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MoS_2 FET based Oxygen Sensors with Gate Voltage Stress Induced Performance Enhancement

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Abstract

2D materials are regarded as promising building blocks for gas sensors due to their high surface-to-volume ratio, ease in miniaturization and flexibility in enabling wearable electronics. Here, we report MoS_2 transistor based O_2 sensor with a back gate configuration on a 285 nm SiO_2/Si substrate. The effects of back gate voltage stress on O_2 sensing performance have been investigated. With a positive gate voltage stress, the sensor has achieved a high drain current response and the response is improved to 29.2% at O_2 partial pressure of 9.9×10^{-5} mBar with a +40 V back-gate bias compared to 21.2% at O_2 partial pressure of 1.4×10^{-4} mBar without back-gate bias; while under a negative gate voltage stress (-40 V), a fast and full sensor recovery can be achieved at room temperature.

1. Introduction

The discovery of graphene ignited a thrust on two-dimensional (2D) materials research. Among a myriad of proof-of-concept demonstrations of 2D materials based devices, gas sensors are particularly interesting because of 2D materials' ultrahigh surface-to-volume ratio. Among various 2D materials, molybdenum disulfide (MoS_2) has been widely investigated and is believed to outperform graphene in sensing applications because of its semiconducting behaviors [1]. There exist a few demonstrations [2–5] reporting on MoS_2 sensing performance, and remarkable progresses have been made. In this report, we successfully demonstrated a MoS_2 based O_2 sensor. According to the best of our knowledge, there is no report on MoS_2 based O_2 sensor up to date. The MoS_2 transistor O_2 sensor was first characterized without applying back gate voltage stress and the sensor exhibits a high response, 21.2% at O_2 partial pressure of 1.4×10^{-4} mBar. The influences of back gate bias on the sensor were then investigated extensively. It is found that by applying a positive gate voltage stress, O_2 adsorption on MoS_2 can be enhanced and results in an improved response, and a response enhancement of 81% was observed. While by applying a negative back gate voltage (-40 V) stress, a fast and full sensor recovery can be achieved at room temperature. The O_2 sensor demonstrated and its associated findings on gate voltage stress would be valuable in paving the way to practical MoS_2 sensors.

2. Experiments

The experiments started with a heavily p-type doped Si substrate coated with a 285 nm SiO_2 layer. MoS_2 nanoflakes were prepared using mechanical exfoliation, "scotch-tape" method, and then put onto the pre-cleaned SiO_2/Si substrate. Suitable MoS_2 nanoflakes were identified under optical microscope inspection with contrast calibrated to approximately estimate the layer number of nanoflakes. After that, MoS_2 nanoflakes were patterned into a strip with a 2 μm width and 30 μm length using EBL. Lift-off process was used to form source and drain electrodes by thermal evaporation of a layer of Au. Finally, back-gated MoS_2 device was wire bonded to the chip. Sensing behavior measurements were conducted in a chamber with a low base pressure of ~3.0×10^{-6} mBar. The flow rate of O_2 is controlled by a mass flow controller and a manual valve, and the partial pressure of O_2 and total pressure within the chamber were recorded by a residual gas analyzer. The electrical behavior of MoS_2 sensor was measured using Keithley 4200 electrical analyzer.

3. Results and discussion

Fig. 1a shows the time domain response of drain current of the MoS_2 sensor when the valve of O_2 gas was turned on and off. The drain current (black line) was measured at V_{DS}=0.1 V and V_{GS}=0 V, and the partial pressure (blue circle dots) of analyte gas O_2 was recorded by residual gas analyzer. The decrease of drain current with increasing O_2 partial pressure can be explained as the increase of O_2 adsorption on MoS_2. Fig. 1b examines the effects of positive gate voltage stress on the time domain response of drain current (black square dots) of the MoS_2 sensor when the valve of O_2 was turned on and off. When drain current dropped to 99% of its initial current value, a positive gate voltage stress was applied in a form with 95 sec duration of +40 V for gate voltage stressing and 5 sec duration of 0 V for relaxation and drain current measurement. The pulse form of gate voltage stress is shown in the inset of Fig 1b. The drain current was measured at the end of 5 sec duration and this hold duration is assumed to be enough for relaxation of carriers generated by gate voltage. It is observed that, under the positive gate voltage stress, the drain current decreased faster than the case without the gate voltage stress. The enhancement of the response can be explained by the positive gate voltage stress inducing an accumulation of electrons on MoS_2, therefore attracting more acceptor-like O_2 on MoS_2. Fig. 2 compares the drain current response of MoS_2 sensor as a function of different O_2 peak partial pressure with (red circle dots) and without gate voltage stress (black square dots). Through curve fitting, it is found that the response was enhanced 81% at 9.0×10^{-5} mBar under +40 V gate voltage stress compared to the one measured without gate voltage stress.

