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Infrared Black Phosphorus Phototransistor with Electrostatically Tunable Responsivity

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Abstract

This work realizes a high sensitivity black phosphorus phototransistor operating at short-wave infrared (SWIR) of 2 µm. By exploiting the electrostatic gating effect, the device shows an excellent tunability of responsivity and photoconductive gain. At an operating source-drain bias of –1 V, a peak responsivity of 8.5 A/W and an ultralow noise equivalent power of ~0.37 pW/Hz$^{1/2}$ are achieved under a nanowatt-level illumination, making the device promising for weak signal sensing without the need for a trans-impedance amplifier due to internal gain.

1. Introduction

Thin film black phosphorus (BP), a two-dimensional material with a direct band gap of around 0.3 eV when its thickness exceeds 4 nm [1], is capable of detecting infrared light. Recent works have demonstrated BP photodetector at near- to mid-infrared wavelengths [2]-[6] alongside with fast response reported in the mid-infrared [7], which reveal the great potential of BP for infrared photodetection.

Nonetheless, a detailed investigation of the ability to tune the photo-response in a BP phototransistor by electrostatic gating effect has not been reported at 2 µm, a wavelength which belongs to short-wavelength-infrared (SWIR) where numerous applications exist such as molecular sensing and thermal imaging of high temperature objects [8]. In this work, we demonstrate a BP phototransistor and investigate the photocurrent generation mechanism under different electrostatic gating effect at 2 µm wavelength. The source-drain bias dependence of detectivity is also investigated and discussed.

2. Device Structure and Fabrication

The BP thin flake was mechanically exfoliated from bulk BP crystals and transferred to 90 nm SiO_2/n+ Si substrate. The metal contacts were patterned by electron beam lithography (EBL), followed by the deposition of 3 nm Ni and 50 nm Au through magnetron sputtering. After lift-off to form the electrodes, a 20 nm Al_2O_3 passivation layer was grown by atomic layer deposition (ALD) at 200 ºC, covering the BP channel to protect it from ambient degradation. The phototransistor structure and BP flake characterization are shown in Fig. 1. The atomic force microscope profile (AFM) shows a BP flake with a thickness of 23 nm. At such a thickness, the flake possesses a small band gap close to bulk, ensuring the occurrence of photon absorption at 2 µm while the active channel maintains the gate control to tune the phototransistor's performance.

3. Results and Discussion

From the transfer curve under different excitation power, the photocurrent I_{ph} is extracted by the equation $I_{ph} = |I_{d,light}| - |I_{d,dark}|$, where $I_{d,light}$ and $I_{d,dark}$ are the source-drain current under illumination and in dark condition, respectively. In Fig. 2 (a), the photocurrent and dark current as a function of gate bias V_g are presented. The photo-response dependence of the electrostatic gating effect is divided into three distinct regions, as marked in the bottom figure of Fig. 2 (a). Negative photocurrents are observed in region I, which indicates a reduced transistor on-current under illumination. Notably, the photocurrent is shown to peak in region II at V_g = 12.5 V when a lightly p-doped channel is induced near the off-state. However, when the V_g increases further into region III, photocurrent is observed to decrease monotonically. We show that the photocurrent of our device is predominantly contributed by two effects. The first one being the photoconductive effect where conductivity is increased by the photo-generated carriers, thus giving rise to an elevated current. The second contributor lies with photo-gating effect [9] where traps in the forbidden band of BP capture electrons or holes and shift the threshold voltage of the transistor. Depending on the region of transistor operation, photocurrent from this effect can be either positive or negative.

To explain the mechanisms in these regions, the energy band diagram of the BP channel and metal contacts are shown in Fig. 2 (b). In region I, when a large negative gate bias is applied, the channel is heavily p-doped with the valence band bending downwards at the BP/drain interface, leading to a barrier for holes. As a result, the photo-generated carriers suffer from severe scattering and recombination. Meanwhile, the empty electron traps in the forbidden band capture the photo-generated electrons and become negatively charged, resulting in a threshold shift to a more negative value. As the gate bias is increased in region II, a reduced transconductance is observed wherein the threshold shift plays a weaker role in contributing to the total photocurrent. At the same time, band bending at the BP/drain interface reduces which enables photo-generated electron-hole pairs to be collected by the electrodes efficiently before recombination. When a larger positive gate bias is applied, negatively charged electrons are induced in the channel and the conduction band bends upwards at the BP/source interface, acting as an electron barrier which increases the probability of carrier recombination. This has led to a reduced photocurrent in region III.

Fig. 3 (a) and (c) show that the device is capable of operating stably as the laser is switched on and off at nanowatt-level power and under various gate biases, respectively. A peak responsivity of 8.5 A/W and a photoconductive gain of 10.5 are achieved. With a further increase in the illumination power, the responsivity eventually decreases (Fig. 3 (b)). This is consistent with the Hornbeck-Haynes model [10] which describes the relationship between photo-response and power absorption. However, by controlling the gate bias, the responsivity can be electrostatically tuned to achieve a higher responsivity and photoconductive gain (Fig. 3 (d)).

