

Self-powered in-sensor computing photodetector based on BiOI/TiO₂ for motion trajectory recognition and dynamic image encryption

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Nano Res., **Just Accepted Manuscript** • <https://doi.org/10.26599/NR.2026.94909168>

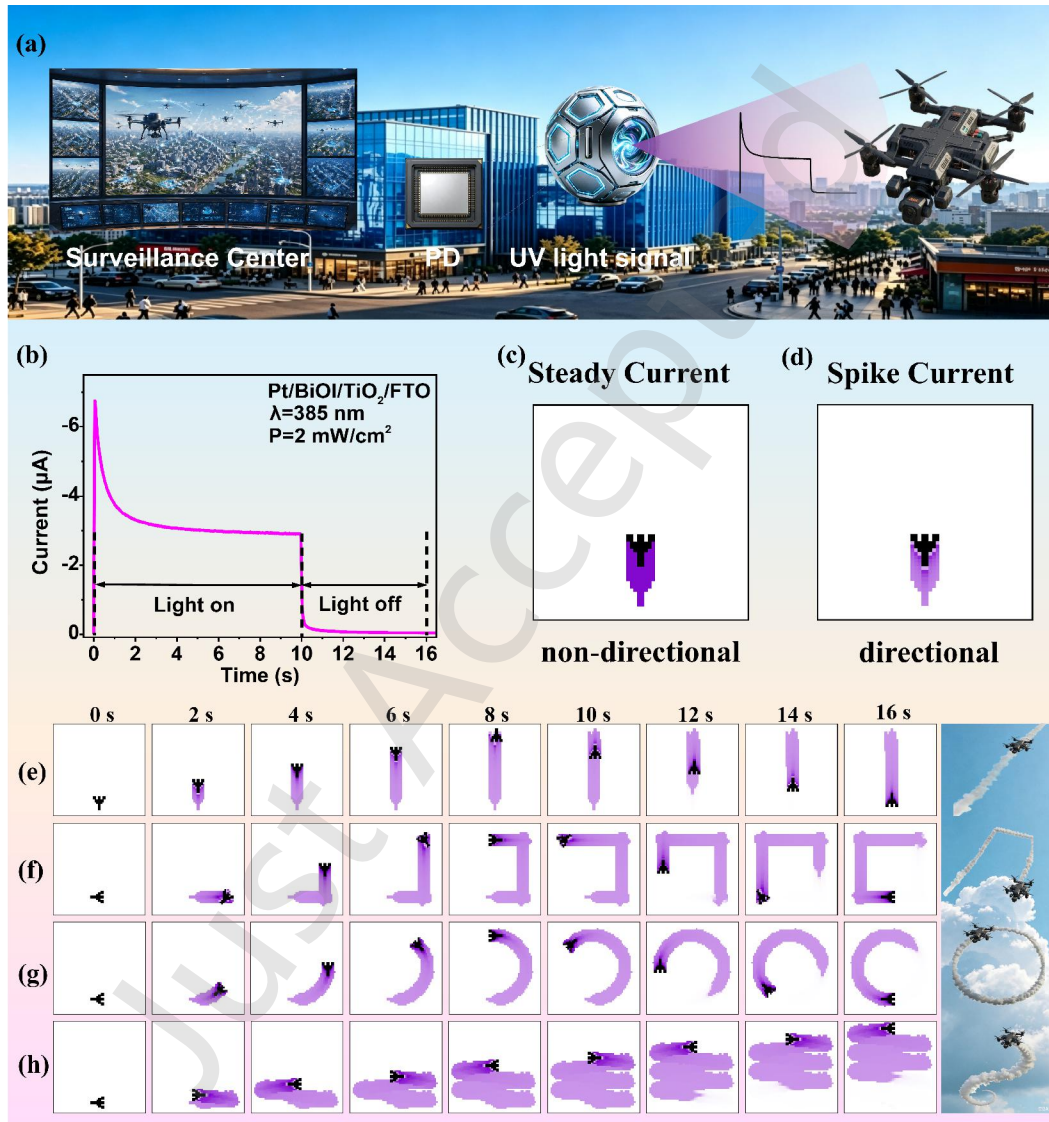
<https://www.sciopen.com/journal/1998-0124> on Sep. 3, 2026

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We report a BiOI/TiO₂ self-powered photodetector that leverages intrinsic nonlinear time-domain photocurrent responses, including instantaneous spikes, exponential decay, and slow stabilization, to enable in-sensor computing for moving target trajectory recognition. Additionally, the unique relaxation dynamics allow the detector array to encode temporal signatures directly into pixel grayscale values, which resolves not only target positions but also motion directions without requiring complex post-processing algorithms.



