Electronic Supplementary Material (ESI) for Nanoscale.

Supplementary Information

Top-gated Black Phosphorus Phototransistor for Sensitive Broadband Detection

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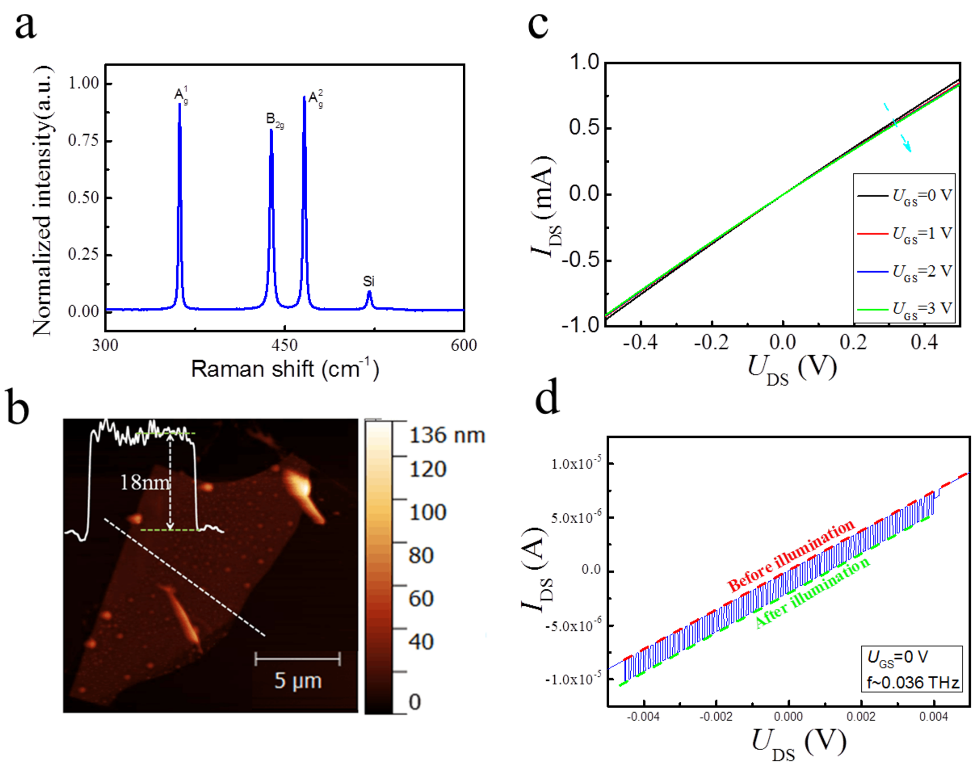

Figure S1. (a) Raman spectrum for the BP flakes is shown where the characteristic A_{g1}, B_{2g} and A_{g2} peaks are clearly visible at the wave numbers of 360 cm^{-1}, 440 cm^{-1} and 470cm^{-1}, respectively. A 532 nm green laser was used to obtain the Raman spectrum. (b) AFM images clearly confirm that thickness of BP flakes about 18 nm are identified for device fabrication. (c) The current-voltage characteristics of BP flakes device at different gate voltage (U_{DS}=0 V, 1 V, 2V, 3 V) with Keithley 4200 under 0.036 THz radiation; Temporal current response at U_{GS}=0 V plotted as a function of U_{GS} with Keithley 4200 under 0.036 THz radiation. (d) Temporal current response at gated voltage U_{GS}=0 V, plotted as a function of U_{DS} with Keithley 4200 under 0.036 THz radiation, and the photocurrent does not greatly fluctuate at different bias voltage U_{DS}.

