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Strain-induced modulation on phonon and electronic properties of suspended black phosphorus field effect transistor

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A B S T R A C T

Black phosphorus has recently appeared as a promising two-dimensional material for applications in high performance nanoelectronics. Its single- and few-atomic layer forms in field-effect transistors have attracted a lot of attention due to the tunable bandgap (0.3–2.0 eV), high carrier mobility (1000 $cm^2\,V^{-1}\,s^{-1}$) and decent on-off ratios (10^5). Here, we demonstrate a suspended black phosphorus field effect transistor (BP-FET) and utilize Raman spectroscope to characterize the strain on the effects of Raman phonon. We find that red shifts appear in all the three vibrational modes (A_g^1, B_{2g} and A_g^2) in different degrees. Among them, A_g^1 mode is most sensitive to the tensile strain. We further investigate the electronic properties with a Cascade semi-automatic probe station. The linear relationships in the output curves indicate the contacts between black phosphorus and electrodes are ohmic contacts. The transfer characteristic curves declare the drain current modulation is $\sim 7.6 \times 10^3$ for the hole conduction and $\sim$57 for the electron conduction. Mobility of this device is found to be 347.5 $cm^2\,V^{-1}\,s^{-1}$ and 4.9 $cm^2\,V^{-1}\,s^{-1}$ for the hole and electron conduction, respectively. These results provide a theoretical basis for the coordination of high-performance black phosphorus electronic components.

1. Introduction

Phosphorus, the 15th element on the Periodic Table, has a lot kind of allotropes, such as red phosphorus, white phosphorus, black phosphorus and so on. Among them, black phosphorus is considered as the most stable one, which possesses primitive performance in the atmosphere for a few of weeks. More importantly, its single- and few-atomic layer forms show semiconductor properties including a direct band gap, high carrier mobility and decent current on-off ratios. In 2014, black phosphorus field effect transistor (BP-FET) had been successfully fabricated for the first time [1]. Since then, there has been an explosive growth of research covering the study of its structural [2], transport [3], electronics [4–6], optical, and photo electricity properties [7,8], as well as applications in gas sensing devices [9,10], battery electrodes [11–13] and thermoelectric devices [14–17]. Nevertheless, black phosphorus is very sensitive to environment. In the process of the preparation and preservation, the original characteristic can be changed by the environment. The substrate surface roughness would affect surface morphology and interface binding energy, and hence have an influence on the electrical properties.

Suspending black phosphorus can eliminate the influence of substrate on the properties. However, the introduction of internal strain is inevitable. It has been theoretically proved by Rodin et al. [18] that the band gap of black phosphorus can be switched from nearly direct bandgap semiconductor to indirect semiconductor, semimetal, and metal by strain. Strain can destroy the lattice symmetry, and then change the electronic band structure [19]. Therefore, introducing strain to BP-FET by suspension is an effective way to coordinate the electrical properties. In this work, we fabricate a back-gated BP-FET with a pre-patterned substrate and investigate the performance of the suspended black phosphorus devices.

2. Methods

Fig. 1(a) shows the fabrication steps of BP-FET with patterned substrates. Process starts with oxidized silicon with the oxide thickness ∼300 nm. Then reactive ion etching (RIE) technique is used to obtain a thin gate oxide layer. Oxide thickness of the patterned hole is ∼10 nm. TiW (5 nm) and Au (100 nm) are deposited onto the substrates as the source and drain electrodes. Black phos-

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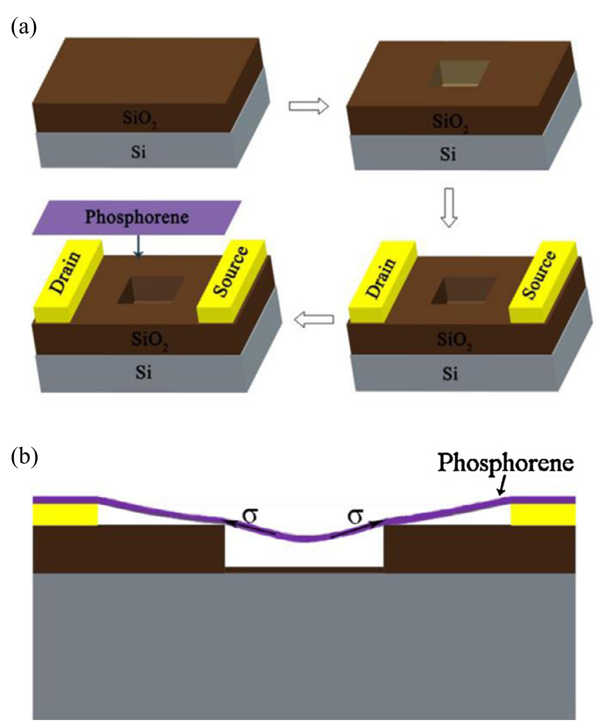

Fig. 1. (a) Schematic of the preparation of BP-FET. (b) Sectional view of BP-FET with patterned hole. Black phosphorus is suspending on the substrates.

phorus flake is obtained through a scotch tape-based mechanical exfoliation method to peel thin flakes from bulk crystal. Then black phosphorus will be transferred to SiO_2 substrate because the binding force between black phosphorus and SiO_2 is stronger than Van der Waals' interactions. In order to minimize the effect of crystal degradation caused by the air, black phosphorus sample is stored in a vacuum container after the fabrication. It is obvious that black phosphorus is suspending on the hole because of the stress, as shown in Fig. 1(b).

