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Full Length Article

Facile, scalable and transfer free vertical-MoS_2 nanostructures grown on Au/SiO_2 patterned electrode for photodetector application

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ABSTRACT

Transition metal dichalcogenides such as molybdenum disulfide (MoS_2) have attracted considerable attention for use in optoelectronic devices. However, their large scale monolayer production seems to be limited due to scalability, layers size and fabrication process. While, a prominent photoluminescence was reported for vertically aligned MoS_2 (V-MoS_2) nanosheets similar to MoS_2 mono- and few- layer, as highly promising counterparts for development of optoelectronic devices. Here, we report a systematic method to fabricate V-MoS_2 nanosheets using a chemical vapor deposition (CVD) technique. The growing density and morphology of V-MoS_2 nanosheets are controlled by adjusting growth parameters. The V-MoS_2 nanosheets form in 2H phase and have thickness of ~10–80 nm and the lateral dimension of 1–2.5 μm. Furthermore, a photodetector platform is fabricated based on V-MoS_2 nanosheets with considerable performance and transfer free process with scalable manufacturing ability. The V-MoS_2 nanosheets are directly deposited on and within patterned gold leads made on SiO_2 substrate to immediately form arrays of photodetector. Optical and electrical response of such a photodetector is examined at different wavelengths and light powers. Such a facile fabrication can convey to a straightforward approach for large scale and transfer free implementing V-MoS_2 nanosheets in optoelectronic elements.

1. Introduction

Transition metal dichalcogenides (TMDCs) from a large family of semiconductors have shown promising impact based on their wide applications in advanced material science and technology. Their exceptional electronic, chemical, mechanical, thermal and optical properties particularize this class of materials with upsurge attention at the nanoscale [1]. Among the categorized TMDC family, the MoS_2 is found to be a well-characterized semiconductor with intriguing properties [2–4]. It has a direct band gap in a form of monolayer with significant optoelectronic properties different to its multilayer counterparts [5,6].

The MoS_2 mono to few-layers are being manufactured by exfoliation of bulk MoS_2 or grown directly by deposition techniques namely via chemical vapor deposition (CVD) [7,8] or sulfurization of Mo layer [9]. It was found that MoS_2 can be formed into vertical layer structures on a substrate via growth or transfer control [10–14]. Particular attentions have been made on the vertical formation, with a large surface area specially when their edge elements represent a highly electro-active response against physical or chemical excitations, such as optical and electrochemical [15,16]. It is understood that such exposed edges with dangling bonds contain a high number of catalytically active sites, which could be efficiently useful in many applications, such as photocatalysis [17], hydrogen evolution reaction (HER) [18,19], lithium batteries [20], water cleaning [15], gas sensor [21], etc.

Photodetector within optoelectronic devices is one of the numerous output products. However, the MoS_2 with great potential ability has shown less impact because of impossible large scale monolayer growth and transfer and fabrication issues which are technically difficult and costly. Recently, a prominent photoluminescence (PL) response was reported for V-MoS_2 similar to mechanically exfoliated few and monolayer MoS_2. This prominent PL is due to the structural discontinuity at the edges of nanosheets which changes the MoS_2 electronic structure. In addition, the Mo-O bonds that exist at the MoS_2 nanosheets edges that occurs during the growth of V-MoS_2 can increase the PL signal [12,22]. As mention above, the exposed edges have a significant role in the PL observation; therefore, these nanosheets can be used as a highly promising media for application in photodetector and optoelectronic devices [22]. Nevertheless, there are a few reports on applying vertical nanosheets in solid state electronic device platform for optoelectronic applications. From TMDC family, we can refer to MoS_2/Si p-n junction heterostructure [23], HfS_2 [24] and SnS_2 [25,26] vertical counterparts toward hoped-for highly efficient photodetector. Hence, this field has open horizons for future research as their initial results have shown to be promising but found technical drawbacks. In

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order to make high quality vertical structures with a reproducible optoelectronic response, their growth control condition and later their electrical contact to form a device needs less complex fabrication steps and requires a vital fabrication control.

In this paper, we investigate experimental parameters to control the growth of vertically aligned MoS_2 nanosheets based on CVD technique. We also examine different substrates of SiO_2, graphite and quartz in order to find the geometry of vertical nanostructures and their growth formation dependent on bottom-layer. After optimization of V-MoS_2 growth, a platform of photodetectors made of gold contacts on SiO_2 substrate is manufactured by optical lithography of SiO_2/Au and the V-MoS_2 nanostructure is grown directly on the detector's platform. This technique is quite different to any other type of metal-semiconductor TMDC family reported so far. First, the manufacturing has no limit and can be scalable for large area as the growth is the final step of photodetector fabrication and secondly, the metallization process for electrical contact is quite simple and is not problematic for reproducibility and Ohmic-contact issues. Furthermore, our photodetector based on V-MoS_2 is examined against green and red laser light with different intensities and their response time against laser irradiation is investigated and found to be less than 100 ms. We have realized this photodetector which shows photoresponsivity of 6 mA/W indicating a considerable performance compared to other MoS_2 based photodetectors [27–29].

