

# Gate-Controlled Schottky Barrier Modulation for Superior Photoresponse of MoS<sub>2</sub> Field Effect Transistor

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## Abstract

An ultrahigh photocurrent (PC) signal which was about thousand times higher compared to the corresponding dark current was achieved in a two-dimensional (2D) multi-layer MoS<sub>2</sub> field effect transistor (FET), owing to a gate-controlled MoS<sub>2</sub>/Ti/Au Schottky barrier (SB) modulation. The SBs can be enlarged for suppressing the electron drift along the channel in dark environment, and be reduced for the collection of photo-excited charge carriers in illuminating environment, providing the great potential for 2D electronic and optoelectronic applications.

## Introduction

Compared to graphene which cannot achieve the low off-state and saturated on-state currents due to its zero bandgap (1), (2), transition metal dichalcogenides (TMDCs) have opened up new opportunities for 2D electronics and optoelectronics such as transistors (3)-(5), memories (6), photodetectors (7) and electro-luminescent devices (8), because of their selectable electronic properties ranging from metallic to semiconducting, and tunable bandgaps with layer-dependence (9). Particularly for semiconducting TMDCs such as MoS<sub>2</sub>, the sub-nanometer thickness with sizable bandgap can provide high on/off ratios and more efficient control over switching. The immunity of short-channel and drain-induced barrier lowering (DIBL) effects and ultralow power dissipation by using 2D materials can break through the scaling limit for future transistor miniaturization (10), (11). In this work, MoS<sub>2</sub> as a representative TMDC was applied to the FET devices for photodetection, and it shows an ultrahigh PC which was about thousand times higher compared to the corresponding dark current. Owing to a gate-controlled modulation of MoS<sub>2</sub>/Ti/Au SBs, the electron drift along the channel was suppressed by the enlarged SBs, whereas the collection of photo-excited charge carriers at metal contacts was promoted by the reduced SBs, giving rise to the ultrahigh photoresponse at certain gate voltage. The gate-controlled SB modulation shows the different effects on carrier transport in dark and illuminating environments, and demonstrates the great potential in 2D electronic and optoelectronic applications.

## Device Fabrication and Measurement

Thin MoS<sub>2</sub> flake is obtained by mechanical exfoliation from bulk crystals, and transferred to a *p*-type Si substrate with a 90-nm-thick SiO<sub>2</sub> surface. The back-gate FET is

fabricated via electron-beam lithography with Ti/Au (3/50 nm) electrodes deposited by evaporation, as shown in Fig. 1(a). The MoS<sub>2</sub> flake has the thickness of ~2.5 nm measured by atomic force microscopy (AFM), as shown in Fig. 1(b). Raman spectrum (532 nm wavelength) shows two typical peaks ( $E_{2g}^1$  and  $A_{1g}$ ) with a separation of 23 cm<sup>-1</sup>, suggesting a few-layer structure (12).

The electrical and optoelectronic characterizations of MoS<sub>2</sub> FET are performed at room temperature with ambient pressure, as shown in Figs. 2 and 3, where the PC signal is defined as the difference of drain current ( $I_D$ ) in dark and laser (655 nm, 15mW) illuminating environments at certain drain and gate voltages ( $V_D$  and  $V_G$ ). The  $I_D$ - $V_D$  output characteristics show a clear current saturation at the high  $V_D$  (see Fig. 2(a)), and a non-linear dependence near zero  $V_D$  suggests a Schottky contact between MoS<sub>2</sub> and Ti/Au. The  $I_D$ - $V_G$  transfer characteristics illustrate an *n*-type carrier transport with a trapping-induced hysteresis which voltage shift ( $\Delta V$  of ~14 V) suggests an equivalent trap density of  $3.35 \times 10^9$  cm<sup>-2</sup> (see Fig. 2(b)). It is interesting that the strong photoresponse in MoS<sub>2</sub> FET is only observed in the negative  $V_G$  range for both forward and reverse sweeps (see Fig. 3(a) and (b)). Compared to a gradual decrease of the light current (laser on), the dark current (laser off) is reduced drastically at the negative  $V_G$ , and therefore gives rise to a high PC generation, although the PCs also show different peak positions for forward and reverse sweeps due to the trapping effect (see Fig. 3(c)). The normalized PC, defined as the ratio of PC to its corresponding dark current, has the maximum about thousand (see Fig. 3(d)). Those clearly demonstrate that the carrier transport in MoS<sub>2</sub> FET has different gate dependence in dark and illuminating environments.

