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Direct evidence of defect-defect correlation in atomically thin MoS_2 layer by random telegraphic signals observed in back-gated FETs

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Abstract

Exfoliated MoS_2 FET characteristics are discussed from the viewpoints of the random-telegraphic-signals (RTSs) observed in FET. Simple and independent RTSs are easily observed in MoS_2 FETs. In addition to that, this paper particularly pays attention to complex RTSs, which are not understandable just from the superposition of a couple of independent RTSs. This fact strongly suggests the defect-defect interaction within an atomically thin layer channel or with the interface states on SiO_2.

1. Introduction

Transition metal dichalcogenides (TMDs) have attracted much attention both in condensed matter physics (1, 2) and in ultimately scaled device research (3, 4). It is surprising that 0.65 nm-thick mono-layer MoS_2 can work as a field-effect-transistor channel. Although its carrier mobility is not so high compared to that of graphene, the off-current is definitely suppressed thanks to a sufficient energy band gap. Resultantly, MoS_2 FETs show a well-controlled subthreshold region. However, it should be noted that perfect crystalline TMDs are difficult to form, because chalcogen atoms are likely to be desorbed and easily become deficient in TMDs (5). These defects are observable in TMD FETs as the random telegraphic signals (RTSs) (6). The objective of this work is to report complex RTSs rather than simple ones, and to discuss the defect-defect interactions possibly causing complex RTSs.

2. Experiments

MoS_2 was mechanically exfoliated from natural MoS_2. A small flake of samples (~μm) on SiO_2 (90 nm)/Si substrate was used for the back-gated FET. The Raman measurement was employed for determining the layer number. The source and drain electrodes were Au/Ni. I-V characteristics were measured in the cryo-probing system in vacuum from 20 to 300 K.

3. Results and Discussion

Fig. 1 shows the schematic image of MoS_2 with S deficiency. Such defects should affect the carrier transport in MoS_2 FETs. Even if no anomaly is observed in I_{ds}-V_{gs} characteristics at 300 K, anomalous behaviors are often observed at lower temperatures. **Fig. 2** shows typical I_{ds}-V_{gs} characteristics, and simple two-level RTSs as a function of time at fixed biases in bilayer MoS_2 FET. Since these characteristics were reported at the last SSDM (8), in the present study, we pay more attention to complex RTSs, because it is considered to be related to a defect-defect correlation which is difficult to detect in conventional spectroscopic measurements.

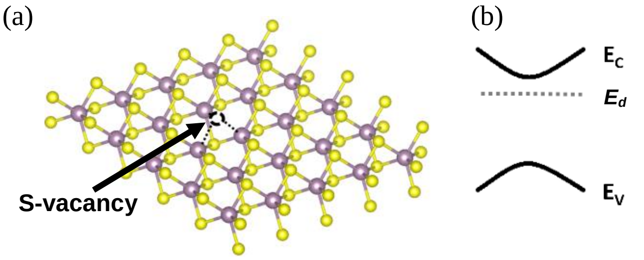

Fig. 1. Schematic image of MoS_2 with S deficiency **(a)** spatially **(b)** energetically. **(a)** Sulfur vacancy is shown by black broken line. **(b)** Defects level (E_d) just below E_C is induced by sulfur vacancy (7).

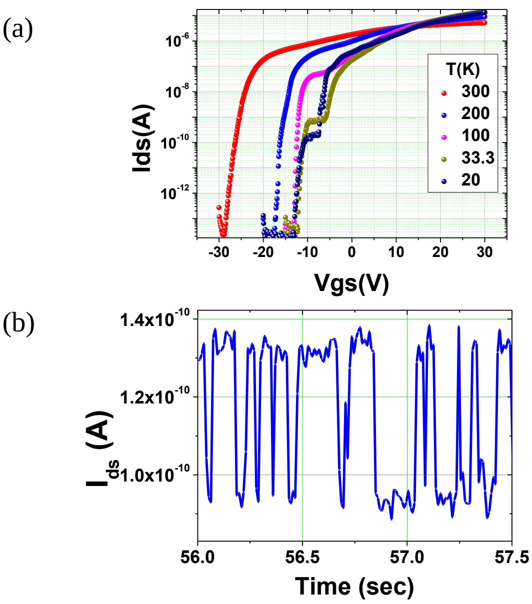

Fig. 2. **(a)**Subthreshold transport characteristics in bilayer MoS_2 FET (V_{ds}=0.1 V). At lower temperatures, reproducible conductance wiggles are observed. **(b)** Temporal characteristics of I_{ds} at 20 K at V_{gs}= -2.1V. Simple two-level RTS are observed.

Next, multi-level RTSs are discussed. Here, it is easily understood that two independent RTSs are superimposed (rapid and slow one) in **Fig. 3(a)**, while RTSs in **(b)** are unlikely to be reproduced just by superposing two independent RTSs. If this RTS is composed of two independent RTSs, quick RTS should also be observed in both high and low states. Why are quick RTSs observed only in the high current states? **Fig. 4** shows another example of correlated RTSs. Slower three-levels and rapid two-levels RTSs are correlated.

