

# High-Responsivity Mid-Infrared Black Phosphorus Slow Light Waveguide Photodetector

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Black phosphorus (BP) offers unique opportunities for mid-infrared (MIR) waveguide photodetectors due to its narrow direct bandgap and layered lattice structure. Further miniaturization of the photodetector will improve operation speed, signal-to-noise ratio, and internal quantum efficiency. However, it is challenging to maintain high responsivities in miniaturized BP waveguide photodetectors because of reduced light-matter interaction lengths. To address this issue, a method utilizing the slow light effect in photonic crystal waveguides (PhCWGs) is proposed and experimentally demonstrated. A shared-BP photonic system is proposed and utilized to fairly and precisely characterize the slow light enhancement. Close to the band edge around 3.8 µm, the responsivity is enhanced by more than tenfold in the BP photodetector on a 10 µm long PhCWG as compared with the counterpart on a subwavelength grating waveguide. At a 0.5 V bias, the BP PhCWG photodetector achieves a 11.31 A W<sup>-1</sup> responsivity and a 0.012 nW Hz<sup>-1/2</sup> noise equivalent power. The trap-induced photoconductive gain is validated as both the dominant photoresponse mechanism and the major limiting factor of the response speed. The BP slow light waveguide photodetector is envisioned to realize miniaturized high-performance on-chip MIR systems for widespread applications including environmental monitoring, industrial process control, and medical diagnostics.

# **1. Introduction**

Mid-infrared (MIR) beyond 3  $\mu$ m is an electromagnetic spectral range that extensively overlaps with several atmospheric

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transparency windows and the characteristic absorption bands of abundant biochemical molecules.<sup>[1,2]</sup> Thus, the MIR possesses enormous potential for various applications, ranging from thermal imaging for homeland security and missile guidance to label-free absorption spectroscopy for environmental monitoring, industrial process control, and medical diagnostics.<sup>[3–7]</sup> The monolithic integration of waveguides and photodetectors enables miniaturization of photonic systems and is an essential step towards the realization of on-chip sensing systems.<sup>[8,9]</sup> Moreover, the waveguide photodetector provides another advantage of decoupling the optical absorption length from the absorption material thickness, thereby offering more flexibility in the device geometry design for performance optimization.<sup>[10]</sup> However, the development of MIR waveguide photodetectors is still in infancy, which is primarily hindered by the huge lattice mismatch between silicon (Si) and typical narrowbandgap semiconductors for MIR photode-

tection, such as II–VI,<sup>[11]</sup> III–V,<sup>[12,13]</sup> and IV–VI<sup>[14]</sup> alloys.

2D materials, whose layered lattice structures ease their monolithic integration with Si, are regarded as promising alternatives to overcome this bottleneck. Compared with graphene that suffers from large dark current due to its zero bandgap,<sup>[15-18]</sup> the lately rediscovered black phosphorus (BP) has been attracting intense research interest for realizing high-performance MIR photodetection because of its narrow direct bandgap of around 0.3 eV in bulk form corresponding to a cut-off wavelength of  $4.13\,\mu m.^{[19,20]}$  Beyond  $4.13\,\mu m,$  through alloying with arsenic  $^{[21,22]}$ or exploring the Stark effect by applying a vertical electric field,<sup>[23]</sup> BP photoresponses have been extend to around 8 µm. Various MIR BP photodetectors with free-space geometry have been reported.<sup>[24-28]</sup> In addition, several BP waveguide photodetectors have been demonstrated in the near-infrared and the short-wavelength infrared.<sup>[29,30]</sup> Recently, MIR grating-couplerintegrated BP photodetectors were reported with a high responsivity of 1.333 A W<sup>-1</sup> at 3.78 µm in a 40 nm zigzag device under 1 V bias and 1.193 µW incident power.[31] Nevertheless, the high responsivity was obtained at the expense of a long device length (i.e., channel width) of 80 µm. Further miniaturization of the photodetector is expected to improve the operation speed, the signal-to-noise ratio (SNR), and the internal quantum



 ${\rm efficiency}.^{[32]}$  Inevitably, undesired weaker photoresponse is accompanied by the reduced light–matter interaction length.

To maintain a high responsivity in the BP waveguide photodetector with a reduced footprint, one strategy is to leverage plasmonic structures.<sup>[33–35]</sup> Plasmonic structures can concentrate the optical field in their vicinity to enhance the light-matter interaction. However, the high ohmic loss from the plasmonic structures severely attenuates the light absorbed by the photodetection material. Slow light, which can be realized by artificially designed periodic dielectric structures such as photonic crystal waveguides (PhCWGs),<sup>[36–38]</sup> is a promising technology to enhance the lightmatter interaction without introducing ohmic loss. Slow light with remarkably low group velocity spatially compresses optical energy, resulting in enhanced light-matter interaction.<sup>[39,40]</sup> To study the slow light effect induced responsivity enhancement, a comparison should be made between identical BP photodetectors on a slow light waveguide and on a normal waveguide. Such a comparison is challenging as the BP photoresponse is dependent on BP properties including thickness, crystal orientation, doping level, and defects. But every mechanically exfoliated BP flake has different material properties.

