

Spatially programmable bipolar photoresponse in Wafer-scale Te/GaN heteroarrays enabled by synergistic photovoltaic-photothermoelectric coupling

Lijian Li^{1,§}, Peng Wan^{1,§}, Yinglin Wang¹, Liangli Chu¹, Zhenyu Cheng², Minghao Liu³, Caixia Kan¹, Daning Shi^{1(✉)}, Zeng Liu^{4(✉)}, Mingming Jiang^{1(✉)}

¹ College of Physics, MIIT Key Laboratory of Aerospace Information Sensing and Physics, Nanjing University of Aeronautics and Astronautics, No. 29, Jiangjun Road, Nanjing 211106, China

² College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, No. 29, Jiangjun Road, Nanjing 211106, China

³ College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 211100, China

⁴ School of Electronic Information Engineering, Electronic-Photonic Smart Sensing Device R&D Team, Inner Mongolia Key Laboratory of Intelligent Communication and Sensing and Signal Processing, Inner Mongolia University, Hohhot 010021, China

§ Lijian Li and Peng Wan contributed equally to this work.

Nano Res., **Just Accepted Manuscript** • <https://doi.org/10.26599/NR.2026.94909110>

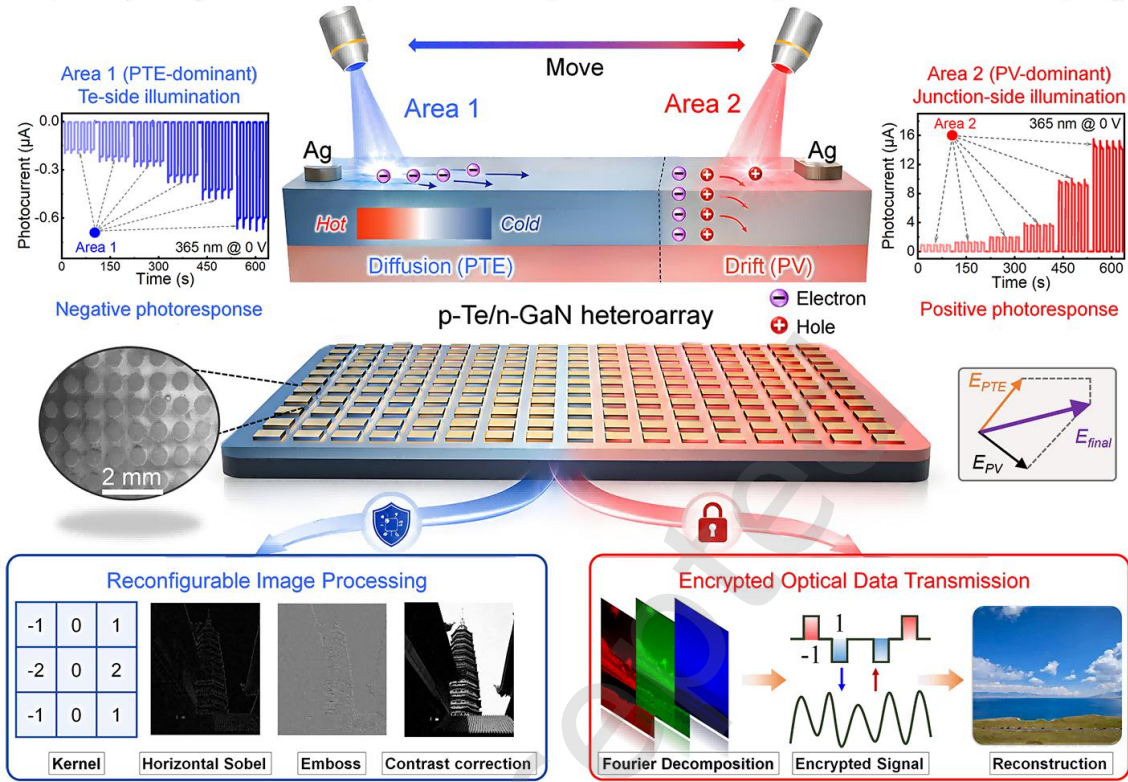
<https://www.sciopen.com/journal/1998-0124> on Aug. 13, 2026

© The Authors(s)

Just Accepted

This is a “Just Accepted” manuscript, which has been examined by the peer-review process and has been accepted for publication. A “Just Accepted” manuscript is published online shortly after its acceptance, which is prior to technical editing and formatting and author proofing. Tsinghua University Press (TUP) provides “Just Accepted” as an optional and free service which allows authors to make their results available to the research community as soon as possible after acceptance. After a manuscript has been technically edited and formatted, and the page proofs have been corrected, it will be removed from the “Just Accepted” web site and published officially with volume and article number (e.g., *Nano Research*, **2025**, *18*, 94906990). Please note that technical editing may introduce minor changes to the manuscript text and/or graphics which may affect the content, and all legal disclaimers that apply to the journal pertain. In no event shall TUP be held responsible for errors or consequences arising from the use of any information contained in these “Just Accepted” manuscripts. To cite this manuscript please use its Digital Object Identifier (DOI®), which is identical for all formats of publication.

Spatially Programmable Bipolar Photoresponse Position-dependent $PTE + PV$ coupling



This study reports bias free, position programmable bipolar photoresponse in large area Te/GaN heterojunction arrays via high quality Te films, overcoming the Shockley-Queisser limit and functional inflexibility of single effect devices. Leveraging intrinsic synergy between photothermoelectric and photovoltaic effects, the developed Te/GaN heterojunction pixel array devices enable reconfigurable image processing and encrypted optical transmission.

Spatially programmable bipolar photoresponse in Wafer-scale Te/GaN heteroarrays enabled by synergistic photovoltaic-photothermoelectric coupling

Lijian Li^{1,§}, Peng Wan^{1,§}, Yinglin Wang¹, Liangli Chu¹, Zhenyu Cheng², Minghao Liu³, Caixia Kan¹, Daning Shi¹ 
, Zeng Liu⁴ , and Mingming Jiang¹ 

¹ College of Physics, MIIT Key Laboratory of Aerospace Information Sensing and Physics, Nanjing University of Aeronautics and Astronautics, No. 29, Jiangjun Road, Nanjing 211106, China

² College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, No. 29, Jiangjun Road, Nanjing 211106, China

³ College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 211100, China

⁴ School of Electronic Information Engineering, Electronic-Photonic Smart Sensing Device R&D Team, Inner Mongolia Key Laboratory of Intelligent Communication and Sensing and Signal Processing, Inner Mongolia University, Hohhot 010021, China

[§] Lijian Li and Peng Wan contributed equally to this work.

Received: 9 June 2026; **Revised:** 27 July 2026; **Accepted:** 13 August 2026

 Address correspondence to Daning Shi, shi@nuaa.edu.cn; Zeng Liu, zengliu@imu.edu.cn; Mingming Jiang, mmjiang@nuaa.edu.cn

 **Cite this article:** *Nano Research*, 2026, 19, 94909110 <https://doi.org/10.26599/NR.2026.94909110>

ABSTRACT: Conventional photodetectors dominated by a single physical effect are strictly constrained by the Shockley-Queisser limit, accompanied by intrinsic performance saturation, inadequate operational flexibility, and a complete absence of functions and secure functionalities. Here, we present large-area integrable Te/GaN heterostructure array devices fabricated from high-quality Te films via glancing-incidence physical vapor deposition. Benefiting from the intrinsic synergy between photovoltaic and photothermoelectric effects, these devices offer bias-free, position-programmable bipolar photoresponse. Under 365 nm illumination, the Te/GaN devices exhibit competitive figures of merit among similar devices, with positive/negative responsivity up to 308.4 mA/W and 54.5 mA/W, specific detectivity exceeding 1.09×10^{13} Jones and 7.52×10^{12} Jones, respectively, at zero bias. By using illumination position and response polarity as dual physical keys, the developed wafer-scale 20×20 -pixel Te/GaN heteroarrays successfully implement reconfigurable image processing and encrypted image transmission, demonstrating unprecedented intelligent and physically secure functionalities for next-generation optoelectronic chips. This work overcomes the performance bottlenecks and limited operational degrees of freedom in single-effect devices, and achieves reliable, scalable array applications without external components, establishing a universal paradigm for high-performance, intelligent and secure integrated optoelectronics systems.

KEYWORDS: Te/GaN heteroarrays; position-programmable bipolar photoresponse; synergistic photothermoelectric-photovoltaic effects; reconfigurable in-sensor image processing; encrypted optical data transmission

1 Introduction

Traditional photovoltaic optoelectronic devices separate photocarriers through built-in electric fields, yet are strictly constrained by both the Shockley-Queisser efficiency limit and poor spectral matching arising from intrinsic material bandgaps. These shortcomings hinder devices from simultaneously satisfying comprehensive performance demands such as high responsivity, broadband spectral response, programmable capability, high integration density and diverse functional applications [1, 2]. In recent years, coupling the photovoltaic (PV) effect with the photothermoelectric (PTE) effect, where a temperature gradient driven directional carrier migration assists photovoltaic carrier separation, has emerged as a key strategy to overcome performance bottlenecks [3-5]. This synergistic coupling mechanism enables the simultaneous exploitation of photon and photothermal energy, achieving precise modulation of photocarrier dynamics. It holds promise in high sensitivity photodetection, full spectrum energy harvesting, and intelligent optoelectronic systems [6, 7].

Despite the prominent merits of multi-effect coupling, current studies still encounter key bottlenecks that impede practical applications [8, 9]. Firstly, most PV-PTE coupling systems demand stringent operating conditions, typically relying on external strain, multilayer heterostructures, or sophisticated geometric design, which prevents intrinsic effect coupling on a simple, large-area material platform [10, 11]. Second, these artificially constructed architectures are poorly compatible with standard semiconductor micro/nanofabrication processes, hindering large-scale fabrication and integration [12, 13]. Third, conventional PTE materials are dominated by polycrystalline thin films, in which high-density grain boundaries and intrinsic structural defects are widely present. These defects not only act as carrier scattering centers to suppress the separation and transport of photocarriers but also disrupt phonon transport pathways and hinder directional thermal conduction [14-16]. As a result, efficient PV conversion and PTE transport cannot be realized concurrently, seriously weakening the synergistic enhancement effect of multi-physical effects. Lastly, existing multi-effect photodetectors focus merely on optimizing fundamental photodetection performance, without

extending unique features such as photoresponse polarity modulation to advanced applications [17-22]. This hinders the iterative upgrading of optoelectronic devices from single detection units to multi-degree-of-freedom and programmable intelligent optoelectronic functional devices.

To address these inherent bottlenecks and fundamental challenges, it remains an urgent scientific challenge to develop large-area materials with intrinsic PTE properties and integrate them with conventional wide-bandgap semiconductors into facile heterojunctions.

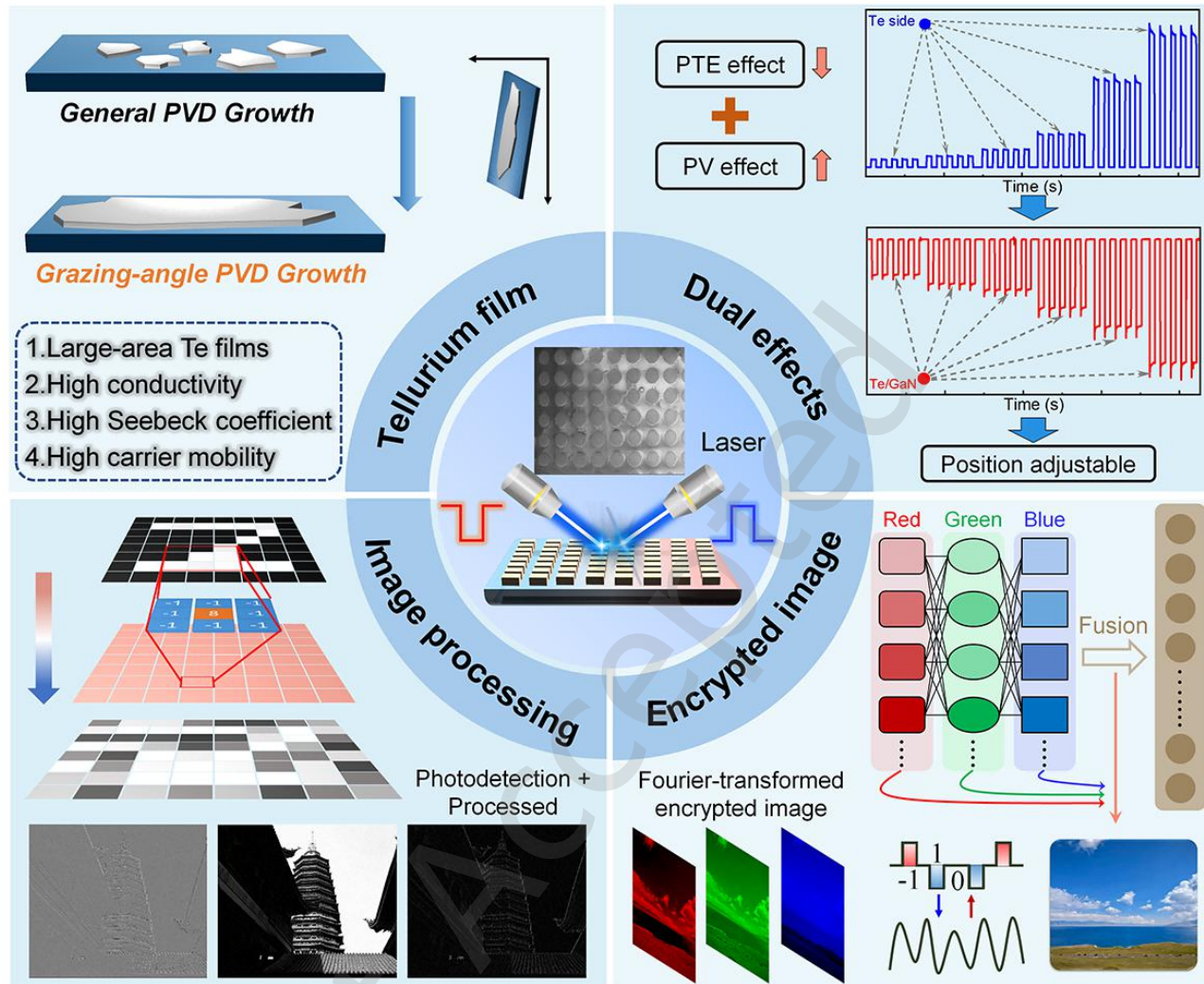


Figure 1. Schematic illustration of the multifunctional optoelectronic system based on Te-based devices. This platform integrates controllable growth of high-quality Te films, dual-effect synergistically enhanced photoresponse, and innovative computing architectures toward reconfigurable image processing and encrypted information transmission.

