HgCdTe/black phosphorus van der Waals heterojunction for high-performance polarization-sensitive midwave infrared photodetector

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New-generation infrared detectors call for higher operation temperature and polarization sensitivity. For traditional HgCdTe infrared detectors, the additional polarization optics and cryogenic cooling are necessary to achieve high-performance infrared polarization detection, while they can complicate this system and limit the integration. Here, a mixed-dimensional HgCdTe/black phosphorus van der Waals heterojunction photodiode is proposed for polarization-sensitive midwave infrared photodetection. Benefiting from van der Waals integration, type III broken-gap band alignment heterojunctions are achieved. Anisotropy optical properties of black phosphorous bring polarization sensitivity from visible light to midwave infrared without external optics. Our devices show an outstanding performance at room temperature without applied bias, with peak blackbody detectivity as high as $7.93 \times 10^{10}$ cm Hz$^{1/2}$ W$^{-1}$ and average blackbody detectivity over $2.1 \times 10^{10}$ cm Hz$^{1/2}$ W$^{-1}$ in midwave infrared region. This strategy offers a possible practical solution for next-generation infrared detector with high operation temperature, high performance, and multi-information acquisition.

INTRODUCTION

Infrared detectors, which use infrared radiation intensity and spectrum to distinguish objects from complex backgrounds, have vitally important applications in many fields, such as environmental monitoring, thermal imaging, and free-space optical communication (1–4). New-generation infrared detectors are supposed to have features including high resolution, multicolor functionality, high operation temperature (HOT), and polarization sensitivity (5–7).

In 1985, the conception of realizing HOT infrared detector was proposed by Ashley and Elliott (8). Up to now, many heterogeneous structures have been proposed to implement HOT detectors (5, 9–11), such as p+/p−/n+ (9), p+/n−/n+ (9), and nBn (9–11) structures. However, high-performance room temperature operation is still a severe challenge for infrared detectors, especially in midwave infrared region. Besides, traditional infrared polarization detector is normally achieved by adding polarization optics components, which undoubtedly increases structure complexity of the detector. Therefore, it is necessary to find advanced materials and device architectures to achieve previously unknown room-temperature infrared polarization detectors.

Van der Waals heterogeneous integration may be an attractive way to solve this problem. In van der Waals heterojunction, materials are combined through intermolecular interaction, and there is no chemical bonding on the interface and surface; thus, they provide a near-perfect heterogeneous interface and high flexibility of heterostructure construction, such as two-dimensional (2D)/0D heterojunctions, 2D/2D heterojunctions, and 2D/3D heterojunctions (12–19), showing great potential for high-performance photodetectors. 2D materials that relied on van der Waals forces between layers have received extensive attention in development of previously undefined and high-performance infrared detectors (17, 20–25). Among 2D materials, black phosphorous (bP) is extremely noteworthy for its high carrier mobility (26, 27), layer-dependent narrow bandgap (28, 29) (from $\sim 0.3$ eV of bulk to $\sim 1.5$ eV of monolayer), and anisotropic crystal structure (28, 30), which makes bP a promising candidate for high-performance infrared polarization detection. Polarization-resolved midwave infrared (MWIR) photodetectors based on bP has been realized, such as bP vertical p-n junction (28), bP/MoS$_2$ heterojunction, and bP/MoS$_2$/graphene unipolar barrier heterojunction (31–33), showing great potential in infrared accurate identification. However, 2D materials with only atomic-scale thickness have weak absorption, which limits the performance in infrared detection. 2D/3D mixed-dimension integration seems especially attractive for infrared detectors since it gives chances to combine advantages of classic infrared materials and emerging 2D materials.

