Chalcogenide Letters Vol. 20, No. 8, August 2023, p. 573 - 578

Structural and device fabrication of 2D-MoS_2 thin film

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In this research paper, we have prepared thin film of MoS_2 by thermal evaporation technique and characterized it. This thin film depositions lead to amorphous thin film. To make it crystalline, thermal annealing of the film have deposited on the substrates at 800 ^oC for two hour under vacuum environment. X-ray diffraction data of thin film shows the poly-crystalline nature. The Atomic Force Microscopy (AFM) image of the thin film shows the crystallinity with regularly arranged grains. Furthermore, an unconventional MoS_2 based FET device has been fabricated by depositing thin film of MoS_2 on p-type silicon. Thereafter, its transfer and output characteristics have been studied. The results show n-type semiconductor behaviour with an on/off ratio of about 10^3 and field-effect mobility of ~0.015 $cm_2/V.\ s$ at V_{DS} of 1 V.

(Received May 25, 2023; Accepted August 7, 2023)

Keywords: 2D-MoS_2, Thermal deposited film, Thin film deposition, XRD, AFM, I-V behaviour

1. Introduction

Nowadays, 2D materials are attracting great interest because of its exceptional properties [1] and applications in various devices [2]. Molybdenum di-chalcogenides are those semiconductors appropriate for applications in various domains like batteries that can be recharged, solar energy based cells, sensors used to detect light as well as gas, surface catalytic devices [3]. Among many materials, MoS_2 (Molybdenum di-sulphide) has a layered structure where van der Waals forces exist between consecutive layers [4]. As in layered structure, molybdenum mono layers are placed in-between sulphur mono layers. Based on the structure of the crystal and arrangements of Sulphur atoms in the individual layer, MoS_2 exist in two phases [5]. The bulky 2-H phase is n type indirect band-gap semiconductor in nature while the other is 1-T metastable phase which is metallic in nature [6-7]. Varieties of such characteristics make MoS_2 flexible with good charge mobility and high optical transmitting validating it for opto-electronics devices. [8-9] Transistor devices that are made-up with MoS_2 thin films have well on/off ratio of current as well as high mobility of the carriers, making it appropriate for next-generation devices [7]. The optical as well as the electronic properties of 2D-MoS2 are excellent making them a prospective contender for proficient solar cells [10,11] and application in lithium batteries [12,13].

There are various methods to synthesize MoS_2 films. The major hurdles to produce uniform 2-d MoS_2 are low- scalability and economic criteria that leads limitation in industry applications. In this work, a low cost effective thermal evaporation technique is used to obtain 2-D

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https://doi.org/10.15251/CL.2023.208.573

thin films of MoS_2 [14-18]. Then, structural and morphological properties are studied by various characterization techniques.

2. Experimental details

MoS_2 thin films have been deposited on the n-type Si substrate using the thermal evaporation technique (Hind Hivac Vacuum Coating (Manual) Model - 12A4D). A commercially available n type (Arsenic doped) silicon substrate was taken. The n-Si has 100 orientation and thickness of 460 ± 20 microns. The size of the substrate is kept $1\times 1\ cm^2$ in size. To begin with, the substrates were cleaned with acetone, trichloroethylene, ethanol and DI water, sequentially in the ultra-sonicator. Then, the substrates were heated on a hot plate for the removal of any kind of moisture content or water molecule. In thermal evaporation process, MoS_2 powder (purity 99% of company Alfa Aesar) was placed in the Molybdenum (Mo) boats. The powder was evaporated at a vacuum of 4×10^{-5} mbar; it gets deposited on the substrates that are placed at some distance above the Mo boat. The deposition was done for 20 minutes at 85 Amp current. Some residue was left in the boat at the end of the process. These depositions led to amorphous thin films. To make it crystalline, thermal annealing of the substrates were done at 800 ^{o}C for 02 hour under vacuum environment. The annealing was done in a thermal furnace unit (Metrex microprocessor programmable furnace).

3. Results and discussion

3.1. Structural analysis by X-ray diffraction

The XRD characterization of MoS_2 thin film sample was done. The Figure 1 shows the XRD of MoS_2 thin film. It has been done on the annealed thin film. XRD data show one peaks with orientation in the direction of (003) confirming that the films are poly-crystalline in nature. One another sharply defined peak represents the Si substrate. Furthermore, this XRD of MoS_2 was the best one among those numbers of deposited films.