In this work, we demonstrate a slow-light-enhanced BP MIR photodetector on a PhCWG of only 10 µm length. By using a shared-BP photonic system, the slow light enhancement is precisely characterized. The system features the PhCWG and a subwavelength grating waveguide (SWGWG) of equal length but without the slow light effect. The spatially close PhCWG and SWGWG share the same BP flake to construct two identical BP photodetectors. The slow light enhancement is validated by comparing the responsivities of these two photodetectors at different wavelengths in the slow light region of the PhCWG. Power-dependent photoresponses and current noises are measured, showing characteristics independent of the slow light effect when the photodetectors work in the trap saturation region. At 3.825 µm with a group index of 103.3, more than tenfold responsivity enhancement is achieved in the BP PhCWG photodetector as compared with the SWGWG counterpart. Correspondingly, the noise equivalent power (NEP) is suppressed to lower than one-tenth. In comparison with the previous works,<sup>[31]</sup> a comparable responsivity is achieved with half of the bias and one-eighth of the device footprint. It is also verified that the trap-induced photoconductive gain not only dominates the photoresponse, but also primarily determines the response speed. Our proposed technology featuring the integration of BP photodetectors and slow light waveguides could be potentially adopted in the realization of miniature high-performance onchip integrated MIR sensing systems.

### 2. Device Configuration and Mechanism

### 2.1. Device Configuration

**Figure 1**a schematically illustrates the proposed shared-BP photonic system. In order to realize a fair and precise comparison for the slow-light enhancement characterization, the proposed photonic system features the simultaneous fabrication of a PhCWG and a spatially close SWGWG with equal length. Thanks to the compactness of photonic waveguides,

such a system is feasible. Consequently, despite the small footprint of the BP flake, the PhCWG and the SWGWG can still share the common BP flake for fair comparison. In both the PhCWG device and the SWGWG device, the light is routed to the photonic system using the fiber-to-chip coupling method via input grating couplers. Next, the light is delivered to the photodetection region through single transverse electric (TE) mode ridge waveguides and absorbed by the BP photodetectors on the waveguide surface. Output grating couplers are employed to couple the residual light out in order to assist the optical characterizations. Specifically at the BP photodetectors shown in Figure 1b, more light is absorbed and consequently more electron-hole pairs are generated in the BP PhCWG photodetector due to the inherent slow light effect, as compared with the SWGWG counterpart. Three titanium/gold (Ti/Au) electrodes are laid directly on the BP flake along the lateral sides of the waveguides and close to the active light-BP interaction region for efficient photocarrier collection. The middle electrode is shared by the two photodetectors as the ground electrode and is equidistant from the other two electrodes to ensure that the two BP photodetectors have equal BP channel lengths. Figure 1c,d shows the microscopic image of the fabricated devices and the zoom-in view of the two photodetectors, respectively. The BP flake was exfoliated from a bulk crystal and transferred onto the waveguides through a polydimethylsiloxane (PDMS) stamp (see Section 6. The SWG cladding is employed to partially fill the air trenches at both sides of the ridge waveguide core in order to assist the transfer of the BP flake by providing a larger surface area for van der Waals force bonding. One edge of the BP flake is aligned with the input ports of the PhCWG and the SWGWG, while the middle electrode terminates at their output ports. As a result, only the photocarriers generated in the part of the BP flake on the PhCWG and the SWGWG are efficiently collected by the electrodes. Thus, the photoresponse contributed by the residual part of the BP flake on ridge waveguides can be neglected. Hereinafter, we name the PhCWG together with its allocated input and output ridge waveguides as the PhCWG system, the same for the SWGWG system. Figure 1e presents the scanning electron microscope (SEM) image of the PhCWG and the SWGWG before the BP transfer process. The waveguide structures are built on a silicon-on-insulator (SOI) platform with a 500 nm thick device layer. The ridge waveguides have a width of 1.2  $\mu$ m. The width of the lateral trenches is designed as 4  $\mu$ m to provide enough optical isolation. The PhC consists of a triangular lattice of air holes with a lattice constant of 1.04 µm and a radius of 320 nm. In the light propagation direction, the PhCWG is composed of 10 periods of PhC and a line defect formed by removing a complete row of air holes. The SWG period is 600 nm, smaller than the Bragg period of around 700 nm.<sup>[41]</sup> The silicon width in the SWG is 180 nm, corresponding to a duty cycle of 0.3. The atomic force microscopy (AFM) height profile shows a uniform BP flake with a thickness of 40 nm (Figure 1f). At such a thickness, the BP flake possesses a small bandgap close to the bulk BP direct bandgap of 0.3 eV, ensuring the occurrence of photon absorption in 3.71-3.84 µm. Figure 1g shows the Raman spectrum of the BP flake on the PDMS stamp before transferred onto the waveguides, where both the incident laser polarization and the detection polarization are parallel to the white dashed line in Figure 1d. The three phonon peaks  $A_{g}^{1}$ ,





**Figure 1.** Configuration of the proposed shared-BP photonic system that consists of a PhCWG with the slow light effect for responsivity enhancement and an SWGWG of equal length but without the slow light effect for comparison. a) Schematic illustration of the shared-BP photonic system. b) Zoom-in view of the black square box in (a) showing the two BP photodetectors on the PhCWG and the SWGWG, respectively. c) Microscopic image of the fabricated devices. d) Zoom-in view of the two BP photodetectors indicated by the black square box in (c). e) SEM image of the PhCWG and the SWGWG before the BP transfer process. f) AFM height profile of the 40 nm thick BP flake along the white dashed line in (d). g) Raman spectrum of the BP flake on the PDMS stamp before transferred onto the waveguide, where both the incident laser polarization and the detection polarization are parallel to the white dashed line in (d).