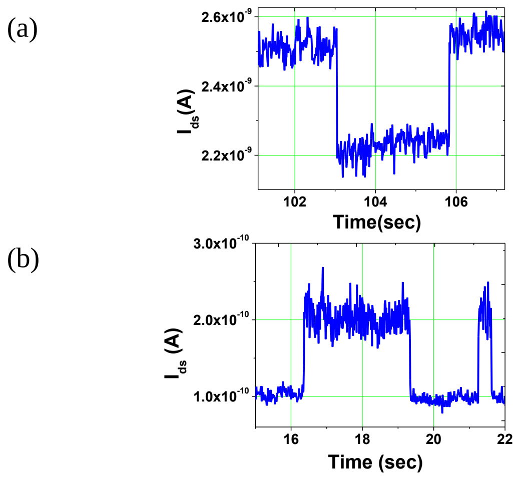

Fig. 3. **(a)** Temporal characteristics of I_{ds} in monolayer MoS_2 FET at 50 K V_{gs}= -6.6V. Rapid RTSs can be observed both in high and low current states of the slow RTSs, which indicates that two RTSs are independent. **(b)** Temporal characteristics of I_{ds} in EB irradiated monolayer MoS_2 FET at 50 K V_{gs}=21.5V. Rapid RTSs can only be observed in high current state of the slow RTSs. This fact indicates that these two types of RTSs are correlated.

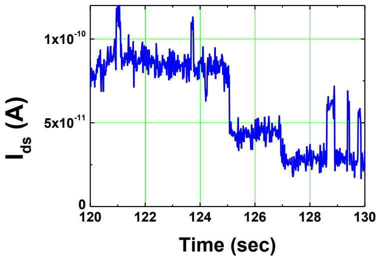

Fig. 4. Temporal characteristics of I_{ds} in monolayer MoS_2 FET at 20 K (V_{gs}=-11.4V). It is clearly seen that slower three-levels and rapid two-levels RTSs are correlated.

RTSs are more frequently observed in the subthreshold region. This implies the defect-defect correlation may be through the Coulomb interaction, because such interaction might be screened in high-carrier density region. To understand the origin of complex RTSs, it is considered that the charging state of a defect-B should affect that of the defect-A in **Fig. 5** (9, 10). To make two defects correlated with each other, they are both spatially and energetically within a reach to each other, as shown in **Fig. 5**. In our experience, those behaviors can be more often observed in mono or a few layered MoS_2 rather than thicker ones. Namely, in real two-dimensional systems, the screening might be less effective, and complex RTS behaviors might be often observed.

The defects causing RTSs were intentionally generated by irradiating electron beam (50 kV, 1.6 C/cm^2) on MoS_2 channel surface. Although it is hard to say that newly observed RTSs were originated by the EB irradiation, generally speaking we can observe RTSs more frequently in the EB irradiation, as shown in **Fig. 3(b)**. It means that the process-induced defect generation is also a big concern in terms of the stable operation of nanometer FETs.

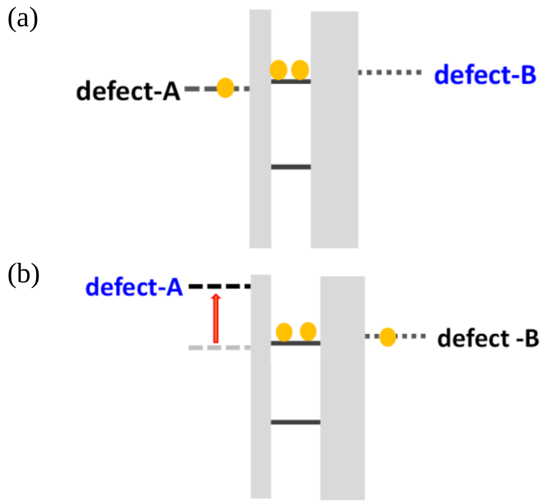

Fig. 5. Schematic description of our model for understanding defect-defect interaction. Defects–MoS_2 are close to each other energetically. Defect-A and defect-B are respectively corresponding to rapid and slow RTSs. **(a)** Carrier capture and emission between defect-A and the channel often occur if no carrier is captured in defect-B. **(b)** When defect-B is charged, the energy level of defect-A is shifted upward possibly due to Coulomb interaction, and no RTSs are observed in defect-A. It is important that defects-A, and -B should be close to each other spatially for effective Coulomb interaction between two defects.

Finally, two implications are addressed from the present results. One is that the defect control should be seriously considered in atomically thin TMD channel. The other one is that the 1/f noise characteristics in TMD FET are often analyzed by the superposition of the simple RTSs (11). However, not only simple independent RTSs but also correlated ones should be taken into consideration in the Fourier transformation process.

Conclusions

We have characterized MoS_2 FETs, focusing on the complex RTSs for the first time. These are originated from the defect-defect interaction in the MoS_2 channel or with interface states on SiO_2. The fact that these behaviors are easily detected in a few layered MoS_2 strongly suggests that defects work very seriously, and that the screening in the atomically confined MoS_2 might be weaker than that in conventional 2DEG systems such as MOSFET or HEMT.

Acknowledgement

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