Here, a HgCdTe/bP van der Waals heterojunction is designed to achieve room temperature polarization-sensitive MWIR detection. Thanks to the broken-gap band alignment of HgCdTe/bP heterojunction, photoinduced direct tunneling (DT) in HgCdTe/bP heterojunction brings low noise and large photocurrent at zero bias, leading to high light-to-dark current ratio over $10^4$. Our photodetector exhibits high sensitivity for MWIR at room temperature and show obvious blackbody response with responsivity of 193 mA/W and detectivity of $7.93 \times 10^{10}$ cm Hz$^{1/2}$ W$^{-1}$. Besides, polarization sensitivity from visible light to 4.0 $\mu$m is confirmed, which is attributed to the anisotropy crystal structure of bP, bringing an additional dimension into photodetection. Therefore, this device shows tremendous potential in MWIR detection under circumstances of room temperature, low power consumption, and multidimensional imaging.
RESULTS
Device structure and interface characterization
To ensure high infrared absorption of our photodetector, we designed the device as a heterojunction consisting of a multilayer bP flake and an 8-μm-thick HgCdTe film, as shown in Fig. 1A. Before transferring bP to the surface of HgCdTe, an area of around 1 mm² of the HgCdTe film is removed to fill the 100- to 150-nm-thick Al₂O₃ for electric isolation. The area of Al₂O₃ is much larger than that of the bP flake and electrodes to ensure reliable isolation so that the signal from HgCdTe/bP heterojunction can be collected sufficiently via electrodes. More details of the device fabrication can be found in Materials and Methods. An optical microscope image of a HgCdTe/bP heterojunction photodetector is shown in Fig. 1B, where multilayer bP is marked with white dashed box, the left half of the image is HgCdTe, and the dark blue area of the image (right half) is Al₂O₃.

The cross-sectional transmission electron microscope (TEM) images in Fig. 1 (C and D) show the interface between bP and HgCdTe. The layered structure of multilayer bP is observed clearly in Fig. 1C, with a corresponding monolayer thickness of 5.5 Å. At the interface, a 2-nm-thick noncrystal layer between bP and HgCdTe was observed, which is attributed to PO₂⁻ from oxidation of bP during device fabrication. Existence of the PO₂⁻ layer introduces unpremeditated defects at the interface, which has a negative impact on photoresponse time and transmission of photogenerated carriers. However, this unintentionally oxide layer also has a positive effect as a natural tunneling barrier in our photodetector, which could be replaced by other suitable materials with well-designed barrier height and width. Moreover, energy-dispersive x-ray spectrometry (EDS) mapping of HgCdTe/bP interface was measured and shown in Fig. 1E, where components of Hg, Cd, Te, P, and O are clearly identified and marked with different colors, demonstrating sharp and clean van der Waals interface between bP and HgCdTe with no interdiffusion. The cross-sectional TEM image of metal/bP/Al₂O₃ interfaces was also shown in Fig. 1F, showing a similar layered structure of bP and clean van der Waals bP/Al₂O₃ interface without impurity. Besides, other interfaces of the device, including metal/HgCdTe and Al₂O₃/HgCdTe, were also measured and analyzed via cross-sectional TEM and EDS mapping (figs. S1 and S2), which all indicate clear and flat interfaces without gap or impurity.

Optical properties and broken-gap band alignment
In semiconductor heterojunction, band alignment is necessary for investigating carrier transport process and correlated optoelectronic characteristics. To determine band alignment of HgCdTe/bP heterojunction in this work, infrared spectroscopy and Kelvin probe force microscope (KPFM) were measured. Noticing that HgCdTe is a pseudo-binary semiconductor, which has tunable bandgap correlated to component and temperature (34), we measured infrared absorption spectra to estimate the cutoff wavelength ($\lambda_c$) and bandgap ($E_g$) of HgCdTe, as shown in Fig. 2A (top). Here, $\lambda_c$ is defined as the wavelength where absorption decreases to 50% of the maximum value. From Fig. 2A, it can be derived that the $\lambda_c$ of HgCdTe is approximately 4.4 μm; thus, the optical $E_g$ of HgCdTe is 0.28 eV, estimated by $E_g = \frac{hc}{\lambda_c}$. The component of Hg₁₋ₓCdₓTe could also be estimated as $x = 0.3$ via Chu’s formula (see details in note S1) (35). Similarly, infrared absorption spectra of HgCdTe/bP heterojunction are shown in Fig. 2A (bottom). The cutoff wavelength $\lambda_c$ of HgCdTe/bP heterojunction is almost the same as that of HgCdTe. However, an unsmoothed segment appeared at $\lambda = 4.2$ μm, which is attributed by absorption edge of bP. Our results also agree well with previously reported theoretical and experimental value (29, 30).