 $B_{2g}$ , and  $A_g^2$  represent BP lattice vibrational modes along out-ofplane, zigzag, and armchair direction, respectively. The intensity of the  $A_g^2$  peak is significantly higher than that of the  $A_g^1$  peak while the  $B_{2g}$  peak vanishes, indicating that the white dashed line, that is, the light propagation direction is aligned with the armchair orientation of the BP flake.<sup>[42]</sup> Therefore, the polarization of the propagation mode and the carrier transport direction are along the zigzag orientation (more details can be found in Note S1, Supporting Information).

#### 2.2. Slow Light Enhancement Mechanism

The absorption induced by the BP flake on the SWGWG system was characterized by measuring the transmission spectra of the SWGWG system before and after the BP transfer. However, the BP absorption on the PhCWG system could not be determined in the same way, as the band edge of the PhCWG shifts due to the change of the modal effective index caused by the BP flake (Figure S2, Supporting Information). Therefore, the following steps were performed to compare the BP absorptions in the two photodetectors by finite-difference time-domain (FDTD) simulation. First, we tested the simulation accuracy. The

extinction coefficient ( $\kappa$ ) of BP was extracted from the measured BP absorption on the SWGWG system. The  $\kappa$  values were then applied to the corresponding FDTD simulation. By maintaining the refractive index (n) of BP (extracted from ref. [28]) unchanged in simulation, the BP absorption was obtained by comparing the transmission spectrum simulated with these  $\kappa$ values active and the transmission spectrum simulated with zero  $\kappa$  values. The good agreement between the measurement and the simulation results of the SWGWG system as shown in Figure 2a confirms the accuracy of the simulation method. The BP absorption weakens as the wavelength approaches its cut-off wavelength at 4.13 µm. The BP absorption coefficient is calculated to be 0.041 dB  $\mu m^{-1}$  at 3.825  $\mu m,$  which is in good agreement with reported values,<sup>[29,30]</sup> indicating efficient interaction between the BP flake and the light propagating in the waveguides (Note S3, Supporting Information). Next, the comparison of BP absorptions on PhCWG and SWGWG was implemented by using the same FDTD simulation method. BP absorptions in the photodetectors could be precisely simulated in this way as the influence of BP on ridge waveguides was omitted. On the SWGWG, due to the shorter light-BP interaction length, the corresponding BP absorption spectrum shows significantly weaker wavelength dependence than that







**Figure 2.** BP absorption spectrum and electric field distribution. a) Green dots: measured BP absorption spectrum of the SWGWG system composed of the SWGWG and its allocated input and output ridge waveguides. Red line: simulated BP absorption spectrum of the SWGWG system. Blue line: simulated BP absorption spectrum of the SWGWG. Yellow line: simulated BP absorption spectrum of the PhCWG. Insets: simulated electric field distributions in the SWGWG and the PhCWG at three wavelengths. b) Longitudinal (top) and transverse (bottom) components of the electric field in the PhCWG at 3.825  $\mu$ m.

of the SWGWG system. On the PhCWG, the BP absorption increases with the strengthening slow light effect as the wavelength approaches the band edge of the PhCWG and becomes remarkably larger than that on the SWGWG. The insets of Figure 2a show the simulated electric field distributions in the SWGWG and the PhCWG at three wavelengths with different distances from the band edge of the PhCWG. Close to the band edge, the electric field in the PhCWG is spatially compressed and its intensity is thereby increased, while the electric field distribution in the SWGWG almost remains the same. As a result, the slow light effect enhances the light-matter interaction, resulting in stronger BP absorption. In addition, as illustrated in Figure 2b, both the longitudinal and the transverse components of the electric field are nontrivial. Therefore, both the armchair and zigzag directions of the BP flake contribute to the photoresponse.

### 3. Results

#### 3.1. Slow Light Characterization

To evaluate the slow light performance, PhCWG is normally embedded into one arm of a Mach–Zehnder interferometer (MZI), which converts the slow-light-induced phase shift into interference patterns in the frequency domain. As the PhCWG employed for the BP photodetector contains only 10 periods of PhC, the induced phase shift is too small to generate distinguishable interference patterns in the MZI transmission spectrum. To bypass this constraint, the slow light properties of the PhCWG before the BP transfer process were characterized by a simultaneously fabricated MZI, where the PhCWG embedded into it (hereafter referred to as MZI-PhCWG to avoid confusion) contains 50 periods of PhC with the same design as that of the PhCWG. As a result, the PhCWG and the MZI-PhCWG present the same group index spectra. **Figure 3**a shows the measured and simulated transmission spectra of the MZI. Close to the band edge, the group velocity in the MZI-PhCWG becomes slower, which increases the phase difference between the two arms of the MZI and leads to the denser interference pattern. Consequently, the free spectral range of the oscillation in the MZI transmission spectrum decreases. The group index of the MZI-PhCWG ( $n_g$ ) can be extracted using the following equation:<sup>[43]</sup>