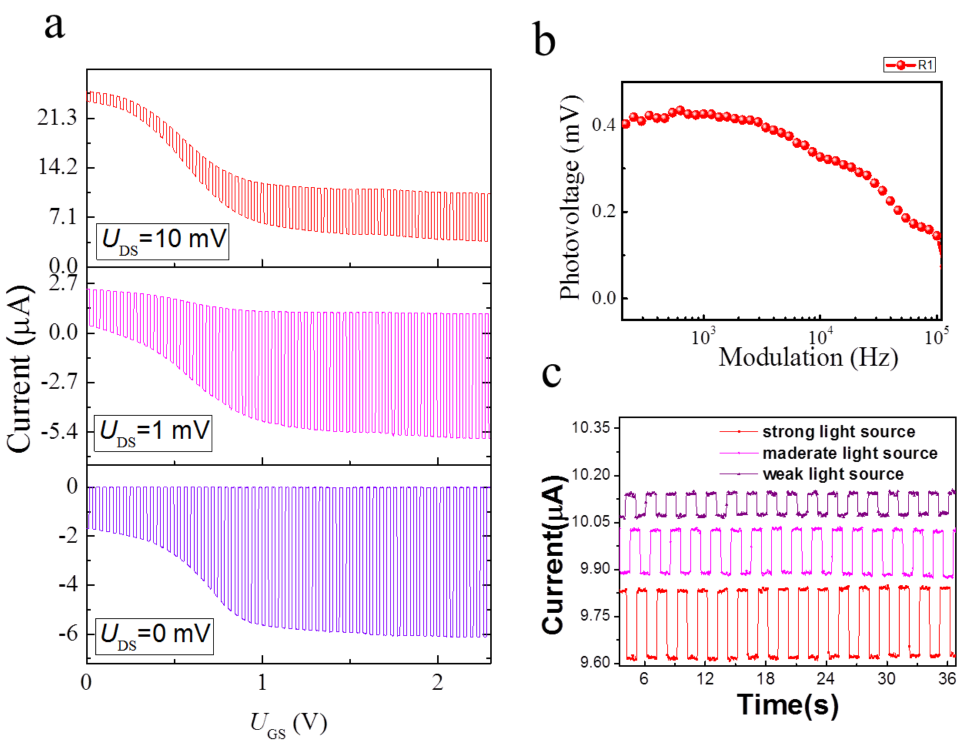

Figure S2. (a) Temporal current response at different bias voltage (U_{DS}=0 V, 1 mV, 10 mV) frequencies, plotted as a function of U_{GS} with Keithley 4200 under 0.036 THz radiation and the resistance increase under illumination and the changing trend of have a similar trend as gated voltage U_{GS} at different bias voltage U_{DS}. (b) The dependence of response ΔU at 0.036 THz on electrically chopped-frequency (0~0.1 MHz far above the mechanical chopper, the supplied bias U~0.1 V. (d) Direct observation of the current variation at U_{TG}=0 V under three different radiation out power (f~0.036 THz).

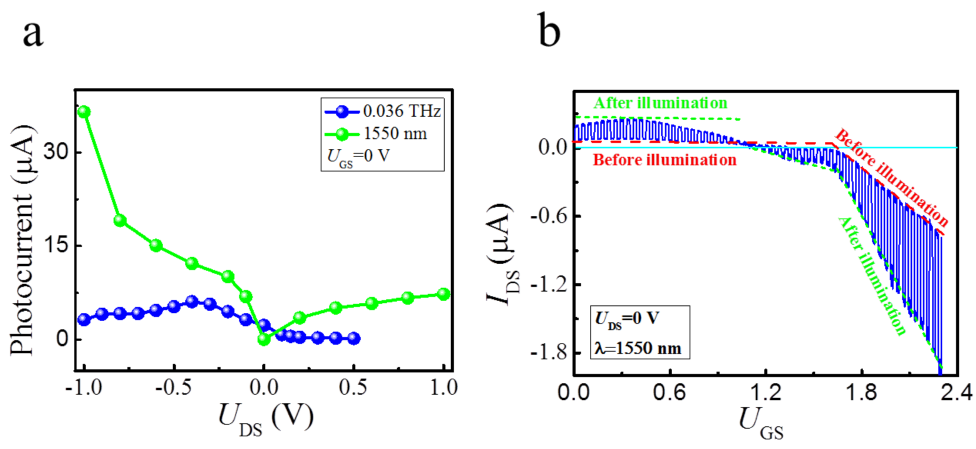

Figure. S3 (a) Direct observation of the photocurrent variation at U_{TG}=0 V under f~0.036 THz and λ~1550 nm radiation, plotted as a function of U_{GS}. This results is consistent with the result of Figure S1d at terahertz and photo-conductive behavior of linear dependent bias voltage U_{DS} is observed at λ~1550 nm (b) Temporal current response at bias voltage U_{DS}=0 V plotted as a function of U_{GS} with Keithley 4200 under 1550 nm radiation. The gated voltage-dependent responses amplitude of our photodetector is intuitively observed, and the polarity of the photocurrent is reversed as gated voltage U_{GS}, resopectively.