Recently, Tellurium (Te), a narrow-bandgap semiconductor with high carrier mobility and strong anisotropy, exhibits a pronounced intrinsic PTE effect, yet its practical deployment in high-performance multi-effect coupling devices remains constrained by insufficient design understanding, necessitating systematic and in-depth exploration. In this regard, this study proposes a facile scheme to prepare a large-area, high-quality Te films on GaN wafer (~2 inches) via glancing-incidence physical vapor deposition (GIPVD). Leveraging Te's high carrier mobility, superior electrical conductivity, and large Seebeck coefficient, the resulting Te/GaN vertical heterostructures exhibit stable, illumination-position-dependent bipolar photoresponse without external bias, strain, or complex structuring, thus enabling bias-free, highly competitive photoresponse performance. This recordable, location-programmable bipolar response arises from an intrinsic synergy of PV and PTE effects. Taking illumination position and response polarity as dual physical keys, the developed wafer-scale 20×20-pixel Te/GaN vertical heteroarrays platform can be

applied to high-security reconfigurable image processing and encrypted optical information transmission. This work transcends the inherent performance and flexibility trade-offs of single-effect devices, achieving intrinsic multi-effect coupling without external components. In doing so, it establishes a new paradigm for high-performance, programmable, and secure integrated optoelectronic chips. The overall concept of multi-effect synergy based on large-area Te films, including film growth, multi-effect coupling, and applications in reconfigurable image processing and encrypted information transmission, is illustrated in Figure 1.

2 Results and discussion

High-quality Te films were successfully fabricated on GaN substrates via GIPVD, and the corresponding growth procedure is depicted in Figure 2(a). In the synthesis, highly-purified Te powder served as precursor was vaporized at 445 °C, followed by deposition onto 30° tilted substrates under argon atmosphere. Compared with conventional normal-incidence deposition and other inclination angles

(Figure S1), this moderate glancing angle can effectively restrain excessive grain coarsening and elemental segregation, facilitating the acquisition of large-area, uniform, smooth and highly crystalline Te films [23-25]. An overly small incident angle restricts the surface migration space and diffusion length of deposited Te atoms, thereby triggering localized dense nucleation, disordered grain accumulation, elevated surface roughness and increased defect density [26]. In contrast, an excessively large incident angle gives rise to a prominent self-shadowing effect, which leads to inhomogeneous atomic flux distribution, impedes uniform film spreading and continuous substrate coverage, and ultimately causes porous, void-containing and island-

like film growth [27, 28]. By contrast, a moderate grazing angle of 30° significantly enhances atomic surface migration and spreading uniformity, promotes ordered grain growth along optimal crystallographic orientations, and thus greatly improves the crystalline quality, surface flatness and electrical performance of the Te films [29]. As revealed by X-ray diffraction (XRD) results in Figure 2(b), all diffraction peaks of the as-prepared films are well consistent with the standard PDF card of trigonal Te, demonstrating better crystalline quality than those of Te samples synthesized via conventional hydrothermal synthesis or thermal evaporation routes [30, 31].

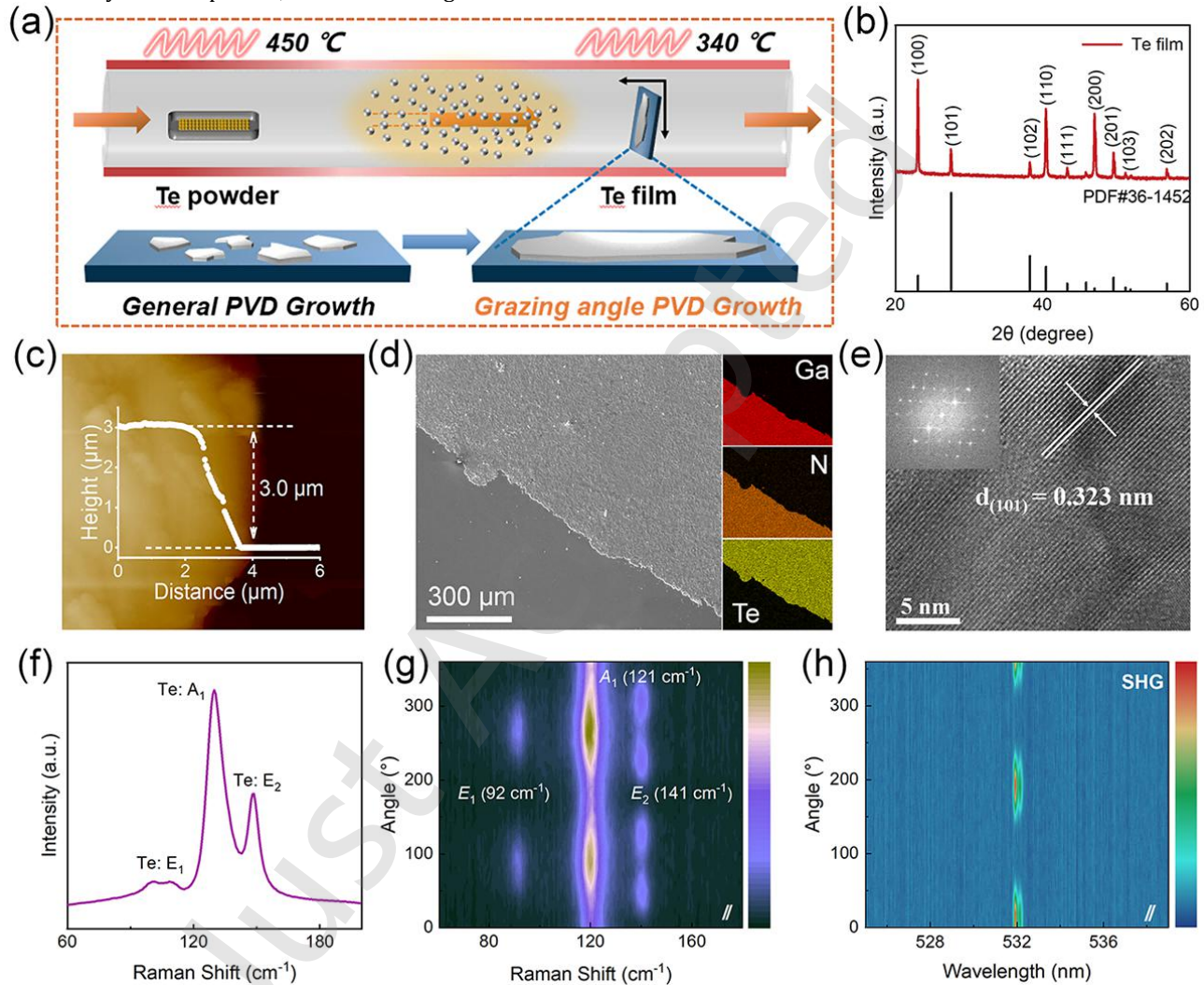


Figure 2 Preparation and characterization of Te films grown on GaN substrates. (a) Schematic illustration of the GIPVD method for fabricating Te films. (b) XRD pattern of the Te film. (c) AFM height profile. (d) SEM image of the Te/GaN heterojunction and corresponding elemental mapping of Ga, N, and Te. (e) HRTEM image of the Te film; the inset shows the FFT pattern. (f) Raman spectrum of the Te film. (g) Angle-resolved Raman mapping of the Te film. (h) Parallel-polarized SHG spectrum of the Te film.

The atomic force microscopy (AFM) height profiles in Figure 2(c) gives a film thickness of around $3.0 \mu\text{m}$ with a surface roughness below 100 nm , indicating good uniformity and controllability. Scanning electron microscopy (SEM) imaging, complemented by corresponding elemental mapping, unequivocally reveals a uniform Te overlayer on the GaN substrate, which are free of detectable voids or composition segregation, with a compact heterointerface (Figure 2(d)). This structural integrity serves as the foundation for efficient carrier transport. High-resolution transmission electron microscopy (HRTEM) in Figure 2(e)

reveals clear lattice fringes of 0.323 nm corresponding to the (101) plane of trigonal Te. The fast Fourier transform (FFT) pattern in the inset shows well-defined diffraction spots [32]. Raman spectroscopy (Figure 2(f)) reveals three characteristic vibration peaks of the Te film at 92 cm^{-1} , 121 cm^{-1} and 141 cm^{-1} , corresponding to the E_1 , A_1 and E_2 modes, respectively, which are fully consistent with the lattice vibration characteristics of Te. The peaks are sharp with no obvious broadening, indicating a low density of lattice defects [33]. Angle-resolved parallel-polarized Raman mapping (Figure 2(g)) clearly resolves these three

characteristic modes and their angular dependence. The E_1 and A_1 modes reach maximum intensity at 0° and 180° , whereas the E_2 mode exhibits an orthogonal angle-dependent behaviors, revealing the anisotropic structure of the Te crystal. Cross-polarized Raman measurements and the extracted polar plots further support the above conclusions (Figure S2). Figure 2(h) reveals a strong second harmonic generation (SHG) signal at 532 nm. Its anisotropic dependence on the parallel-polarization angle confirms the non-centrosymmetric structure and strong nonlinear optical activity of the Te film. The relating cross-polarized SHG measurements and polar plots further verify these anisotropic behaviors. In addition, the fitted slope of the SHG signal intensity of Te films versus excitation power is 2.09, which is highly consistent with the standard nonlinear response law of SHG (Figure S3). Rivaling the SHG

response intensity of previously reported two-dimensional Te nanosheets, the Te film unequivocally demonstrates exceptional nonlinear optical activity [34]. The linear output characteristic curves of the fabricated Te-based field-effect transistors (FET) verify the formation of high-quality ohmic contact between Te material and silver electrodes (Figure S4). Table S1 lists the key electrical parameters of the Te film obtained via quantitative calculations: a resistance of 22.8Ω , a conductivity of 146.2 S/cm , a carrier concentration of $4.7 \times 10^{16} \text{ cm}^{-3}$, and a carrier mobility of up to $217 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ determined by Hall measurement. These results clearly demonstrate that the as-prepared Te film exhibits superior carrier transport properties and high crystalline quality, providing a solid electrical foundation for the construction of high-performance optoelectronic devices.

