Controllable growth of type-II Dirac semimetal PtTe₂ atomic layer on Au substrate for sensitive room temperature terahertz photodetection

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Abstract
Platinum telluride (PtTe₂), a member of metallic transition metal dichalcogenides, provides a new platform for investigating various properties such as type-II Dirac fermions, topological superconductivity, and wide-band photodetection. However, the study of PtTe₂ is largely limited to exfoliated flakes, and its direct synthesis remains challenging. Herein, we report the controllable synthesis of highly crystalline 2D PtTe₂ crystals with tunable morphology and thickness via chemical vapor deposition (CVD) growth on Au substrate. By adjusting Te amount and substrate temperature, anisotropic and isotropic growth modes of PtTe₂ were realized on the solid and molten Au substrates, respectively. The domain size of PtTe₂ crystal was achieved up to 30 μm, and its thickness can be tuned from 5.6 to 50 nm via controlling the growth time. Furthermore, a metal–PtTe₂–metal structural device was fabricated to validate the wide-band terahertz (THz) photodetection from 0.04 to 0.3 THz at room temperature. Owing to the high crystallinity of PtTe₂ crystal, the photodetector acquires high responsivity (30–250 mA W⁻¹ from 0.12 to 0.3 THz), fast response rate (rise time: 7 μs, decay time: 8 μs), and high-quality imaging ability. Our work demonstrates the feasibility for realistic exploitation of high-performing photodetection system at THz band based on the CVD-grown 2D Dirac semimetal materials.
1 | INTRODUCTION

Atomically thin 2D transition metal dichalcogenides (TMDs) have drawn tremendous attention owing to their remarkable optical and electrical properties such as tunable bandgap and high carrier mobility for next-generation device applications.\(^1\) Beyond the widely studied semiconducting TMDs (e.g., MoS\(_2\) and WS\(_2\)), metallic TMDs (e.g., 1T\(^0\) MoTe\(_2\)/WTe\(_2\), PtTe\(_2\), and PdTe\(_2\)) with exotic properties offer a new platform for investigating newfangled...
physically potential in synthesizing 2D semiconductors. Chemical vapor deposition (CVD) growth has productivity, small domain size, and uncontrolled layer restricted to the mechanically exfoliated samples with low example, large-area, high crystal quality MoS2, WS2, and heavy Pt and Te atoms in PtTe2 bring a strong spin-orbital interaction, which enables the occurrence of weak anti-localization. Furthermore, the type-II Dirac semimetal allows the surface plasmon resonance without dissipation at terahertz (THz) band, and thus can enhance the absorption ability of free electron via constructing THz antenna to form a strong coupling effect. The high mobility of such Dirac material permits the carriers oscillation under THz electromagnetic field avoid the distortion of temperature variation, and thus generate photocurrent directly under THz field. In this regard, the topological Dirac semimetal is an ideal material for realizing the THz imaging with low power consumption at room temperature. These novel properties of PtTe2 provide tremendous opportunities for exploring its potential applications in electronics, optoelectronics, spintronics, and catalysis.

However, present studies on PtTe2 are largely restricted to the mechanically exfoliated samples with low productivity, small domain size, and uncontrolled layer number. Chemical vapor deposition (CVD) growth has shown perfect potential in synthesizing 2D semiconducting TMDs materials in a well-controlled fashion. For example, large-area, high crystal quality MoS2, WS2, and ReS2 with tunable thickness as well as their heterostructures and alloys have been synthesized via CVD growth. Notably, only a few works reported the CVD synthesis of 2D PtTe2 crystals, and several critical issues need to be resolved for satisfying its practical device applications. For instance, utilizing the tellurium-vapor transformation approach, large-scale 2D PtTe2 layers were obtained from the predeposited Pt film. As is well known, although this method can acquire large-area 2D materials, it is difficult to guarantee their crystal quality. Very recently, 2D PtTe2 flakes were successfully grown on mica and SiO2/Si substrates by using the direct CVD approach. However, the strong interlayer coupling of PtTe2 crystal together with the low migration coefficient of Pt and Te atoms on presently used substrates make its in-plane epitaxy to be difficult, and thus it easily grows into thick flakes with small domain size. Hence, developing an effective CVD approach to synthesize PtTe2 crystal in a controlled manner is highly desired.

