Supporting Information for

Tunable black phosphorus heterojunction transistor for multifunctional optoelectronics

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Section 1. Raman spectrum of BP flake for heterojunction device fabrication.

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Section 12. Zero-power-consumption infrared photodetection with D2 and D3. (Indicating potential of heterostructure design for improved optoelectronic performance)
Section 1. Raman spectrum of BP flake for heterojunction device fabrication.

![Raman spectrum of BP flake](image)

Figure S1. Raman spectrum of the BP flake used for device fabrication. Three peaks are identified at 363.5 cm\(^{-1}\), 439.9 cm\(^{-1}\) and 467.9 cm\(^{-1}\), corresponding to \(A_1^g\), \(B_{2g}\) and \(A_2^g\) phonon mode, respectively, confirming the good crystal quality of the BP flake.

Section 2. Transfer characteristics of BP heterojunction transistors D2 and D3.

![Transfer characteristics](image)

Figure S2. Transfer characteristics of device (a) D2 and (b) D3 on semi-logarithmic scale and linear scale (inset) at different \(V_d\) biases, showing hole-dominating conduction, similar to device D1.
Section 3. $I_d$-$V_g$ characteristics and $V_{th}$ shift of D1 under various illumination situations.

Figure S3. (a) $I_d$-$V_g$ characteristics of the device D1 under varying illumination situations at 1550 nm and at 2 V $V_d$. Inset shows the portion near $V_g=0$ V on linear scale. (b) Extracted threshold voltage ($V_{th}$) shift as a function of incident light power. (c) Transconductance curve of D1 at 2 V $V_d$. 
Section 4. Photoresponse of BP heterojunction phototransistor D1 operating at 1 V $V_d$.

Figure S4. Tunable photoresponse of lateral BP heterojunction phototransistor D1 under 1 V $V_d$ bias at 1550 nm wavelength. (a) Bottom panel: Conductance of the device as a function of $V_g$ under dark condition. Top panel: gate-bias-dependent photocurrent under varying light excitation power at 1 V $V_d$. (b) Top panel: Extracted photocurrent at typical $V_g$ values (0 V, 20 V, 30 V, corresponding to on-state, subthreshold-state and off-state of the transistor) as a function of excitation light power. Bottom panel: Calculated photoresponsivity at typical $V_g$ values and its dependence on light power. The highest responsivity is obtained to be $2.17 \times 10^5$ mA/W at 0 V $V_g$ and 1.8 nW light power.
Section 5. Photodetection results on BP heterojunction phototransistor D2.

Figure S5. Tunable photoresponse of lateral BP heterojunction phototransistor D2 under 1 V $V_d$ bias at 1550 nm wavelength. (a) Bottom panel: Conductance of the device as a function of $V_g$ under dark condition. Top panel: gate-bias-dependent photocurrent under varying light excitation power at 1 V $V_d$. (b) Top panel: Extracted photocurrent at typical $V_g$ values (0 V, 20 V, 30 V, corresponding to on-state, subthreshold-state and off-state of the transistor) as a function of excitation light power. Bottom panel: Calculated photoresponsivity at typical $V_g$ values and its dependence on light power. The highest responsivity is obtained to be 2.23×10^5 mA/W at 0 V $V_g$ and 2.8 nW light power.

Figure S6. (a) Responsivity of lateral BP heterojunction phototransistor D2 as a function of $V_g$ at 2.8 nW incident power at 1550 nm ($V_d$=1 V). (b) Noise-equivalent-power (NEP) of the device in dependence of $V_g$ at 1 V $V_d$. The smallest NEP less than 10^{-2} pW/Hz^{1/2} is obtained
near 10 V gate bias. (d) Detectivity of the device in dependence of $V_g$ at 1 V $V_d$. Value of $2.7 \times 10^{10}$ Jones is obtained near 10 V $V_g$. 
Section 6. Photodetection results on BP heterojunction phototransistor D3.

