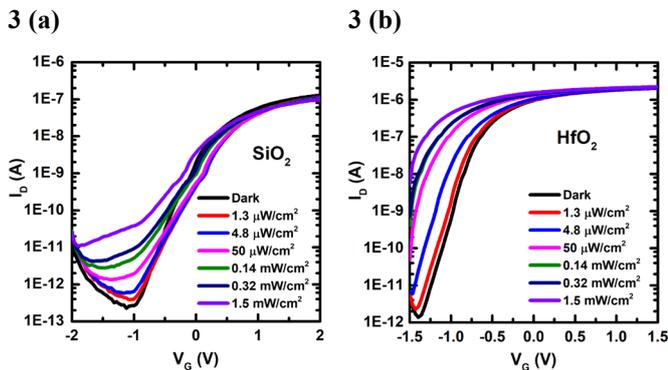


Fig. 3 Effects of illumination with blue LED at different optical power densities (a) SiO₂ (b) HfO₂.

References

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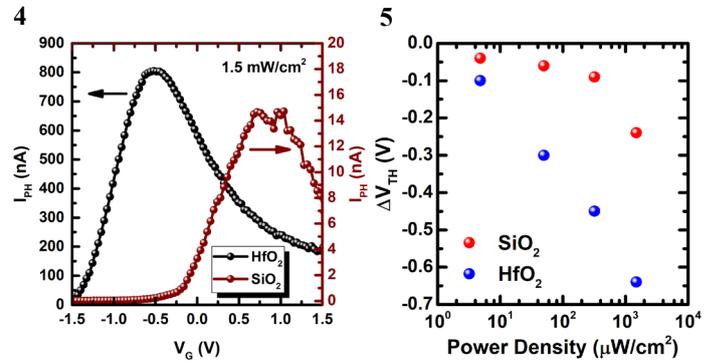


Fig. 4 Photocurrent vs. V_G of both phototransistors at $V_D=150\text{mV}$.

Fig. 5 Threshold voltage shift (ΔV_{TH}) vs. optical power density at $V_D=150\text{mV}$.

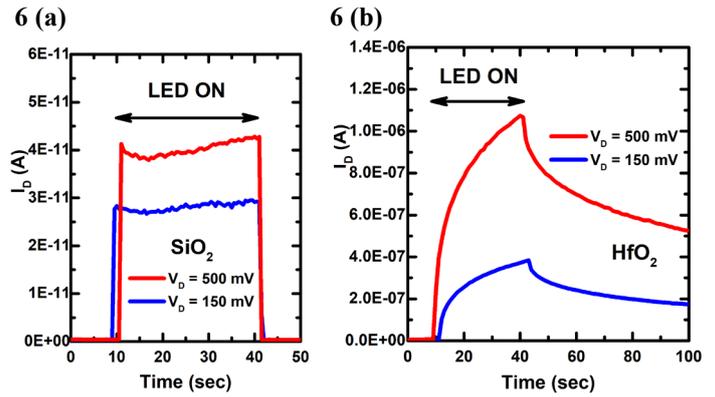


Fig. 6 Time response of (a) SiO₂ (b) HfO₂ phototransistors at $1.5\text{mW}/\text{cm}^2$.

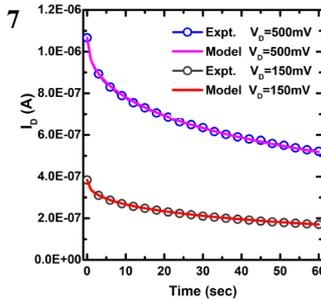


Table I. Fitting parameters of PPC model

Drain Voltage	Relaxation Time Constant	Decay Exponent
150mV	96 sec	0.45
500mV	120 sec	0.47

Fig. 7 Decay current of HfO₂ phototransistor fitted with PPC model using the parameters from Table I.

Table II. Performance Metrics for Photodetection

Dielectric	Responsivity (A/W)	Photogain	Detectivity (Jones)
HfO ₂	1.7×10^5	2.02×10^8	1.0×10^{15}
SiO ₂	1030	2.63×10^5	1.0×10^{13}