3. Results and discussion

The microscope optical picture of black phosphorus on substrate is depicted in Fig. 2(a). Black phosphorus is suspending on the substrate as conductive channel. Fig. 2(b) shows the atomic force microscope (AFM) image of the white dashed square in Fig. 2(a) (AFM: Bruker Dimension Edge). Black phosphorus sheet is attached to the patterned substrate, covering the hole. There are no obvious "bubbles" appearing on the surface of the sample, indicating the crystal structure of black phosphorus has not been destroyed by the H_2O and O_2 molecular in the air [20]. Fig. 2(c) shows the height line profile at the white line shown in Fig. 2(b). AFM measure verifies a thickness of ∼42 nm in this device. Meanwhile, that the depth of the black phosphorus on the hole is ∼88 nm can be easily seen in Fig. 2(c). Compared with the depth of the hole in the substrate (∼290 nm), black phosphorus is suspending on the patterned hole.

Raman spectroscopy was carried out by a Horiba Jobin Yvon LabRAMHR800 Raman system with 532 nm excitation within half an hour. The laser power was kept below 0.25 mW to avoid laser

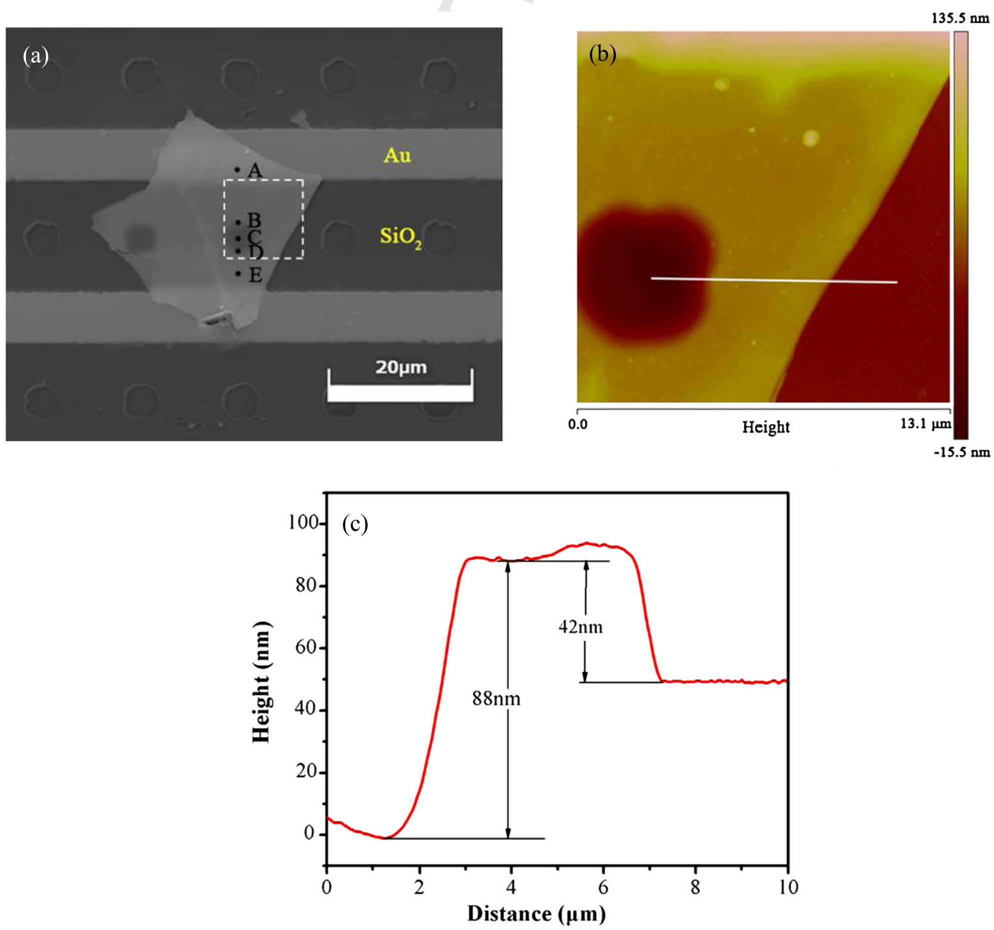

Fig. 2. (a) An optical image of black phosphorus crystal on the patterned substrates. (b) AFM image of a black phosphorus device. Black phosphorus sheet is attached to the patterned substrate with a hole. (c) Height line profile of the white line shown in (b).