Research Article

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Received: 3 July 2026; **Revised:** 28 August 2026; **Accepted:** 3 September 2026

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Cite this article: *Nano Research*, 2026, 19, 94909168 <https://doi.org/10.26599/NR.2026.94909168>

ABSTRACT: Traditional optoelectronic detection systems suffer from the functional separation of sensing and computing, low data transmission efficiency, and insufficient real-time performance for dynamic scene detection. To address these limitations, BiOI/TiO₂ heterojunction film was synthesized via a two-step hydrothermal route, and Pt/BiOI/TiO₂/FTO self-powered photodetector (PD) was accordingly fabricated in this work. The morphological features, crystal structure, band structure, and optoelectronic response characteristics were characterized. The results show that the PD exhibits excellent photoresponse characteristics to ultraviolet (UV)-blue light in the 300-475 nm wavelength range under zero bias. Under 385 nm illumination, the PD achieves a responsivity (R) of 0.68 A/W, a detectivity (D^*) of 7.0×10^{11} Jones, an external quantum efficiency (EQE) of 225%, and a linear dynamic range (LDR) of 99 dB. Owing to the synergistic effects of the Z-scheme band configuration, built-in electric field, and the interface potential well, the device

exhibits a distinctive nonlinear time-domain photocurrent response under UV light illumination, consisting of an instantaneous sharp peak, exponential decay, and slow steady-state saturation. Leveraging this unique photoelectric characteristic, software simulations were performed to validate the practical applications of PD arrays in moving target trajectory recognition and dynamic ultraviolet image encryption. Real-time tracking of directional motion trajectories was realized, and gradual concealment of encrypted text “TJUT” within 5.5 s was achieved through dynamic imaging. This study demonstrates that the fabricated BiOI/TiO₂ self-powered PD integrates in-situ sensing and computing capabilities, rendering it promising for advanced applications including intelligent perception, secure communication, and dynamic image.

KEYWORDS: BiOI/TiO₂ heterojunction, self-powered photodetector, nonlinear time-domain response, in-sensor computing

1 Introduction

With the deep integration of the Internet of Things (IoT) and artificial intelligence (AI) technologies, cutting-edge applications such as autonomous driving, smart healthcare, dynamic target tracking, and real-time image encryption impose higher demands on the data processing capacity of optoelectronic systems[1-4]. However, conventional optoelectronic detection systems generally suffer from the separation of sensing and computing modules. Sensors merely capture optical signals, while subsequent complex computational tasks rely on external processors. Frequent data transmission between sensors and processors introduces severe transmission latency and redundant power consumption, failing to meet the urgent demands for real-time operation, parallel processing of massive data, and low power consumption in dynamic scenarios[5-7]. In addition, traditional photodetectors (PDs) typically can only acquire light intensity information and lack the ability to deeply analyze multidimensional optical features such as the temporal dynamics, spectral characteristics, and spatial distribution. They are unable to perform in-situ signal preprocessing or feature extraction directly at the sensing terminal, making it difficult to support intelligent computing tasks at the edge devices[8]. To address the above

issues, researchers have proposed a new class of PDs featuring in-sensor computing, which deeply integrates sensing and computing functions at the sensor level. While responding to incident light, these devices can leverage intrinsic physical properties including spectral response, relaxation time, and nonlinear photoelectric response to directly complete signal encoding, weighting assignment, and feature extraction on-chip. This architecture reduces or even eliminates frequent data exchange with external processors, substantially boosting system energy efficiency and real-time performance[9-11].

At present, four mainstream strategies have been developed to realize PDs with in-sensor computing functionality. First, PDs with reconfigurable photoresponse polarity have been adopted. Electrical or optical stimuli dynamically modulate the magnitude, polarity, response speed and spectral coverage of photocurrent, enabling weight adjustment based on optoelectronic signals to directly perform dynamic image enhancement, motion deblurring and multispectral computing at the sensing terminal[12, 13]. Second, material anisotropy has been exploited. Tunable polarization spectral ratios and intrinsic nonlinear optoelectronic responses of devices substitute discrete external computing units, establishing a direct mapping from polarization information to in-sensor computation[14]. Third, gate-programmable in-sensor computing modulates dual built-in electric fields (originating from heterojunctions and Schottky junctions) via single-gate or back-gate bias voltages, rendering photocurrent polarity and magnitude programmable. This transforms PDs into hardware units capable of executing convolutional operations[11]. Fourth, optical or electrical pulse excitation switches devices between linear steady-state response and spiking nonlinear response regimes. The nonlinearity of spike signals supports on-chip pulse encoding, event-driven sensing and noise suppression, thereby achieving integrated sensing and computing[15].