Figure S7. Tunable photoresponse of lateral BP heterojunction phototransistor D3 under 1 V $V_d$ bias at 1550 nm wavelength. (a) Bottom panel: Conductance of the device as a function of $V_g$ under dark condition. Top panel: gate-bias-dependent photocurrent under varying light excitation power at 1 V $V_d$. (b) Top panel: Extracted photocurrent at typical $V_g$ values (0 V, 20 V, 32 V, corresponding to on-state, subthreshold-state, off-state of the transistor) as a function of excitation light power. Bottom panel: Calculated photoresponsivity at typical $V_g$ values and its dependence on light power. The highest responsivity is obtained to be $7.01 \times 10^5$ mA/W at 0 V $V_g$ and 2.3 nW light power. This higher responsivity value for device D3 (than D1 and D2) can be well attributed to more light absorption due to its larger BP thickness.

Figure S8. (a) Responsivity of lateral BP heterojunction phototransistor D3 as a function of $V_g$ at 2.3 nW incident power at 1550 nm ($V_d=1$ V). (b) Noise-equivalent-power (NEP) of the device in dependence of $V_g$ at 1 V $V_d$. The smallest NEP of $7 \times 10^{-3}$ pW/Hz$^{1/2}$ is obtained near
15 V gate bias. (d) Detectivity of the device in dependence of $V_g$ at 1 V $V_d$. A value of $3.8 \times 10^{10}$ Jones is obtained near 15 V $V_g$.

**Section 7.** Detailed comparison of infrared responsivity of BP heterojunction phototransistor with reported values.

**Table 1:** Detailed comparison of photoresponsivity (R) between BP heterojunction device and reported BP-based photodetectors.

<table>
<thead>
<tr>
<th>Structure</th>
<th>$\lambda$ (nm)</th>
<th>$R$ (mA/W)</th>
<th>BP thickness (nm)</th>
<th>$P_{in}/P_{density}$</th>
<th>$V_d$ (V)</th>
<th>Reference in main text</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP heterojunction phototransistor</td>
<td>1550</td>
<td>383000</td>
<td>3-6</td>
<td>1.8 nW</td>
<td>2</td>
<td><em>This work</em></td>
</tr>
<tr>
<td>BP heterojunction phototransistor</td>
<td>1550</td>
<td>217000</td>
<td>3-6</td>
<td>1.8 nW</td>
<td>1</td>
<td><em>This work</em></td>
</tr>
<tr>
<td>Waveguide-integrated phototransistor</td>
<td>1550</td>
<td>657</td>
<td>100</td>
<td>1.91 mW</td>
<td>0.4</td>
<td>[14]</td>
</tr>
<tr>
<td>Phototransistor (interdigitated electrodes)</td>
<td>3390</td>
<td>82000</td>
<td>12</td>
<td>1.6 nW</td>
<td>0.5</td>
<td>[15]</td>
</tr>
<tr>
<td>Phototransistor</td>
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<td>8500</td>
<td>23</td>
<td>10 nW</td>
<td>1</td>
<td>[17]</td>
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<tr>
<td>Phototransistor</td>
<td>2500</td>
<td>47</td>
<td>15</td>
<td>25 µW</td>
<td>0.1</td>
<td>[18]</td>
</tr>
<tr>
<td>Phototransistor</td>
<td>3700</td>
<td>21</td>
<td>15</td>
<td>25 µW</td>
<td>0.1</td>
<td>[18]</td>
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<td>Phototransistor</td>
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<td>5</td>
<td>120</td>
<td>3.1 kW/cm²</td>
<td>0.2</td>
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<td>10000</td>
<td>20</td>
<td>82 µW</td>
<td>1.5</td>
<td>[21]</td>
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<td>Vertical BP junction</td>
<td>1200</td>
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<td>30-50</td>
<td>1.35 mW</td>
<td>0.1</td>
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<td>MoS₂/BP vertical junction</td>
<td>1550</td>
<td>153.4</td>
<td>12</td>
<td>1 nW</td>
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<td>1470</td>
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<td>50 W/cm²</td>
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<tr>
<td>p-n junction</td>
<td>1064</td>
<td>120000</td>
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<td>62.5 mW/cm²</td>
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<tr>
<td>BP-on-WSe₂ phototransistor</td>
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<td>500</td>
<td>7</td>
<td>1 mW/cm²</td>
<td>0.5</td>
<td>[37]</td>
</tr>
</tbody>
</table>
Section 8. Calculation of NEP and $D^*$. 

Figure S9. Calculated Johnson noise and shot noise of BP heterojunction transistor D1 as a function of $V_g$, showing shot noise being dominant over Johnson noise.

