Fabrication of Thin-Film HfS_2 FET

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Introduction: 2D materials are expected to be favorable channel materials for field-effect transistor (FET) with extremely short channel length (< 10 nm) because of their superior immunity to short-channel effects. Graphene, which is the most famous 2D material, has no intrinsic bandgap and this property is major hindrance in reducing the drain leakage. Therefore, 2D materials with finite band gap are required for the low power consumption FETs. Recently, transition metal dichalcogenides (TMDs) such as MoS_2 [1] and other kinds of 2D materials (e.g. phosphorene [2]) have been widely and actively studied. Figure 1 shows the plot of the calculated acoustic phonon limited electron mobility [3] vs. energy band gap [4] of typical TMDs. It suggested that there is a trade-off between mobility and band gap (It is similar to that observed in bulk semiconductors). From Fig. 1, HfS_2 is expected to have both good acoustic phonon limited mobility (~ 1800 cm^2/Vs) and reasonable energy band gap (~ 1.2 eV) with single layer structure.

In this paper, we report a thin-film HfS_2 FET. Fabricated FETs showed definitive transistor operation. To our knowledge, this is the first operation of a layered HfS_2 FET.

Basic Properties: Figure 2 shows crystal structure and physical parameters of HfS_2. HfS_2 has an octahedral coordinated structure with the gap of around 0.6 nm between monolayers. The strong anisotropy of effective mass is expected in the conduction band. Optical images of HfS_2 materials ((a) bulk, (b) on tape, and (c) mechanically exfoliated on a 285-nm-thick SiO_2/Si substrate) are shown in Fig. 3. In Raman spectrum from several layers of HfS_2 on SiO_2/Si (Fig. 4), the peak is observed at 337 cm^{-1} with some satellite peaks. This spectrum shape is very similar to that reported for bulk HfS_2.

Device Fabrication: The schematic of the device structure formed in this report is shown in Fig. 5 (a). The gate stack consisted of a p+-Si back gate and a 75-nm-thick Al_2O_3 dielectric. The fabrication process is as follows. First, an Al_2O_3 layer was deposited on Si substrate by atomic layer deposition. Next, HfS_2 flakes were transferred on to substrate by mechanical exfoliation. Then, source and drain electrodes were formed by electron beam lithography and evaporation of Ti/Au. Finally, back contact was formed by the evaporation of Cr/Au. Figure 5 (b) shows an optical image of a fabricated FET. The channel width W_{ch} was 10 µm and gate length L_G was 2 µm, respectively. According to the atomic force microscopy (AFM) measurement, the thickness of HfS_2 channel layer is at most 7.5 nm.

Measurements: Figures 6 and 7 indicate the output and transfer characteristics of the fabricated HfS_2 FETs. The clear saturation behavior was observed in I_D-V_D characteristics. From the I_D-V_G characteristics, the maximum drain current of 0.2 µA/µm was obtained at V_D = 3 V and V_G = 40 V. The on/off ratio at V_D = 3 V is more than 10,000. This device had a large hysteresis and sweep condition dependence. It could have been caused by response of traps at the interface between HfS_2 and Al_2O_3. Therefore, the on current and other performances of the present device can be improved by an efficient modulation of the surface potential using the thinner gate dielectric with good interface properties.

Conclusion: In conclusion, we demonstrated the fabrication and I-V characteristics of HfS_2 FETs. For the channel thickness of less than 7.5 nm, a clear saturation behavior and drain current of 0.2 µA/µm were observed with reasonably good on/off current ratio. These results provide basic knowledge of HfS_2 as a channel material for FET.

References

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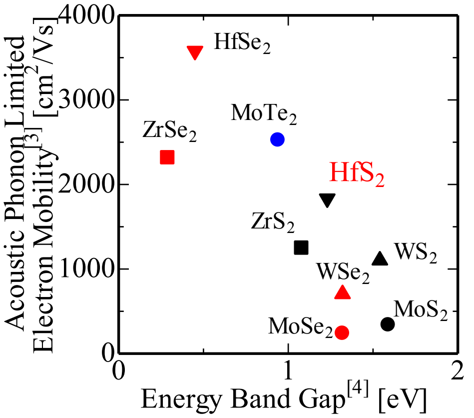
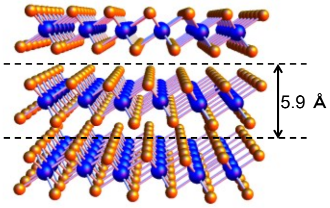


Fig. 1. Plots for calculated Acoustic Phonon Limited Electron Mobility[3] vs. Energy Bandgap[4] of the typical transition metal dichalcogenides.