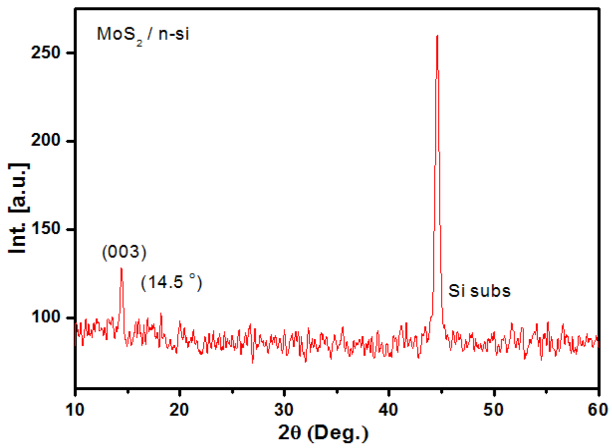

Fig. 1. XRD of MoS_2 thin films on n-Si substrate.

3.2. Morphological studies by atomic force microscopy

The AFM image for MoS_2 thin film on the n-Si substrates is shown in Figure 2. The image of the film clearly shows the crystallinity with regularly arranged grains. The large grain size indicates the crystalline nature of the deposited thin films.

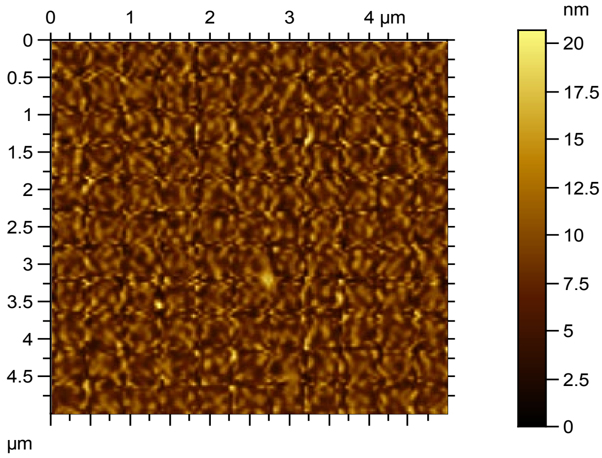

Fig. 2. AFM of MoS_2 thin films on n-Si substrate.

3.3. Device fabrication

A simple MoS_2 based FET was fabricated. Thin films of MoS_2 were deposited on p-type Si using thermal evaporation following the same procedure as used for thin films deposited on n-Si. There are various reasons to use p-Si substrate for device. P-type substrate was used since theoretically it has given more current at the same voltage values as compared to n-Si [9]. A thermally grown SiO2 layer already on p-Si substrate was used. SiO_2 was used as the dielectric since it has higher k values and consequently provides better surface passivation as compared to SiO. Contact deposition was done at 8.81 x 10^{-6} mbar using 1.6 Kilo Amp current for 05 min. Aluminium which has a melting point of 660 ^{o}C was used as contact. Al wire of 1 mm thickness and 99.999% purity was used.

A back gate top electrode configuration FET was fabricated using the mask and shown in the Figure 3. The I-V test of large area devices with different channel length on a single chip sample was done to obtain their transfer (I_{DS} vs. V_{GS}) and output (I_{DS} vs. V_{DS}) characteristics. The currents were obtained and plotted on origin.

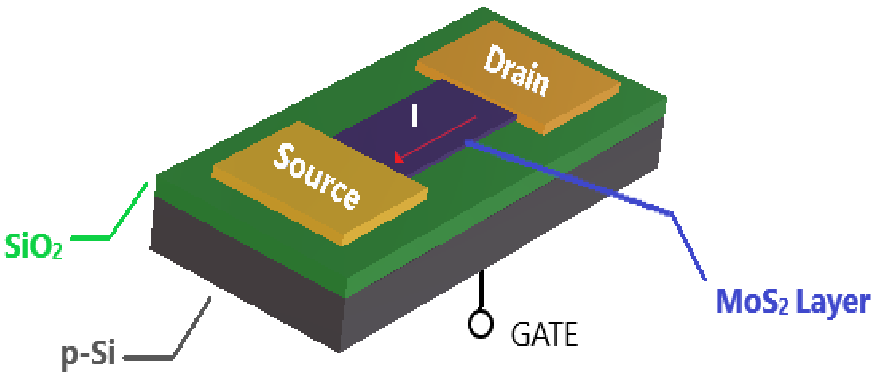

Fig. 3. Three-dimensional diagram of 2D MoS_2 FET for I-V characterization.

The model of FET fabricated was not a conventional FET model. In this type of FET as shown, semiconductor material MoS_2 was deposited on Si-SiO_2 substrate and the thickness of as deposited MoS_2 film was 175 nm, drain and source terminals were deposited on MoS_2 layer such that a channel of MoS_2 can be formed between drain and source terminal [16]. Source-Drain voltage was applied between source and drain terminal and gate voltage was applied on Si substrate (Back gate) that controls the conduction between drain and source terminal as shown in Figure 4.