$$n_{\rm g}(\lambda) = n_{\rm g}^{\rm ref}(\lambda) + \frac{\lambda_{\rm max}\lambda_{\rm min}}{2L_{\rm s}|\lambda_{\rm max} - \lambda_{\rm min}|}$$
(1)

where  $n_g^{\text{ref}}$  is the group index of the ridge waveguide in the reference arm and is nearly constant at 4.23 over the studied spectral range (Note S4, Supporting Information),  $L_s$  is the length of the MZI-PhCWG,  $\lambda_{\text{max}}$  and  $\lambda_{\text{min}}$  are the wavelengths of adjacent maxima and minima of the oscillation, corresponding to constructive and deconstructive interference, respectively. The group indices of the MZI-PhCWG extracted from the measured and the simulated MZI transmission spectra are plotted in Figure 3b, showing good agreement with each other.

Next, we evaluated the slow light properties of the PhCWG after BP transfer. As it is not feasible to transfer another BP flake with identical optical properties onto the MZI-PhCWG, simulation was performed for evaluation. The simulation set up the MZI-PhCWG covered by a BP flake with the same thickness and orientation as the BP flake used for the PhCWG experimentally. The complex refractive index of BP obtained from the BP characterization on the SWGWG system was adopted. As shown in Figure 3c, the simulated MZI transmission spectrum is consistent with the measured





**Figure 3.** Slow light characterization utilizing an MZI embedded with a 50-period PhCWG with the same design as that of the 10-period PhCWG used for BP integration. a) Measured and simulated MZI transmission spectra. b) Spectral group indices extracted from the MZI transmission spectra in (a). c) Measured transmission spectrum of the PhCWG system after the BP transfer process, and simulated transmission spectrum of the MZI with an identical BP flake covered on top (inset: zoom-in near the band edge). d) Spectral group index extracted from the MZI transmission spectrum in (c). Solid line: fitting curve of the group index.

transmission spectrum of the PhCWG system in terms of the band edge position. Using Equation (1), the group index of the PhCWG after the BP transfer process is extracted from the MZI transmission spectrum in Figure 3c and plotted in Figure 3d. Compared with Figure 3b, it is observed that the group index almost keeps its value unchanged and shifts its corresponding wavelength with the band edge due to the presence of BP on the waveguide surface. The result reveals that the slow light in the PhCWG is dominated by the structural dispersion, that is, the contribution from the BP material dispersion is negligible. As for the SWGWG, its group index after the BP transfer process was calculated in the same way as  $n_{\rm g}^{\rm ref}$  and is nearly constantly to be 3.94, which is close to  $n_{\rm g}^{\rm ref}$ , confirming the absence of slow light or resonance effects in the SWGWG (Note S4, Supporting Information).

#### 3.2. Spectral Photoresponse

The slow light enhancement on the photoresponse was evaluated by measuring the responsivities of the two BP photodetectors on the PhCWG and the SWGWG, respectively. The same BP flake shared by the two BP photodetectors minimizes the comparison inaccuracy. As revealed in the previous work,<sup>[31]</sup> the BP photoresponse is dependent on the excitation power on BP. Therefore, we fixed the excitation power on BP (*P*), that is, the incident power to the BP waveguide photodetectors, to be 126.9 µW. The power calibration method is presented in Note S5, Supporting Information. Figure S6, Supporting Information, shows the measured relationships between photocurrent  $(I_{\rm ph} = I_{\rm light} - I_{\rm dark})$  and voltage bias  $(V_{\rm bias})$  of the two photodetectors under varying incident power. The photocurrent is nearly proportional to the voltage bias and increases with the increasing incident power. At a fixed  $V_{\text{bias}}$  of 0.5 V, temporal responses of the two photodetectors under switched illumination were measured. Figure 4a,b shows the measured photocurrents in the two photodetectors at 3.725, 3.775, and 3.825  $\mu$ m. With illumination, the photocurrent increases sharply and saturates. The highly repeatable photocurrent generation reveals stable and reversible photoresponses in both devices. Photocurrents at different wavelengths were measured and corresponding responsivities (responsivity =  $\frac{I_{\rm ph}}{2}$ ) were extracted.

As shown in Figure 4c, in the BP PhCWG photodetector, the responsivity increases as the wavelength approaches the band edge of the PhCWG and reaches a maximum of 0.098 A W<sup>-1</sup> at 3.825  $\mu$ m. Differently, the responsivity of the BP SWGWG photodetector does not show significant wavelength dependence, due to the nearly constant group index and the weak wavelength dependence of the BP absorption on the short SWGWG. The responsivity enhancement ratio of the BP PhCWG photodetector to the BP SWGWG photodetector is plotted together with the group index enhancement ratio of the PhCWG to







**Figure 4.** Spectral photoresponse. Temporal response of a) BP PhCWG photodetector, b) BP SWGWG photodetector, at three wavelengths. c) Spectral responsivities of the two BP photodetectors on the PhCWG and the SWGWG, respectively. d) Responsivity enhancement ratio of the BP PhCWG photodetector, and group index enhancement ratio of the PhCWG to the SWGWG.

the SWGWG in Figure 4d. The two enhancement ratios show consistent spectral trend, verifying that the responsivity is enhanced by the slow light effect. At 3.825  $\mu$ m, the group index is increased by about 26 times, resulting in more than fivefold enhancement of responsivity under 126.9  $\mu$ W incident power.

