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Subthreshold transport in mono- and multi-layered MoS_2 FETs

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Abstract

The subthreshold transport in exfoliated MoS_2 FETs is discussed. Temperature dependence of the subthreshold characteristics suggests that there are electrically active gap states. The defect density is one-order different between mono- and multi-layered MoS_2 FETs. In addition, conductance fluctuations in I_{ds}-V_{gs} curves have been observed only in mono-layered FETs. From those results, interlayer interactions in MoS_2 are discussed from the viewpoint of effective screening of defects inside MoS_2 layers by neighboring layers.

1. Introduction

Transition metal dichalcogenides have attracted much attention both in condensed matter physics (1, 2) and in ultimately scaled device research (3, 4). The mono-layer thickness of MoS_2 corresponds to 0.65 nm, which can work as a field-effect-transistor channel. Although the mobility is not so high compared to graphene FET, the off-current is definitely suppressed thanks to a sufficient energy band gap. Resultantly, MoS_2 FETs show a well-controlled subthreshold region. However, quite a few reports on the subthreshold transport in MoS_2 FETs have been reported. The objective of this work is to measure the subthreshold transport characteristic, and to discuss its difference between mono- and multi-layered MoS_2 FETs.

2. Experiments

MoS_2 was mechanically exfoliated from natural MoS_2. It is generally known that large size flakes are rarely obtained, and a couple of micrometer size sample on SiO_2/Si should be characterized. Raman measurement was carried out to determine the layer number. The SiO_2 thickness was 90 nm, and Si substrate was used for the gate electrode. The source and drain electrodes were Au/Ni evaporated in vacuum. *I-V* characteristics were measured in cryo-probing system.

3. Results and Discussion

Fig. 1 shows the subthreshold characteristics in multi-layered MoS_2 FET as a parameter of measurement temperature from 300 K to 50 K. Very sharp cut-off characteristics are observed, and the threshold voltage shifts to positively higher by lowering the temperature. The subthreshold swing (*S*-factor) determined from the slope in Fig. 2 is plotted as a function of temperature for several current levels in **Fig. 2**. According to the conventional semiconductor theory, *S*-factor should be in proportion to the measurement temperature. The field effect mobility was also estimated, but the sample shape was not well-defined. Therefore, the temperature dependence of the mobility is plotted in Fig. 2.

Furthermore, we measured mono-layered MoS_2 FET. The subthreshold *I-V* characteristics are shown in **Fig. 3**. *S*-factor is more degraded, and conductance fluctuations are observed at lower temperatures. This conductance wiggle was reproducible in a respective sample.

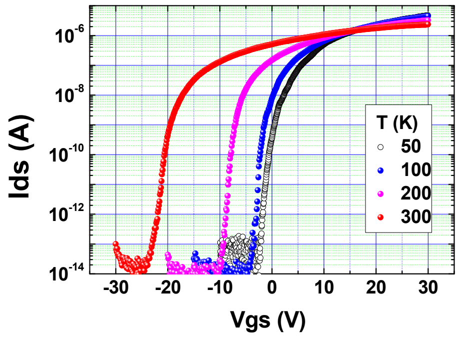

Fig. 1. Subthreshold transport characteristics in multi-layered MoS_2 FET as a function of measurement temperature (V_{ds}=0.1 V). A clear cut-off characteristic is observed even at 300 K.

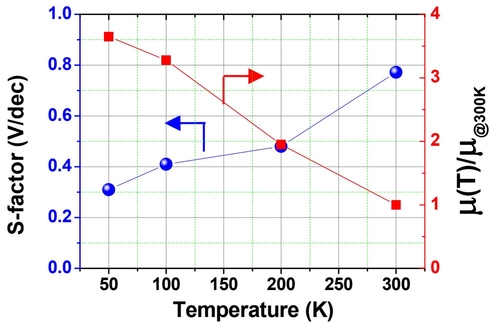

Fig. 2. Measurement temperature dependence of subthreshold swing. Almost linear dependence is observed, which means the conventional device physics for the subthreshold characteristics can be applied for MoS_2 FET case as well. Temperature dependence of the normalized mobility by 300K result is also plotted, because absolute value was not well-defined due to the sample shape.

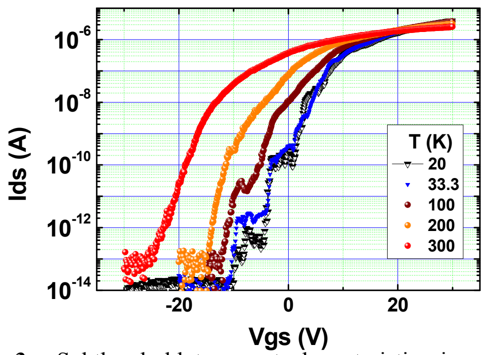

Fig. 3. Subthreshold transport characteristics in mono-layered MoS_2 FET (V_{ds}=0.1 V). At lower temperatures, reproducible conductance wiggles are observed. The peak and valley position seems to change systematically.