NEP indicates the excitation power needed to generate a signal equal to the device noise level in 1 Hz bandwidth and can be expressed by $\text{NEP} = \text{noise} / R$. Primarily, there are three contributions to the total noise: flicker noise, Johnson noise and shot noise. Among them, flicker noise are usually related to the defects acting as traps in the channel, and could be a dominating element in the total noise at low frequencies.¹ Johnson noise is caused by the thermal agitation of the charge carriers in the channel and can be expressed by

$$\sqrt{4k_B^T \Delta f / R_{\text{ch}}}$$

where $k_B$ is the Boltzmann constant, $T$ the temperature in Kelvin, and $R_{\text{ch}}$ the channel resistance. Shot noise is related to the dark current and determined by $\sqrt{2qI_{\text{dark}} \Delta f}$. In our work, $I_{\text{dark}}$ is recorded, and $R_{\text{ch}}$ can be deduced by $R_{\text{ch}} = V_d / I_d$. Then, according to the above equations, the Johnson noise and shot noise of the device are calculated as a function of $V_g$ for $V_d=2$ V. As shown in Figure S9, Johnson noise is almost one order of magnitude smaller than the shot noise. Therefore, the gate-dependent shot-noise-limited NEP of our device ($\text{NEP}_{\text{shot}}$) can be calculated as given in Figure 3b. Here, we would like to point out that at $V_g=20$ V (where lowest $\text{NEP}_{\text{shot}}$ is obtained), our device can work at a relatively high frequency (4.2 kHz). Therefore, we believe that by combining with other advanced techniques, for example, lock-in technique at a high frequency of 4 kHz, it will be possible to avoid a large part of $1/f$ noise contribution and the $\text{NEP}_{\text{shot}}$ will represent an ultimate limit of the device detection ability.
By the way, we would like to note that the calculated $NEP_{\text{shot}}$ for $V_g$ near 30 V is, although slightly higher than at 20 V $V_g$, still under 0.1 pW/Hz$^{1/2}$. In such case, since almost no traps contribute to the photocurrent generation (photoconductive effect dominates) and the device can work at a much higher frequency, it will be entirely possible to avoid 1/f noise on limiting the device $NEP$ by employing lock-in technique. In this case, the $NEP_{\text{shot}}$ represent the ultimate $NEP$ of our device still is the smallest value compared to reported works.

Specific detectivity ($D^*$, in Jones) is an important figure of merit for photodetectors, which signifies the sensitivity of a photodetector normalized with its active area, thus can be used for comparison between different devices. It is given by $D^* = \sqrt{A}/NEP$, where $A$ is the area of the detector in cm$^2$. For device D1, the channel length $L=3.5$ µm and channel width $W=3$ µm, resulting an area of 10.5 µm$^2$. Hence, the detectivity at $V_g=0$ V and $V_g=20$ V can be calculated to be $2.3\times10^{10}$ Jones and $6.1\times10^{10}$ Jones, respectively.
Section 9. Carrier lifetime and band width analysis.

Figure S10. (a) Photocurrent ($I_{ph}$) as a function of incident laser power ($P_{in}$) at 0 V $V_g$ and 2 V $V_d$, and the Hornbeck-Haynes model fitting for determining the carrier lift time. (b) Photoconductive gain of the device as a function of $P_{in}$ when operating at 0 V $V_g$ and 2 V $V_d$.

We adopt Hornbeck-Haynes model to describe the photocurrent dependence on the incident light power:\(^2\)

$$ I_{ph} = q \eta \frac{\tau_0}{\tau_{tr} + (\frac{F}{F_0})^n} $$

where $\eta$ is the absorption of BP channel, $\tau_0$ and $\tau_{tr}=\frac{L^2}{\mu_h V_d}$ ($L$ is the channel length, $V_d$ is drain-source voltage, and $\mu_h$ is hole mobility) are the carrier lifetime and transit time, respectively, $F$ is the photon absorption rate expressed by $F=\eta P_{in}/h\nu$ ($h\nu$ is the photon energy), $F_0$ is the absorption rate when trap saturation occurs, and $n$ is a fitting parameter.

According to the gain $G=(I_{ph}/P_{abs})(h\nu/q)$, where $P_{abs}=\eta P_{in}$ is the power absorbed by the channel, we have

$$ G = \eta \frac{\tau_0}{\tau_{tr} + (\frac{F}{F_0})^n} $$

For $V_d=2$ V and $\mu_h=100$ cm$^2$/Vs, a carrier transit time of $\tau_{tr}=0.6$ ns can be estimated.