#### 3.3. Power-Dependent Photoresponse

To analyze the power dependence of photoresponses, the photocurrents of the two photodetectors under different incident powers were measured. Figure 5a,b shows the measured relation curves between photocurrent and incident power in the two photodetectors, whose slopes gradually flatten as the power increases. This phenomenon can be explained by the trapinduced photoconductive gain. Due to the higher mobility of holes than electrons in BP, the photocurrent is dominated by the collection efficiency of photogenerated holes, which strongly depends on the trap-induced photoconductive gain.<sup>[24]</sup> Defects such as dislocations and grain boundaries in BP results in the formation of trap states in the bandgap of BP. Trap states with energies above the Fermi level of BP are empty and are able to capture electrons. Under illumination, electron-hole pairs are generated and electrons are subsequently captured by the electron traps. The electron trapping suppresses electron-hole recombination, prolongs the lifetime of the photogenerated holes, and leads to photoconductive gain. Under higher incident power, more electron traps are occupied by the photogenerated electrons, thus the availability of vacant electron

traps is reduced. Once the electron traps are filled, the number of free electrons increases and the probability of electron–hole recombination increases, leading to a decrease in the responsivity, as illustrated in both Figure 5c,d. The trap-saturationinduced power-dependent photoresponse can be described by the Hornbeck–Haynes model which contains the following set of equations:<sup>[44]</sup>

responsivity = 
$$\frac{C}{1 + \left(\frac{P}{P_0}\right)^k}$$
 (2.1)

$$P_0 = \frac{hvF_0}{\eta} \tag{2.2}$$

$$\eta = 1 - e^{-\alpha L} \tag{2.3}$$

$$C = q \frac{\tau_0}{\tau_{\rm tr}} \frac{\eta^2}{h\nu}$$
(2.4)

$$\tau_{\rm tr} = \frac{L_{\rm c}^2}{\mu_{\rm h} V_{\rm bias}} \tag{2.5}$$

where  $P_0$  is the incident power when trap saturation occurs, *C* is the responsivity under low incident power, *k* is a phenomenological fitting parameter describing how fast the responsivity decays with increasing incident power after trap saturation, *h* is Planck's constant, *v* is the frequency of the excitation light,  $F_0$  is the photon absorption rate when trap saturation occurs,

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**Figure 5.** Power-dependent photoresponse. Relationship between photocurrent and incident power in a) BP PhCWG photodetector, b) BP SWGWG photodetector, at three wavelengths. Power-dependent responsivity of c) BP PhCWG photodetector, d) BP SWGWG photodetector, at three wavelengths. Solid lines: fitting curves by the Hornbeck–Haynes model. Inset of (d): relationship between the responsivity enhancement ratio and incident power at 3.825  $\mu$ m.

 $\eta$  is the absorption percentage of BP,  $\alpha$  is the absorption coefficient of BP, *L* is the light-BP interaction length, *q* is elementary charge,  $\tau_0$  and  $\tau_{\rm tr}$  are the carrier life time and transit time,  $\frac{\tau_0}{\tau_{\rm tr}}$  is the photoconductive gain, *L*<sub>c</sub> is the channel length,  $\mu_{\rm h}$ 

is the hole mobility. The solid lines in Figure 5c,d shows the Hornbeck-Haynes model fitting curves. The responsivities of both devices present strong power dependence at all three wavelengths. Under the measurable range limited by our testing setup, the responsivity keeps increasing as the incident power decreases and does not show perceptible sign of saturation even with incident power lower than  $0.1 \mu$ W, implying low  $P_0$  in both photodetectors. The nearly parallel fitting curves intimate that k, the phenomenological fitting parameter in Equation (2.1), is dominated by the inherent properties of BP. In the BP PhCWG photodetector, a responsivity of 1.445 A  $W^{-1}$  was achieved at 3.825 µm under 1.118 µW incident power. Compared with the 40 nm zigzag device with nearly the same channel length in the previous work under similar conditions of wavelength and power,<sup>[31]</sup> a comparable responsivity was achieved with half of the applied voltage bias and one-eighth of the device length. Under a lower incident power of  $0.035 \mu$ W, a higher responsivity of 11.31 A W<sup>-1</sup> was obtained. The accurately measurable incident power and photocurrent are limited by the SNRs of the power meter and the Keithley source measurement unit, respectively. In addition, as revealed by the measured BP extinction spectra (Figure S3, Supporting Information), the BP

absorption decreases with the increasing wavelength and drops dramatically beyond the roll-off wavelength of  $\approx 3.6 \ \mu m$  along the armchair direction. If the incident power can be further lowered through the the improvement of the measurement methods and/or instruments, and if the working wavelength is designed at wavelengths shorter than the roll-off wavelength, an even higher responsivity is expected.<sup>[24,45]</sup> Not only is the absolute value of the responsivity higher, the responsivity enhancement ratio enabled by the slow light effect also increases when the incident power decreases and can exceed ten, as shown in the inset of Figure 5d. Theoretically, the slow light effect helps increase the absorption coefficient  $\alpha$  by providing stronger light-matter interaction. According to Equation (2.3), the slow light effect subsequently enhances  $\eta$  and correspondingly tends to lower down  $P_0$ , suggesting the easier saturation of electron traps by providing lower optical energy. As a result, the responsivity enhancement ratio could be even higher before trap saturation. Unfortunately, this tendency was not able to be verified, because of the above-mentioned SNR limitations.

