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Substrate-dependent morphology and photoluminescence of MoS_2 nanobelt arrays

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ABSTRACT

As important two-dimensional nanostructures, MoS_2 nanobelts grown on (AlGa)N and ZnO substrates, respectively, are facilely and economically fabricated by one-step chemical vapor deposition without using any catalyst. The characterizations for morphologies, compositions, and optical properties are performed by scanning electron microscopy (SEM), energy dispersed X-ray spectrometry (EDS), and photoluminescence spectroscopy (PL). SEM confirms that MoS_2 nanobelts grown on (AlGa)N substrates compared with ones grown on ZnO substrates have higher quality although EDS shows that both of the nanobelt arrays are composed of the same constituents, that is, pure MoS_2. In addition, the room-temperature optical properties show that MoS_2 nanobelts on (AlGa)N substrates possess excellent photoluminescence superior to ones on ZnO substrates.

1. Introduction

Two-dimensional (2D) semiconducting transition metal dichalcogenides (TMDs), including MX_2 (M = Mo, W; X = S, Se), have attracted a great deal of attention because of their unique structure as well as remarkable chemical, electrical, optical, and photoelectric properties [1]. As a member of TMDs, molybdenum disulfide (MoS_2) is a prominent 2D semiconductor that has been extensively studied; compelling results have been achieved such as a large direct band gap (~1.85 eV for a monolayer) [2], an excellent on/off ratio [3], high carrier mobility [4]. Recently, possible application, including field effect transistors [5], light emitting devices [6], and photonic detectors [7], have been widely investigated. Besides, substantial effort also has been devoted to the synthesis of different MoS_2 nanostructures, such as nanosheets [8], nanorods [9], nanoflowers [10], nanotubes [11], etc. However, no reports on the growth of MoS_2 nanobelts grown on (AlGa)N and ZnO nanowires substrates are available by using the CVD method, although MoS_2 nanostructures based on other substrates, such as SiO_2/Si, h-BN, sapphire, SiC, and mica, have widely been reported [12–17]. Driven by this and our previous work [18,19], in this letter, we report a facile and controllable CVD process to produce MoS_2 nanobelt arrays grown on (AlGa)N and ZnO substrates, respectively, and substrate-dependent morphology and photoluminescence of MoS_2 nanobelt arrays are discovered, which will open up new basic science and application possibilities in electronic and optoelectronic nanodevices.

2. Experimental

Fig. 1a presents a typical experimental setup to synthesize MoS_2 nanobelts on (AlGa)N and ZnO substrates. Typically, MoS_2 nanobelts were grown by a CVD method in a quartz tube furnace, using 66.0 g S powders (99.999%, Ourchem) and 144.0 g MoO_3 powders (99.999%, Ourchem) as initial sources, one of both (AlGa)N nanowires and ZnO nanowires as substrates, and ultra high-purity argon as carrier gas. In fact, the nanowires substrates were synthesized by our previous method [18]. The ceramic boat with sulfur powders was located upstream wrapped with a heating belt. Another boat containing MoO_3 powders was put into the center of a furnace and the substrates were placed downstream close to the MoO_3 powder. The furnace was degassed and filled with N_2 gas for 60 min and then ramped up to 600 °C in 40 min. Meanwhile, the heating belt temperature was raised to ~100 °C. The CVD growth was performed at ~120 mTorr for ~60 min while flowing ultra-high purity argon gas at 50 sccm (standard cubic centimeter per minute). Afterward, the furnace was cooled down naturally to room temperature and some gray black like-hair samples were found in substrates, and a typical yield of the as-synthesized products is about 65% according to our calculation.

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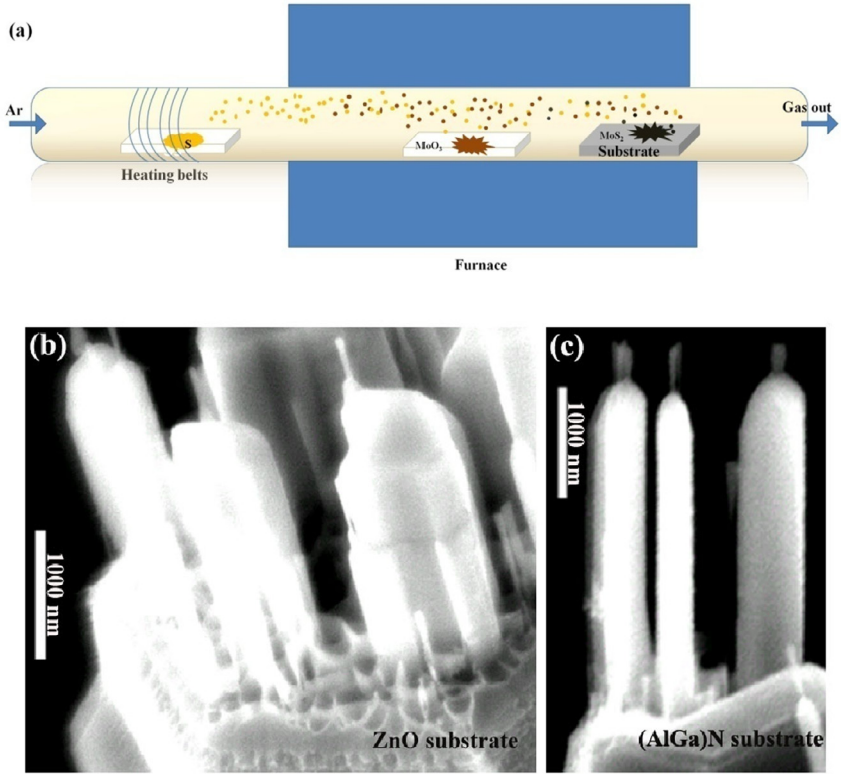