Regarding the absorption of our device, in ref[3], Zhang et al. has revealed absorption around 1%-3% for BP flake with 6 layers and 13 layers at 1550 nm (0.8 eV) wavelength. Therefore, we assume an absorption percentage of 3% of the incident light on the device for calculation, and a carrier lifetime of $\tau_0=39$ µs is derived from the fitting results.
Consequently, the 3dB bandwidth $f_{3dB}=1/2\pi\tau_0$ is derived to be 4.2 kHz. Furthermore, when working at 30 V $V_g$, although a relatively smaller responsivity is obtained due to dominant photoconductive effect, the device frequency performance will be primarily determined by the carrier transit time (0.6 ns), implying its potential for GHz application.$^4$
Section 10. Photoresponse of the device in dependence of $V_d$.

Figure S11. (a) $I_d$-$V_d$ characteristics of the device under various illumination conditions at 20 V $V_g$. (b) Calculated photocurrent as a function of $V_d$ at 20 V $V_g$. (c) Calculated responsivity as a function of $V_d$ at 20 V $V_g$. (d) $I_d$-$V_d$ characteristics of the device under various illumination conditions at 30 V $V_g$. (e) Calculated photocurrent as a function of $V_d$ at 30 V $V_g$. (f) Calculated responsivity as a function of $V_d$ at 30 V $V_g$. Moved to Supporting Information.
Section 11. Source/drain contact nature of the device and explanation of gate-dependent rectifying behavior

**Figure S12.** $I_d$-$V_d$ characteristics at varying $V_g$ values of devices on BP flakes of uniform thickness of (a) 3.5 nm, (b) 4.5 nm and (c) 7 nm. It is clear that these devices, which have similar flake thicknesses as in the BP heterojunction devices, display symmetric and linear $I_d$-$V_d$ behaviours, indicating Ohmic-like nature of the Ni-electrode/BP contacts in this work. This fact implies that the metal/BP contact cannot explain the observed current rectification behavior of BP heterojunction device.

Therefore, concerning the gate-tunable rectifying behaviour in our BP device, it can be ascribed to the existence of a heterojunction between the thin and the thick portion in the channel, as a result of their distinct band gaps and different responses to the gate control. This rectifying behavior enables our device for photodetection at zero $V_d$, which is not allowed by other phototransistors with a homogeneous channel.

As for the $V_g$ dependence, briefly, when $V_g$ has a large enough negative value, both the regions (of different layer numbers) of the device are electrostatically modulated into heavy $p$-type forming a $p^*-p^+$ junction. Hence no significant rectifying phenomenon is expected at the thick-thin flake interface. Therefore the device shows no obvious current rectification.

Regarding the evident rectifying behavior in the 10 to 30 V $V_g$ range, it can be explained by the combined effect of the BP hetero-interface and BP/Ni contacts. First, the bands of the thin flake bend upwards at the interface due to its higher Fermi level (as a result of easier holes depletion and inversion) than the thick flake, which will induce a depletion region in the vicinity if the interface. Additionally, compared with the thick flake, the thin one has a larger band gap, and the valence band maximum is slightly lower than that for the thick flake. This will result in a slightly higher contact barrier at the source end, giving rise to a less effective injection of holes into the flake. Further increase of $V_g$ results in degradation of rectifying behavior (rectifying ratio decreases) because the electron conduction is no longer...
negligible and electron injection is easier at the drain end. This can also help explain the reverse of rectifying direction when both flakes enter into the heavy electron doping regime.
Section 12. Zero-power-consumption infrared photodetection with D3. (Indicating potential of heterostructure design for improved optoelectronic performance)

Figure S13. Zero-power-consumption infrared photodetection with D3. (a) $I_d-V_d$ curves of the device for -2 V to 2 V $V_d$ at different $V_g$ showing current rectifying behavior. (b) Gate-tunable photocurrent arising from BP heterojunction transistor under varying laser powers with zero external $V_d$ applied. (c) Extracted photocurrent (left axis) and photoresponsivity (right axis) in dependence of $P_{in}$. A maximized responsivity of 10.5 mA/W is obtained.
References