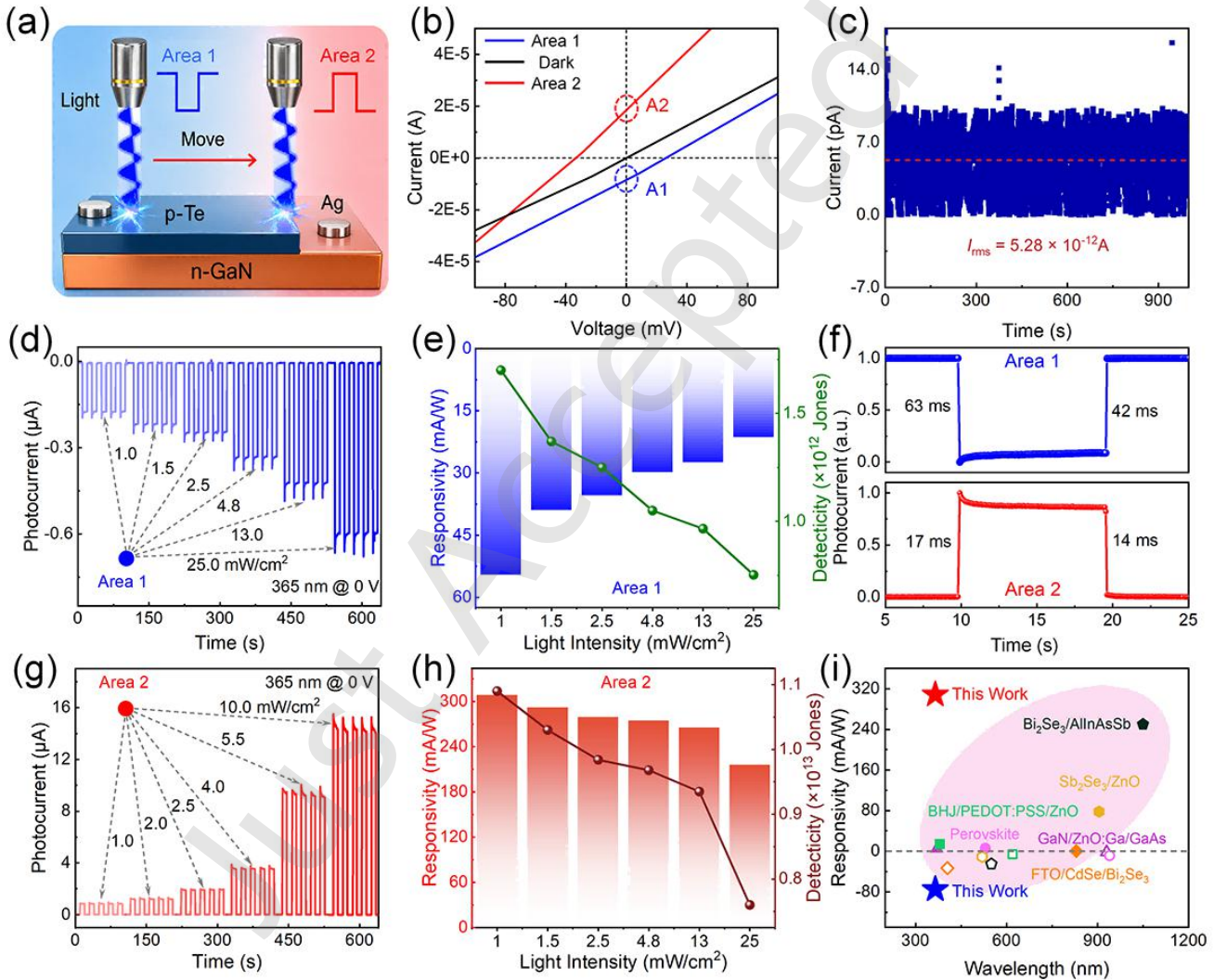


Figure 3 Photoresponse properties of the p-Te/n-GaN heterojunction device when operated under 365 nm illumination. (a) Schematic of the device structure and local photocurrent measurement. (b) I-V curves measured at Area 1, Area 2, and under dark state. (c) Time stability test of the dark current. (d) Transient photocurrent response as a function of light intensity under illumination on the Te side when tested under 365 nm light illumination. (e) When operated upon 365 nm illumination, the recorded R and D^* as functions of light intensity for the device at Te side. (f) Comparison of photoresponse speed for 365 nm illumination on the Te side versus at the Te/GaN interface. (g) Transient photocurrent response as a function of light intensity under illumination at the interface. (h) R and D^* as functions of light intensity for the device under interface illumination. (i) Performance comparison of R between this work and previously reported bipolar photodetectors.

The structure of the p-Te/n-GaN heterojunction device is shown in Figure 3(a). By irradiating pulsed light at Area 1 and Area 2, spatially resolved photocurrent measurements can be performed. The current-voltage (I - V)

curves of the heterojunction device under dark conditions show clear rectification, suggesting a strong built-in electric field at the junction (Figure S5). Under the same optical power, the photocurrent measurement of the device

within the 300-400 nm band shows a response peak at 365 nm (Figure S6). Under 365 nm illumination, the I - V curves of the device in Figure 3(b) exhibit a typical bipolar photoresponse behavior, confirming spatially switched polarity states of the photocurrent. The time stability test of the dark current (Figure 3(c)) shows a low root-mean-square dark current of $I_{\text{RMS}} = 5.28 \times 10^{-12}$ A, demonstrating excellent low-noise characteristics that provide a crucial foundation for high-sensitivity photodetection. The transient photocurrent responses under varying optical powers (Figures 3(d) and 3(g)) further reveal bipolar photocurrent behaviors when the illumination spot is positioned on the Te side versus at the heterojunction interface. Figures 3(e) and 3(h) extract the power-dependent responsivity and specific detectivity at different illumination positions. The corresponding spectral responsivity (R) and specific detectivity (D^*) of the device were calculated using Eqs. (1) and (2):

$$R = (I_{\text{ph}} - I_{\text{dark}}) / PS \quad (1)$$

$$D^* = \frac{R}{\sqrt{2eI_{\text{dark}} / S}} \quad (2)$$

Here, I_{ph} and I_{dark} represent the photocurrent and dark current, respectively. P and S denote the incident optical power density and the effective detection area. The parameters e , h , c , and λ stand for the elementary charge, Planck's constant, speed of light, and the incident light wavelength, respectively. Under positive and negative bipolar photoresponses, the maximum R and D^* reach 308.4 mA/W (54.5 mA/W) and 1.09×10^{13} Jones (7.52×10^{12} Jones), respectively. Furthermore, the bipolar photocurrent increases linearly with incident light power, and the

photocurrent curve on the Te side exhibits a larger slope, which is well consistent with the characteristics of the PTE effect (Figure S7) [35]. Additionally, the maximum LDR extracted from area 2 reaches 24.8 dB, indicating that this heterojunction device has a relatively wide signal-to-noise ratio performance.

Response speed measurements (Figure 3(f)) show that the rise/fall times are 63 ms and 42 ms, respectively, when the illumination is on the Te side, whereas the response speed is significantly improved when the heterojunction interface is illuminated, with rise/fall times of only 17 ms and 14 ms. This difference in response can be attributed to the fact that the PV effect is intrinsically faster than the thermal diffusion time scale (ms) of the PTE effect [36]. Stability tests confirm the excellent reliability of the bipolar device. Under continuous illumination for 3000 s and multiple cycling tests, the photocurrent shows no obvious decay or fluctuation, demonstrating outstanding long-term operational stability and anti-interference capability (Figure S8). Compared with a pristine GaN device, the Te/GaN heterojunction exhibits superior photodetection performance, with both responsivity and specific detectivity improved by three orders of magnitude and response speed increased by one order of magnitude (Figure S9). Figure 3(i) compares the performance of this work with that of previously reported bipolar photodetectors. The results indicate that the Te/GaN heterojunction achieves ultra-high responsivity in both positive and negative bipolar regimes, significantly outperforming most polarity-switchable photodetector material systems. This extraordinary photoresponse enhancement and reversible polarity switching go beyond the explanation based solely on a built-in electric field, and will be discussed in detail below.

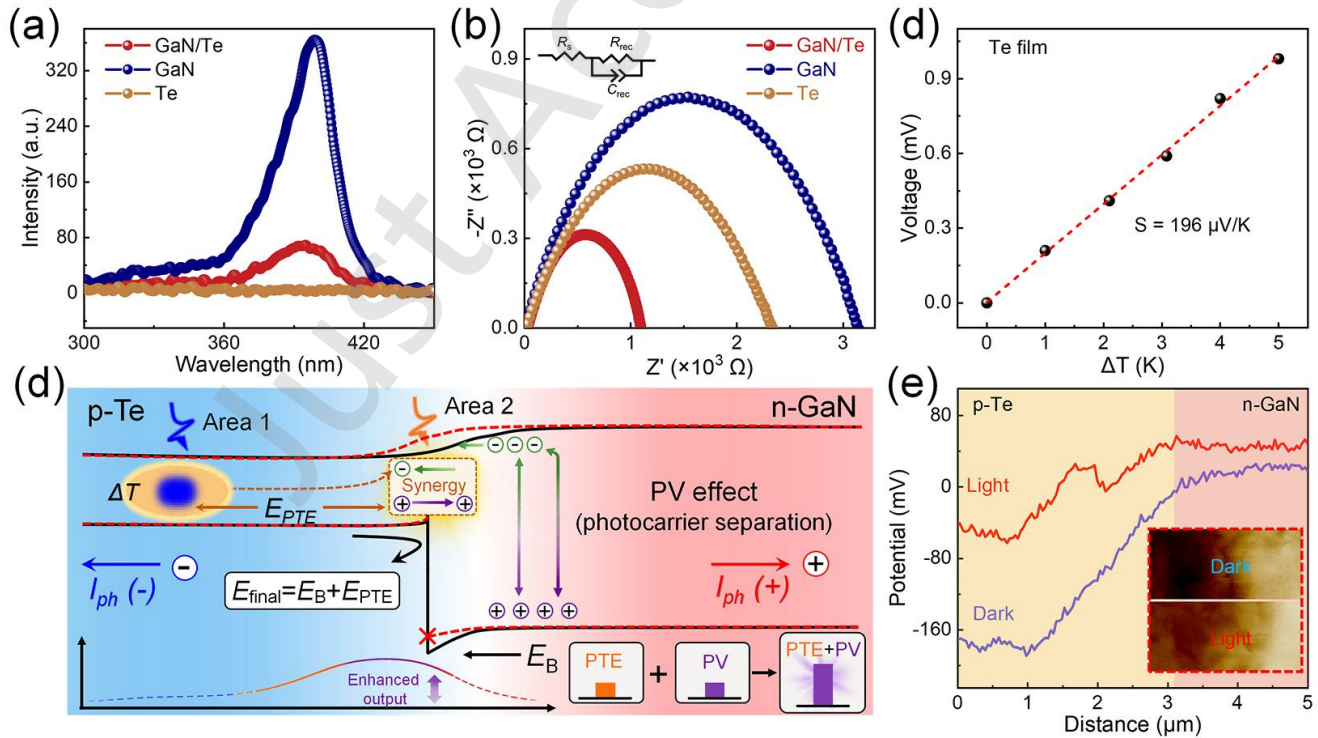


Figure 4 Optical, electrical and physical mechanism analysis of the Te/GaN heterojunction. (a) PL of Te, GaN, and the resulted Te/GaN heterostructure. (b) Impedance spectra of the three samples. (c) Seebeck coefficient measurement of Te films. (d) Schematic diagram of carrier transport mechanism. (e) Surface potential distribution of the Te/GaN heterojunction under dark and illuminated conditions.

To understand the origin of this position-dependent bipolar device behavior and the enhanced photovoltaic effect,

it is essential to elucidate the interfacial band engineering and multiphysics coupling mechanisms of the Te/GaN heterojunction. Photoluminescence spectroscopy (PL) shows that, compared with pristine GaN, the emission peak intensity of the Te/GaN heterojunction is significantly reduced and the peak position is red-shifted, which is attributed to charge transfer and energy relaxation processes at the heterointerface (Figure 4(a)). Electrochemical impedance spectroscopy (Figure 4(b)) further reveals the interfacial transport characteristics. The charge transfer resistance (R_{ct}) of the Te/GaN heterojunction is substantially lower than that of the GaN and Te samples. This indicates that the construction of the heterojunction effectively promotes the separation and transport of photocarriers, suppresses carrier recombination, thus providing a crucial interfacial foundation for the enhanced

photoresponse and stable bipolar modulation [37]. The effective charge density overlap between Te and GaN is less than $1.0 \times 10^{-1} \text{ e } \text{\AA}^{-3}$, indicating that the two materials are bonded through van der Waals interactions (Figure S10) [38]. The PTE characteristics of the Te film can be directly characterized by Seebeck coefficient measurements. Figure 4(c) shows a Seebeck coefficient $S = 196 \text{ } \mu\text{V/K}$. The positive value indicates that the film is a p-type semiconductor with holes as the majority carriers. Compared with conventional PTE materials, the as-prepared Te film exhibits a stronger thermoelectric effect and superior thermoelectric performance (Table S2). Moreover, we experimentally verified the presence of a pronounced PTE effect in the pure Te film using a lateral photodetector device structure (Figure S11).

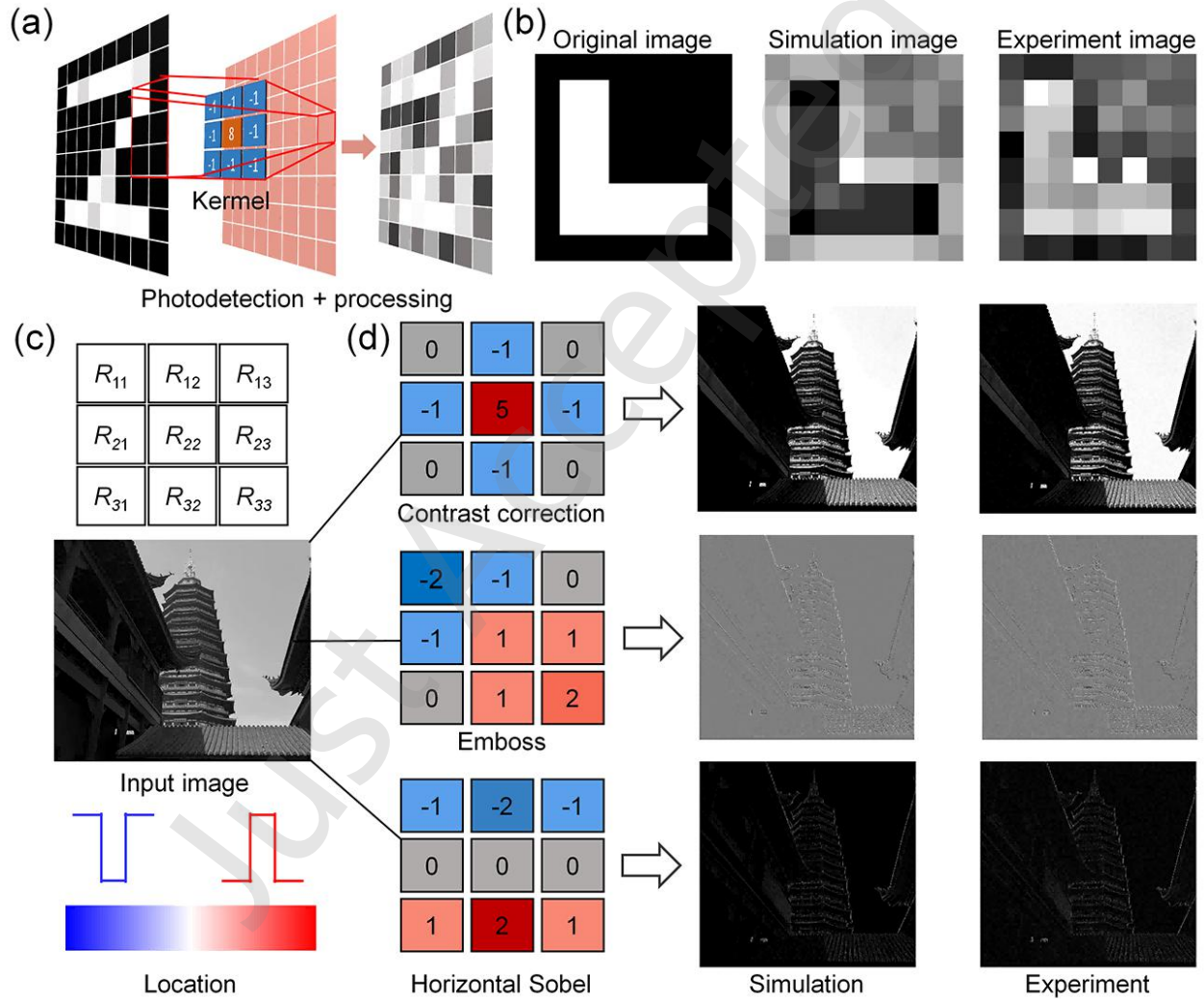


Figure 5 In-sensor convolutional image processing enabled by reconfigurable photodetection. (a) Schematic diagram of simultaneous sensing and preprocessing using array devices as convolutional kernels. (b) Edge enhancement demonstration of the letter “L” pattern. (c) Working principle of the mapping kernel for projecting input optical images onto the device pixel array. (d) Grayscale output images obtained by convolving the original input images with different functional processing kernels.