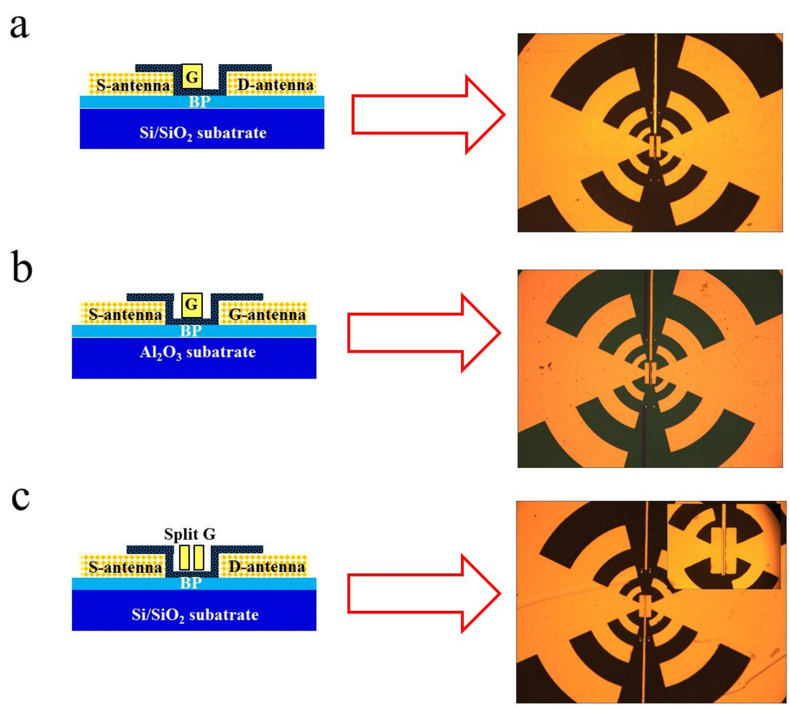

Figure. S4. Optical microscopy image of the BP flakes detector using different structure and Substrate. (a) Sample A, gate closed to source (asymmetrical structure), (b) Sample

B, Al_2O_3 substrate (symmetrical structure), and (c) Sample C, split gate (symmetrical structure).

Section 1. The responsivity to the incident and absorbed power

In order to quantitatively analyze the responsivity of the device in the main text, we consider the results with respect to the incident and absorbed power. We measured the power intensity distribution of the laser beam for a short distance. Since our device's active area (antenna gap) is much smaller than the light spot size, we can approximate the device as a small area. Due to the amplification of the near-field by the antenna element, the incident power onto the sensitive element is larger than that without antenna by an antenna gain g~$|E_c|^2/|E_0|^2$ ~ 200 (E_c is the electric field in the channel and E_0 is the electric field of the incident wave) at 0.036 THz. Taking into account that our maximum photovoltage signal is ~1.2 mV with zero voltage, the peak responsivity is then expressed as:

$$P_{\text{active}}^{\text{in}} = P_{\text{out}} \times \frac{S_{\text{active}}}{S_{\text{b}}} \times g \qquad (1)$$

$$R^{\text{in}} = \frac{\sqrt{2}\pi}{2} \times \frac{U_{\text{photo}}}{P_{\text{active}}^{\text{in}}} \qquad (2)$$

Where $V_{\text{photo}}^{\text{max}}$ is the output signal of the detector, $S_{\text{active}} = 5 \times 60\ \mu\text{m}^2$ is the receiving area of the detector, S_{b} is the beam spot area of the light source, $P_{\text{active}}^{\text{in}}$ is the power reached to the detector， P_{out}~30 mW is the output power, g is the antenna gain, $R_{\text{max}}^{\text{in}}$ is the responsivity of the detector, 2 is due to peak-to-peak amplitude, $\sqrt{2}$ originates from the lock-in amplifier rms amplitude, and π/4 is the fundamental sine wave Fourier component of the square wave produced by the chopper.

In addition, the BP flakes absorbs only a small fraction of the incident power. At terahertz and millimeter wave regimes with photon energy $\hbar\omega \ll \hbar\omega_{op}$ (phonon energy), the absorption is mainly due to the Drude response of free electron. The absorption rate $\eta = P_{\text{active}}^{\text{abs}}/P_{\text{active}}^{\text{in}}$ of BP flakes is calculated by the finite difference time domain (FDTD) method . Only $\eta \sim 10\ \%$ of terahertz photons can be absorbed for BP flakes. We consider the absorption rate of BP flakes to write the responsivity as:

$$R^{\mathrm{abs}} = \frac{\sqrt{2}\pi}{2} \times \frac{U_{\mathrm{photo}}}{P_{\mathrm{active}}^{\mathrm{in}} \times \eta} \tag{3}$$