	HfS_2
E_g [1]	1.23 eV
μ_{AP} [2]	1833 cm²/Vs
$m^*_{M\text{-}K}$ [2]	0.24 m_0
$m^*_{\Gamma\text{-}K}$ [2]	3.30 m_0

Fig. 2 Schematic image of the crystal structure and physical constants of HfS_2.

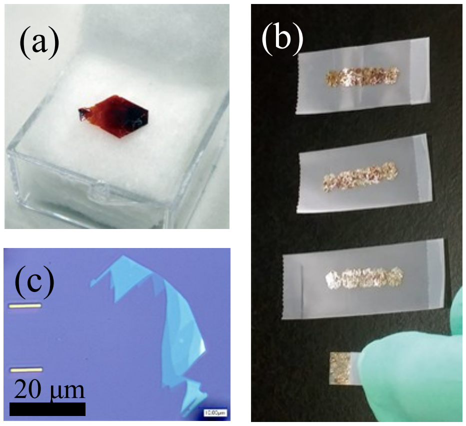


Fig. 3 Optical images of HfS_2 ((a) bulk, (b) on tape (c) mechanically exfoliated on a SiO_2 285 nm/Si substrate).

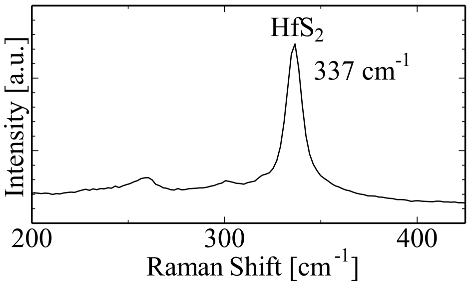


Fig. 4 Raman spectrum of an exfoliated HfS_2 on a SiO_2/Si substrate

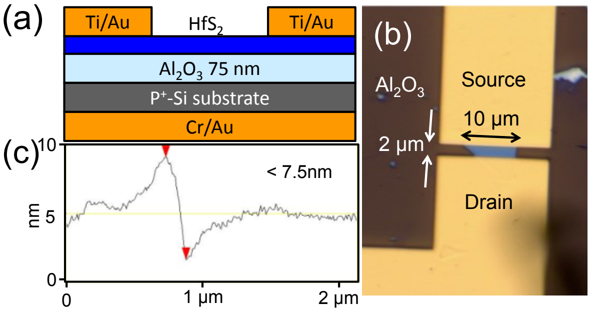


Fig. 5 (a) Schematic and (b) optical image of a HfS_2 FET discussed in this report and (c) AFM height profile of its channel layer.

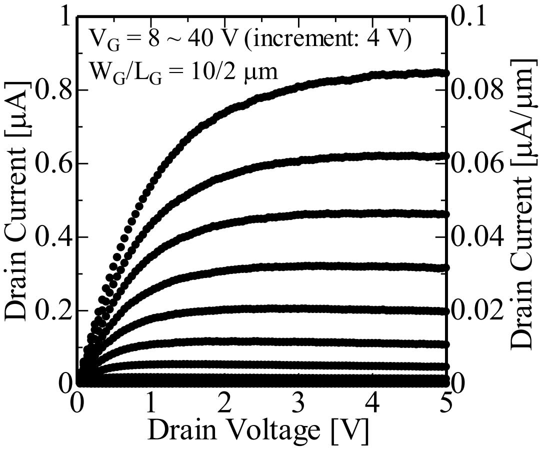


Fig. 6 Output characteristics of the fabricated HfS_2 FET with channel length of 2 µm. Clear saturation behavior and gate modulation were observed.

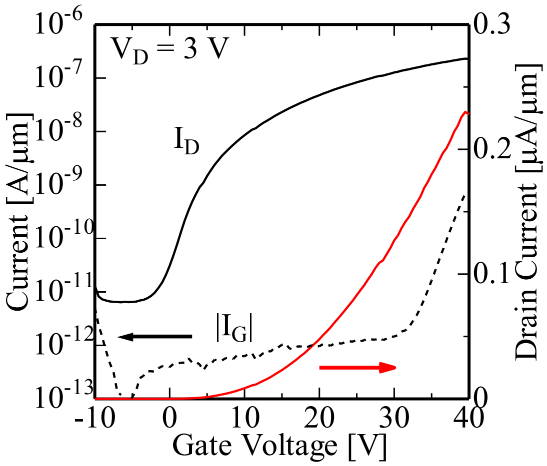


Fig. 7 Transfer characteristics of the HfS_2 FET. A black solid line and a black dashed line indicate I_D and I_G plots in logarithmic scale respectively. A red solid line shows I_D plots in linear scale.