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Enhanced performance of multilayer MoS_2 transistor employing a polymer capping layer

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ABSTRACT

Two-dimensional (2D) MoS_2 field-effect transistors (FETs) have attracted many attentions due to their intriguing electronic, optical, and mechanical properties. In this work, the electrical properties of multilayer MoS_2 FETs are significantly enhanced by using water-soluble polyvinyl alcohol (PVA) polymer as the capping layer. The key parameter, field-effect mobilities (μ), can be increased from 0.28 cm^2/Vs to 269.2 cm^2/Vs after applying the PVA capping layer, which means it has almost three orders of magnitudes increase. An energy band diagram based on Schottky barrier modulation is proposed to understand the device mechanism. The results represent a significant step towards applications of 2D MoS_2 FETs for future integrated circuit, sensors, and flexible electronics.

1. Introduction

As a series of new layered materials appearing, two-dimensional (2D) materials have strong chemical bonds in-plane, however, show weak out-of-plane bonding [1–9]. Recently, graphene exfoliated from graphite has opened a market of 2D materials [10–17]. These materials expand normally to the in-plane direction, and they display interesting electronic and optical behaviors due to their layered structures. However, although graphene is very promising for some applications due to their high mobility and fascinating electrical properties [10–12], the absence of a band gap makes it unsuitable as an electronic switching material for conventional device applications, such as field-effect transistors (FETs) [18].

As a kind of transition-metal dichalcogenides (TMDs), molybdenum disulfide (MoS_2) is a layered material with covalent bonds between the Mo–S–Mo atoms [19–24]. The MoS_2 layers are weakly held together by van der Waals interaction, which has a band gap from 1.2 eV in the bulk to 1.8 eV in monolayer [19–24]. Recently, MoS_2-based FETs have shown considerable interests for different applications, such as ultra-thin integrated circuit, gas sensor, and photoelectrical detector et al. [25–27]. However, one of the obstacles for the real application is the low field-effect mobility (μ). The typical value is about 0.1–10 cm^2/Vs for the normally exfoliated MoS_2 device [19]. Up to now, there are few reports for improving the μ in MoS_2 FET. For example, Al_2O_3 and HfO_2 capping layer with high dielectric constant (high-k) were proposed to significantly improve the μ up to ~200 cm^2/Vs [19,28]. This mobility improvement using a high-k dielectric could be attributed to the suppression of Coulomb scattering due to the high-k dielectric environment and modification of phonon dispersion in MoS_2 layer [19]. However, although this approach is very promising, the deposition of high-k metal oxide usually needs expensive vacuum-based atomic-layer-deposition (ALD) process. Therefore, exploring a new efficient and low-cost method to replace the previous ALD process is of great importance for the MoS_2 FETs applications.

In this paper, a new kind of polymer materials is demonstrated as the capping layer in MoS_2 FETs configuration. A facile route to synthesize the polyvinyl alcohol (PVA) capping layer is developed employing water as the solvent. By using this capping layer, a significantly enhanced performance was achieved in multilayer MoS_2 FETs. The on-off ratio (I_{on-off}) were increased from 4×10^3 to 10^5, and subthreshold swing (S) were increased from 7.1 V/dec to 102 mV/dec, respectively. Most importantly, the μ was observed to be greatly increased from 0.28 cm^2/Vs to 269.17 cm^2/Vs, which is

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almost three orders increase and even more than that obtained by using high-*k* dielectric method. Our results represent a significant step towards applications of 2D MoS_2-based FET for future integrated circuit, sensors, and flexible electronics.

2. Experimental details

MoS_2 FETs are fabricated by a conventional Scotch-tape approach. Firstly, we mechanically exfoliate multilayer MoS_2 flakes from a bulk crystal using Scotch tape, and subsequently transfer to a piece of heavily doped silicon substrate with a 290 nm SiO_2 capping layer. The source/drain electrodes with 30-nm-thick Ni film were deposited by photolithography and DC sputtering. PVA solution (10 wt% in water solution) was then drop-casted onto the MoS_2 layer as the capping layer. The MoS_2 thickness was examined by atomic force microscopy (AFM). Raman spectroscopy was used to evaluate the number of layers in MoS_2 besides the AFM measurement. After lift-off process, electrical properties of the devices were measured by a Keithley 4200 semiconductor parameter analyzer in the dark at room temperature.

3. Results and discussion

Fig. 1(a) and (b) display the schematic diagram of a traditional multilayer MoS_2 transistor and a PVA-capped MoS_2 transistor, respectively. Fig. 1(c) is the thickness information of MoS_2 flake performed by the atomic force microscopy (AFM). It is found to be ~5 nm, which corresponds to ~8 layers based on a 0.65 nm thickness per layer value [19]. The Raman spectroscopy of MoS_2 flake in our device is showed in Fig. 1(d). Both in-plane E^1_{2g} mode (~384 cm^{-1}) and out-of-plane A_{1g} mode (~409 cm^{-1}) are observed in this MoS_2 flake. From this figure, the Raman spectrum of MoS_2 flake is very similar to that of MoS_2 bulk, suggesting a good crystalline characteristic and negligible structural modifications in our exfoliated flake.