Besides the widely used insulating substrates, Au foil is also usually utilized as a growth substrate to synthesize large-size 2D TMDs. For instance, millimeter-size WS2 and MoS2 have been successfully grown on Au substrate, where the low surface energy and catalytic ability of Au surface are beneficial to the high efficiency growth. Moreover, the synthesis of graphene, h-BN, ReS2, and PtSe2 on Au substrate have also been reported, while the synthesis of Te-based TMDs on it is still lacking to date. Because Te can lower the melting point of Au by forming Te-Au eutectic alloy, we can obtain a quasi-atomic smooth and homogeneous molten Au surface, which is considered as an ideal substrate for the epitaxial growth of 2D materials. Therefore, it is quite promising to develop the controllable synthesis of 2D PtTe2 crystals on Au substrate, which is essential for their successful application in high-speed photodetection over wide-band wavelength regime benefiting from their gapless nature.

Herein, we reported the high-efficiency synthesis of 2D PtTe2 crystals with tunable morphology and thickness via CVD growth on Au substrate, and explored its potential application in THz photodetection. By altering the amount of Te precursor, we realized the anisotropic and isotropic growth of PtTe2 on the solid and molten Au substrates, and thus selectively obtained the rectangular and triangular PtTe2 crystals, respectively. The domain size of PtTe2 crystals up to dozens of micrometer, and the thickness can be modulated from 5.6 to 50 nm via controlling the growth time. Furthermore, a metal–PtTe2–metal structural device was constructed to achieve the wide-band THz photodetection from 0.04 to 0.3 THz at room temperature. The photodetector acquires a high responsivity (−147.14 mA W−1 without bias voltage at 0.04 THz) and fast response rate (rise time: 7 μs, decay time: 8 μs). To further provide concrete exploitation in quality control application, a high-resolution scanned imaging with high signal-to-noise ratio was achieved based on the PtTe2 device, demonstrating great potential of such 2D Dirac semimetal material in future THz technology.

2 | RESULTS AND DISCUSSION

The strategy for controllable synthesis of 2D PtTe2 crystal via CVD growth is schematically illustrated in Figure 1B. Briefly, platinum dichloride (PtCl2) and tellurium (Te) powder were used as precursors, and Au foil was utilized as the growth substrate. During the growth process, controlling the amount of Te is critical to modulate the state (solid state or molten state) of Au substrate and to modulate the growth behavior of PtTe2. At a few amount of Te (few-Te) growth condition, the Au foil (melting point: 1064.18 °C) maintains solid state during the general growth temperature (600–800°C). In contrast, at
excess amount of Te (rich-Te) growth condition, the solid Au foil easily melts into molten state due to the formation of Te-Au binary eutectic alloy (Figure S1). Thus, we explored the growth of PtTe2 on both solid and molten Au substrates by adjusting the amount of Te precursor. More details about the sample synthesis are shown in the Experiment section.

Scanning electron microscopy (SEM) images of PtTe2 crystal grown on the solid and molten Au substrates are shown in Figure 1C,D and Figure S2. Apparently, PtTe2 crystals grown on solid Au substrate show a rectangle morphology (Figure 1C), indicating an anisotropic growth of PtTe2. In contrast, PtTe2 crystals grown on molten Au substrate show a triangle morphology (Figure 1D), which is consistent with its sixfold symmetry 1T structure feature, implying an intrinsic isotropic growth behavior. The mechanism of the different growth behavior of PtTe2 on solid and molten Au substrates will be discussed detailedly in the following section. The length of rectangular PtTe2 crystal grown on solid Au substrate is in the range of 20–200 μm, and the domain size of triangular PtTe2 crystal grown on molten Au substrate is about 10–30 μm, as shown in Figure S2. Atomic force microscopy (AFM) images of the rectangular PtTe2 nanosheet (Figure 1E) and the triangular PtTe2 nanosheet (Figure 1F) show their thickness values are 25.6 and 28.5 nm, respectively. Note that the surface of these samples is quite smooth, indicating the high-quality epitaxy of the PtTe2 on Au substrate.