Fig. 1. (a) Schematic diagram for CVD synthesis; Cross-section SEM images of (b) MoS_2/ZnO and (c) MoS_2/(AlGa)N nanobelt arrays.

The as-prepared specimens were characterized using scanning electron microscopy (SEM) (JSM5600LV) with energy dispersed X-ray spectrometry (EDS) attachment (6853-H, Horiba, England). Room temperature photoluminescence (PL) measurements were carried out by a fluorescence spectrophotometer (JY HORIBA FluoroLog-3).

3. Results and discussion

Morphology of the MoS_2 nanobelts grown on (AlGa)N and ZnO substrates is analyzed by using a representative cross-section SEM. The images shown in Fig. 1(b–c) clearly indicate that the as-synthesized two typical samples have belt-like nanostructures obtained in chemical vapor deposition. It can be calculated from Fig. 1b that MoS_2 nanobelts grown on ZnO nanowires substrates possess a diameter range from 500 to 1000 nm, and lengths up to 2000 nm. It should be noted that these nanobelts have somewhat irregular shapes and non-uniform distribution. From a typical cross-section SEM image of MoS_2 grown on (AlGa)N, we clearly see that nearly all of the nanobelts grow vertically on the (AlGa)N substrate with smooth surfaces and uniform sizes (Fig. 1c). The average length and diameter of the nanobelts are around 5.0 μm and 300 nm, respectively. By comparing the Fig. 1b with c, we can see the cross-section SEM image of MoS_2/(AlGa)N show a better morphology than that of MoS_2/ZnO, which should be ascribed to a more matching substrate [20–22].

To further elucidate the elemental composition of the as-synthesized materials, the typical EDS of MoS_2/(AlGa)N and MoS_2/ZnO are recorded (Fig. 2). It is noted that C, Zn, O, Mo and S elements are the all peaks in the EDS spectra as shown in Fig. 2a and C, Al, N, Ga, S and Mo peaks are displayed in Fig. 2b, which demonstrates that one of the used substrate is (AlGa)N or ZnO, respectively. No other peaks of impurities are observed in the as-obtained samples except for the peaks of C originating from the conductive adhesive that was used to fix the samples during the SEM observations. Furthermore, the quantitative EDS analysis shows that the element ratios between Zn/O (18.5:16.8), Mo/S (29:57), and (Al + Ga)/N (22:21.6) are close to stoichiometric ZnO (1:1), MoS_2 (1:2), and (AlGa)N (1:1), respectively, providing a strong evidence that these MoS_2 nanobelts surely grow on the ZnO and (AlGa)N substrates.

It seems that MoS_2 could be simply formed by a following chemical reaction (1) [22,23].

$$7S + 2MoO_3 = 2MoS_2 + 3SO_2 \quad (1)$$

Beyond question, in fact, the growth of MoS_2 nanobelt arrays is not as simple as the chemical equation described above but rather extremely sophisticated process [18,22,23]. We speculate that the different formation mechanisms of MoS_2 nanobelt arrays on (AlGa)N and ZnO substrates, respectively, as the following procedures (shown in Fig. 3a and Fig. 3b). At high temperature, MoO_3 is vulcanized by the sulfur vapor into MoS_2, which will be conveyed downstream by Ar carrier gas, depositing on(AlGa)N/ZnO substrates and eventually nucleation and growth to form the MoS_2 nanobelt arrays [18,19,22–25]. (AlGa)N belongs to hexagonal system [18] but ZnO is cubic one [26], so MoS_2 nanobelt arrays grown on (AlGa)N and ZnO substrates show different morphologies, which is in agreement with SEM results mentioned above [18,20,21].

To study optical properties of MoS_2 nanobelts grown on ZnO and (AlGa)N substrates, typical three room-temperature PL spectra of ZnO, (AlGa)N, MoS_2/ZnO, and MoS_2/(AlGa)N are respectively recorded in Fig. 3(b–d). Fig. 3b and c show the PL spectrum for the ZnO and (AlGa)N substrates with a very sharp peak at 380 nm and 451 nm, respectively. As can be seen, by contrast with Fig. 3b and c, Fig. 3d from MoS_2 nanobelts grown on ZnO and (AlGa)N substrates shows two wide red emissions with different intensity where only one peak at 677 nm and 669 nm appears,