PDs hold promising prospects for moving object monitoring. Real-time position signals captured by such devices can be combined with corresponding algorithms to reconstruct motion trajectories. However, conventional PDs only record light intensity and lack direct perception of temporal information. Without complex post-processing

algorithms, they struggle to resolve complete motion trajectories, especially those containing directional cues. Therefore, developing PDs with intrinsic nonlinear temporal characteristics that can directly extract time-dependent motion features at the sensor side is critical to enhancing real-time monitoring performance and simplifying system hardware.

Bismuth oxyiodide (BiOI) is a layered tetragonal material alternately stacked by $[\text{Bi}_2\text{O}_2]^{2+}$ slabs and halogen interlayers via weak van der Waals forces[16]. This layered architecture creates an intrinsic built-in electrostatic field between adjacent layers, which effectively accelerates the dissociation of photo-generated electron-hole pairs, suppresses carrier recombination, and enhances the photoelectric conversion efficiency[17-19]. As a p-type semiconductor with a bandgap of approximately 1.7 eV, BiOI exhibits strong visible-light absorption, making it an ideal candidate for visible-spectrum-responsive optoelectronic materials[20]. Rutile TiO_2 is a typical wide-bandgap n-type semiconductor with a bandgap width of approximately 3.0 eV and excellent light UV light absorption. In particular, one-dimensional TiO_2 nanorod arrays (NRs) enhance light scattering and absorption, while providing oriented transport channels for photo-generated carriers, effectively reducing carrier transport loss and thereby improving the device photoresponse performance[21, 22].

Taking advantage of the complementary merits of BiOI and TiO_2 NRs described above, in this study we deposited a BiOI nanosheet film on the surface of TiO_2 NRs via a hydrothermal method to fabricate Pt/BiOI/ TiO_2 /FTO PDs responsive to UV-Vis light. Benefiting from the built-in electric field of the BiOI/ TiO_2 p-n heterojunction, the device achieves self-powered photodetection without an external bias. Under UV illumination, the device exhibits pronounced light-tunable relaxation dynamics featured by transient spike photocurrents. Leveraging this physical trait, the device encodes temporal signatures and historical illumination information of incident light into time-evolving photocurrent signals, realizing the fusion of sensing and computing within a single pixel. Accordingly, array-structured PDs are proposed to verify their feasibility for moving trajectory recognition and dynamic image encryption. On one hand, the divergent temporal responses of devices to dynamic optical stimuli facilitate

the identification of trajectory positions and motion directions. On the other hand, the photoresponse relaxation process enables a temporal-coding-based strategy for dynamic image encryption. This work not only delivers a feasible material and device solution to resolve the sensing-computing separation and poor real-time performance of traditional optoelectronic systems, but also opens up a new technical pathway toward high-efficiency, self-powered and multifunctional optoelectronic sensing-computing hardware for edge intelligence.

2 Experimental section

TiO₂ NRs films were prepared on fluorine-doped tin oxide (FTO) conductive glass substrates using a hydrothermal method. First, 15 mL of hydrochloric acid was added to a solution consisting of 0.5 mL of anhydrous ethanol and 14.5 mL of ultrapure water. After stirring at room temperature for 10 minutes, 0.5 mL of tetrabutyl titanate was added dropwise, and stirring was continued until the solution became clear and transparent. The FTO substrate was ultrasonically cleaned sequentially with deionized water, acetone, isopropanol, and anhydrous ethanol, then dried at 80°C for 1 h and subjected to UV treatment for 10 min. Afterwards, the substrates were placed obliquely with the conductive side facing down into a 100 mL polytetrafluoroethylene liner, into which the as-prepared TiO₂ precursor solution was poured. The liner was sealed in an autoclave and heated in a drying oven at 170°C for 3 h. After the reaction, the autoclave was cooled naturally to room temperature, the samples were taken out and dried, and finally annealed in a muffle furnace under air atmosphere at 450°C for 2 h to obtain TiO₂ NRs film.