The composition and atomic structure of the CVD-grown PtTe2 crystals were confirmed using X-ray diffraction (XRD), energy-dispersive X-ray spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS), and aberration-corrected annular dark-field scanning transmission electron microscopy (ADF-STEM). XRD spectrum (Figure S3a) shows three prominent diffraction peaks of (001), (110), and (003) patterns, matching well with the standard PtTe2 crystal (PDF#18-0977). The low-magnification TEM image of one rectangular PtTe2 crystal and the corresponding EDS elemental mapping images (Figure 2A–D) clearly show the uniform spatial distribution of Pt and Te throughout the entire PtTe2 sample. The atomic ratio of Pt and Te determined by EDS spectrum is ≈1:1.94, indicating the formation of stoichiometric PtTe2 crystal (Figure S3b). XPS full survey spectrum of the as-grown PtTe2 on Au substrate (Figure S3c) reveals the existence of four elements (Pt, Te, Au, and C). As shown in Figure 2I, the peaks located at ≈75.9 and 72.5 eV are attributed to Pt 4f_5/2 and 4f_7/2 of PtTe2, and the peaks located at ≈586.9 and 576.4 eV correspond to Te 3d_3/2 and 3d_5/2 of PtTe2, respectively. Note that the two peaks located at ≈583.6 and 573.2 eV are assigned to the Te 3d_3/2 and 3d_5/2 of zero-valent Te, respectively. The raise of zero-valent Te is reasonable because it can melt into the Au substrate during the growth process, which consistent with our synthesis strategy of adjusting the Te amount to modulate substrate state and PtTe2 growth behavior.

Figure 2E shows a typical atomic-resolution ADF-STEM image of the PtTe2 crystal, where the brighter and dimmer sites corresponding to the Pt and Te atoms, respectively. The uniform atomic arrangement and almost absence of local defect in the STEM image confirm the high crystallinity of the CVD-grown PtTe2. The enlarged STEM image (Figure 2F) reveals a clearly resolved hexagonal lattice arrangement with the lattice spacings of 0.198 and 0.209 nm corresponding to the (2-10) and (110) planes of PtTe2 crystal. Apparently, the PtTe2 crystal presents a hexagonal 1T phase structure with each hexagonally arranged Pt atom surrounded by six Te atoms, which can be intuitively seen from the corresponding structural model. Additionally, the contrast variation and atom arrangement of the experimentally acquired STEM image are consistent with the simulated STEM image of 1T phase PtTe2 crystal (Figure S4). As shown in Figure 2G, the periodic arrangement of Pt and Te atoms can be observed from the intensity profile along the yellow dashed line in Figure 2E. Furthermore, the selected area electron diffraction (SAED) patterns acquired at five different regions of one rectangular PtTe2 show perfect coincidence (Figure 2H), confirming the single-crystal nature of the CVD-grown PtTe2.