## Gate-Controlled Schottky Barrier Modulation

A gate-controlled SB modulation is proposed which can interpret the gate-dependent carrier transport in MoS<sub>2</sub> FET for both dark and illuminating environments. Firstly, the gating effect on electron density in MoS<sub>2</sub> is shown differently for various  $V_G$  conditions. When  $V_G > 0$ , the electrons are attracted to the interface between MoS<sub>2</sub> and SiO<sub>2</sub> to form an accumulation layer. When  $V_G < 0$ , the electrons are repelled from the interface to establish a depletion layer. Further increasing the negative  $V_G$  may create an inversion channel which gives rise to the high mobilities (13). Secondly, the SBs at both source and drain ends are modulated capacitively by the gate. The SBs are induced due to a mismatch between the work functions of MoS<sub>2</sub> and Ti, and they can be enlarged or reduced by

applying the positive or negative  $V_G$ , respectively. Thirdly, the carrier transports in both dark and illuminating environments are affected by the gate-dependent SB modulation. For the electron drift along the channel driven by a positive  $V_D$ , the SBs are reduced with increasing  $V_G$ , allowing the electrons to transport through by tunneling effect or thermionic emission in the dark environment, as shown in Fig. 4(a). As a comparison, for the photon-excited charge carriers generated within the channel, the SBs only allow the electron collection at the drain end, but suppress the hole collection at the source end when  $V_G < 0$ , and vice versa when  $V_G > 0$ . In this way, the SBs can contribute to a peak PC generation at the certain  $V_G$  (a negative  $V_G$  for MoS<sub>2</sub> in this work) where the collection of both electrons and holes is promoted due to the minimized SBs at source and drain ends concurrently, as shown in Fig. 4(b). Finally, the light current, which is the sum of both dark current and PC, shows the gate dependence following a combined SB modulation for both electron drift and photo-excited charge carriers.

### Superior Photoresponse of MoS<sub>2</sub> FET

The photoresponse of MoS<sub>2</sub> FET is recorded in time ( $t$ ) evolution, as shown in Fig. 5. The rise and decay of PC signal are illustrated, fitted with theoretical simulation as  $I(t)=I_{eq}-(I_{eq}-I_0)\exp(-t/\tau)$  (see Fig. 5(a)). Here  $\tau$  is the time constant,  $I_0$  and  $I_{eq}$  are the channel current at the starting and equilibrium states, respectively. The time-resolved PC of MoS<sub>2</sub> FET shows a strong dependence on the illuminating period (30, 60 and 120 s),  $V_G$  levels (10 and -10 V) and  $V_D$  levels (0.1, 0.2, 0.3 and 0.4 V) (see Fig. 5(b)-(d)). According to the time evolution, the incident power dependence of PC is also obtained (see Fig. 5(e) and (f)). As the power increases further, the PC generation cannot follow the linear dependence but show a saturation due to the screening effect, being similar with the graphene and other conventional semiconductor photodetectors (14).

### Conclusion

In this work, the ultrahigh PC which was about thousand times higher compared to the corresponding dark current was obtained in MoS<sub>2</sub> FET, due to the gate-dependent SB modulation. The transport of electron drift along the channel was suppressed by the enlarged SBs, whereas the collection of photo-excited charge carriers at the metal contacts was promoted by the reduced SBs. The gate-dependent SB modulation shows the different effects on carrier transport in dark and illuminating environments, and presents the great potential in 2D TMDCs for electronic and optoelectronic applications.

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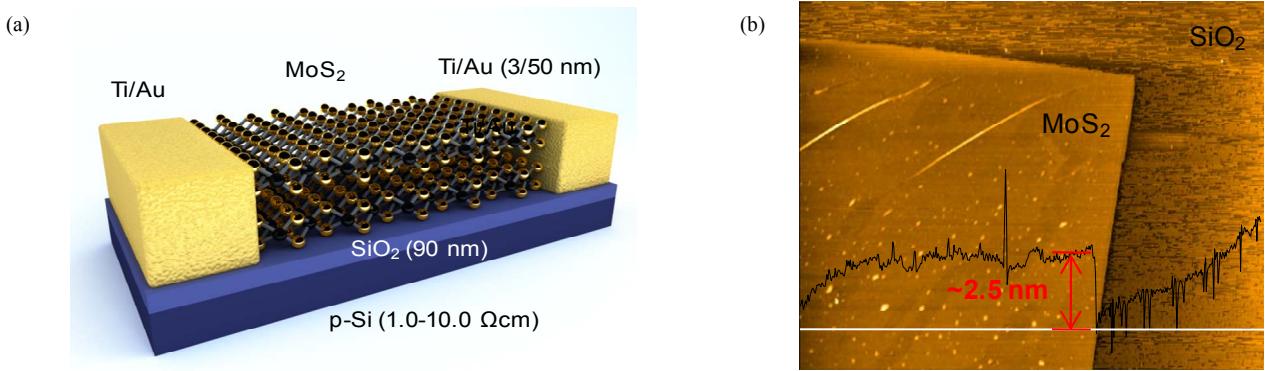