To elucidate the negative photoresponse behaviors in the heterojunction device, Figure 4(d) presents a schematic energy band based on the PTE effect and barrier modulation. Based on ultraviolet photoelectron spectroscopy (UPS) and density functional theory (DFT) calculations, Figure S12 presents the band structure of the Te/GaN heterojunction

before contact, providing a theoretical basis for understanding the formation of the built-in electric field and the charge transfer mechanism at the interface. When light illuminates the Te side, the photon energy is efficiently absorbed by the narrow-bandgap Te and converted into local heat, generating an asymmetric temperature gradient

along the device direction. Due to the PTE of Te, the photogenerated hot holes, as majority carriers, diffuse from the high-temperature region to the low-temperature region in response to the temperature gradient. Their migration direction is opposite to the forward carrier transport path of holes from Te to GaN, thereby producing a negative photocurrent signal in the external circuit. At the heterojunction interface, PTE-driven hot holes accumulate positive charge on the Te side of the Te/GaN interface. This accumulation induces a local upward band bending at the interface (indicated by the red dashed line in the figure), leading to a widening of the depletion layer on the Te side and a narrowing of the depletion layer on the GaN side. This band reconstruction significantly raises the barrier height, strongly impeding the forward transport and diversion of photogenerated holes from Te to GaN. Meanwhile, the diffusion direction of the PTE-driven holes is highly consistent with the direction of the built-in electric field, resulting in an energy superposition effect ($E_{\text{Final}} = E_B + E_{\text{PTE}}$) that further reinforces the reverse migration of holes toward the Te side. This synergistic effect of blocked forward transport and enhanced reverse diffusion ultimately amplifies the negative photocurrent on the Te side, revealing the coupling mechanism between the PTE effect and interfacial band engineering in device transport. Kelvin probe force microscopy characterization in Figure 4(e) directly visualizes the potential distribution at the heterojunction interface. Under dark conditions, the contact potential difference between p-Te and n-GaN is approximately 160 mV and decreases to 80 mV upon illumination. This interfacial potential variation originates from charge accumulation, confirming that PTE-driven hot holes induce positive charge accumulation on the Te side of

the Te/GaN interface.

Moreover, the structural model clearly reveals that obvious lattice distortion occurs in the Te layer after heterojunction formation (Figure S13). Such structural distortion effectively suppresses carrier-carrier scattering, prolongs the carrier relaxation lifetime, and increases the carrier mean free path, thereby prominently boosting the generation and transport of hot carriers [39, 40]. Infrared thermography intuitively characterizes the thermal distribution evolution of the device under light irradiation (Figure S14). Under dark conditions, the device exhibits a uniform surface temperature of approximately 22.9 °C. Under 365 nm illumination on the GaN and Te sides, the surface temperature increases to 24.1 °C and 29.7 °C, respectively, forming distinct localized hot spots at the irradiation regions. The more prominent temperature rises under Te-side illumination benefits from the superior light absorption and photothermal conversion capability of Te. When the GaN side is illuminated, ultraviolet-excited photocarriers in GaN are efficiently collected by the external circuit, producing a positive photocurrent (Figure S15). However, the interfacial valence-band barrier impedes the transport of photogenerated holes toward the Te side, resulting in reduced collection efficiency and consequently a significantly lower photocurrent amplitude than that under heterojunction illumination. The above physical mechanisms are highly consistent with the position-dependent photocurrent measurements (Figure S16). Notably, the heterojunction device still outputs a stable negative photocurrent under broadband illumination on the Te side (Figure S17), which further verifies the dominant role of the intrinsic PTE effect of Te films [41].

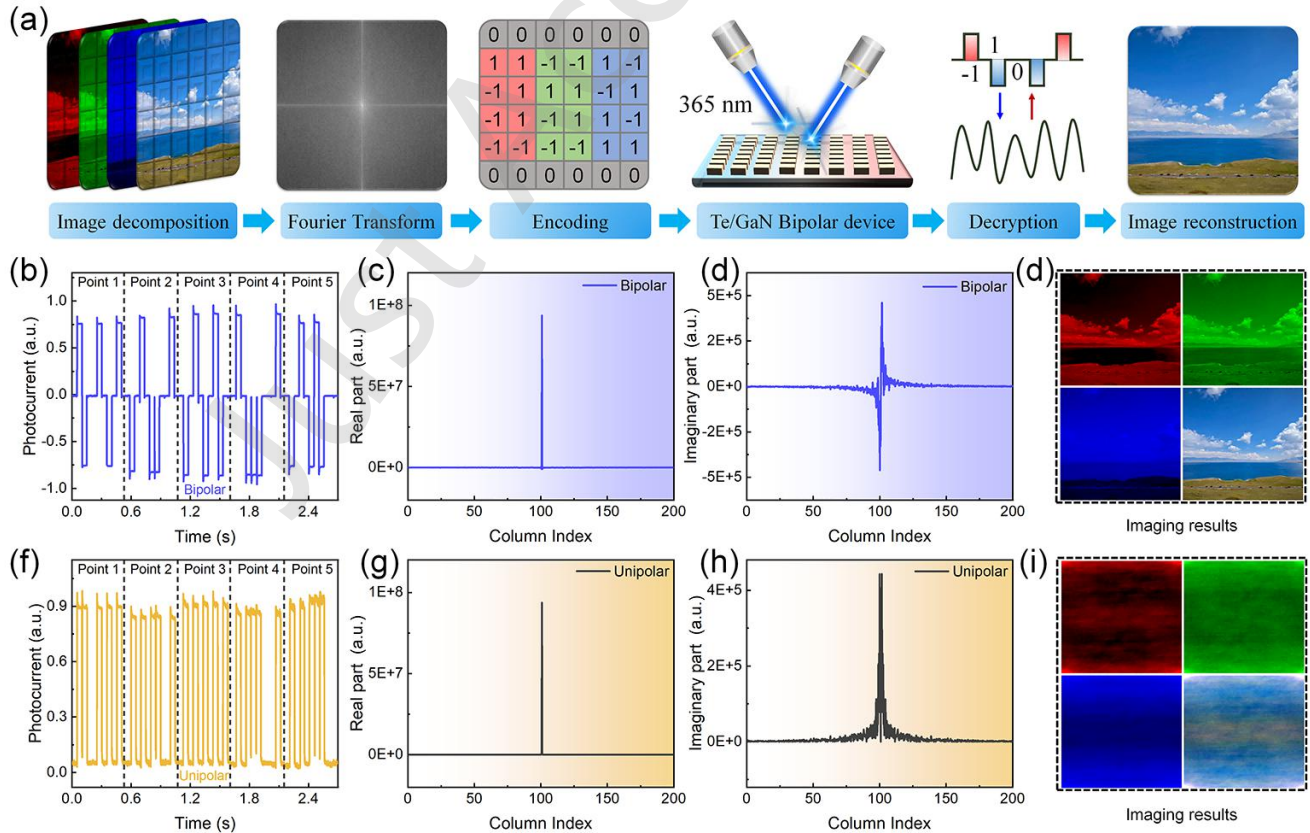


Figure 6 Secure optical image transmission system. (a) Schematic illustration of Fourier transform-based secure optical image communication strategy. Relationships between photocurrents and Fourier transform values for (b) bipolar devices and (f) unipolar devices, respectively. The real parts of (c) bipolar devices and (g) unipolar devices after Fourier transformation. The imaginary parts of (d) bipolar devices and (h) unipolar devices after Fourier transform. Image transmission results based on (e)

bipolar devices and (i) unipolar devices.

To explore the practical application potential of bipolar photoresponse devices, we fabricated a wafer-scale 20×20 Te film array on an n-GaN substrate. Systematic macroscopic and microscopic morphological characterizations were performed on the as-fabricated Te/GaN heterojunction arrays (Figure S18). The arrays exhibit excellent uniformity and structural integrity across the wafer-scale GaN substrate, featuring well-defined and densely distributed Te pixel units, which confirms the high uniformity and reproducibility of the fabrication strategy. The core superiority of this array lies in its unique spatial multiplexing capability: each pixel can independently generate photocurrent with precisely tunable polarity and amplitude relying on localized illumination positions, thereby extending the “illumination position” as a brand-new parallel multichannel encoding resource. Featuring tunable photoresponse polarity and high responsivity, the Te/GaN heterojunction devices provide a reliable hardware foundation for high-efficiency in-sensor image preprocessing. Leveraging the unique bipolar photoresponse of the Te/GaN heterojunction, a proof-of-concept in-sensor convolutional network for edge image computing is demonstrated (Figure 5(a)). The position-programmable bipolar photoresponse of each pixel unit in the device array can be equivalent to reconfigurable analog convolutional kernel weights, while the excellent linear correlation between photocurrent and incident optical power ensures the accurate mapping of image pixel gray values to the photoelectric signal domain.

This principle leverages linear photoresponse to accurately map the grayscale value of each pixel to photocurrent, and adopts position-programmable bipolar photoresponse as reconfigurable analog convolutional kernels. Relying on this mechanism, the output photocurrent collected from the device array directly realizes edge enhancement for the binary image of the letter “L” (Figure 5(b)). This characteristic further enables direct encoding of convolutional weights into a responsivity matrix (R_{ij}), transforming the sensor array into a dynamically programmable image processor (Figure 5(c)). On this basis, the array device is capable of performing multiple grayscale image processing tasks, including contrast correction, emboss, and horizontal Sobel edge detection, demonstrating its excellent adaptability to diverse image transformation tasks (Figure 5(d)). The experimental results are in highly consistent with the simulation results, verifying the outstanding operational reliability and scalable application potential of the bipolar array devices in the field of reconfigurable vision. Integrating synchronous photodetection and on-chip image preprocessing, the Te/GaN heterojunction array fundamentally optimizes the hardware architecture of image processing, achieving substantial improvements in computational speed and data processing efficiency for visual perception tasks.

Leveraging the position-dependent bipolar photoresponse of Te/GaN devices, this device possesses unique advantages in secure image information processing. Figure 6(a) illustrates the technical route for encrypted image reconstruction. The input image is split into red, green and blue channels, and frequency-domain information is acquired through Fourier transformation (Figure S19). The bipolar signals from the Te side and the heterojunction region are encoded as dual-mode electrical signals of “1” and “-1”, enabling full encoding of both real and imaginary components. After modulation by bipolar devices, these

signals are decoded and reconstructed to realize high-fidelity image output. Figure 6(b) compares photocurrent values collected at typical sampling points on the 100th row of Fourier-transformed blue-channel data (Table S3). The Fourier transform results from the bipolar device (Figures 6(c) and 6(d)) show distinct sharp peaks and an ultralow noise level, demonstrating excellent signal processing precision and anti-interference capability, which ensures accurate decoding. The reconstructed images match well with the original ones in color and fine details, benefiting from complete coded information transmission based on bipolar photoresponse characteristics (Figure 6(e)). Both bipolar and unipolar devices can receive coordinate information, whereas only bipolar devices can accurately restore the polarity features of real and imaginary part signals. In contrast, the transient photocurrent response of the unipolar device (Figure 6(f)) only generates single-polarity photocurrent and fails to encode negative signal components. Its Fourier transform results (Figures 6(g) and 6(h)) present obviously broadened signal peaks and elevated background noise, leading to a marked decrease in signal fidelity. These waveform differences result in pronounced changes in the reconstructed image. The reconstructed image (Figure 6(i)) presents obvious color distortion and severe detail loss. Benefiting from its unique bipolar photoresponse characteristics and pixelated integrated structure, this parallel multi-channel optical communication array effectively boosts both signal transmission efficiency and information security. By introducing new dimensions such as illumination position, it effectively suppresses signal crosstalk and improves anti-decryption capability, providing an innovative and promising strategy for constructing high-security optical communication systems.