BiOI films were deposited on the surface of a TiO₂ NRs film using the hydrothermal method. 4 mmol Bi(NO₃)₃·5H₂O was dissolved in 30 mL ethylene glycol under magnetic stirring for 80 min to form clear Solution A. 4 mmol of KI was dissolved in 10 mL ethylene glycol with magnetic stirring for 80 min to prepare clear Solution B. Solution B was poured into Solution A, and the mixture was magnetic stirred for 120 min to yield a homogeneous transparent BiOI precursor solution. The TiO₂ NRs films were placed face-down in the inner vessel of a 100 mL autoclave, and 40 mL of the precursor solution was added. The hydrothermal reaction proceeded at

160°C for 5 h. After cooling to ambient emperature, the samples were retrieved, rinsed thoroughly with deionized water and absolute ethanol, and dried in an oven at 80°C for 1 h to fabricate BiOI/TiO₂ heterojunction thin films. Finally, Pt with an area of 0.2 cm × 0.2 cm was sputtered onto the heterojunction film to construct Pt/BiOI/TiO₂/FTO PDs.

Scanning electron microscopy (SEM, Hitachi S-8010), energy dispersive spectroscopy (EDS, Model 550i), X-ray diffraction (XRD, Rigaku D/max 2500/pc) and Raman Spectrometer (Raman, LabRAM HR Evolution, France) were performed to characterize the surface morphology and crystal structure of the samples. X-ray photoelectron spectrometer (XPS, Thermo ESCALAB-250) was used to analyze the elemental composition and valence states on the sample surface. The absorption, diffuse reflectance, and transmission spectra of the film were measured using UV-Vis spectrophotometer (Hitachi U4100). A three-electrode electrochemical workstation (Multi Autolab/M204) was adopted to measure electrochemical impedance spectroscopy (EIS), Mott-Schottky (M-S) curves, and linear sweep voltammetry (LSV) curves in a 1 M Na₂SO₄ aqueous solution, with a Pt wire serving as the counter electrode, Ag/AgCl as the reference electrode, and the sample as the working electrode. The optoelectronic performance of the device was characterized by a Keithley 2450 source meter, and the noise current density spectra were measured using an FS-Pro semiconductor parameter testing system, with light sources provided by a monochromatic LED and a spectrometer. Software simulation was performed to explore the application of the PDs in the recognition of moving target trajectories and dynamic encryption of UV images.

3 Results and discussion

Figure 1(a) shows the SEM image of the TiO₂ film. It can be seen that the top end face of TiO₂ nanorods presents a quadrilateral shape, with diameters ranging from 40 nm to 122 nm. The cross-sectional inset in Figure 1(a) reveals that TiO₂ nanorods grow vertically and orderly on the FTO substrate, exhibiting tight adhesion and a distinct interface with the substrate. The nanorods are approximately 1.52 μm in length. Figure 1(b) shows the SEM image of the BiOI/TiO₂ composite heterojunction

film. BiOI grown on the surface of TiO₂ NRs exhibits a nanosheet structure with a lateral size of approximately 220 nm and a single-sheet thickness of roughly 13 nm. These nanosheets tend to self-assemble into spherical clusters and are densely and uniformly distributed over the TiO₂ surface. As shown in the cross-sectional SEM inset in Figure 1(b), the thickness of the BiOI layer is approximately 1.12 μ m. BiOI nanosheets not only cover on the top of TiO₂ NRs but also wrap around the sidewalls of the nanorods, filling the inter-nanorod voids. The intimate contact between TiO₂ nanorods and BiOI nanosheets creates abundant heterojunction interfaces, thereby effectively promoting the separation and transport of photo-generated charge carriers.

Figure S1 shows the EDS elemental mapping results from top-view SEM images of the pristine TiO₂ films and BiOI/TiO₂ composite films. In the EDS mappings of the single-layer TiO₂ film (Figure S1(a) for Ti and Figure S1(b) for O), both elements exhibit a valley-like distribution, indicating the uniform and ordered growth of TiO₂ nanorods on the FTO substrate. For the BiOI/TiO₂ composite film, the signal intensity of Ti in Figure S1(c) is significantly weaker and more uneven compared with that in the pristine TiO₂ film (Figure S1(a)). This phenomenon arises primarily from two factors: on one hand, the shielding effect of the BiOI layer on the elemental signals of the TiO₂ substrate; on the other hand, it stems from the clustered growth of BiOI nanosheets. Bi, I and O elements in the BiOI/TiO₂ composite film follow consistent continuous distribution patterns, which is consistent with the morphological features of BiOI observed in SEM images.