To unveil the mechanism behind the difference in PtTe2 growth behavior on solid and molten Au substrates, we systematically studied the effect of substrate temperature and Te amount on the growth behavior of PtTe2. At a fixed Te amount of 50 mg, the morphology of PtTe2 always keeps the rectangle shape with the growth temperature increasing from 600 to 800°C (Figure 3A–C). Moreover, at a fixed growth temperature of 700°C, the morphology of PtTe2 changes from rectangle to triangle when Te amount increasing from 30 to 70 mg (Figure 3E–G). Apparently, the growth behavior and accompanied morphology of PtTe2 on Au substrate are highly dependent on the Te amount. It was found that the Au foil maintains the solid feature when growing in 30 mg of Te, while it presents a molten state when growing in 70 mg of Te, as shown in Figure S5. This is reasonable because the excess Te can serve as a fluxing agent to decrease the melting point of Au, and thus make the solid Au substrate transform into molten Au substrate. In this regard, the essence of the difference in Te amount during CVD growth should be the difference in the state of Au substrate, the few-Te, and rich-Te growth conditions corresponding to the solid and molten Au substrates, respectively. To assess the morphology of solid and molten Au substrates, AFM characterization was conducted.
on the Au substrates after grown under few Te (50 mg) and rich Te (70 mg) conditions. As shown in Figure 3G, the solid Au substrate shows clear orientated terraces with identical steps at a height of ≈3 nm, which should be the reason for the anisotropic growth of PtTe$_2$. The orientated terraces can act as a template to guide PtTe$_2$ to grow along the edge of the step, and finally grow into rectangle-shaped grains. In contrast, the Te-Au alloy substrate displays relatively smooth surface (root mean square roughness: ~1.2 nm) (Figure 3H), implying the formation of molten Au substrate during the growth process. Notably, the quasi-atomic smooth and homogeneous molten Au surface is beneficial to the intrinsic isotropic growth of PtTe$_2$, and thus grows into the regular triangle domains, which are the typical shape of CVD-grown 1T phase 2D materials. Moreover, the molten Au substrate could provide a low surface potential energy for the atom migration, which facilitates the epitaxial growth of 2D ultrathin PtTe$_2$ crystals. Therefore, we can effectively modulate the state of Au substrate and the growth behavior of PtTe$_2$ by precisely controlling the Te amount. Moreover, the Au substrate can serve as a buffer to achieve a modest supply of Te, which is beneficial for the growth of high-quality PtTe$_2$ crystal.
Besides the above morphology evolution, the thickness of PtTe$_2$ crystal can also be modulated by controlling the growth time. AFM characterization shows that the thickness of as-grown PtTe$_2$ varies from $\approx 5.6$ to $\approx 50$ nm with growth time increasing from 5 to 15 min (Figure S6).

**FIGURE 3** (A–C) SEM images of PtTe$_2$ grown at 600, 700, and 800 °C, and the Te amount is fixed at 50 mg. (D–F) SEM images of PtTe$_2$ grown at 700 °C with Te amount of 30, 50, and 70 mg. (G–H) AFM images of Au substrates after grown at 700 °C with Te amount of 30 and 70 mg.

**FIGURE 4** (A, C) OM images of rectangular and triangular PtTe$_2$ transferred on SiO$_2$/Si substrate. (B, D) Raman intensity ($E_g$ mode) mapping images of triangular and rectangular PtTe$_2$. (E) Raman spectra of PtTe$_2$ with different thickness. (F, G) Polarized Raman spectra of PtTe$_2$ under parallel and cross-polarization configurations.
rectangular PtTe\textsubscript{2} crystals, and the corresponding Raman intensity mapping images (Figure 4B,D) present a homogeneous contrast, indicating the high quality of PtTe\textsubscript{2} with uniform thickness. Figure 4E shows the Raman spectra of PtTe\textsubscript{2} crystals with different thickness transferred on SiO\textsubscript{2}/Si substrate, where the two prominent Raman peak located at 110 and 155 cm\textsuperscript{-1} correspond to the in-plane E\textsubscript{g} and out-of-plane A\textsubscript{1g} modes, respectively.\textsuperscript{13} Both the Raman intensity and frequency of E\textsubscript{g} and A\textsubscript{1g} modes vary apparently with the increase of PtTe\textsubscript{2} thickness. The E\textsubscript{g} mode shifts from 117 to 110 cm\textsuperscript{-1} and the A\textsubscript{1g} mode shifts from 158 to 155 cm\textsuperscript{-1} as the thickness increases from 5.6 nm to bulk. Furthermore, we also explored the polarization-dependent Raman spectra of PtTe\textsubscript{2} under parallel and cross-polarization configurations. As shown in Figure 4G, the intensity of both E\textsubscript{g} and A\textsubscript{1g} modes show periodic variation with sample rotation angle changing from 0° to 90° under parallel configuration. Meanwhile, the intensity of E\textsubscript{g} mode shows periodic variation and the A\textsubscript{1g} mode nearly vanishes with sample rotation angle changing from 0° to 90° under cross configuration (Figure 4H). These distinctive characteristics imply the polarization-dependent anisotropic behavior of as-grown PtTe\textsubscript{2}.\textsuperscript{17,45,46} Moreover, both the Raman spectra and AFM images of PtTe\textsubscript{2} nanosheet maintain well during 6 months of aging in ambient air (Figure S7), indicating excellent environment stability, which is quite important to its practical device application.