3 Conclusions

In summary, this work introduces large-area, wafer-scale Te/GaN heterojunction arrays that transcend the fundamental constraints of single-effect photodetectors, thereby breaking through the Shockley-Queisser limit and overcoming rigid operational modes. By growing highly crystalline, oriented Te films on GaN chips via a GIPVD scheme, we harness the intrinsic PTE property of Te to achieve bias-free, position-programmable bipolar photoresponse. The synergy between the PTE effect in Te and the PV effect at the heterointerface yields exceptional figures of merit: positive and negative responsivities of 308.4 mA/W and 54.5 mA/W, specific detectivities reaching 1.09×10^{13} Jones and 7.52×10^{12} Jones, alongside ms-level response speed, respectively, outperforming previously reported bipolar detectors. Leveraging illumination position and response polarity as dual physical keys, our array devices enable reconfigurable convolutional image preprocessing and Fourier-transform-based encrypted optical image transmission, dramatically enhancing processing efficiency and security. This work conclusively demonstrates that multi-effect synergy can be realized in an integrable platform without external fields or complex structuring, thereby breaking the performance and functional bottlenecks of conventional optoelectronics. The wafer-scale, intelligent Te/GaN chips establish a universal route toward high-security, programmable, integrated photonic systems, propelling photodetection from isolated

sensing units to multi-degree-of-freedom smart processing platforms.

4 Experimental

4.1 Preparation of Te films

In this work, high-purity Te powder (99.99%, Aladdin) was adopted as the precursor for the well-controlled growth of Te films via grazing-incidence physical vapor deposition (GIPVD). All experiments were conducted in a two-temperature-zone vacuum tube furnace equipped with independent temperature control units. Before film growth, substrate was ultrasonically cleaned to eliminate surface residual impurities for high surface cleanliness. In the deposition process, Te powder was loaded into the first temperature zone as the evaporation source, and the substrate was placed in the second zone at a fixed tilted angle, with the source-to-substrate distance kept at about 25 cm. Prior to synthesis, the furnace chamber was configured to an oxygen-free atmosphere. The system was vacuumized and flushed with high-purity argon for 10 min to exhaust air, and such evacuation and gas flushing operations were repeated to fully eliminate internal impurities. During synthesis, the first temperature zone was heated to 445 °C within 30 min, and the second zone was raised to 335 °C in 25 min. Both zones were maintained at the set temperatures for 30 min. After deposition finished, the system was naturally cooled down to room temperature under continuous argon protection at a flow rate of 25 sccm. Ultimately, large-area, high-quality Te films with tunable morphology were successfully prepared on the substrate.

4.2 Fabrication of the Te/GaN Array Photodetectors

The n-GaN substrates were ultrasonically cleaned with deionized water to guarantee superior surface cleanliness. A tailored shadow mask was then affixed onto the substrate surface, and the assembled sample was transferred into the second temperature zone of the vacuum tube furnace. The following growth parameters and procedures, including the natural cooling process, remained identical to those used for pure Te film preparation. After the growth process finished and the shadow mask was detached, well-defined 20×20 n-GaN/p-Te heterojunction device arrays were successfully fabricated.

4.3 Material characterization

The crystal structure of Te films was characterized via an X-ray diffractometer (XRD) with Cu K α radiation. The surface morphology and microscale size information were observed by an Olympus BX51 optical microscope and a JSM-7500F scanning electron microscope (SEM), and energy-dispersive X-ray spectroscopy (XPS) was adopted to conduct qualitative and quantitative elemental analysis of Te/GaN heterojunctions. The surface roughness and film thickness were accurately tested using a Bruker Dimension Icon atomic force microscope. Raman and second-harmonic generation (SHG) spectra were collected on a high-resolution and high-speed multi-physical scanning integrated characterization system (Metatest, ScanPro Advance). In terms of optoelectronic property measurement, a wavelength-tunable xenon lamp served as the light excitation source, and the photoresponse behaviors of Te/GaN photodetectors were systematically investigated by combining a Metatest ScanPro laser scanning system and a

Keysight B1500A semiconductor parameter analyzer.

4.4 Theoretical Simulation

All theoretical simulations in this work were performed using the CASTEP module within the Materials Studio software package. All structural optimizations were implemented by solving the Kohn-Sham equations, adopting the electron density functional $\rho(r)$ to describe the quantum state of the system. The exchange-correlation interaction was treated using the generalized gradient approximation (GGA) with the Perdew-Burke-Ernzerhof (PBE) functional. Norm-conserving pseudopotentials were employed to describe the ion-electron interactions. The plane-wave cutoff energy was set to 280.0 eV, and a $2 \times 2 \times 2$ k-point grid was used. The self-consistent field (SCF) convergence threshold for the energy per atom was set to 1.0×10^{-5} eV. During structural optimization, the convergence criteria for atomic forces and maximum atomic displacement were defined as 0.02 Ha nm $^{-1}$ (approximately 0.01 eV Å $^{-1}$) and 0.0005 nm, respectively. The optimization was terminated only when all convergence requirements were simultaneously satisfied.

Electronic Supplementary Material: Supplementary material is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909110>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

Acknowledgements

This work was supported by National Natural Science Foundation of China (Grant Nos. 12374257, 62404101 and 62564011). Interdisciplinary Innovation Fund for Doctoral Students of Nanjing University of Aeronautics and Astronautics (No. KXKCXJJ202609), the Young Scientists Fund (Type A) of the Natural Science Foundation of Inner Mongolia Autonomous Region of China (Grant No. 2026QA016), the Youth Scientific Research Talent Cultivation Project of Inner Mongolia University (Grant No. 21700-5263702) and the Inner Mongolia University Experimental Technology Research Project in 2026 (Self-Made and Modified Equipment Project) (Grant No. SYJS2026007). We acknowledge the facilities in the Center for Microscopy and Analysis at Nanjing University of Aeronautics and Astronautics, and the Jushang Scientific Research Service Platform (www.jsceshi.cn).

Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

L. J. L.: Validation, writing manuscript. P. W.: Writing manuscript, experimental design. W. Y. L. and L. L. C.: Data curation, validation. Z. Y. C. and M. H. L.: Data curation. C. X. K.: Project administration. D. N. S.: Project administration, funding acquisition. Z. L.: Funding acquisition. M. M. J.: Project administration, writing manuscript. All the authors have approved the final manuscript.

Use of AI statement

None.

References

- [1] Li, Z. and Wei, B.; Surpassing Shockley-Queisser Efficiency Limit in Photovoltaic Cells. *Nano-Micro Lett.* **2025**, 17, 330.
- [2] Zhang, X.; Wang, S.; Zhang, Z.; Ma, L.; Tao, L.; Chen, J.; Zhong, Z.; Wang, S.; Zhang, J.; Huang, Z.; Lin, Z.; Bo, X.; Yan, Z.; Pan, W.; Bai, Y.; Ouyang, C.; Zhu, C.; Yang, X., and Li, Y.; Minimizing the VOC deficit by regulating facets of wide-bandgap perovskite for monolithic perovskite/silicon tandem solar cells. *eScience* **2026**, 6, 100563.
- [3] Liu, G.; Guo, F.; Zhang, M.; Liu, Y.; Hao, J.; Yu, W.; Li, S.; Hu, B.; Zhang, B., and Hao, L.; All-in-One Optoelectronic Logic Gates Enabled by Bipolar Spectral Photoresponse of CdTe/SnSe Heterojunction. *ACS Appl. Mater. Interfaces* **2023**, 15, 29375-29383.
- [4] Zeng, Z.; Ge, C.; Braun, K.; Eberle, M.; Wang, Y.; Zheng, B.; Zhu, C.; Sun, X.; Huang, L.; Luo, Z.; Chen, Y.; Duan, H.; Wang, S.; Li, D.; Gao, F.; Pan, A., and Wang, X.; Manipulating Picosecond Photoresponse in van der Waals Heterostructure Photodetectors. *Adv. Funct. Mater.* **2022**, 32, 2200973.
- [5] Kettemann, S. and Guillemoles, J.-F.; Thermoelectric field effects in low-dimensional structure solar cells. *Physica E* **2002**, 14, 101-106.
- [6] Guo, C.; Qian, W.; Dan, H.; Xu, Y.; Xu, L.; Bowen, C. R., and Yang, Y.; Programmable Bipolar Photocurrents in Water-Templated Nanoporous Ferroelectrics for Filter-Free Spectral Recognition. *Adv. Mater.* **2026**, 38, e72876.
- [7] Fu, P.; Yang, D.; Chen, Y.; Lu, R.; Haque, M. A.; Liu, Y.; Han, Y.; Li, H.; Chen, R.; Liu, J.; Qin, W.; Hernandez, L. H.; Fan, F.; Wu, K.; Baran, D.; Zhou, H., and Li, C.; Synergistic cooperation between photovoltaic and thermoelectric effects in solar cells. *Energy Environ. Sci.* **2025**, 18, 7082-7088.
- [8] Yu, X.; Ji, Y.; Shen, X., and Le, X.; Progress in Advanced Infrared Optoelectronic Sensors. *Nanomaterials* **2024**, 14, 845.
- [9] Li, X.; Zhao, L.; Luo, H.; Zhang, M.; Tang, Z.; Liu, Z.; Ma, N., and Wang, G.; Ferroelectricity and Interfacial Engineering in Low-Bandgap $\text{Ag}_{0.9}\text{K}_{0.1}\text{NbO}_3$: Achieving Robust Coexistence of Piezo/Pyro/Photovoltaic Effects for Multimodal Tactile Sensing. *Adv. Funct. Mater.* **2025**, 35, 2508001.
- [10] Guo, C.; Qian, W.; Dan, H.; Xu, Y.; Xu, L.; Bowen, C. R., and Yang, Y.; Programmable Bipolar Photocurrents in Water-Templated Nanoporous Ferroelectrics for Filter-Free Spectral Recognition. *Adv. Mater.* **2026**, 38, e72876.
- [11] Xu, D.; Liu, Q.; Liang, B.; Yu, N.; Ma, X.; Xu, Y.; Taniguchi, T.; Ding, C.; Lake, R. K.; Yan, R., and Liu, M.; Deciphering photocurrent mechanisms at the nanoscale in van der Waals interfaces for enhanced optoelectronic applications. *Sci. Adv.* **2025**, 11, eadv7614.
- [12] Liu, Y.; Sun, W.; Sa, Z.; Li, R.; Yang, Z.; Jia, Y.; Sun, X., and Chen, F.; Ultrafast and Ultra-Broadband Ferroelectric Photo-Pyroelectric Detectors with Long-Term Stability. *Adv. Funct. Mater.* **2025**, 35, 2502467.
- [13] Hu, C.; Liu, X.; Dan, H.; Guo, C.; Zhang, M.; Bowen, C. R., and Yang, Y.; Quantifying the pyroelectric and photovoltaic coupling series of ferroelectric films. *Nat. Commun.* **2025**, 16, 828.
- [14] Zhu, R.; Liu, X.; Lu, H.; Long, G.; Ji, X., and Liang, J.; Solid-State N-Type Ionic Thermoelectric Based on Polyanions Enabled by Water State Regulation via MXenes. *Adv. Mater.* **2026**, 38, e17406.
- [15] Ma, X.; Zhao, J.; Shou, D., and Liu, Y.; A Highly-Flexible and Breathable Photo-Thermo-Electric Membrane for Energy Harvesting. *Adv. Energy Mater.* **2024**, 14, 2304032.
- [16] Zhang, M.; Shen, Y.; Wu, C.; Liu, R.; Xie, W.; Zhang, Y.; Weidenkaff, A.; Cai, K., and Lu, Y.; Screen-printed Bi_2Se_3 -modified Ag_2Se -based free-standing nanocomposite films for high-performance flexible thermoelectrics. *Adv. Compos. Hybrid Mater.* **2026**, 9, 136.
- [17] Liu, Z.; Wang, R.; Han, J.; Chen, T.; Deng, Z.; Sun, Y.; Zhao, Y., and Chen, A.; Double-Sided Bifunctional Blue-Green Light Photodetector Based on Liquid Crystalline Polymer for Light Positioning and Health Monitoring. *Adv. Funct. Mater.* **2025**, 35, 2424645.
- [18] Liu, Z.; Zhang, N.; Zhao, X.; Liu, M.; Shi, Y.; Qi, L.; Zou, Y.; Chang, C.; Tan, F.; Li, D., and Li, S.; High-Performance Broadband Integrated Detection System for Multifunctional Applications. *ACS Nano* **2025**, 19, 22414-22423.
- [19] Sun, Y.; Tang, Y.; Jiang, X.; Yan, A.; Zhao, J.; Wang, Y.; Luo, J.; Jiang, J.; Ding, K.; Zhang, H.; Li, H.; Pang, D.; Ye, L., and Li, W.; Multiband bipolar photoresponse in $\text{Cu@CuOx@a-Ga}_2\text{O}_3$ core-shell heterostructure-based self-powered photoelectrochemical-type photodetector for secure underwater optical communication. *Chem. Eng. J.* **2025**, 525, 170508.
- [20] Zhang, Y.; Su, H.; Li, H.; Xie, Z.; Zhang, Y.; Zhou, Y.; Yang, L.; Lu, H.; Yuan, G., and Zheng, H.; Enhanced photovoltaic-pyroelectric coupled effect of $\text{BiFeO}_3/\text{Au}/\text{ZnO}$ heterostructures. *Nano Energy* **2021**, 85, 105968.
- [21] Park, T.; Na, J.; Kim, B.; Kim, Y.; Shin, H., and Kim, E.; Photothermally Activated Pyroelectric Polymer Films for Harvesting of Solar Heat with a Hybrid Energy Cell Structure. *ACS Nano* **2015**, 9, 11830-11839.
- [22] Wang, K.; Hou, Y.; Poudel, B.; Yang, D.; Jiang, Y.; Kang, M.-G.; Wang, K.; Wu, C., and Priya, S.; Melanin-Perovskite Composites for Photothermal Conversion. *Adv. Energy Mater.* **2019**, 9, 1901753.
- [23] Grüner, C.; Liedtke, S.; Bauer, J.; Mayr, S. G., and Rauschenbach, B.; Morphology of Thin Films Formed by Oblique Physical Vapor Deposition. *ACS Appl. Nano Mater.* **2018**, 1, 1370-1376.
- [24] Xiao, X.; Dong, G.; Shao, J.; He, H., and Fan, Z.; Optical and electrical properties of $\text{SnO}_2\text{:Sb}$ thin films deposited by oblique angle deposition. *Appl. Surf. Sci.* **2010**, 256, 1636-1640.
- [25] Lintymer, J.; Gavaille, J.; Martin, N., and Takadom, J.; Glancing angle deposition to modify microstructure and properties of sputter deposited chromium thin films. *Surf. Coat. Technol.* **2003**, 174-175, 316-323.
- [26] Li, K.-D. and Dong, Y.-W.; Modeling the influence of incident angle and deposition rate on a nanostructure grown by oblique angle deposition. *J. Phys. D: Appl. Phys.* **2017**, 50, 065302.
- [27] Mes-adi, H.; Saadouni, K., and Mazroui, M.; Effect of incident angle on the microstructure properties of Cu thin film deposited on Si (001) substrate. *Thin Solid Films* **2021**, 721, 138553.
- [28] Weng, Z.; Zhang, F.; Xu, C., and Zhou, J.; The effect of incident energy, incident angle and substrate temperature on surface morphology and atomic distribution of NiTi films. *Mater.*

Des. **2020**, 187, 108350.