Though the adsorption of O_2 in MoS_2 sensor is enhanced with positive gate voltage stress as shown in Fig. 1, it is observed that its recovery is slow and a complete recovery seems unlikely after the valve of O_2 was turned off. As shown in Fig. 3a for the sensors without negative gate voltage stress, drain current (black line) decreased when the valve of O_2 was turned on for the first two cycles, with its O_2 peak partial pressure at 1.4×10^{-5} and 3.1×10^{-5} mBar respectively. The higher O_2 partial pressure (3.1×10^{-5} mBar) in the second cycle causes the drain current to decrease further after the first cycle of O_2 injection, although significant recovery after first two injections was not observed. It is also noted that, with the third cycle of O_2 injection with a partial pressure 1.3×10^{-5} mBar, there is not any obvious decrease in drain current. This implies that the insufficient recovery limits the use of O_2 sensing to few cycles. Fig. 3b examines the effects of negative gate voltage stress on the desorption process. The drain current (black square dots) decreased when the valve of O_2 was turned on and increased slowly during recovery after the valve of O_2 was turned off. It is observed that after recovery for 1000 sec, the sensor was still not fully recovered (less than 40% recovery) and its recovery rate nearly saturated. Then, a -40 V gate voltage stress was applied for 400 sec in a similar pulse form (95 sec duration of -40 V for gate voltage stress and 5 sec duration of 0 V for current measurement) as shown in the inset of Fig. 3b, and the recovery rate was significantly enhanced compared to the case without gate voltage stress. After turning off the -40 V gate voltage stress, drain current has returned to its initial value, implying a full recovery at room temperature. The enhancement of the recovery can be explained by the negative gate voltage stress reducing electron concentration on MoS_2 and encouraging desorption of acceptor-like O_2 on MoS_2.

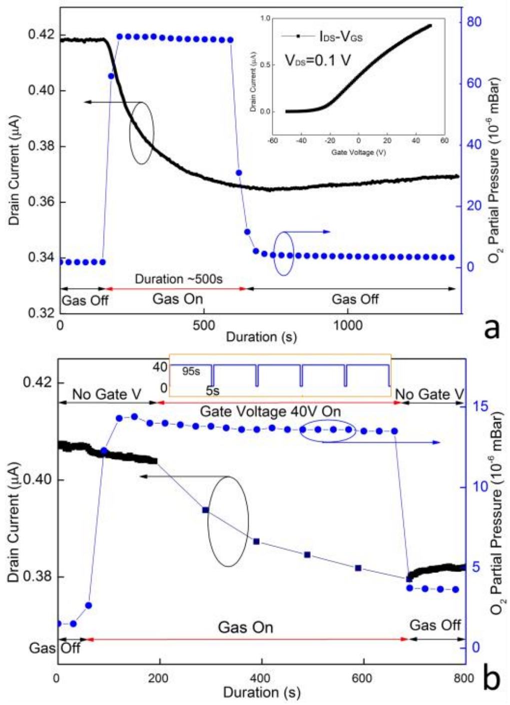

Fig. 1 Time domain response of drain current (a) without and (b) with +40V gate voltage stress. Fig.1a inset shows the I_{DS}-V_{GS} curve of the MoS_2 transistor.

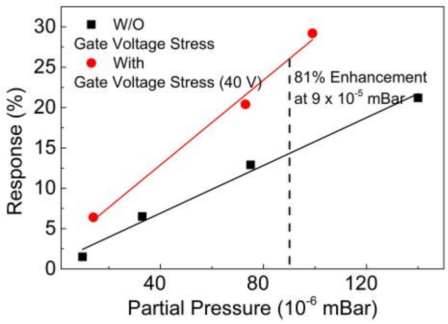

Fig. 2 O_2 sensing response as a function of partial pressure with or without +40V gate voltage stress.

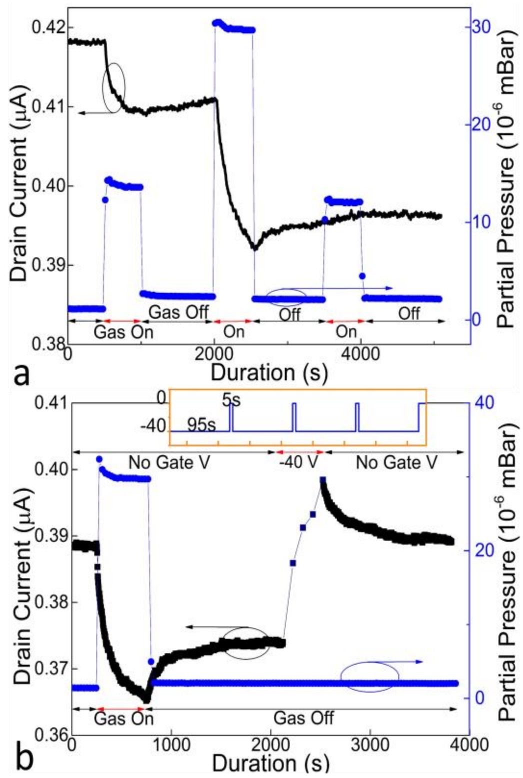

Fig. 3 (a) Time domain response of drain current under cyclic O_2 injections. (b) Time domain response of drain current with O_2 injection and negative gate voltage stress.

4. Conclusion

In this study, MoS_2 transistor based O_2 sensors have been demonstrated and the effects of gate voltage stressing on O_2 sensing performance have been investigated. It is found that employing gate voltage stress can enhance the sensor response and achieve a fast and full recovery at room temperature.

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