Work function of bP (Φ_bP = 4.92 eV) and of HgCdTe (Φ_HgCdTe = 5.18 eV) are derived from KPFM results (see details in note S2 and
between electrodes and bP (HgCdTe) are given in fig. S4D (fig. S4A, I–III). To exclude influence of electrode contacts, characteristics at reverse bias, and (iii) at large forward bias. Directions of electrons transferring are shown as blue arrows.

Energy band diagram of HgCdTe/bP heterojunction after contact under equilibrium. (i) Energy band diagram of HgCdTe/bP heterojunction (i) at reverse bias, (ii) at small forward bias, and (iii) at large forward bias. Directions of electrons transferring are shown as blue arrows.

In addition, carrier concentration and Hall mobility of the HgCdTe film measured via KPFM, indicate that HgCdTe is an n-type semiconductor (fig. S4B). Besides, the Hall effect measurement results, which are consistent with the Fermi level position of HgCdTe and bP measured via KPFM, indicate that HgCdTe is an n-type semiconductor (fig. S4B). In addition, carrier concentration and Hall mobility of the HgCdTe film are 2.5 × 10^{16} cm^{-3} and 390.2 cm^{2} V^{-1} s^{-1}, respectively. Note that the Fermi level of a thick bP flake is below its VBM, indicating that the bP is a degenerate p-type semiconductor, which correspond with previous investigations (39–41) and transfer characteristics in fig. S4C. Therefore, a vertical p-i-n junction is formed between bP and HgCdTe, where i is the insulated PO_{x} layer. The current-voltage relation (I-V) characteristics of the HgCdTe/bP p-i-n junction are given in Fig. 2C, which show backward-rectifying diode characteristics. It can be observed that the backward current is larger than forward current, which is caused by the band-to-band tunneling (BTBT) effect (42). However, no negative differential resistance was observed in small forward bias, which is attributed to large excess current caused by tunneling via defect states in PO_{x} tunneling barrier. To exclude influence of electrode contacts, I-V characteristics between electrodes and bP (HgCdTe) are given in fig. S4D (fig. S4A, inset), showing a good ohmic contact. After bP and HgCdTe contact, the broken-gap band alignment of HgCdTe/bP heterojunction leads to a built-in potential barrier Δ = 0.26 eV. Hence, electrons in bP will move into HgCdTe and accumulate. Similarly, accumulation layer of holes will appear at the bP side. The bilateral accumulation layer leads to a huge band bending (Fig. 2C, inset), thereby generating a built-in field from bP to HgCdTe, which is opposite to type II p-n junction (28, 43). Under different bias conditions, as shown in Fig. 2D, at reverse bias, tunneling window of HgCdTe/bP heterojunction opens wider with appearance of BTBT effect, leading to high backward current. When the heterojunction is at small forward bias, barrier of heterojunction is depleted and tunneling window is relatively narrow, causing small forward tunneling current. At large forward bias, carrier transport in heterojunction will be dominated by drift-diffusion mechanism, which is similar to that in type II p-n junction. To further indicate the broken-gap band alignment of HgCdTe/bP heterojunction, we measure the temperature-dependent I-V characteristics in dark condition at room temperature and show the results in fig. S5. The thermionic emission model is used in fig. S5B, and the plot (extracted from fig. S5A at small forward bias) does not show a linear dependency, demonstrating that the thermionic emission model is not suitable for the device. This can indicate that the band structure of HgCdTe/bP heterojunction is not type II band alignment. To investigate the tunneling mechanism of the device, ln(I_{DT}/V^2) versus −1/V curves extracted at small bias are shown in fig. S5C. The slopes of the curves at various temperatures are all positive, indicating that DT dominates in HgCdTe/bP heterojunction, which is consistent with band alignment analysis. The DT current transport model is described as I_{DT} \propto V \exp\left(-\frac{4\pi d \sqrt{2m^* \varphi}}{h}\right)$, where $I_{DT}$ is the DT current, $V$ is the applied bias voltage, $m^*$ is the effective mass of the carrier, $h$ is Planck’s constant, and $d$ and $\varphi$ are...
tunneling thickness and tunneling barrier height, respectively. The equation could be reduced as \( \ln \left( \frac{I}{V^2} \right) \propto \ln \left( \frac{1}{V} \right) - \frac{4\pi \sqrt{2m^*}{\varphi_h}}{h} \). Meanwhile, the barrier height is estimated via DT fitting curves of \( \ln \left( \frac{I}{V^2} \right) \propto \ln \left( \frac{1}{V} \right) - \frac{4\pi \sqrt{2m^*}{\varphi_h}}{h} \). Considering the existence of the PO\(_x\) layer, the barrier width of the device could be estimated as ~2 nm. Therefore, the tunneling barrier height of ~1.47 eV is derived, which is attributed to the PO\(_x\) layer.