In order to examine the performance of the fresh MoS_2 device, we test the output curves and transfer curve of our device in the dark at room temperature. Thus, Fig. 2(a) shows the output curves of fresh MoS_2 transistor by sweeping the value of source-drain voltage (V_{DS}) from 0 V to 5 V with a bottom-gate bias (V_{GS}) from −5 V to 20 V, with 5 V steps. According to the output curve, good linear characteristics in the low V_{DS} and pinch-off characteristics in the high V_{DS} regimes are exhibited, indicating a good consistence with the traditional FET theory. The transfer curve is shown in Fig. 2(b) by sweeping the V_{GS} from −20 V to 20 V with a fixed bias of $V_{DS} = 0.1$ V. From this figure, a current on/off ratio ($I_{on/off}$) of ~4×10^3 and a subthreshold swing (S) of 7.1 V/dec are obtained, respectively. A positive threshold voltage (V_{th}) of ~3.1 V can be extracted by extrapolating the linear portion of I_{DS}-V_{GS} curve (as shown in right linear-scale axis) to a zero drain current. Finally, the field-effect mobility (μ) of the fresh MoS_2 device can be calculated based on the following equation [29]:

$$\mu = \frac{L}{W \times C_i \times V_{DS}} \times \frac{dI_{DS}}{dV_G} \tag{1}$$

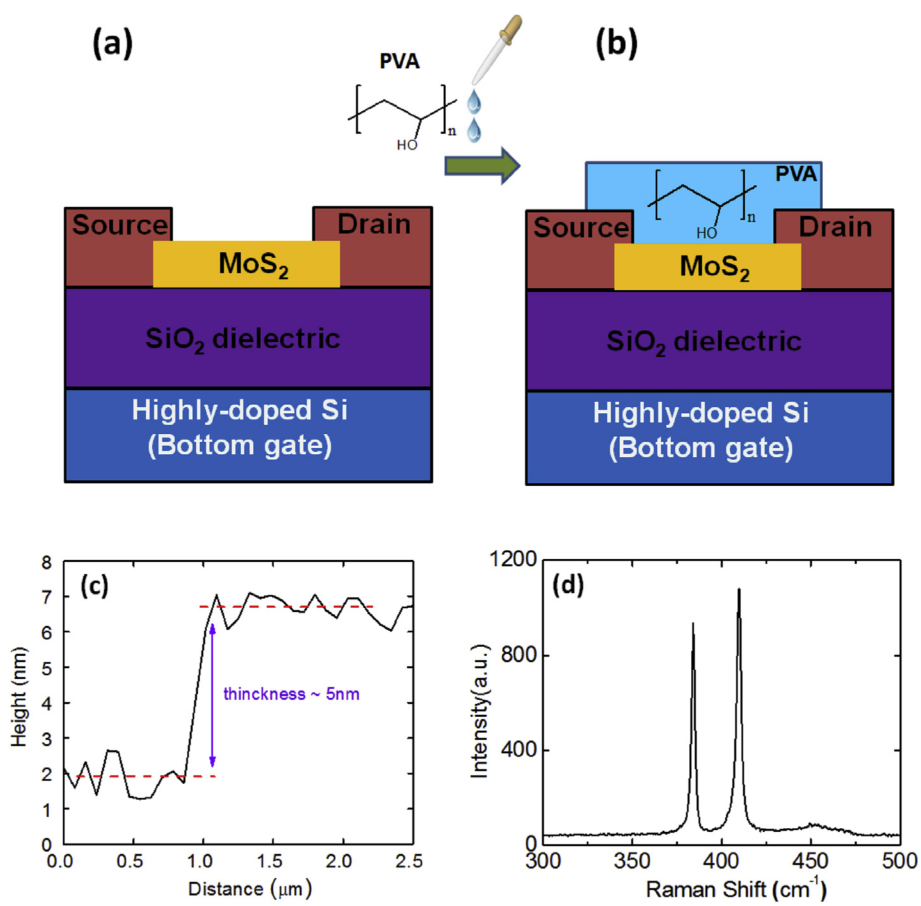

Fig. 1. (a) The schematic diagram of MoS_2 FETs without PVA capping layer; (b) The schematic diagram of MoS_2 FETs with PVA capping layer; (c) Thickness measurement using AFM at the MoS_2 flake edge; (d) The Raman spectroscopy result of MoS_2 flake.

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