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# Photoresponse Enhancement in $MoS_2$ Phototransistors by the Photogating Effect

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**Abstract**

**We investigated the effect of dielectric selection and its influence on the photoresponse of $MoS_2$ phototransistors. Out of the two dominant photoresponse mechanisms for $MoS_2$, we found $SiO_2$ showed the photoconductive effect and high-k $HfO_2$ showed the photogating effect. As a result of the photogating effect for $HfO_2$, we obtained simultaneously a very high responsivity of $1.7x10^5$A/W and a record high detectivity of $1.0x10^{15}$ Jones under low power operation and low light detection. Whereas the $SiO_2$ device had a responsivity of 1030 A/W with a detectivity of $1.0x10^{13}$ Jones.**

## 1. Introduction

Recently, 2D transition metal dichalcogenides such as $MoS_2$ 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. $MoS_2$ 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~300 nm $SiO_2$ as a dielectric layer. Here, we explore for the first time $HfO_2$-based $MoS_2$ phototransistors.

The overall light detection process is explained. Incident light whose energy satisfies the condition $E_{photon} \geq E_{g,MoS2}$ 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]. $MoS_2$ 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 $MoS_2$ channel region for light illumination (Fig.1). Heavily doped n++ silicon was used a back-gate where ~10 nm of thermally oxidized $SiO_2$ or ALD $HfO_2$ was deposited. Next, mechanically exfoliated few layered $MoS_2$ was transferred onto the dielectric layer and was followed by depositing source/drain top contacts [Ti(5nm)/Au(50nm)]. A commercial blue LED (λ=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 $SiO_2$ and $HfO_2$ phototransistors with a channel length of 5 μm at different drain voltages ($V_D$ = 150mV, 250 mV, and 500 mV). At $V_D$ = 150 mV, the $SiO_2$ device displayed an $I_{on}/I_{off} = 2x10^6$, $V_{TH}$ = -0.12 V, and a field effect mobility of 2.19 $cm^2/V^*s$. The $HfO_2$ device had $I_{on}/I_{off} = 1x10^6$, $V_{TH}$ = -0.91 V, and a field effect mobility of 3.5 $cm^2/V^*s$. The effects of light illumination on both of the $MoS_2$ 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: $SiO_2$ showed the photoconductive effect and $HfO_2$ showed the photogating effect.

The photocurrent vs. $V_G$ is shown in Fig. 4. Under the same biasing and illumination conditions, the $HfO_2$ device provided a 55 times higher photocurrent generation compared to the $SiO_2$ device. The peak photocurrents ($I_{PH}$) were 804 nA for $HfO_2$ and 14.6 nA for $SiO_2$. The change in $V_{TH}$ vs. incident optical power density can be seen in Fig. 5 where $\Delta V_{TH} = V_{TH,LIGHT}-V_{TH,DARK}$. The $HfO_2$ device displayed a larger shift in $V_{TH}$ as the optical power was increased. This result shows that the $HfO_2$ device is more sensitive to the photogating effect than the $SiO_2$ device. Next, we measured the time response of both devices under the same biasing and illumination conditions ($V_G$ = -1V, $V_{DS}$ = 150mV, 500mV, and $P_{opt}$ = 1.5mW/$cm^2$) 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 $SiO_2$ device, it displayed a faster response to light where its rise and fall times were in the millisecond range. On the other hand, the $HfO_2$ 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].

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

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 $HfO_2$ phototransistor.

## 4. Conclusion

The effect of dielectric selection and its influence on the photoresponse of $MoS_2$ phototransistors has been investigated. We found that the photogating effect strongly influenced the $HfO_2$ phototransistor's photoresponse and as a result offered simultaneously a very large responsivity and detectivity.

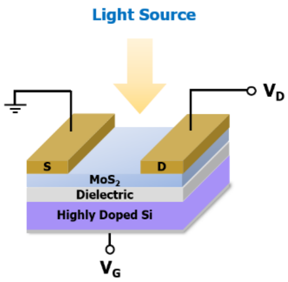
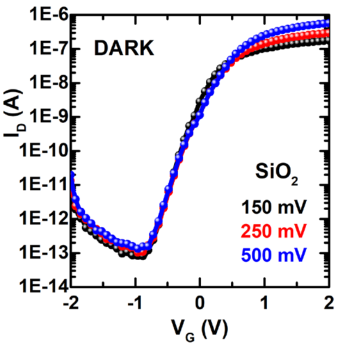



**Fig. 1** Device structure and operation of back-gated $MoS_2$ phototransistor.

2 (a)