**Room temperature MWIR detection of HgCdTe/bP heterojunction**

With the high absorption of light by the HgCdTe/bP heterojunction, the device exhibits a sensitive response to incident light wavelength from visible to MWIR. The classic \( I-V \) characteristics of the device with illumination of 637 nm are shown in Fig. 3A. The device exhibits obvious negative open-circuit voltage \( V_{oc} \) and positive short circuit current \( I_{sc} \) under different incident light powers. It is completely different from the photoresponse characteristics of traditional p-n junctions, which has positive \( V_{oc} \) and negative \( I_{sc} \). This photoresponse near zero bias owes to the accumulation of opposite carriers in the heterojunction as a result of band bending, which is also experimental evidence of broken bandgap. For a comprehensive display of this photoresponse characteristic, the \( I-V \) characteristics in logarithmic coordinates are given in fig. S4E. It clearly shows that at zero bias, the light-to-dark current ratio, defined by the ratio of current under light \( I_{light} \) and dark \( I_{dark} \), reaches a high value of \( 3.1 \times 10^4 \) (with incident power density of \( 7.14 \text{ W/mm}^2 \)), which is due to the low dark current and high photocurrent at zero bias. Compared with reported traditional infrared detectors listed in table S1, the dark current density of our device is much lower even at higher operation temperature. The low dark current is attributed to the potential barrier at zero bias, which suppresses the movement of thermal emission carriers, while the high photocurrent is due to DT.

As shown in Fig. 3B, under 637-nm laser illumination, the fitting curves of \( \ln \left( \frac{1}{V} \right) \) versus \( \ln \left( \frac{I}{V^2} \right) \) exhibit good linear relationship with positive slope at various powers, indicating the existence of DT in the heterojunction with light illumination. As band schematic shown in Fig. 3C, on account of the huge band bending and the bilateral accumulation layers at zero bias, a built-in field from bP to HgCdTe emerges in the heterojunction. With the excitation of light, electrons will jump into the conduction band, and photogenerated carriers will be separated by the built-in electric field.
Consequently, photogenerated electrons are transferred from HgCdTe to bP via DT, thereby generating large forward photocurrent flows from bP to HgCdTe.

To further investigate the photoresponse mechanism of the photodetector at zero bias, the photocurrent mapping is measured with the micro-area laser scanning. Figure 3 (D to F) shows photocurrent mappings with 637-, 1060-, and 1310-nm laser illumination, respectively, where the heterojunction area and an electrode are marked with white dashed boxes, and the corresponding optical microscope image is shown in Fig. 3D (inset). Photocurrent mapping indicates that the photodetector exhibits a strong photoresponse mainly in the overlapping region between bP and HgCdTe. Taking I–V characteristics and photocurrent mapping into consideration, photoresponse of the HgCdTe/bP photodetector is mainly contributed to photoinduced DT mechanism at HgCdTe/bP heterojunction area. It also further indicates that the HgCdTe/bP photodetector embraces the capability to detect visible to near-infrared light. The photoresponse spectrum from visible light to 4.3 μm is measured as a function of polarization angle from 0° to 180°, with a rise time τr ~ 150 μs and a decay time τd ~ 110 μs.