#### 3.4. Current Noise and Noise Equivalent Power

In addition to the responsivity, another essential evaluation criterion of photodetectors is the NEP. The NEP is defined as the excitation power needed to generate a signal equal to the noise level in 1 Hz bandwidth, thus is a measure of the detection







Figure 6. Current noise and noise equivalent power. a) Spectral current noise power densities of the two BP photodetectors on the PhCWG and the SWGWG, respectively. b) Spectral NEP calculated from the measured responsivities and noise power densities.

limit of photodetector. The NEP is estimated according to NEP =  $\frac{\sqrt{\text{noise power density}}}{\sqrt{\text{noise of a photodetector}}}$ . The noise of a photodetector

to  $NEP = \frac{\sqrt{10000 \text{ Priver Heisery}}}{\text{responsivity}}$ . The noise of a photodetector

mainly consists of three parts: 1/f noise, shot noise, and Johnson noise. Figure 6a shows the measured current noise power density spectra of the two photodetectors. The two spectra virtually overlap with each other and are parallel to the 1/f reference line, implying the noise is dominated by the 1/f noise, which mainly originates from the defects in the BP channel acting as traps.<sup>[46]</sup> The measured noise is orders of magnitude higher than the sum of shot noise and Johnson noise calculated from the dark current (Note S7, Supporting Information). As the noise power densities are approximately equal, the slow light effect enhanced responsivity equivalently lowers down the NEP. The NEP as a function of wavelength at a signal modulation frequency of 800 Hz is extracted from Figures 5c,d,6a, and plotted in Figure 6b. The NEP of the BP PhCWG photodetector decreases as the wavelength approaches the band edge of the PhCWG, while the NEP of the BP SWGWG photodetector does not show significant wavelength dependence due to its nearly constant responsivity. At 3.825 µm, the NEP of the BP PhCWG photodetector can be suppressed to lower than one-tenth of that of the BP SWGWG photodetector, and reaches 0.012 nW  $Hz^{-1/2}$ .

### 4. Discussion

To further investigate the BP material properties, two more BP field-effect transistors with free-space geometry were fabricated on a heavily doped silicon substrate covered with 90 nm silicon dioxide (SiO<sub>2</sub>), as shown in Figure S8a,e, Supporting Information. Same as the above-studied waveguide photodetectors, Ti/Au electrodes are employed for electrical contacts. The thickness of the BP flake in device A is 16.5 nm and in device B is 45 nm (Figure S8b,f, Supporting Information). The same polarization-resolved Raman spectroscopy was used to determine the crystal orientation of the BP flake in device A and B (Figure S8c,g, Supporting Information). Consistent with the waveguide photodetectors, the carrier transport direction is aligned with the zigzag orientation of the BP flake in both devices. The measured transfer curve using a back gate

(Figure S8d, Supporting Information) shows good gate control of the device A performance with an on-off ratio of  $\approx 10^2$ . Applying a 23 V gate bias, the dark current can be suppressed from 1.06 to 0.37 µA. A better gate control could be achieved in the waveguide photodetectors by depositing a thinner top gate dielectric layer. The field-effect mobility is estimated according to  $\mu_{\rm eff} = (\Delta I_{\rm d}/\Delta V_{\rm g}) (L_{\rm c}/W_{\rm c}V_{\rm d}C_{\rm ox})$ , where  $I_{\rm d}$  is the source-drain current,  $V_{\rm g}$  is the back gate bias,  $\Delta I_{\rm d}/\Delta V_{\rm g}$  is extracted from the slope of the linear region in the transfer curve,  $L_c$  is the channel length,  $W_c$  is the channel width,  $V_d$  is the source-drain bias, and  $C_{ox}$  is the gate capacitance. The field-effect mobility is calculated to be 78.91 cm<sup>2</sup> V<sup>-1</sup> s<sup>-1</sup>, which is about 25% lower than that in our previous work due to the lower carrier mobility along the zigzag direction than that along the armchair direction.<sup>[20]</sup> Yet, the 78.91 cm<sup>2</sup> V<sup>-1</sup> s<sup>-1</sup> mobility is at the same level as those in other reported zigzag devices with similar flake thickness.<sup>[24,29,47]</sup> Four electrodes with different spacings are paved on device B, as shown in Figure S8e, Supporting Information. Using the transmission line method (TLM) (Figure S8h, Supporting Information), the contact resistance of Ti/Au electrodes on BP is measured to be 9.05 k $\Omega$ · $\mu$ m, which is close to the reported values.<sup>[48]</sup> From the TLM result, the resistances of both BP waveguide photodetectors are estimated to be 14.03 k $\Omega$ , which is close to the measured value of 18.5 k $\Omega$  (Figure S7a, Supporting Information). This consistency reveals an acceptable level of material property variations and good repeatability of fabrication process.