- [29] Tian, G.; Li, X.; Chai, P., and Wang, Y.; Effect of deposition angle on the deposition rate, microstructure, electrical and optical properties of magnetron sputtered ZrB_2 thin films. *Mater. Lett.* **2023**, 348, 134696.
- [30] Zhang, P.; Liang, Q.; Zhou, Q.; Chen, J.; Li, M.; Deng, Y.; Liang, W.; Zhang, L.; Zhang, Q.; Gu, L.; Ge, C.; Jin, K.-j.; Zhang, C., and Yang, G.; High-performance terahertz modulators induced by substrate field in Te-based all-2D heterojunctions. *Light Sci. Appl.* **2024**, 13, 67.
- [31] Zhao, Y.; Zhao, S.; Pang, X.; Zhang, A.; Li, C.; Lin, Y.; Du, X.; Cui, L.; Yang, Z.; Hao, T.; Wang, C.; Yin, J.; Xie, W., and Zhu, J.; Biomimetic wafer-scale alignment of tellurium nanowires for high-mobility flexible and stretchable electronics. *Sci. Adv.* **2024**, 10, eadm9322.
- [32] Dasika, P.; Samantaray, D.; Murali, K.; Abraham, N.; Watanabe, K.; Taniguchi, T.; Ravishankar, N., and Majumdar, K.; Contact-Barrier Free, High Mobility, Dual-Gated Junctionless Transistor Using Tellurium Nanowire. *Adv. Funct. Mater.* **2021**, 31, 2006278.
- [33] Hussain, N.; Ahmed, S.; Tepe, H. U.; Ullah, K.; Shehzad, K.; Wu, H., and Shcherbakov, M. R.; Giant Thermomechanical Bandgap Modulation in Quasi-2D Tellurium. *Adv. Funct. Mater.* **2024**, 34, 2407812.
- [34] Fu, Q.; Cong, X.; Xu, X.; Zhu, S.; Zhao, X.; Liu, S.; Yao, B.; Xu, M.; Deng, Y.; Zhu, C.; Wang, X.; Kang, L.; Zeng, Q.; Lin, M.-L.; Wang, X.; Tang, B.; Yang, J.; Dong, Z.; Liu, F.; Xiong, Q.; Zhou, J.; Wang, Q.; Li, X.; Tan, P.-H.; Tay, B. K., and Liu, Z.; Berry Curvature Dipole Induced Giant Mid-Infrared Second-Harmonic Generation in 2D Weyl Semiconductor. *Adv. Mater.* **2023**, 35, 2306330.
- [35] Liao, J.; Shao, H.; Zhang, Y.; Yan, Y.; Zeng, J.; Lan, C.; Gao, B.; Chen, D.; Quan, Q.; Xie, P.; Meng, Y., and Ho, J. C.; Infrared In-Sensor Computing Based on Flexible Photothermoelectric Tellurium Nanomesh Arrays. *Adv. Mater.* **2025**, 37, 2419653.
- [36] Yoo, C.; Lee, C. W.; Kamyani, A. M. S. S. A.; Han, S. S.; Cao, J.; Shin, H.-K.; Song, Y.-J.; Kim, J. H., and Jung, Y.; Wafer-Scale Tellurium Nanotube Meshes for Optically Modulated and Mechanically Flexible Artificial Synapses. *Nano Lett.* **2025**, 25, 9166-9174.
- [37] Sun, H.; Wang, Y. F.; Liu, Y. F.; Wu, R. F.; Chang, A. M.; Zhao, P. J., and Zhang, B.; Enhanced Thermal Stability and Broad Temperature Range in High-Entropy $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})\text{NbO}_4$ Ceramics. *ACS Appl. Mater. Interfaces* **2024**, 16, 12821-12832.
- [38] Li, W.; Lu, X.-M.; Li, G.-Q.; Ma, J.-J.; Zeng, P.-Y.; Chen, J.-F.; Pan, Z.-L., and He, Q.-Y.; First-principle study of SO_2 molecule adsorption on Ni-doped vacancy-defected single-walled (8,0) carbon nanotubes. *Appl. Surf. Sci.* **2016**, 364, 560-566.
- [39] Sha, S.; Tang, K.; Liu, M.; Wan, P.; Liu, Z.; Shi, D. N.; Kan, C., and Jiang, M.; Ferro-Pyro-Phototronic Effect Enhanced Self-Powered UV Photodetectors Based on $\text{BaTiO}_3/\text{MXene}/4\text{H-SiC}$ Heterojunction. *ACS Photonics* **2024**, 11, 4472-4485.
- [40] Liu, T.; Zhang, C., and Li, X.; 2D MXenes for Hot-Carrier Photodetection. *Adv. Opt. Mater.* **2022**, 10, 2201153.
- [41] Jiang, H.-T.; Chen, Y.-F.; Lv, Y.-Y.; Ren, H.; Kan, Y.-C.; Chen, X.; Wang, G.-Y.; Yuan, X.; Zhou, J.; Lv, X.-J.; Yao, S.-H.; Chen, Y.-B., and Chen, Y.-F.; High-Performance Mid-Wave Infrared Photothermoelectric Response in Magnetic Semiconductors MnTe and MnTe_2 Crystals. *Adv. Funct. Mater.* **2026**, 36, e12818.

Spatially programmable bipolar photoresponse in Wafer-scale Te/GaN heteroarrays enabled by synergistic photovoltaic-photothermoelectric coupling

Lijian Li^{1,§}, Peng Wan^{1,§}, Yinglin Wang¹, Liangli Chu¹, Zhenyu Cheng², Minghao Liu³, Caixia Kan¹, Daning Shi¹ 
, Zeng Liu⁴ , and Mingming Jiang¹ 

¹ College of Physics, MIIT Key Laboratory of Aerospace Information Sensing and Physics, Nanjing University of Aeronautics and Astronautics, No. 29, Jiangjun Road, Nanjing 211106, China

² College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, No. 29, Jiangjun Road, Nanjing 211106, China

³ College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 211100, China

⁴ School of Electronic Information Engineering, Electronic-Photonic Smart Sensing Device R&D Team, Inner Mongolia Key Laboratory of Intelligent Communication and Sensing and Signal Processing, Inner Mongolia University, Hohhot 010021, China

[§] Lijian Li and Peng Wan contributed equally to this work.

 Address correspondence to Daning Shi, shi@nuaa.edu.cn; Zeng Liu, zengliu@imu.edu.cn; Mingming Jiang, mmjiang@nuaa.edu.cn

Supporting information to <https://doi.org/10.26599/NR.2026.94909110>

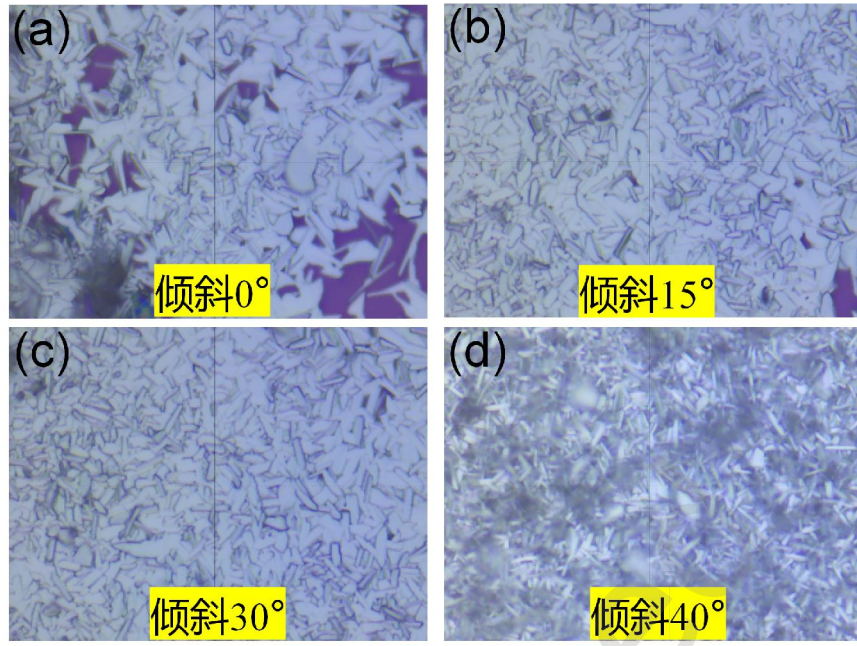


Figure S1 Optical images of Te films grown at different incident angles.

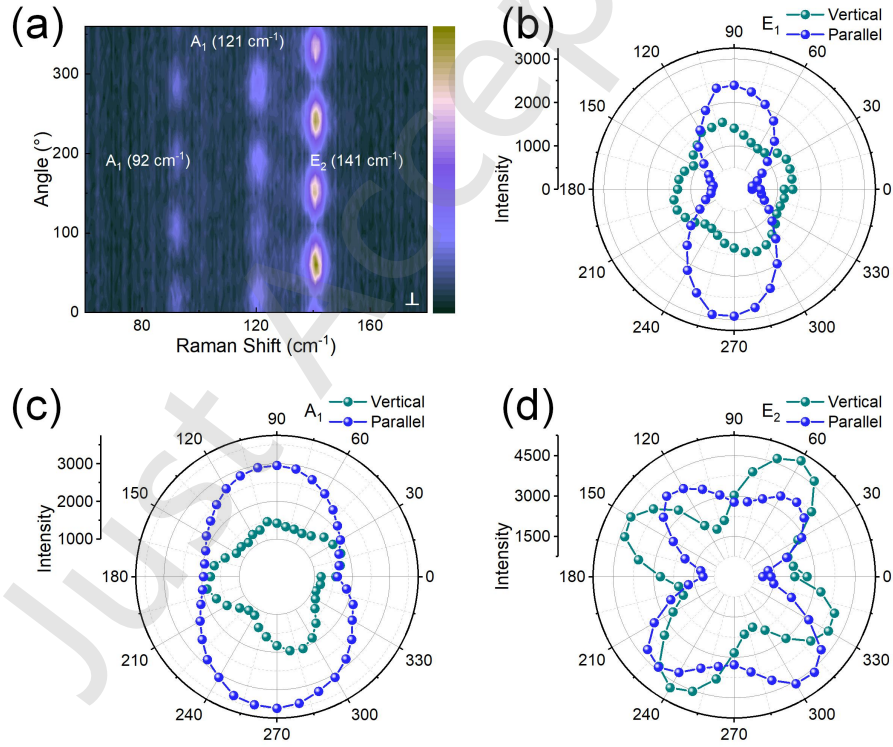


Figure S2 (a) Contour plot of angle-resolved polarized Raman in the vertical polarization configuration. Polar plots of the intensities for (b) E_1 , (c) A_1 , and (d) E_2 modes in parallel and vertical polarization configurations.

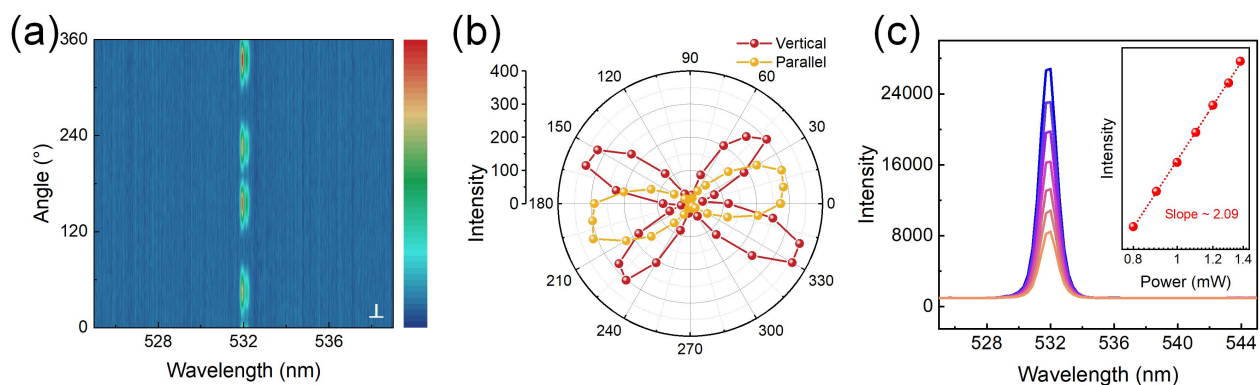


Figure S3 (a) The vertical polarized SHG spectrum of the Te film. (b) Angle-resolved polarized SHG spectra of Te film measured in the parallel and perpendicular polarization configurations. (c) Power-dependent SHG spectra of Te film.