In view of the peculiar band structure and the topologically protected electronic properties of Dirac semimetal PtTe\textsubscript{2}, long-wavelength detection at THz band was implemented. Figure 5A shows the schematic diagram of PtTe\textsubscript{2}-based photodetector, where the PtTe\textsubscript{2} crystal serves as the channel material to contact with source and drain electrodes (Ti/Au, 10 nm/80 nm), forming a subwavelength metal-topological semimetal–metal (MTM) structure. As

![Figure 5](image-url)
shown in Figure 5B, a log-periodic structure was designed to enhance the THz electric-field intensity along the 6 μm PtTe$_2$ channel; moreover, it also serves as electrodes for electrical readout. Before the THz detection study, we first evaluated the electrical transport properties of the PtTe$_2$ device. The output curves of the device (Figure 5C) exhibit Ohmic behavior with the resistance of 1200 Ω and the transport curves (Figure 5D) feature neglect gate-modulation, which is consistent with the semimetal nature of PtTe$_2$.\textsuperscript{47}

To explore the sensitivity of PtTe$_2$-based MTM device, electromagnetic waves with different frequencies were generated from electronic multipliers (Section 4), and all the photoresponse measurements were performed at room temperature under ambient environment. Figure 5E shows the time-resolved photoresponse of the device under bias voltage of 10, 50, and 100 mV at 0.12 THz radiation. Clearly, the device exhibits fast and stable THz photoresponse accompanied with large signal-to-noise ratio, and the photocurrent can be enlarged by more than an order of magnitude under bias voltage. Furthermore, the rapid relaxation of nonequilibrium carriers allows fast operation speed of PtTe$_2$-based photodetector as shown in Figure 5F. The rise time, which is defined as the time needed to reach 90% of the maximum photocurrent, is about $\tau_r \approx 7$ μs, while the decay time, which is defined as the time needed to drop to 10% of the maximum photocurrent, is about $\tau_d \approx 8$ μs, which is fast enough to meet the requirement for frame-rate imaging.

To gain insight into the performance of our device, the power density dependence of PtTe$_2$ device is also measured in Figure 5G, in which the photocurrent exhibits excellent linear dependence on the power verifying the mechanism as the free electron absorption of the Dirac fermions. As shown schematically in Figure 5H, the type-II Dirac semimetal PtTe$_2$ allows strong coupling of electrons with the THz wave at the Fermi surface of tilted Dirac cones, which results in excitation of non-equilibrium carriers. At zero bias voltage, the carriers can dislodge from metal–material interface due to the electromagnetic field formed between the electrodes, and thus increasing a tiny photocurrent (Figure S8). When applying a bias voltage traversing the channel, the carriers derived by the large potential difference could dislodge from metal–material interface easily, forming a large photocurrent. These activated carriers will be accelerated under electric-field across the channel, which leads to a photoconduction gain.\textsuperscript{48}