On the other hand, additional capacitance contribution to S factor is calculated from the temperature dependence of S factor. Through this analysis, N_x cm^{-2} is estimated both for multi- and mono-layered MoS_2. This is equivalent to the interface states density in the conventional MOSFET analysis (5), but it is not self-evident in MoS_2 FETs whether the interface states of MoS_2 on SiO_2 really respond to degraded S-factor or not. By the conventional analysis using

$$N_x = \frac{C_{ox}}{q}\left(S\frac{q}{k_B T}\frac{1}{\ell n 10}-1\right),$$

N_x is roughly estimated to be ~5x10^{11} cm^{-2} and ~5x10^{12} cm^{-2} for multi-layered and for mono-layered case, respectively. Since the interface of MoS_2 on substrate SiO_2 should nominally be the same, we cannot simply assume N_x is the number density of *interface states*. We think that it is reasonable to consider that N_x difference comes from defects inside MoS_2. Suppose that defects of MoS_2 can communicate with channel electrons, but trapped carriers at defects are immobile in the channel. Here, we propose the effective screening model for defects in multi-layered MoS_2. We assume defects are distributed randomly in a single layer, and no correlation of defect sites between neighboring layers, as schematically shown in **Fig. 4(a)**. Nevertheless, when one layer becomes conductive, defects in neighboring layers are affected through the screening effect and might not work as active N_x, even though areal defect density apparently increases in multi-layered case. In the mono-layer case, however, electrons are confined in a layer, should flow through the percolation path within the layer, as shown in **Fig. 4(b)**.

This view explains not only N_x difference but also why conductance fluctuations in the subthreshold region are observed only in the mono-layered case. Namely, the conductance fluctuations originate from the percolation switch in mono-layered MoS_2 channel, which are marked by arrows.

(a)

(b)

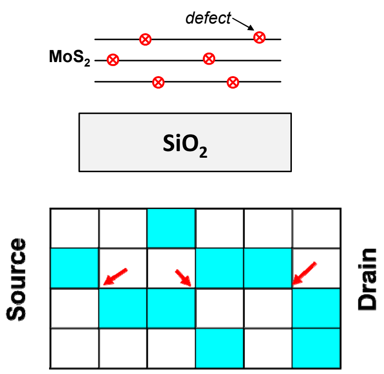

Fig. 4. Schematic description of our model for understanding the subthreshold transport difference between mono- and multi-layered MoS_2 FETs. **(a)** In multi-layered case, defect in a layer can be effectively screened by neighboring conductive layers. So, N_x is mainly originated from MoS_2 inside. **(b)** Mono-layered MoS_2 channel model with the percolation path conduction, where colored area is conductive. Arrows indicate critical paths determining the total conduction. The connection bridge might work as the switch showing the conductance wiggles.

Finally, we discuss the temporal behavior of the drain current in mono-layered MoS_2. If the above-mentioned model is correct, we expect to see the random telegraphic type of signals caused by the critical point conduction due to the percolation switching. We carefully measured the drain current at fixed V_{ds} and V_{gs} in the subthreshold region. **Fig. 5** shows I_{ds}*-time* characteristics in the subthreshold region at 20 K, in which clear random telegraphic signals are observed. Since there should be a wide spectrum of time constant in N_x, note that long time constant switching can only be seen at 20 K. We have never seen them at higher temperatures or in multi-layered MoS_2. This fact is also consistent with our model. Practically, in order to reduce the noise in TMD channel, multi-layered one will be obviously appropriate.

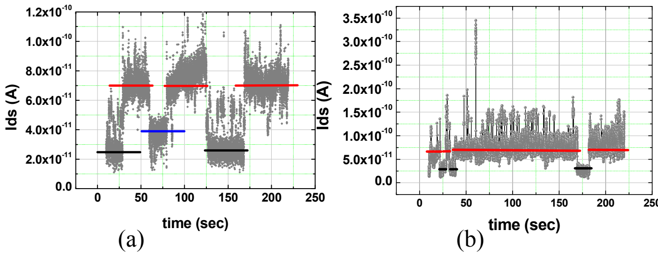

Fig. 5. Temporal characteristics of I_{ds} at 20 K (a) V_{gs}= -11.4, and (b) V_{gs}=-11.2. Clear random telegraphic characteristics are observed. The pattern is dependent on V_{gs} very sensitively.

Although the present MoS_2 sample was not high quality one (the field effect mobility in mono-layered MoS_2 was about 5 cm^2/Vsec at room temperature). But it is reported that MoS_2 has an amount of defects intrinsically (6), which should hamper the mobility improvement. The most advantageous point of MoS_2, however, is not the mobility but atomically thin layer with a sufficient energy band gap. Therefore, to comply with requirements such as ultra-thin, small S, and high mobility, multi-layered MoS_2 will be more viable for stable operation in practical applications. This is quite different from the approach in graphene FET.

Conclusions

We have characterized both mono- and multi-layered MoS_2 FETs, focusing on the subthreshold transport. The poor subthreshold slope is mainly due to very thick SiO_2 thickness (90 nm). If we can reduce gate oxide thickness down to EOT=1 nm on multi-layered MoS_2, the subthreshold slope in MoS_2 FET will be below 70 mV/dec and becomes comparable to existing Si devices. Thus, multi-layered MoS_2 will be better to achieve more stable and less defective subthreshold and higher mobility transport in MoS_2 FETs.

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