The photoresponse characteristics of the detector to MWIR radiation have also been validated. Figure 3L shows a typical time-dependent photoresponse of HgCdTe/bP heterojunction at λ = 4.3 μm. With illumination of laser at frequency f = 1 Hz, the photodetector shows sensitive and quick response. To estimate performance of photodetectors, responsivity and detectivity are two primary parameters. Responsivity is defined as $R = \frac{I_{ph}}{P}$, where $I_{ph} = I_{light} - I_{dark}$ and P is effective incident light power. For our photodetector, R is 168 mA/W at $\lambda = 4.3$ μm, with $P = 0.23$ μW, derived from Fig. 3H. Specific detectivity $D^*$ is defined as $D^* = \frac{\sqrt{\Delta f}}{\text{NEP}} = \frac{R \sqrt{\Delta f}}{I_n}$, where $A_D$ is the active area of detector; in our sample, $A_D$ is the area of overlap between bP and HgCdTe, $I_n$ is the noise current, and $\Delta f$ is the measurement bandwidth with a value of 1 Hz. The $D^*$ of our photodetector at 4.3 μm is calculated as 1.81 × 10^4 cm Hz^{1/2} W^{-1}, which has a comparable value with commercial cooled HgCdTe photovoltaic (PV) photodetectors [44]. It indicates that our HgCdTe/bP heterojunction photodetector has the capability of high-performance MWIR detection at room temperature without external bias and cooler. Overall, the photoresponse spectrum from visible light to 4.3 μm is shown in Fig. 3L, and the photoresponse peak wavelength $\lambda_p$ of our photodetector is approximately 3.2 μm.

**Polarization-resolved photodetection for visible MWIR**

On the basis of the anisotropic optical properties of bP, the HgCdTe/bP heterojunction is able to achieve polarization-resolved photodetection, which adds a additional information dimension to infrared detection. Figure 4A is a schematic of detecting the polarization-sensitive characteristics of the detector. Linearly polarized light is attained via a polarizer, and the polarization angle $\theta$ could be adjusted via a half-wave plate. To investigate optical characteristics of bP, polarization-solved infrared relative extinction spectra of bP with different polarizing angles are shown in Fig. 4B, where $T$ represents the transmission of bP on sapphire substrate and $T_0$ represents the transmission of only sapphire substrate. The top inset shows optical photograph of the measured sample, and directions of different polarizing angles are marked with dashed lines. It can be
clearly found that bP exhibits different transmission characteristics with polarizing angle changing. When polarizing angle $\theta = 90^\circ$ (blue line), bP shows minimum absorption, which indicates the zigzag direction of the bP flake. With $\theta$ decreasing, absorption of bP increases (red line) and reaches maximum value when $\theta = 0^\circ$ (black line). The relative extinction shows a sharp increase at around 2400 cm$^{-2}$, indicating 0.3-eV bandgap of bP. The polarization-sensitive absorption of bP originates from its anisotropic crystal structure (27, 30). Figure S3F shows schematics of bP crystal structure from top view (top) and lateral view (bottom), with bP’s zigzag and armchair directions marked. Incident polarized light parallel to the armchair direction sees an obvious absorption, while transmittance of light along the zigzag direction is relatively high (45).

A classic polarization-resolved performance of HgCdTe/bP heterojunction photodetector is shown in Fig. 4C, which was measured with illumination of linearly polarized laser at $\lambda = 637$ nm. Here, the dots are experimental data, and the line is the fitting curve, which is fitted by the sinusoidal function as $I_{pb}(\theta) = I_{pb} \cos^2(\theta + \phi) + I_{pb} \sin^2(\theta + \phi)$, where $I_{pb}$ is the photocurrent of the photodetector; $\theta$ is the polarized angle; and $I_{pb}$, $I_{pb}$, and $\phi$ are the fitting parameters. The extinction ratio defined by $I_{pb\ max}/I_{pb\ min}$ is ~1.45 with 637-nm laser illumination. To comprehensively confirm the polarization sensitivity of our photodetector, we applied illumination of linearly polarized laser, which is at $\lambda = 940$ nm, 1310 nm, 3.4 $\mu$m, and 4.0 $\mu$m. Last, the devices showed obvious polarization-resolved characteristics under all conditions above (see details in fig. S6). The results indicate that the HgCdTe/bP heterojunction photodetector has the potential for polarized light detection, and its detection wavelength range covers visible to MWIR, without additional optical modules.

