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Facile growth of large-area and high-quality few-layer ReS_2 by physical vapour deposition

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ABSTRACT

As a new two-dimensional semiconductor, rhenium disulfide (ReS_2), has lots of distinctive features and exhibits great potential for future novel device applications due to its unusual structure and unique anisotropic properties. In this study, for the first time, large-area few-layer ReS_2 has been grown on the SiO_2/Si substrate by physical vapour deposition (PVD) using ReS_2 powder as source material. XPS and Raman data confirm the composition and bonding configurations of ReS_2. Clear lattice fringes of the high-resolution TEM images reveal that the ReS_2 is few-layer with highly crystalline quality. It suggests that PVD is promising to synthesize wafer-scale ReS_2 film to realize its applications in electronics, optoelectronics, valleytronics and spintronics. The PVD method can be extended to grow other two-dimensional semiconductors with few-layer thickness and high quality.

1. Introduction

Two-dimensional (2D) transition metal dichalcogenides (TMDs), have recently been a research hot topic due to their unique and appealing electronic and optical properties, which make them promising materials for a variety of applications related to electronics, optoelectronics, valleytronics, spintronics and energy sources [1]. As one kind of the TMDs, rhenium disulfide (ReS_2) has lots of distinctive characteristics due to its unique crystal structure [2]. Unlike reported MoS_2, ReS_2 possesses weak interlayer coupling and a unique distorted octahedral (1T) structure with triclinic system [3]. Such distinctive characteristics result that bulk and monolayer ReS_2 have nearly the same band structures, both belonging to direct bandgap semiconductors [2]. Additionally, ReS_2 exhibits unique anisotropic properties in electrics and optics because of distorted 1T structure [4]. Therefore, ReS_2 with electrical, optical, catalytic and electrochemical behavior has been studied based on field effect transistors, [3] photodetectors, [5] electrocatalysts, [6] lithium-ion battery [7] and lithium-sulfur battery [8].

Recently, several methods, for example, mechanical exfoliation, [3] chemical exfoliation, [6] and chemical vapour deposition (CVD), [7,9–13] have been used to synthesize few-layers ReS_2. It is well-known that the mechanical or chemical exfoliation can only produce ReS_2 sheets with a size of nanometer to micrometer scale. CVD has been utilized to successfully grow large-area and high-quality 2D semiconductors, e.g. graphene, [14] MoS_2, [15] WS_2, [16] etc. However, it is still difficult to controllably synthesize large-area ReS_2 by CVD. K. Keyshar et al. [10] reported the growth of monolayer and few layer ReS_2 by CVD using NH_4ReO_4 source at low temperature; however, the size of ReS_2 film is only about micrometer and there are many impurity nanoparticles on the surface. F. Cui et al. [11] grown highly crystalline ReS_2 atomic layers on mica substrates by CVD using Re powder source with the assistant of tellurium, and the size of ReS_2 layers is also only hundred of micrometers. Very recently, M. Hafeez et al. [12] successfully grew centimeter-size ReS_2 film on sapphire substrates by CVD using ReO_3 source, however, so far, only bi-layer ReS_2 continuous film or multilayer nanoflakes are obtained and the control for the thickness should be further investigated. The complexity of the chemical reaction for different staring materials and various temperature, gas atmosphere and partial pressure might be responsible for the difficult synthesis of large-area continuous ReS_2. It is urgent to present a simple and low-cost method with easier controllability to synthesize large-area and high-quality ReS_2 film.

In this study, for the first time, large-area few-layer ReS_2 has been grown on the SiO_2/Si substrate by a facile physical vapour deposition (PVD), which is much simpler, cheaper and more controllable than conventional chemical vapour deposition. The results show that the as-synthesized centimeter-size ReS_2 layer is few-layer with highly crystalline quality. The presented PVD is a prospective method to fabricate wafer-size 2D TMDs films to realize the applications in electronics, optoelectronics, valleytronics and spintronics.

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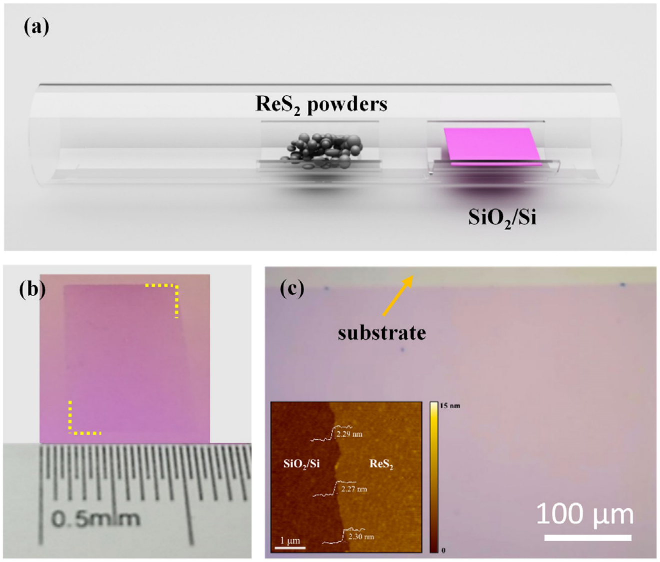

Fig. 1. (a) Schematic diagram of synthesized ReS_2 film by PVD. Optical (b) photograph and (c) microscope image of grown ReS_2 film on the SiO_2/Si substrate. The inset of Fig. 1c is the AFM iamge.