2 (b)

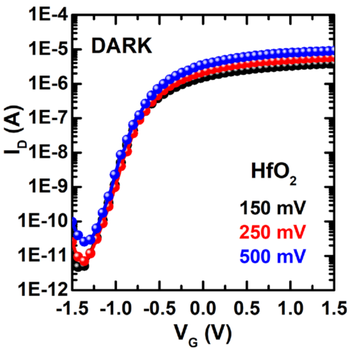
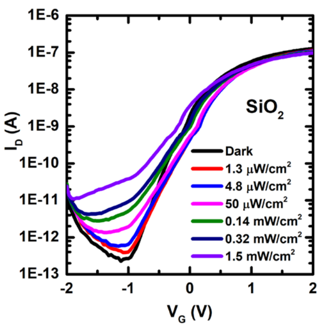



**Fig. 2** Dark Condition Transfer Characteristics of $MoS_2$ Phototransistor at different drain voltages (a) $SiO_2$ (b) $HfO_2$.

3 (a)




3 (b)

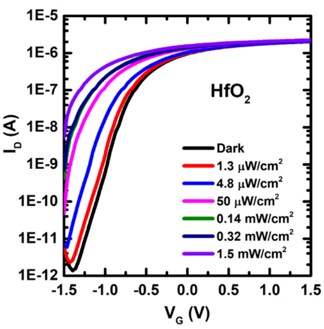



**Fig. 3** Effects of illumination with blue LED at different optical power densities (a) $SiO_2$ (b) $HfO_2$.

## References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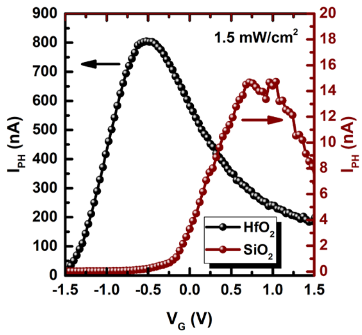


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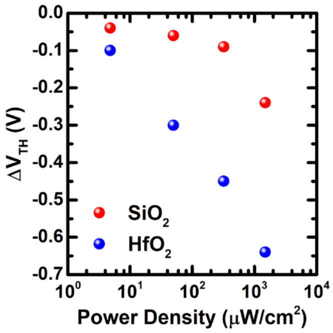
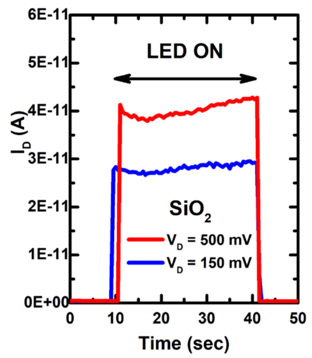



**Fig. 4** Photocurrent vs. $V_G$ of both phototransistors at $V_D$=150mV.
**Fig. 5** Threshold voltage shift ($\Delta V_{TH}$) vs. optical power density at $V_D$=150mV.

6 (a)




6 (b)

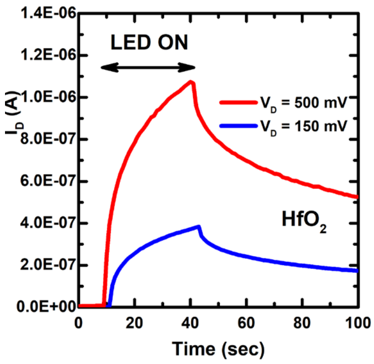



**Fig. 6** Time response of (a) $SiO_2$ (b) $HfO_2$ phototransistors at 1.5mW/cm$^2$.

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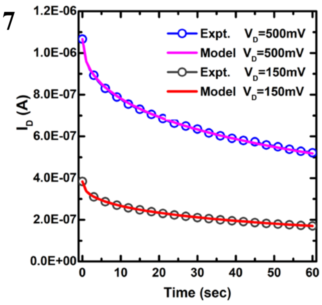


**Fig. 7** Decay current of $HfO_2$ phototransistor fitted with PPC model using the parameters from Table I.

**Table I. Fitting parameters of PPC model**

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

**Table II. Performance Metrics for Photodetection**

| Dielectric | Responsivity (A/W) | Photogain | Detectivity (Jones) |
|---|---|---|---|
| $HfO_2$ | 1.7x10$^5$ | 2.02x10$^8$ | 1.0x10$^{15}$ |
| $SiO_2$ | 1030 | 2.63x10$^5$ | 1.0x10$^{13}$ |