Polarized photocurrent mapping can further confirm the origin of the detector’s polarization detection. Figure 4D shows the polarization-resolved photocurrent mapping images with different polarization angles at $\lambda = 637$ nm. It can be clearly seen that with $\theta$ changes from 0° to 180°, the photocurrent of overlapping region between bP and HgCdTe obviously decreases to a minimum value at $\theta = 90^\circ$ and then increase to maximum value at $\theta = 180^\circ$. By contrast, there is no notable change in the photocurrent around the HgCdTe electrode. This phenomenon strongly proves that the polarization sensitivity of HgCdTe/bP heterojunction is attributable to the anisotropic crystal structure of bP.

**Blackbody response and noise characteristics**

To further estimate application potential of this photodetector, we used a blackbody as a radiation source to simulate the infrared detection circumstances. The schematic of blackbody response measurement system is shown in fig. S7A. Note that for no shield mask in this system, ambient light and radiation could attribute to both dark current and noise so that the noise and dark current of blackbody response seems to be much larger compared with photoresponse characteristics under laser illumination. Typical response characteristics of our device are shown in fig. S7 (B to F), with different temperature blackbody radiation at $f = 1$ Hz. It is natural that as the blackbody temperature reduces, the response amplitude of the photodetector decreases simultaneously, which is due to the decrease of the blackbody radiant exitance and the red shift of the peak wavelength. In the case of the incident light offered by blackbody, blackbody responsivity $R_{bb}$ is given by $R_{bb} = \frac{I_{bb}}{P_{bb}}$, where $P_{bb}$ is the effective incident blackbody radiation power. $P_{bb}$ can be estimated by $P_{bb} = \frac{\sigma(T_b^4 - T_0^4)}{2\sqrt{\pi} L^2}$, where $\sigma = 5.67 \times 10^{-12}$ W cm$^{-2}$ K$^{-4}$ is the Stefan-Boltzmann constant and has an approximate value of 5.67 $\times$ 10$^{-12}$ W cm$^{-2}$ K$^{-4}$. $T_b$ is the blackbody temperature, $T_0$ is the background temperature, $A_b$ is the area of blackbody radiation aperture, $A_p$ is the active area of detector (in our sample, $A_p$ is the overlap area between bP and HgCdTe), and $L$ is the distance from blackbody to detector. It can be derived from fig. S7F that the peak blackbody responsivity of the device is 193 mA/W, which appears at blackbody temperature $T_b$ = 605 K. Figure 5A shows the measured current noise spectrum of the device from 1 to 10$^4$ Hz at room temperature. When the frequency exceeds 10$^2$ Hz, the noise behavior is 1/f noise. The low-frequency noise current $I_n$ was estimated as $1 \times 10^{-14}$ A Hz$^{-1/2}$; thus, noise equivalent power (NEP) at $T_b$ = 605 K is calculated as $5.95 \times 10^{-14}$ W Hz$^{-1/2}$, which is one to two orders of magnitude lower than reported low-dimensional MWIR detectors (see in table S1). Consequently, the blackbody detectivity of our HgCdTe/bP photodetector could be estimated by $D^* = \frac{\sqrt{A_b} 2 N}{\sqrt{A_p} A_p A_p N E P}$. As shown in Fig. 5B, peak detectivity is evaluated as high as $7.93 \times 10^{10}$ cm Hz$^{1/2}$ W$^{-1}$, which is comparable to commercial MWIR detectors. Besides, average detectivity in MWIR region is above $2.1 \times 10^{10}$ cm Hz$^{1/2}$ W$^{-1}$, indicating that our HgCdTe/bP photodetector has great potential in MWIR detection applications.

To exhibit advantages of our HgCdTe/bP photodetector, we show the performance comparison of our device and other reported MWIR detectors in Fig. 5 (C and D). Figure 5C shows a comparison of dark current density and detectivity with traditional bulk infrared detectors, such as InSb, HgCdTe, and InAsSb/InSb superlattices, and background temperature of 300 K is shown by dash-dot lines. PC, photovoltaic; SL, superlattice; S, superlattice.