Fig. 1. (a) Schematic of a back-gate MoS<sub>2</sub> FET with symmetric metallization. (b) Thickness (~2.5 nm) of MoS<sub>2</sub> flake measured by AFM.

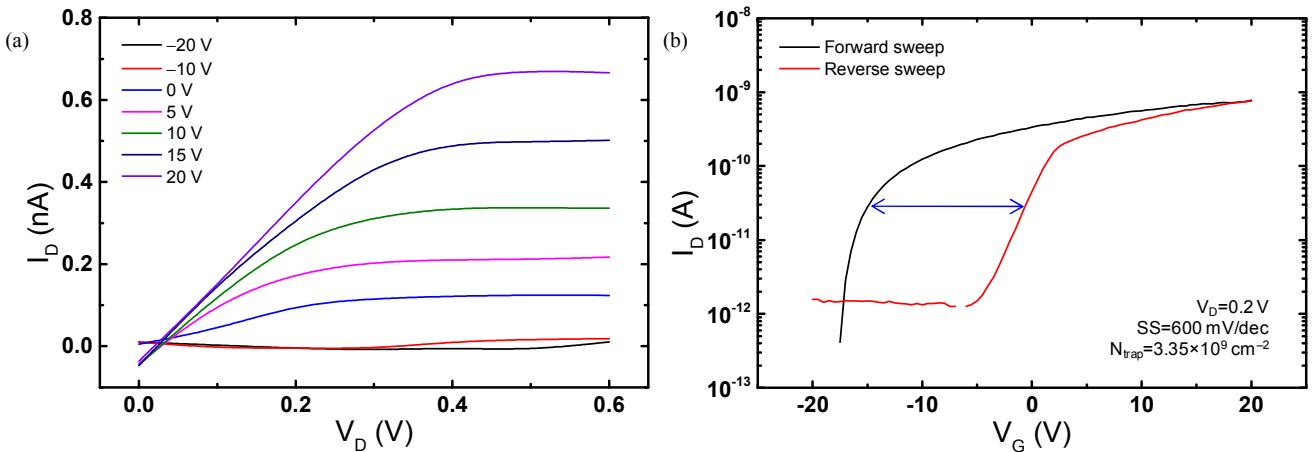


Fig. 2. (a)  $I_D$ - $V_D$  output characteristics for various  $V_G$  levels, and (b)  $I_D$ - $V_G$  transfer characteristics at  $V_D$  of 0.2 V in MoS<sub>2</sub> FET.