In order to figure out the dominant mechanism of the photocurrent generation in our devices, we assessed the photoresponse of the transistor formed between electrodes 3 and 4 in device B at 3.825  $\mu$ m wavelength. As the absorption loss caused by the SiO<sub>2</sub> cladding starts to increase from 3.6  $\mu$ m onward,<sup>[6]</sup> the bolometric effect could contribute to the photoresponse in our devices, where the SiO<sub>2</sub> cladding absorbs the light and increases the temperature, leading to a BP conductance change. To explore possible bolometric contributions to the detection mechanism, we measured the temporal photoresponse of device B at different temperatures, as shown in **Figure 7**a. The relationship between photocurrent and temperature are extracted from Figure 7a and plotted in Figure 7b. As illustrated in Figure 7b, the photocurrent decreases with the increasing temperature, which implies the decrease of BP conductivity.





**Figure 7.** Investigation of the dominant photoresponse mechanism and the major limiting factor of the response speed. a) Temporal response at varying temperature. b) Relationship between photocurrent and temperature. c) Measured frequency response under various incident powers. Inset: variation of 3-dB bandwidth with varying incident power. d) Calculated frequency response using the equivalent circuit model shown in the inset.

However, as shown in Figure 5a,b, the photocurrent rises upon illumination. This contradiction provides direct evidence to rule out the bolometric effect as the dominant photoresponse mechanism in our devices.<sup>[25,29,49]</sup> Nevertheless, the potential negative effects caused by the bolometric effect can be suppressed by employing other material platforms without SiO<sub>2</sub> cladding, such as silicon-on-sapphire,<sup>[50]</sup> silicon-on-nitride,<sup>[51]</sup> and silicon-on-calcium-fluoride.<sup>[5]</sup>

As the bolometric effect has been ruled out, the strong power dependence of the photoresponse implies that the other possible dominant photoresponse mechanism is the photogating effect, which is generally referred to as the above-mentioned trap-induced photoconductive gain. To verify this, we examined the frequency response of device B by modulating the laser beam with an optical chopper and collecting the photocurrent using a lock-in amplifier. As shown in Figure 7c, the 3-dB bandwidth decreases rapidly from 1.64 to 0.78 kHz as the incident power drops from 107.52 to 53.76  $\mu$ W, as a result of the reduced free carrier concentration in the channel. By further decreasing the incident power, the photogenerated free carrier concentration in the channel becomes significantly lower than the trap state concentration. Consequently, the 3-dB bandwidth is solely determined by the effective charge trapping time and tends to saturate at ≈0.55 kHz. The corresponding rise/decay time can be estimated as  $1/2\pi\!f_{3dB}$  and is shorter than 0.3 ms.  $^{[20,52]}$  Such a trend agrees well with the prediction given by the above-mentioned Hornbeck-Haynes model and validates that the photoresponses of our devices are dominated by the photogating effect. The photogenerated electrons are trapped in the localized states and act as a local gate, while the free photogenerated holes circulate multiple times until annihilated by recombination, leading to a large photoconductive gain.<sup>[24,53]</sup>

In addition to the photoresponse mechanisms, the RCconstant is another important factor that may limit the response speed. In order to understand the RC-constant limit, we established an equivalent circuit model for device B, as shown in the inset of Figure 7d, in which  $R_{\rm BP}$  is the BP resistance,  $C_{\rm BP}$  is the BP capacitance,  $R_{\rm C}$  is the BP-metal contact resistance,  $C_{\rm P}$  is the contact pad capacitance,  $R_{\rm S}$  is the serial resistance from the contact pads, and  $R_{\rm L}$  is the 50  $\Omega$  load resistance.  ${\it R}_{\rm BP}$  and  ${\it R}_{\rm C}$  are extracted from the TLM measurement result.  $C_{\rm BP}$  is estimated from the BP channel dimensions and by taking a similar photodetector for reference.<sup>[30]</sup>  $C_{\rm P}$  and  $R_{\rm S}$  are calculated according to the contact pad dimensions. The values of these parameters are listed as the Set 1 in Table S2, Supporting Information. As presented in Figure 7d, the RC-limited 3-dB bandwidth is 1.0 GHz, which is many orders larger than the measured 3-dB bandwidth. As illustrated in Note S9, Supporting Information,  $C_{\rm BP}$  needs to be as large as tens of nF to lower down the RC-limited 3-dB bandwidth to the same level as the measured one, which is out of reach for BP transistors.<sup>[54]</sup> These results indicate that the major limiting factor of the response speed in the present photodetectors is not the RC-constant, but the abovementioned trap-induced photoconductive gain. Although the prolonged hole lifetime inevitably compromises the detection speed, this may not be a critical problem in MIR sensing applications. Because unlike in telecommunications, high speed is