The fast and stable optical response can be preserved across the range from 0.04 to 0.3 THz in our PtTe$_2$-based device (Figure 6A), certifying the prospect of broadband operation. The photocurrent of the device irradiated at different THz waves shows a linear increase with bias voltage ranging from –100 to 100 mV (Figure S8). Correspondingly, the responsivity ($R_A$) can be calculated from the formula $R_A = I_{ph}/P_{in}S_a$, where $I_{ph}$ is the photocurrent, $P_{in}$ is the power of incident THz radiation, and $S_a$ is the channel area of the device.\textsuperscript{20} As shown in Figure 6B,

![Figure 6](image-url)

**Figure 6** (A) Photoresponse of the device irradiated with 0.04, 0.12, and 0.3 THz waves under bias voltage of 50 mV. (B) Responsivity of the device irradiated with 0.04, 0.12, and 0.3 THz waves under bias voltage from –100 to 100 mV. (C, D) Noise spectra of the PtTe$_2$ device and corresponding NEP at 0.04, 0.12, and 0.3 THz. (E) 2D scan imaging of a key at 0.3 THz.
$R_A$ of the device irradiated with 0.04, 0.12, and 0.3 THz waves under bias voltage of 0 mV up to 0.2, 2.2, and 3.8 mA W$^{-1}$, respectively. Notably, by increasing the bias voltage to 100 mV (or –100 mV), $R_A$ can further increase to 30, 250, and 600 mA W$^{-1}$ for 0.04, 0.12, and 0.3 THz waves detection, respectively. Moreover, noise equivalent power (NEP), which is defined as the minimum detectable power in 1 Hz bandwidth, is another figure of merit used to assess the performance of the device (NEP = $v_n/R_A$, see Section 4). As shown in Figure 6C, the total current noise of the PtTe$_2$ device comprises the thermal Johnson–Nyquist noise ($v_b$) associated with the non-zero resistance of the device channel, shot noise ($v_{1/f}$) due to the uncorrelated arrivals of electrons under bias voltage, and system-specific flicker noise ($v_{1/f}$). The device is dominated by $v_{1/f}$ noise at low-frequency (1–150 Hz). When the frequency exceeds 150 Hz, $v_{1/f}$ noise decreases rapidly, so that it could be ignored (inset of Figure 6C) under experimental condition. Hence, $v_b$ and $v_{1/f}$ primarily contribute to the noise of PtTe$_2$ device. The NEP derived from the noise spectra of PtTe$_2$ device are $\approx 42$ pW/Hz$^{0.5}$ at 0.04 THz and $\approx 92$ pW/Hz$^{0.5}$ at 0.12 THz, as well as $\approx 149$ pW/Hz$^{0.5}$ at 0.3 THz at 0.1 V (Figure 6D), which are in line with the theoretical values. Benefiting from the high responsivity, fast response, and broadband nature of our device, we further demonstrated its high-resolution THz transmission imaging application as shown in Figure 6E. As a test object, a key (material is plastic and metal) was fixed at a focal plane of $x$–$y$ axis with the photodetection operating under 50 mV bias voltage at 0.3 THz. The obtained high-contrast THz imaging picture clearly reveals the shape of the key, indicating the exploitable for fast THz imaging applications. Hence, the controllable preparation of PtTe$_2$ together with the high responsivity, large signal-to-noise ratio, and fast response of its THz photodetector suggest tremendous prospect of such topological semimetal for future THz technology.

3 | CONCLUSIONS

In summary, we have successfully synthesized highly crystalline 2D PtTe$_2$ crystals with tunable morphology and thickness by CVD growth on Au substrate. By adjusting the amount of tellurium and growth temperature, we achieved the anisotropic and isotropic growth of PtTe$_2$ on solid and molten Au substrates, respectively. We believe that the growth approach developed in this work could be extending to controllable synthesis of other Te-based metallic TMDs materials. Furthermore, the CVD-grown PtTe$_2$ crystals have high crystallinity and air stability. Importantly, the Dirac semimetal PtTe$_2$-based THz photodetector displays wide-band response with high responsivity and fast response rate at room temperature, exhibiting great prospects for THz imaging application. Overall, the high crystallinity and superior THz photoreponse of PtTe$_2$, combined with controllable growth, make it a promising 2D semimetallic material for future THz applications.