2. Experimental methods

The growth of vertically oriented MoS_2 nanosheets was performed in a conventional CVD furnace with 2 in. quartz tube. A schematic of the CVD setup and the temperature profiles of the precursors are shown in Fig. 1a, b. The SiO_2/Si substrate was cleaned in piranha solution, followed by acetone, isopropanol alcohol and deionized water and then dried with Ar gas. MoO_3 powder (50 mg, 99%, Merck) was located in the center of the furnace and substrate was placed next to the MoO_3 powder. A quartz boat containing 80 mg sulfur (98%, Samchun chemical) was placed in the upstream region outside the furnace. The quartz tube was first flushed at 200 °C with 1000 sccm Ar flow to remove the oxygen. Afterwards, the MoO_3 powder was heated to 700 °C at a rate of 16 °C/min and maintained at this temperature for 10 min with 100 sccm Ar flow. After growth, the furnace was cooled down to room temperature. We also performed the deposition of V-MoS_2 under the conditions listed in Table 1 to investigate the effect of growth parameter on morphology and quality of samples. For the fabrication of the photodetector, we first deposited Ta (5 nm)/Au (100 nm) layers on SiO_2/Si substrate using sputtering technique. The gold patterns were made via a direct standard optical lithography technique. V-MoS_2

Table 1
Sample list studied in this work.

Sample	Sulfur (mg)	Gas flow (sccm)	Growth time (min)
A	50	100	10
B	80	100	10
C	110	100	10
D	80	50	10
E	80	200	10
F	80	100	1
G	80	100	2.5

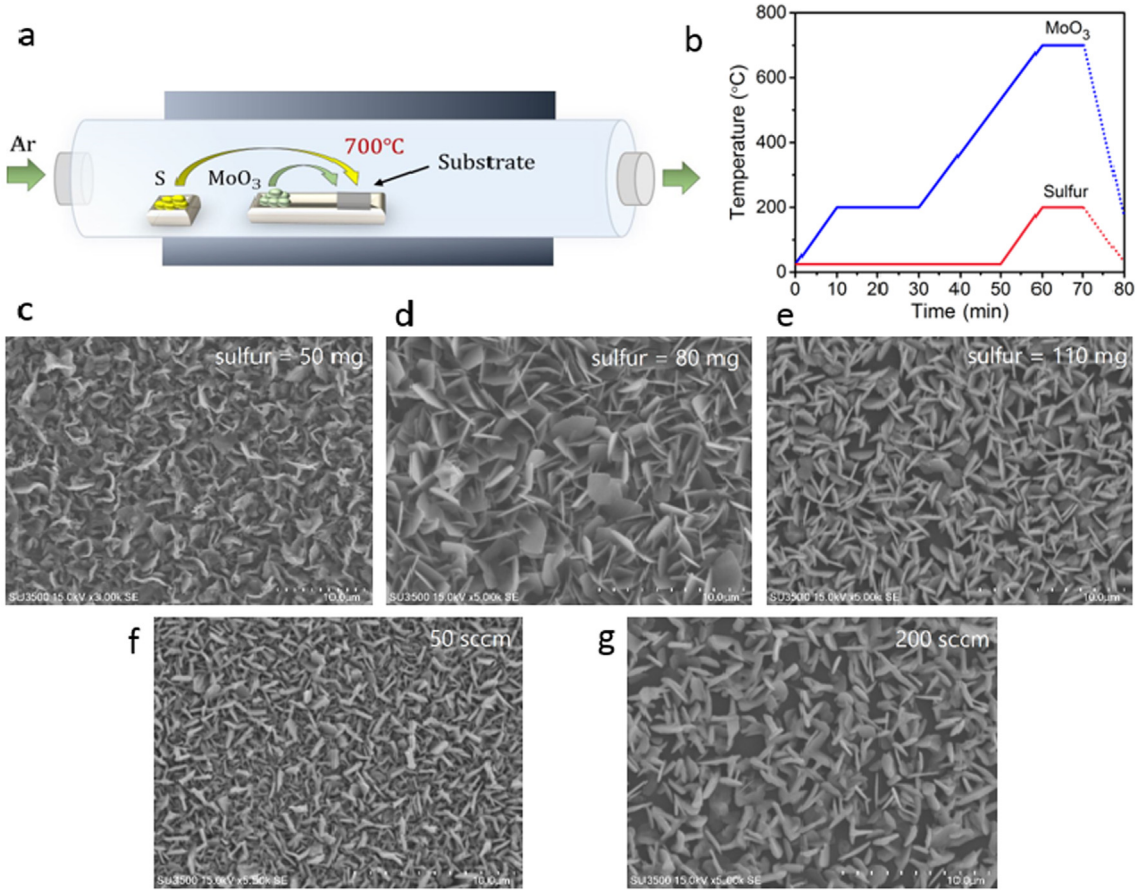

Fig. 1. (a) Schematic diagram of the CVD system for V-MoS_2 growth. (b) Temperaturetime profile of the CVD proces. SEM images of material coverage and morphology of the asgrown V-MoS_2 at 700 °C for 10 mins under 100 sccm of Ar gas with three different sulfur precursor concentration. (c) 50 mg (sample A), (d) 80 mg (sample B) and (e) 110 mg (sample C). (f), (g) SEM images of V-MoS_2 at 700 °C for 10 mins under 50 (sample D) and 200 sccm (sample E) of Ar gas.