**Fig. 5. Blackbody response and noise characteristics.** (A) Noise spectrum measured at background temperature of 300 K and zero bias. (B) Detectivity as functions of wavelength at various blackbody temperature measured at background temperature of 300 K. (C) Comparison of dark current density and detectivity with reported MWIR detectors, where traditional bulk detectors are marked with triangular dots and low-dimensional detectors are marked with square dots. References can be found in table S1. (D) Comparison of detectivity with other classic infrared photodetectors at room temperature. The background-limited infrared performance (BLIP) of PV infrared photodetectors calculated for field of view = 2x and background temperature of 300 K is shown by dash-dot lines. PC, photovoltaic; SL, superlattice; S, superlattice.
and emerging low-dimensional detectors, such as bP/MoS$_2$ heterojunctions. Combining advantages of both traditional bulk infrared materials and 2D materials, our photodetector exhibits low dark current density and high room temperature detectivity. Figure 5D gives classic room temperature detectivity of MWIR detectors with different structures, indicating that our HgCdTe/bP photodetector has comparable detectivity with commercial HgCdTe detectors and much higher detectivity than many other detectors in the MWIR region. The HgCdTe/bP photodetectors with broken-gap band alignment could have promising prospects in uncooled infrared polarization detection.

**DISCUSSION**

In conclusion, we have designed and fabricated a high-performance room temperature polarization-resolved MWIR photodetector using HgCdTe/bP van der Waals heterojunction. By means of van der Waals integration, both advantages of bP and HgCdTe are fully integrated. As a photodetector, the broken-gap band alignment between bP and HgCdTe can efficiently suppress dark current, and photoinduced DT brings a large photocurrent. This enables the photodetector to achieve outstanding MWIR detection ability at room temperature, which greatly reduces power consumption compared to traditional cooling infrared detectors. Besides, we demonstrate the polarization sensitivity of HgCdTe/bP photodetector from visible light to MWIR without other optical structures, which is achieved by bP for its anisotropy crystal structure. Furthermore, our photodetector has sensitive blackbody response, with the peak blackbody detectivity as high as 7.93 × 10$^{10}$ cm Hz$^{1/2}$ W$^{-1}$, indicating that it embraces great potential for practical application. Our investigation shows that the van der Waals mixed-dimensional integration provides a feasible method for manufacturing high-performance HgCdTe photodetectors, which has superior interface characteristics and high flexibility. By delicate design of band alignment and device structure, more advanced functions and excellent performances can be realized in HgCdTe-based detectors.

**MATERIALS AND METHODS**

**Device fabrication**

HgCdTe film with a thickness of 8 μm was deposited on the 900-μm-thick germanium substrate by molecular beam epitaxy. For electrical isolation, HgCdTe film was patterned by ultraviolet lithography, and about 150-nm-thick HgCdTe was etched by argon ion bombardment. Then, a 150-nm-thick Al$_2$O$_3$ was deposited by electron beam evaporation (EBE) to fill the removed HgCdTe area. bP flakes with thickness of 50 to 150 nm were mechanically exfoliated from bulk materials onto the silicon substrates. HgCdTe was handled with Br$_2$/ethanol solution for 5 to 10 s to remove damaged layer and clear contamination on surface, and then, bP was transferred to the surface of HgCdTe in a nitrogen environment immediately. Electrodes were patterned by electron beam lithography, and 15/30-nm Ti/Au was deposited by EBE.

**Electrical and optoelectrical measurements**

All electrical and optoelectrical measurements were performed at room temperature in a room with blackout curtain to avoid interference of ambient light. Sample devices were placed in a vacuum Dewar with pressure of 10$^{-4}$ Pa to avoid degradation and oxidation of bP and HgCdTe. The device electrical and optoelectrical properties were measured with an Agilent B1500A semiconductor parameter analyzer when the incident light wavelength was below 2 μm. In the case of MWIR (2.77 to 4.32 μm), an Agilent B2912 source meter was used to measure its electrical and optoelectrical properties. In the photocurrent mapping measurement, lasers were focused on the device with a ×20 objective lens, and current signals are processed with a low-noise SRS-SR570 preamplifier and a Signal Recovery Model 7270 DSP lock-in amplifier.

**Blackbody response measurements**

All blackbody response measurements were performed at room temperature, and the measured sample was placed in a vacuum Dewar. Blackbody radiation was obtained from a Newport Oriel 67000 blackbody source. The distance between the blackbody and the sample is about 10 cm. A mechanical chopper is placed in front of the blackbody to generate blackbody radiation signal at a certain frequency. Response characteristics of our device were measured with an Agilent B2912 source meter.

**SUPPLEMENTARY MATERIALS**

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