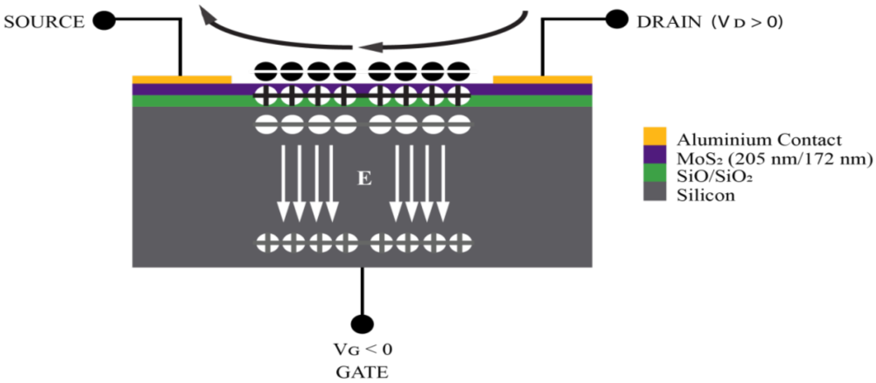

Fig. 4. Charge carrier movements.

Figure 5 demonstrates the transfer and output characteristics of MoS_2 thin films. In the output curves, current is measured by changing drain voltage keeping gate voltage fixed whereas in the transfer curves current is measured by changing gate voltage keeping drain voltage fixed. As can be seen from the figure, on increasing the negative potential on the gate terminal, current increases w.r.t. the drain voltage. The device showed current characteristics which confirmed electrons as the majority charge carriers in the MoS_2 film while holes were minority charge carriers. Post annealing the hole current virtually disappears. This confirms the intrinsic n-type semiconductor behaviour of MoS_2 as mentioned in the literature surveyed [17].

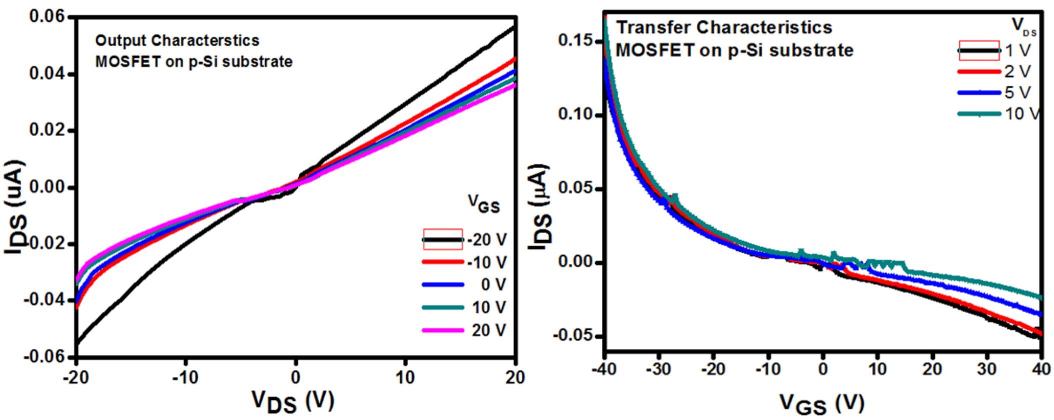

Fig. 5. Transfer and output characteristics of device made by using MoS_2 thin films.

Current-voltage (I-V) characteristics of the MOSFET were measured by varying drain voltage (I_{DS} vs. V_{DS}) at fixed gate voltages (V_{GS}) and varying gate voltage (I_{DS} vs. V_{GS}) at fixed drain voltages (V_{DS}) as can been seen in the aforementioned results [17, 18].

$$\text{Using, } (\mu) = (\Delta I_{DS} / \Delta V_{GS}) * (L/ (C * W * V_{DS}))$$

Here, L is length of channel (0.1 mm); W is width of channel (1.5 mm); C is capacitance of gate dielectric material (1.15 x 10^{-8} F/cm_2). The charge carrier mobility was calculated from transfer characteristics curve. The results show typical n type semiconductor behaviour with an on/off ratio of about 10^3 and field-effect mobility of ~0.015 cm_2/V. s at V_{DS} of 1 V.

4. Conclusions

A FET transistor device based on 2D thin films of MoS_2 has been fabricated and demonstrating the capability of two dimensional molybdenum di-chalcogenides semiconductor materials for emerging electronic device systems. Furthermore, thermal evaporation deposition technique has used to fabricate thin film of 2D-MoS_2 and the same is used to deposit the metal contacts. As a conclusion that we have prepared easily as well as effective physical vapour deposition method.

Acknowledgments

I acknowledge CIR Lab, MNNIT Allahabad for thin film characterization facilities.

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