Following the investigation of electrostatic gating effect, we studied the dependence of source-drain bias on the phototransistor's performance. The dark and photocurrent are measured under different source-drain biases, from which the noise equivalent power (NEP) (Fig. 4) and detectivity (Fig. 5) are calculated. An ultralow NEP in the order of picowatt per Hz$^{1/2}$ is achieved in this work. For a source-drain bias of –1 V, a detectivity of 1.7×10^9 Jones is demonstrated. We also show that an enhanced photoconductive gain can be obtained with an increased source-drain bias, as plotted in Fig. 6. This is attributed to a stronger lateral electric field in the channel which reduces the carrier transit time between electrodes, thus giving rise to a larger gain. Consequently, the detectivity is also enhanced, implying that source-drain bias can be exploited as another degree of tunability for further performance enhancement.

4. Conclusions

A high sensitivity black phosphorus phototransistor with a peak responsivity of 8.5 A/W at 2 µm wavelength has been demonstrated. Through electrostatic gating effect, the photo-response of our device can be effectively modulated alongside with a tunable photoconductive gain. Additionally, the achievement of an ultralow noise equivalent power renders it promising for weak signal detection applications in the SWIR range such as bio-molecular sensing.

References [1] X. Ling *et al.*, Proc. Natl. Acad. Sci. **112** (2015) 4523. [2] N. Youngblood *et al.*, Nat. Photonics **9** (2015) 247. [3] Q. Guo *et al.*, Nano Lett. **16** (2016) 4648. [4] L. Wang *et al.,* Adv. Funct. Mater. **27** (2017) 1604414. [5] M. Xu *et al.,* Appl. Phys. B **123** (2017) 130. [6] J. Na *et al.,* Nanotechnology **28** (2017) 085201. [7] R. J. Suess *et al.,* 2D Mater. **3** (2016) 041006. [8] M. P. Hansen *et al.,* Proc. SPIE **6939** (2008) 69390I. [9] M, Buscema *et al.,* Chem. Soc. Rev. **44** (2015) 3691 [10] C. Soci *et al.*, Nano Lett. **7** (2007) 1003.

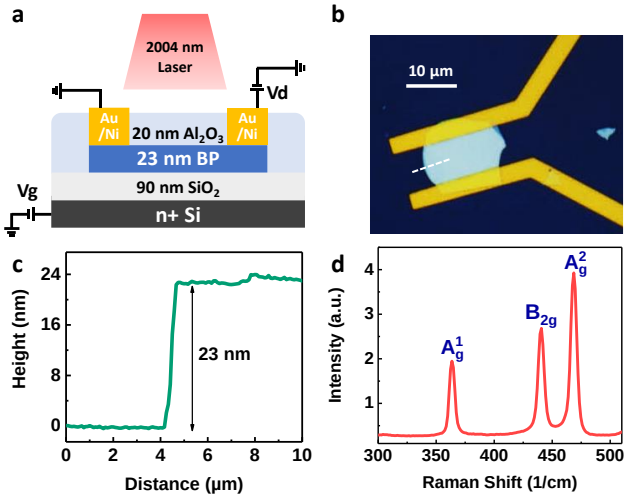

Fig. 1 BP phototransistor structure and material characterizations. (a) Cross section schematics. (b) Optical microscope image. (c) Atomic force microscopy (AFM) profile along the dash line in (b), showing the BP flake thickness of ~23 nm. (d) Raman spectrum of the BP flake, with the out-of-plane (A^1_g) and in-plane (B_{2g} and A^2_g) phonon modes clearly presented.

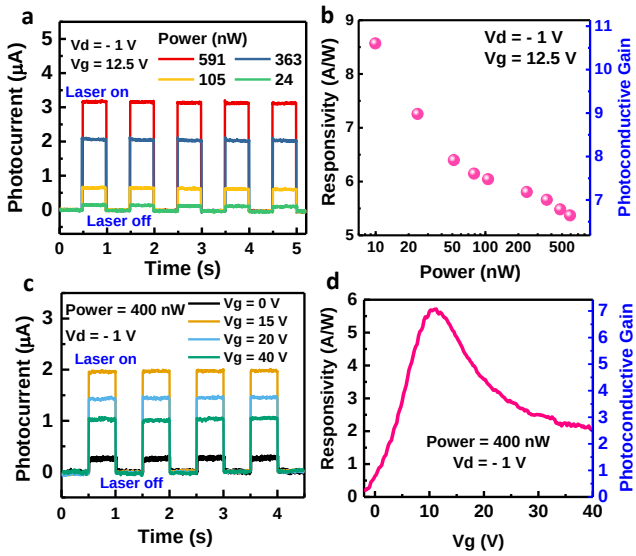

Fig. 3 Temporal photo-response for (a) different power on device and (c) different gate biases. Responsivity and photoconductive gain under varied (b) power and (d) gate biases. Higher responsivity is achieved at lower excitation power.