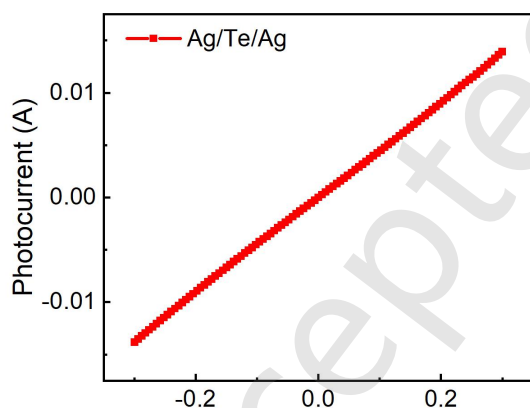


Figure S4 The I-V curves at V_g of 0 V of Te devices.

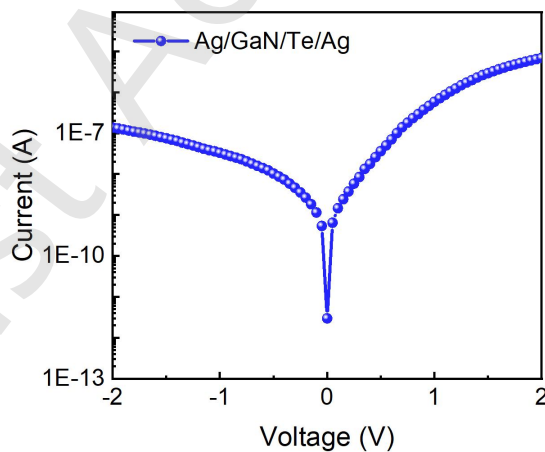


Figure S5 Logarithmic I-V curves of the Ag/Te-GaN/Ag device measured under dark conditions.

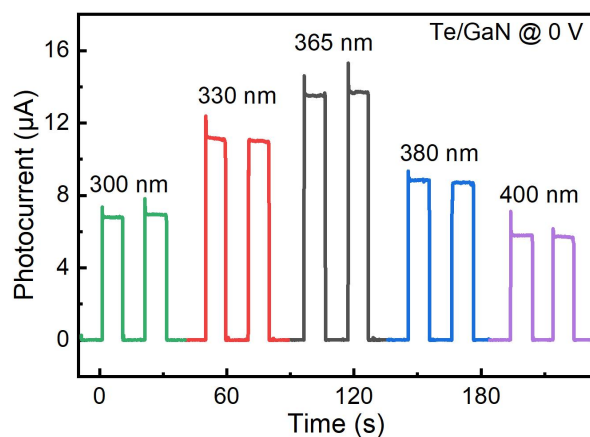


Figure S6 The I-t curves of the heterojunction device measured under ultraviolet irradiation of 300, 330, 365, 380 and 400 nm.

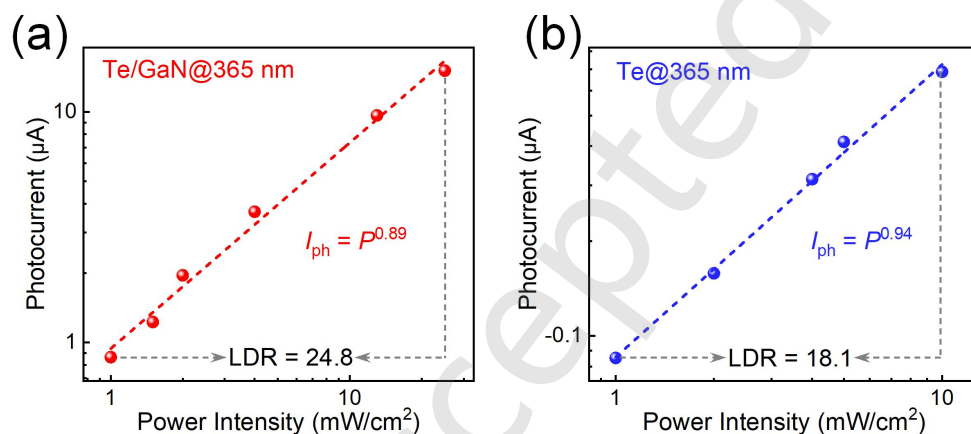


Figure S7 Fitted photocurrent-power relationships and linear dynamic range values for (a) area 1 and (b) area 2 under varying incident optical powers.

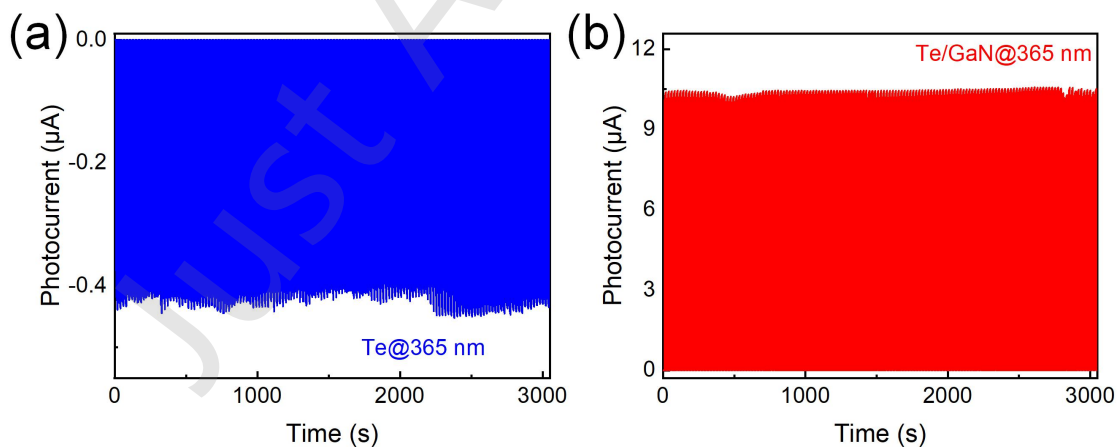


Figure S8 Long-term stability tests of Te/GaN heterojunction devices under irradiation at (a) the Te area and (b) the junction interface.

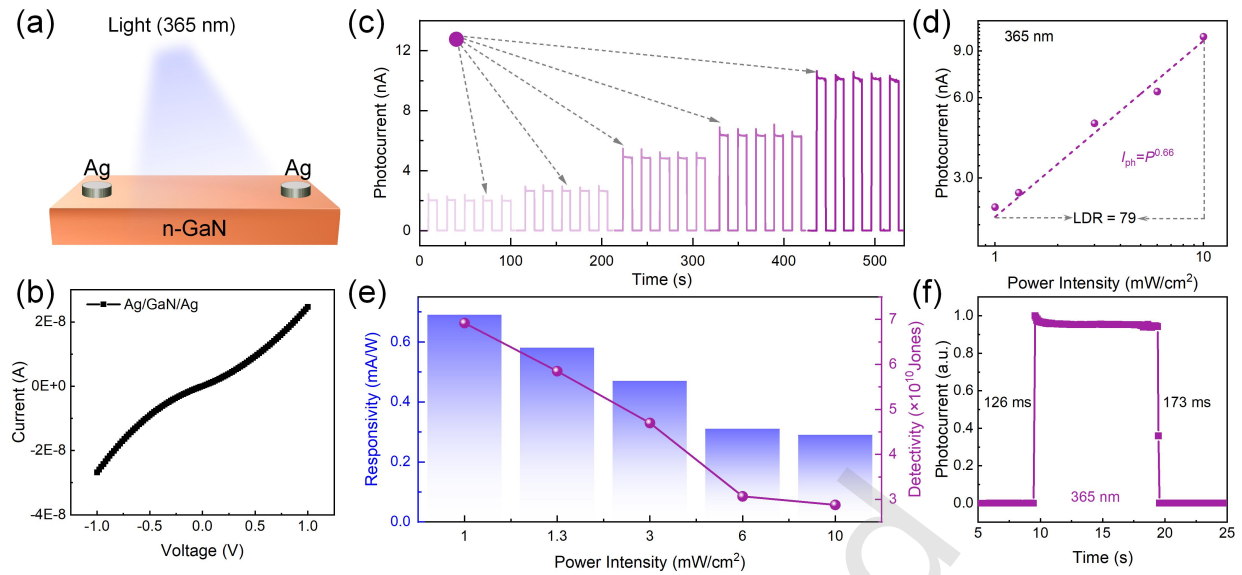


Figure S9 (a) Schematic of the GaN device. (b) I-V curves measured in the dark. (c) Time-dependent photocurrent (I-t) measurements of the GaN device under varying optical powers. (d) Fitting analysis of photocurrent versus incident light intensity at different excitation powers. (e) Dependence of responsivity and specific detectivity on incident optical power. (f) Transient photoresponse of the device measured under 365 nm light on-off switching.

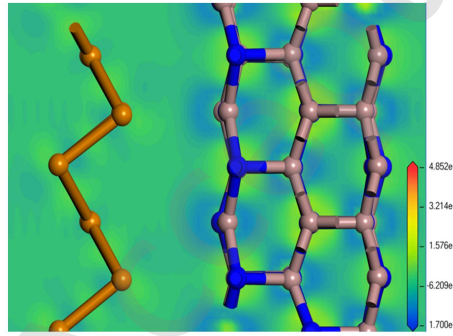


Figure S10 Charge density distribution toward the Te/GaN heterointerface model.

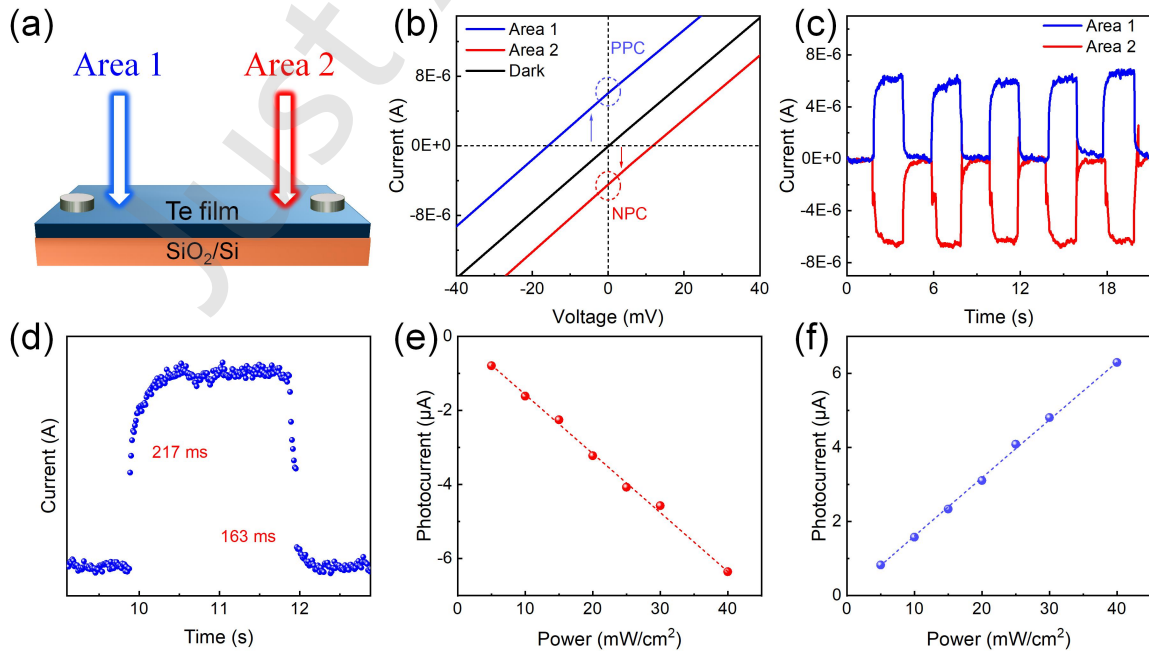


Figure S11 (a) Schematic of the Te-based device, showing two local illumination spots (Area 1 and Area 2). (b) I-V curves measured in the dark and under local illumination at Area 1 and Area 2, respectively. (c) Dependence of the polar photocurrent on the illumination position. (d) Response speed of the device. (e) Photocurrent as a function of optical power in the negative response mode and (f) positive response mode.

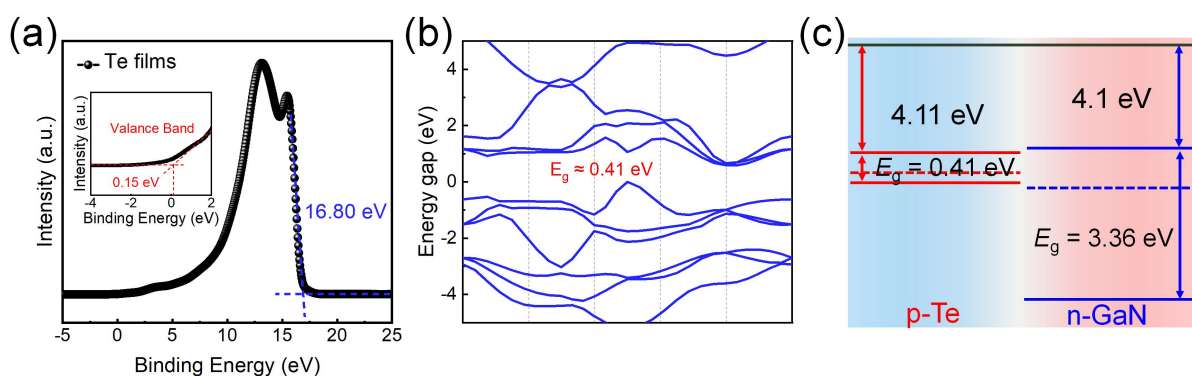


Figure S12 (a) Ultraviolet photoelectron spectroscopy spectra of Te films. (b) DFT calculated band structures for Te. (c) Band structure diagram of Te and GaN before and after contact.