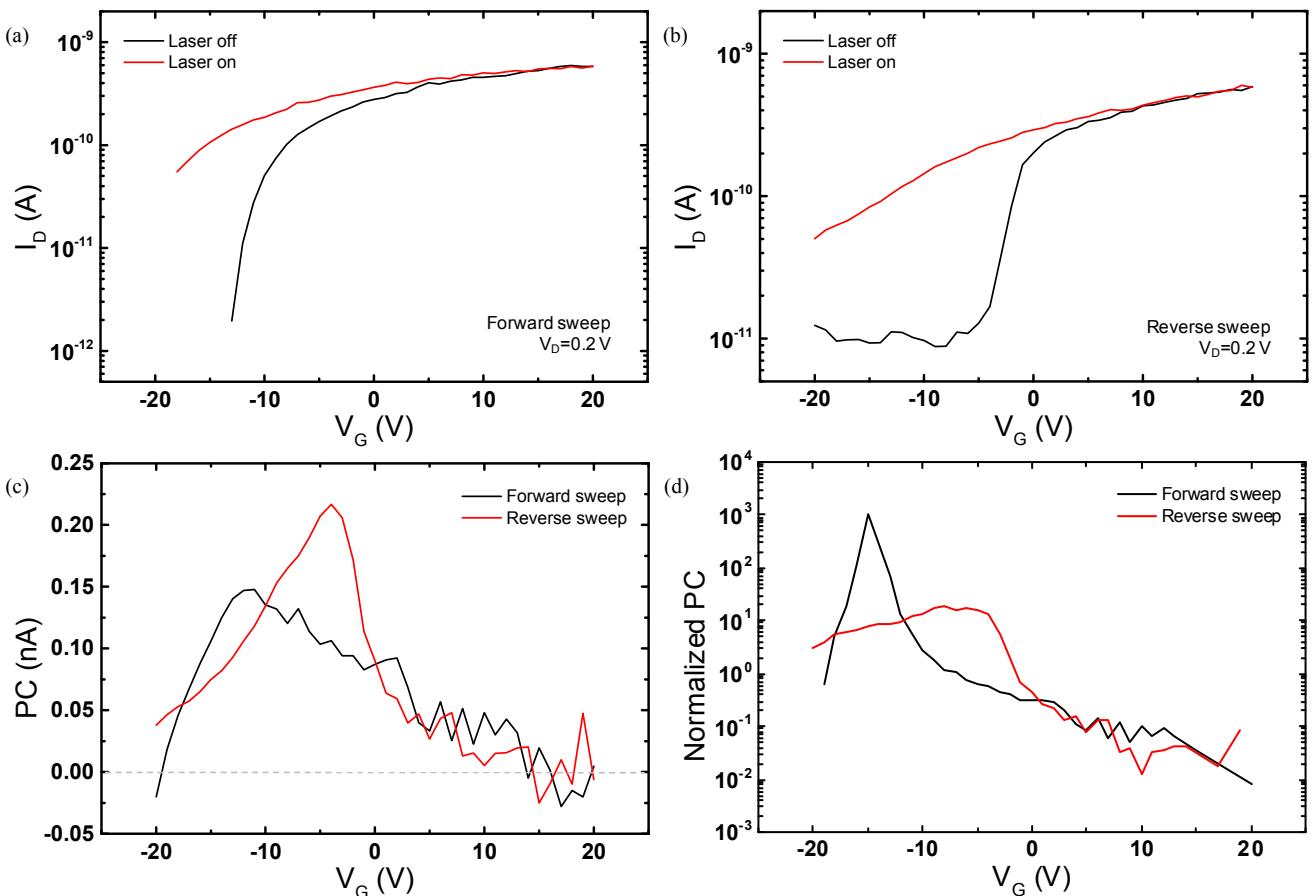


Fig. 3. (a, b) Photoresponse of  $I_D$ - $V_G$  transfer characteristics, (c) PC, and (d) normalized PC in both forward and reverse sweeps in MoS<sub>2</sub> FET.

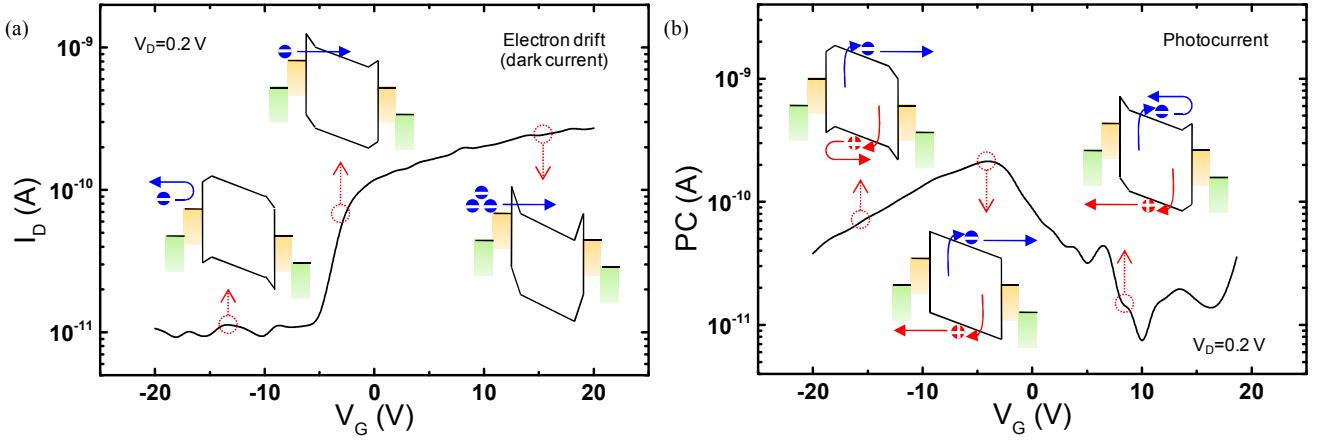


Fig. 4. Gate-controlled SB modulation shows different effects on (a) the unipolar transport of electron drift along the channel in dark environment, and (b) the collection of photo-excited charge carriers in illuminating environment.