4 | EXPERIMENTAL SECTION

4.1 | Sample growth and transfer

PtTe$_2$ samples were synthesized on Au substrates by CVD growth under atmospheric pressure. The PtCl$_2$ powder (99.5%, Alfa Aesar) and tellurium powder (99.999%, Alfa Aesar) were used as Pt and Te precursors, respectively. The Au foil (thickness 30 μm, Advanced Material Professional Manufacture, purity 99.99%) was cleaned with dilute HCl, ethanol, acetone, and deionized water, and then annealed at 1030 °C for 30 min. The PtCl$_2$ powder (3 mg) in a ceramic boat with upper Au foil was placed at the center of the furnace, and Te powder (30–70 mg) in another quartz boat was placed at the upstream of the quartz tube furnace. The quartz tube was purged with ultrahigh-purity argon (Ar) gas (99.999%) before heating, and then ramped up to 600–800 °C at 30 °C/min with Ar (50 sccm) and H$_2$ (3 sccm) as carrier gas under atmospheric pressure. After maintaining for 10 min to grow PtTe$_2$ samples, the furnace was naturally cooled to ~500 °C, followed by a rapid cooling process by opening the furnace. After growth, the PtTe$_2$ samples were detached from the Au foils and transferred onto the target substrate by using a wet-chemical etching approach for further structure and property characterization.

4.2 | Structure and composition characterization

The morphology and crystal plane of annealing Au foil were characterized via SEM (FEI Nova system) and EBSD (SU3500). The morphology of as-grown PtTe$_2$ samples was analyzed via SEM (FEI Nova system) and Olympus BX51 optical microscope. The thickness of PtTe$_2$ samples and surface morphology of Au substrates were measured by using AFM on a Bruker ICON microscope. The element composition and electronic structure of PtTe$_2$ samples were analyzed by EDS mapping on a TEM (Tecnai G2 F20; accelerating voltage, 200 kV) and XPS (Kratos Analytical LtdAXIS ULTRA). Raman spectra were explored on a Renishaw inVia micro-Raman spectroscope with 532 nm laser. The atomic structure and crystal
quality of PtTe$_2$ samples were evaluated via HAADF-STEM imaging on a probe aberration-corrected Thermo-Fisher Titan cubed Themis G2 300 operated at 300 kV.

4.3 Device fabrication and photoelectrical measurements

The PtTe$_2$ based MTM structure was patterned by using the ultraviolet lithography technique, and the metal electrodes (Ti/Au = 10/80 nm) were deposited by thermal evaporation. The electrical transport properties (output curves and transport curves) of the devices were measured using Keithley 4200 semiconductor parameter analyzer. For the photoresponse measurements, the THz waves with different frequencies (0.04, 0.12, and 0.3 THz) were generated from a multiplier of electronic source, and the photocurrent was collected by Keithley 4200 and magnified by a lock-in amplifier and preamplifier. The 0.04 THz source based on frequency multipliers was employed in the photoresponse experiments. The power density of the THz radiation was 1.05 mW cm$^{-2}$, calibrated by a Golay cell. The figure of merit used to evaluate the performance of the device is NEP $= n^2/2R_A$, where $n$ is the root mean square of the noise current and $R_A$ is the current responsivity of the device. For our devices, the thermal Johnson–Nyquist noise ($n$) associated with the nonzero resistance of the device channel and the noise ($b$) owing to the bias current must be included, described as $n = b = (4k_B^2 T/r + 2qI_{th})^{1/2}$, where $k_B$ is Boltzmann constant, $T$ is the temperature, $r$ is the resistance value of the material, $q$ is the elementary charge, and $I_{th}$ is the bias current of the device.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of this article.

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