2. Experimental

The large-area, continuous ReS_2 film was grown by PVD using ReS_2 powder (Alfa-Aesar, 99% purity). The detailed growth procedure is as follows. A ceramic boat which contains 30mg ReS_2 powder was placed into the center of 1inch quartz tube, as shown in Fig. 1a. The SiO_2 (280nm)/Si substrate was placed downstream far from the ReS_2 powder. The quartz tube was firstly pumped to vacuum, then the argon carrier gas (50sccm) was filled into the quartz tube. The furnace was then increased to 900°C in 60min and kept at 900°C for 1h to grow the ReS_2 film. And then the furnace was cooled down. Finally, the ReS_2 was annealed to further improve the crystalline quality. 400mg sulfur powder placed at the upstream end of the furnace was heated to 165°C with 10min and held for 90min by a heating belt. The ReS_2 positioned at the center of the furnace was annealed at 800°C for 60min with a heating rate of 20°C/min and an argon flux of 100 sccm at ambient pressure.

The morphologies, crystalline structures, compositions, bonding configurations of ReS_2 film were characterized by optical microscope (OLYMPUS, BX53), atomic force microscope (AFM, Seiko SPA-300), scanning electron microscope (SEM, JEOL, JSM-7000F), Raman Spectrometer (Renishaw), transmission electron microscope (TEM, Tecnai, F20), X-ray photoelectron spectroscopy (XPS, Kratos XSAM800, Al Ka radiation). The preparation procedure of ReS_2 TEM sample is as follows. A PMMA layer was spin coated onto the surface of ReS_2/SiO_2/Si substrate. The PMMA/ReS_2 was

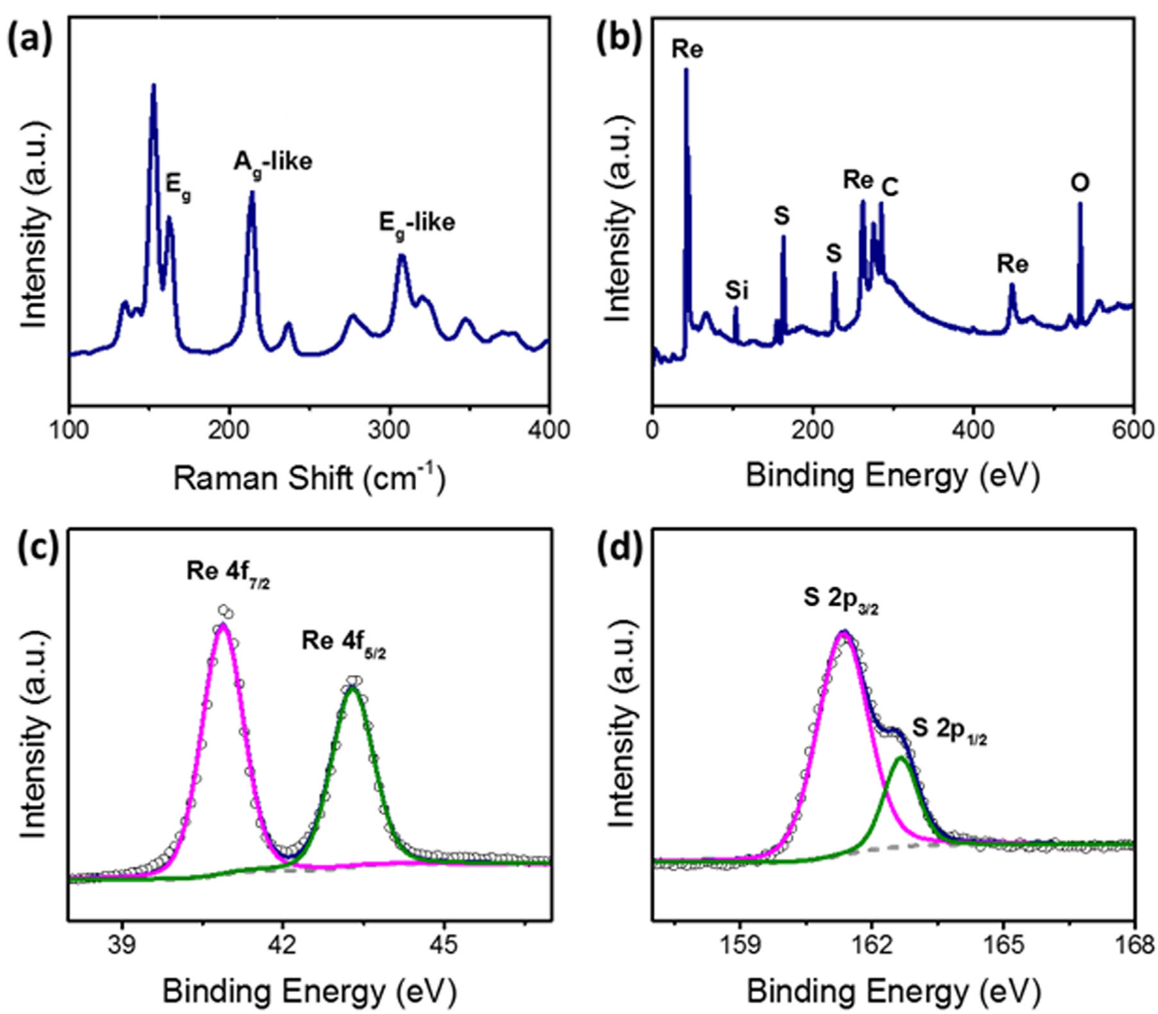

Fig. 2. (a) Raman spectrum of ReS_2 from 100 cm^{-1} to 400 cm^{-1}. (b) Full XPS spectrum of ReS_2 film. (c) and (d) XPS spectra of Re 4f and S 2p state, respectively.