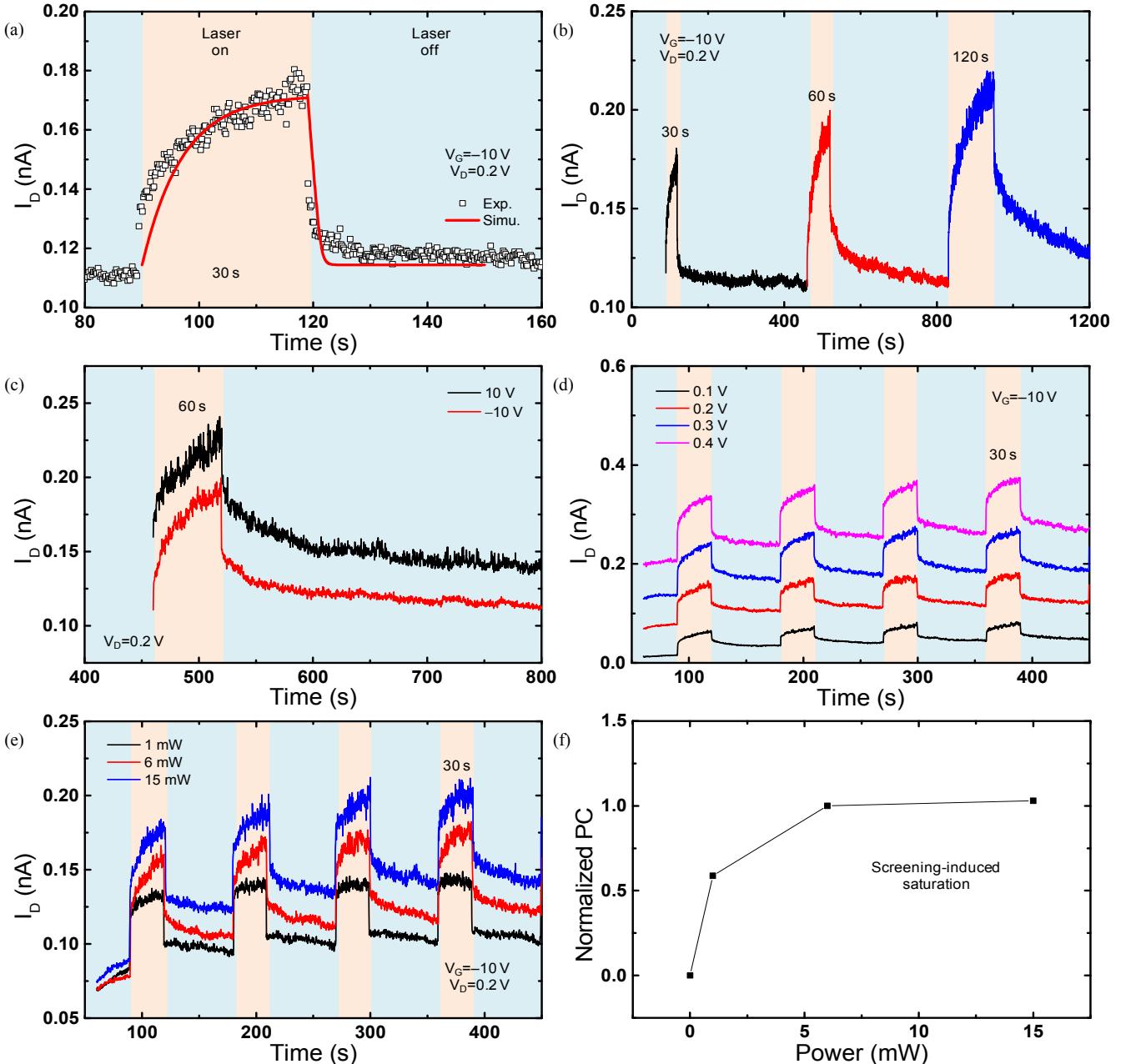


Fig. 5. (a) Rise and decay of PC as a function of time and its simulation. (b-f) Dependence of PC on the illuminating period,  $V_G$  and  $V_D$  levels, and laser power. A PC saturation is observed for high incident power due to the screening effect as in conventional photodiodes.