not mandatory in most sensing scenarios where sensitivity is a major concern. Nevertheless, for applications that require a high responsivity and a fast response speed simultaneously, there are also a few feasible methods that can be employed to enhance the response speed of photogating-dominated BP photodetectors. First is to engineer the defect types and densities during crystal growth and device fabrication, so as to reduce trapped carrier lifetime. Second is to utilize heterostructures by stacking BP with other 2D materials with different bandgaps and work functions, such as transition-metal dichalcogenides<sup>[28,55]</sup> and graphene.<sup>[56]</sup> The built-in electric fields at the heterojunctions not only make the photocarrier separation and collection more efficient, but also effectively suppress the dark current. However, these two approaches improve the response speed at the expense of reduced trapped carrier lifetime, thus inevitably sacrifice the responsivity. This might be compensated by increasing the carrier mobility through exploring nanostructures such as nanoribbons and nanomeshs.<sup>[57]</sup> Third is to apply a gate voltage pulse.<sup>[58,59]</sup> The pulse reduces the potential barrier and discharges trapped carriers, yielding efficient electron-hole recombination. Applying the gate voltage pulse at the falling edge of the laser pulse, the decay time can be decreased while the responsivity is maintained. As a result, a high responsivity and a fast response speed could be simultaneously achieved. Fourth is to employ general photogating such as photovoltage FET<sup>[60]</sup> and interfacial gating,<sup>[61]</sup> where the channel materials do not respond to the detected light itself and the gain is only produced by the photovoltage instead of a prolonged carrier lifetime, permitting simultaneous high responsivity and fast response speed.

### 5. Conclusion

In conclusion, we address the issue of reduced responsivity during photodetector miniaturization through light-matter interaction enhancement by leveraging the slow light effect in PhCWG. The slow light effect spatially compresses the optical field, consequently enhances its interaction with the BP atomic layer, leading to stronger light absorption. A shared-BP photonic system is designed and utilized for the fair and precise characterization of the slow light enhancement. The system features two identical BP photodetectors fabricated based on the same BP flake shared by a PhCWG and a spatially close SWGWG with equal length but without the slow light effect. The slow light enhancement is verified by comparing the responsivities between the two BP photodetectors. It is also revealed by experiment that both the noise and the power dependence in the trap saturation region of the BP photodetector are not aggravated by the slow light effect. At a wavelength of  $3.825 \,\mu\text{m}$  with a group index of 103.3, more than tenfold enhancement of responsivity is achieved, leading to a responsivity of 11.31 A  $W^{-1}$  and a NEP of 0.012 nW  $Hz^{-1/2}$ under a bias of 0.5 V in the BP PhCWG photodetector with a device length of only 10 µm. In comparison with the previous works on BP waveguide photodetector, this work presents a device that maintains high responsivity with low voltage bias and small device footprint even when working beyond the roll-off wavelength and near the cut-off wavelength of BP

(Note S10, Supporting Information). Through the systematic investigations, the dominant photoresponse mechanism is verified to be the trap-induced photoconductive gain, which also primarily determines the response speed. Our proposed device could be potentially employed to construct compact high-performance on-chip integrated MIR sensors.

### 6. Experimental Section

Fabrication: The fabrication of the BP waveguide photodetectors started from an 8" SOI wafer with a 500 nm thick device layer and a 2 µm thick buried oxide insulation layer. The waveguide patterns were defined by e-beam lithography (EBL) (Jeol JBX-6300FS) using ZEP-520A resist, then transferred to the Si device layer by  $SF_6/C_4F_8$  deep reactive-ion etching (Oxford Plasmalab System 100). Oxygen plasma etching (SPI Plasma Prep III) was performed to remove the residual resist, as well as to oxidize the waveguide surface in order to assist the following BP transfer. BP flakes were first mechanically exfoliated from a bulk crystal by a tape and then transferred onto a PDMS stamp on a glass slide. Next, a selected BP flake was transferred onto the waveguides using a homemade transfer station consisting of a microscope, a micromanipulator, and a sample stage. Electrodes were patterned by another EBL step with poly(methyl methacrylate) as resist. Subsequently, 10 nm Ti and 100 nm Au were deposited by e-beam evaporation (AJA), followed by lift-off in acetone to form the metal contacts. For device A and B, the BP flakes were mechanically exfoliated from the same bulk crystal by a tape and then transferred onto a heavily doped Si substrate covered with 90 nm thermal SiO2. The source/ drain electrodes were fabricated using the same process as that for the waveguide photodetectors.

Characterization: The Raman spectrum was measured by WITec Alpha 300R with a 532 nm laser. The height profile of BP flake was measured by AFM (Bruker Fastscan). Keithley 4200-SCS semiconductor characterization system was used to apply voltage bias and measure current. A continuous-wave laser (Daylight Solutions MIRcat-1200) was launched into a ZrF4 MIR fiber (Thorlabs P3-23Z-FC-2) by a ZnSe focusing lens (Innovation Photonics LFO-5-6) and aligned to the devices with a six-axis alignment stage (Kohzu). For the waveguide photodetectors, the output light was coupled to another MIR fiber and directed to a PbSe MIR detector (Thorlabs PDA20H-EC). An optical chopper (Stanford Research Systems SR540) was used to modulate the optical signal. A lock-in amplifier (Stanford Research Systems SR830) was employed to collect the photoresponse signals from the commercial detector or the fabricated detectors. The light intensities at different fiber ports were calibrated with a power meter (Newport 843-R). A low-noise current preamplifier (Stanford Research System SR570), a dynamic signal analyzer (Hewlett-Packard 35670A), and a parameter analyzer (Agilent 4155B) were used to measure the noise power density. The measurement setups are illustrated in Note S11, Supporting Information. All the measurements were performed at ambient and at room temperature.

# **Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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## **Conflict of Interest**

The authors declare no conflict of interest.

### Keywords

black phosphorus, mid-infrared, photodetectors, slow light, waveguides

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