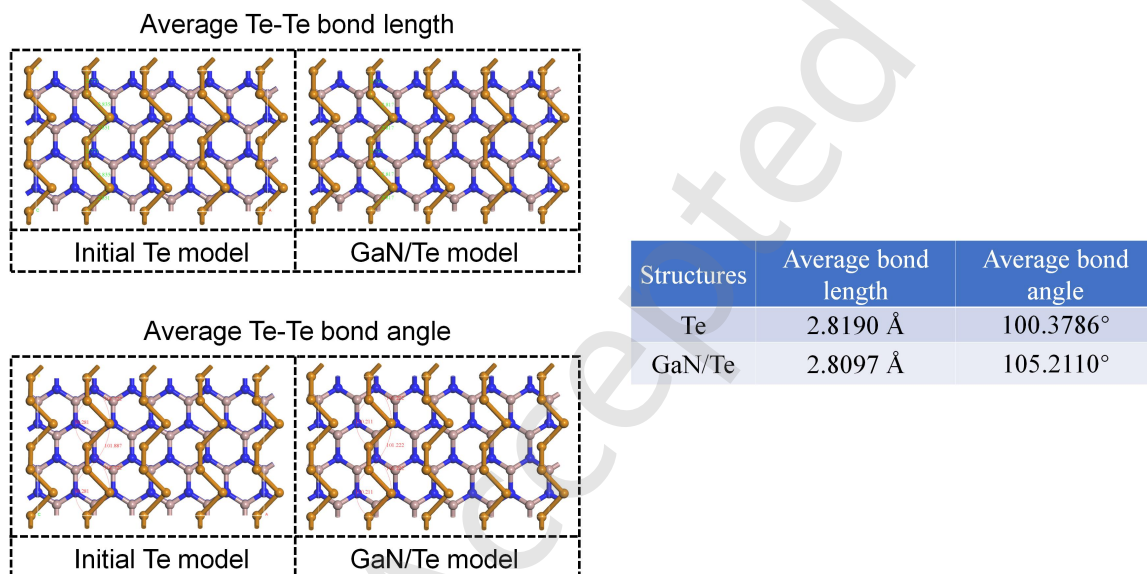


Figure S13 Comparison of the average Te-Te bond lengths and bond angles in Te and GaN/Te structures before and after optimization.



Figure S14 (a) Thermal images of the device surface in the dark state, (b) under 365 nm illumination on the GaN area, and (c) on the Te area.

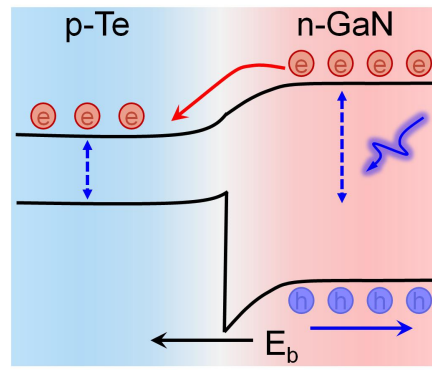


Figure S15 Schematic illustration of charge transport and band alignment in the GaN area of a heterojunction when exposed to light.

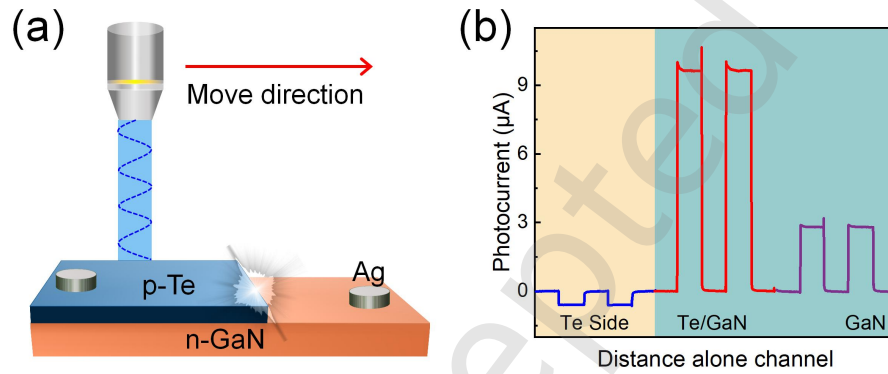


Figure S16 (a) Schematic of the Te/GaN heterojunction device under laser illumination at varying positions. (b) Photocurrent under illumination at different positions.

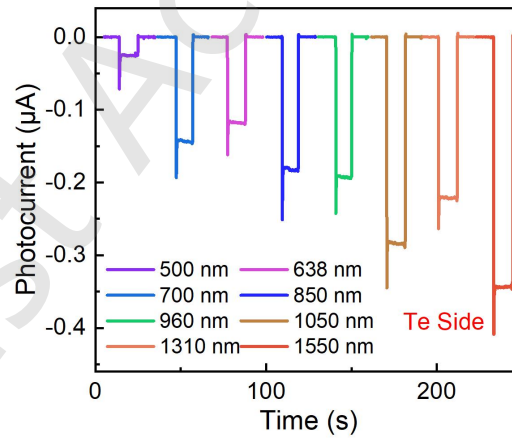


Figure S17 Photoresponse of the heterojunction device under illumination at the Te area with different light wavelengths.

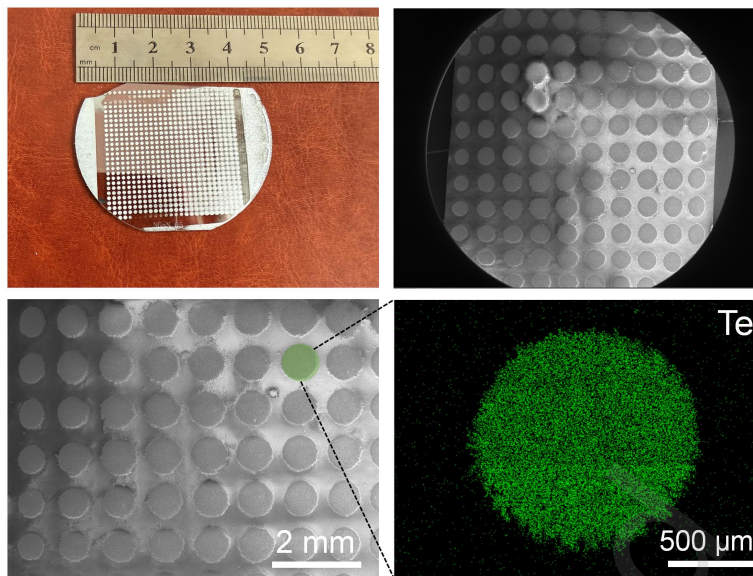


Figure S18 The (a) optical image and (b)-(d) SEM image of the n-GaN/p-Te pixel array.

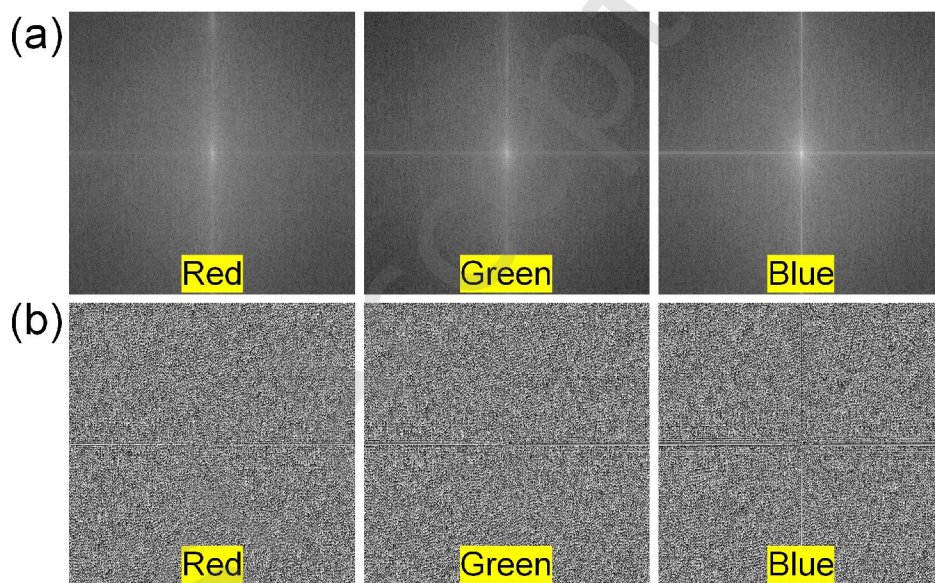


Figure S19 (a) Amplitude of the red, green, and blue channels. (b) Phase of the red, green, and blue channel.

Table S1. Electrical Transport Properties of As-Synthesized Te films.

Parameters	Te films
Resistance	22.8 Ω
Conductivity	146.2 S/cm
Carrier mobility	217 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$
Carrier density	$4.7 \times 10^{16} \text{cm}^{-3}$

Table S2. The Seebeck coefficient of different PTE materials.

Materials	Seebeck coefficient ($\mu\text{V/K}$)	Ref.
TaSe ₃	-1~-5	[1]
PbSe	50	[2]
SnSe	85	[3]
Bi ₁₃ S ₁₈ I ₂	95	[4]
PdTe	100	[5]
Bi ₂ Se ₃	-111	[6]
Te/MWCNT	125	[7]
InSb	150	[8]
SiGe	150	[9]
BiSbTe	155	[10]
This Work (Te films)	196	/

Table S3. The specific values (x, y, Re, Im) of the points.

Location	X	Y	Re	Im
Point 1	100	1	-33525	6469
Point 2	100	2	-45536	7181
Point 3	100	3	-11885	449
Point 4	100	4	-8539	7781
Point 5	100	5	-4449	17674

References

- [1] Zhu, B.; Wu, J.-J.; Li, D.; Zhu, C.; Huang, P.-Y.; Yue, L.-Q.; Sun, R.-Y.; Qiang, S.; Zhen, L.; Qin, J.-K., and Xu, C.-Y.; Orientation-Related Giant Photothermoelectric Energy Conversion in Quasi-One-Dimensional van der Waals TaSe₃ Crystals. *ACS Nano* **2024**, 18, 35696-35704.
- [2] Wang, H.; Pei, Y.; LaLonde, A. D., and Snyder, G. J.; Weak electron-phonon coupling contributing to high thermoelectric performance in n-type PbSe. *Natl. Acad. Sci. USA* **2012**, 109, 9705-9709.
- [3] Yin, H.; Xie, H.; Gao, D.; Bai, S.; Shi, J.; Fu, P.; Zhao, L.-D., and Li, C.; Controlled doping and growth of SnSe thin films via pulsed laser deposition. *J. Mater. Sci.* **2025**, 11, 101121.
- [4] Chen, M.; Tian, H.; Qi, L.; Zhang, Y.; Yang, H.; Ge, S.; Zhang, L.; Zhang, Y.; Li, L.; Cui, K., and Yu, J.; Photothermal-thermoelectric synergy coupling localized surface plasmon resonance for enhanced flexible photoelectrochemical sensor performance. *Chem. Eng. J.* **2025**, 503, 158393.

- [5] Heremans, J. P.; Jovovic, V.; Toberer, E. S.; Saramat, A.; Kurosaki, K.; Charoenphakdee, A.; Yamanaka, S., and Snyder, G. J.; Enhancement of Thermoelectric Efficiency in PbTe by Distortion of the Electronic Density of States. *Science* **2008**, 321, 554-557.
- [6] Zhang, Y.; Meng, Y.; Wang, L.; Lan, C.; Quan, Q.; Wang, W.; Lai, Z.; Wang, W.; Li, Y.; Yin, D.; Li, D.; Xie, P.; Chen, D.; Yang, Z.; Yip, S.; Lu, Y.; Wong, C.-Y., and Ho, J. C.; Pulse irradiation synthesis of metal chalcogenides on flexible substrates for enhanced photothermoelectric performance. *Nat. Commun.* **2024**, 15, 728.
- [7] Wang, Z.; Wang, Y.; Wu, W.; Zhu, P.; Fang, Y.; Wu, Y.; Sha, W.; Wang, S.; Zeng, W.; Zhao, J., and Ruan, L.; MXene half-coated Te/MWCNT photothermoelectric film for enhanced energy harvesting and non-contact sensing. *Chem. Eng. J.* **2025**, 524, 169091.
- [8] Zhang, D.; Wu, H.; Zhou, Z.; Zheng, S.; Zhang, B.; Zhou, Y.; Lu, X., and Zhou, X.; Enhanced thermoelectric performance of InSb through deep level impurity donor state induced by La doping. *Mater. Today Phys.* **2023**, 32, 101020.
- [9] Joshi, G.; Lee, H.; Lan, Y.; Wang, X.; Zhu, G.; Wang, D.; Gould, R. W.; Cuff, D. C.; Tang, M. Y.; Dresselhaus, M. S.; Chen, G., and Ren, Z.; Enhanced Thermoelectric Figure-of-Merit in Nanostructured p-type Silicon Germanium Bulk Alloys. *Nano Lett.* **2008**, 8, 4670-4674.
- [10] Poudel, B.; Hao, Q.; Ma, Y.; Lan, Y.; Minnich, A.; Yu, B.; Yan, X.; Wang, D.; Muto, A.; Vashaee, D.; Chen, X.; Liu, J.; Dresselhaus, M. S.; Chen, G., and Ren, Z.; High-Thermoelectric Performance of Nanostructured Bismuth Antimony Telluride Bulk Alloys. *Science* **2008**, 320, 634-638.