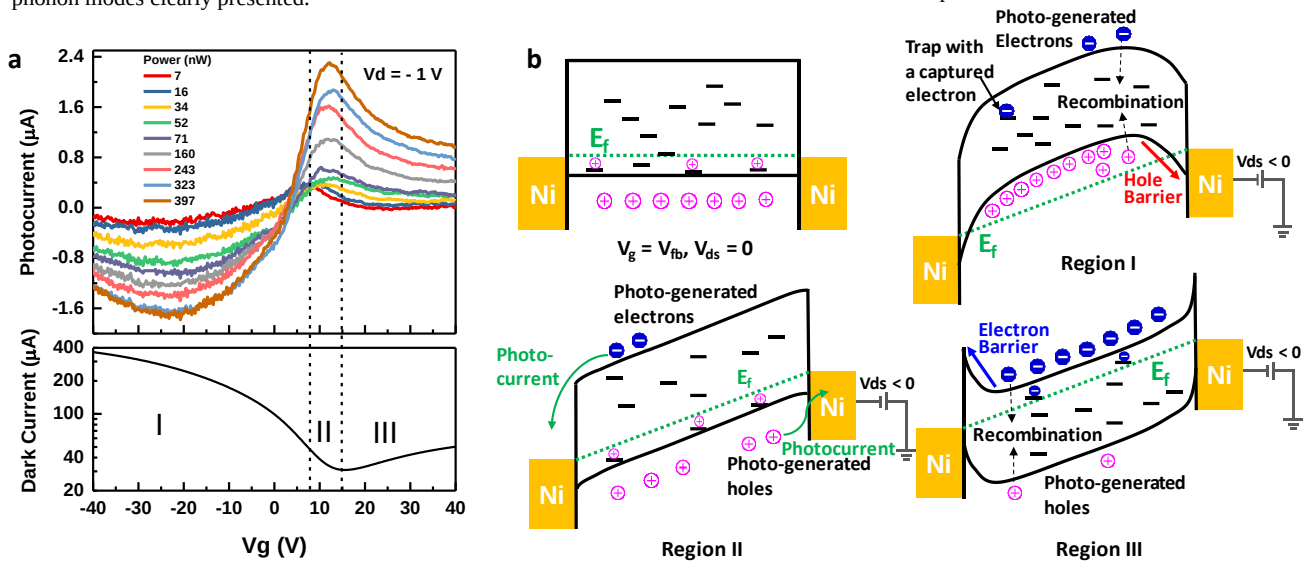

Fig. 2 Photo-response tuned by electrostatic gating effect. (a) Top figure: Dependence of photocurrent on gate bias under varied excitation power. Bottom figure: Transfer curve of the BP transistor. The peak responsivity is achieved when the BP channel is lightly p-doped. (b) Band alignment of BP channel and Ni contacts for different regions of the transfer curve, accounting for the distinct photo-response characteristics in the three regions.

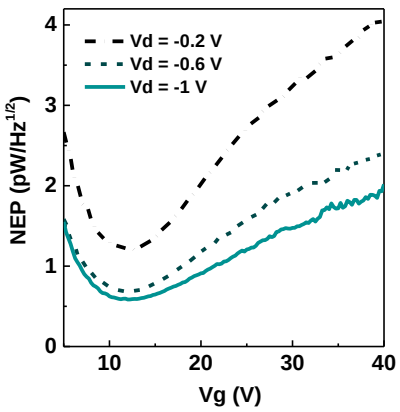

Fig. 4 Noise equivalent power (NEP) in the order of picowatt per $Hz^{1/2}$ is demonstrated. Lower NEP is achieved by increasing source-drain bias.

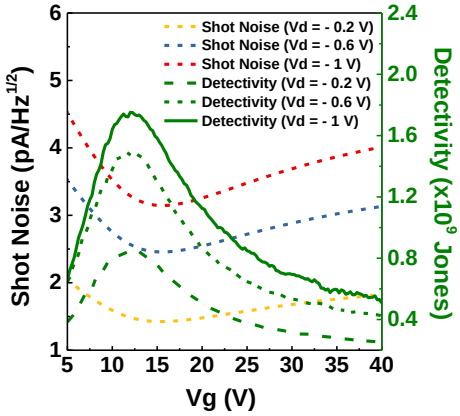

Fig. 5 Shot noise in the order of picoampere per $Hz^{1/2}$ is achieved. Larger source-drain bias leads to a higher detectivity in the order of 10^9 Jones.

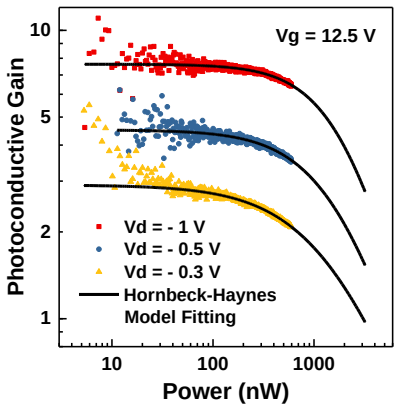

Fig. 6 Enhanced photoconductive gain is achieved by a larger source-drain bias due to a stronger lateral electric field which reduces the carrier transit time.

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