Figure 1(c) shows the XRD patterns of bare FTO substrate, pristine TiO₂ film, and BiOI/TiO₂ composite film. The diffraction peaks at 36.08°, 54.32°, and 69.08° correspond to the (101), (211), and (301) crystal planes of rutile TiO₂ (JCPDF 21-1276), respectively. The strong diffraction peak of the (101) crystal plane indicates that TiO₂ crystals preferentially grow along the (101) crystal plane. In the XRD pattern of the BiOI/TiO₂ composite film, three new diffraction peaks at 29.74°, 31.74°, and 45.49° correspond to the (012), (110), and (014) crystal planes of the orthorhombic BiOI phase (JCPDF 73-2062). Among these, the diffraction peak at the

(014) crystal plane exhibits relatively high intensity, indicating that BiOI was successfully deposited on the surface of TiO₂ NRs and exhibits good crystallinity. In addition, weak diffraction peaks at 29.22° and 31.92° are attributed to the (107) crystal plane of Bi₂O_{2.3} and the (103) of Bi₂O_{2.7}, respectively, indicating the presence of trace amounts of Bi₂O_{2.3} and Bi₂O_{2.7} impurity phases in the composite film. The formation of these impurity phases is primarily related to two factors: first, hydrolysis of Bi³⁺ induced by trace water in the reaction solution and surface hydroxyl groups on the TiO₂; second, volatilization of iodine and changes in its oxidation state during the reaction. At elevated temperatures, trace water adsorbed during room-temperature stirring or generated from ethylene glycol decomposition (ethylene glycol acts as a mild reducing agent and partially decomposes into byproducts such as acetaldehyde and water) triggers incomplete hydrolysis of Bi³⁺ to form intermediates like Bi₂O₂(OH)_x. Subsequent dehydration or oxidation forms non-stoichiometric bismuth oxides (i.e., Bi₂O_{2.3} and Bi₂O_{2.7}). Meanwhile, the TiO₂ surface is rich in hydroxyl groups and oxygen vacancies that strongly adsorb Bi³⁺, preferentially inducing the nucleation of the aforementioned impurities at the heterointerface. Furthermore, the reaction temperature (160°C) exceeds the sublimation point of iodine (~113°C), causing partial oxidation of I⁻ into volatile I₂. This shifts the initial Bi:I stoichiometric ratio of 1:1 toward Bi enrichment. Insufficient iodide prevents full conversion of Bi³⁺ to BiOI, and excess bismuth ions bond with oxygen to form bismuth-rich bismuth oxide impurities.

Figure 1(d) shows the Raman spectra of the pristine TiO₂ film and BiOI/TiO₂ composite thin film. For pristine TiO₂ film, vibrational peaks at 144.4, 233.5, 446.8, and 609.5 cm⁻¹ correspond to the B_{1g}, (A_{1g}+E_g), E_g, and A_{1g} multiphoton Raman vibrational modes of rutile TiO₂[23]. The BiOI/TiO₂ composite film retains all characteristic Raman peaks of TiO₂ while exhibiting three additional peaks at 95.9, 159.3, and 170 cm⁻¹, corresponding to the A_{1g}, E_g, and A_{1g} phonon stretching modes of Bi-I, respectively. No distinct characteristic vibrational signals of Bi₂O_{2.3} and Bi₂O_{2.7} impurities were detected. The peak at 170 cm⁻¹ may originate from the superposition of the A_{1g} stretching mode of Bi-I and bending vibrations of Bi layers and Bi-O

polyhedra. This observation arises from the low loading of impurity phases, whose weak vibrational signals are masked by the strong characteristic peaks of BiOI and TiO₂, consistent with the weak intensity of impurity diffraction peaks in XRD patterns.

Figure 1(e)-(i) shows the XPS spectra of pristine TiO₂ film and BiOI/TiO₂ composite films, with all spectra calibrated against the C1s peak at 284.8 eV. Figure 1(e) shows the Ti 2p XPS spectrum of TiO₂ film. Two characteristic doublet peaks appear at binding energies of 458.6 eV and 464.3 eV, with a spin-orbit splitting energy of 5.7 eV, corresponding to Ti 2p_{3/2} and Ti 2p_{1/2} of Ti⁴⁺, respectively, indicating that Ti⁴⁺ is present in TiO₂ film[24]. Figure 1(f) shows the O 1s XPS spectrum of TiO₂ film, whose asymmetric profile can be deconvoluted into two sub-peaks. The dominant peak at 529.8 eV (O_L) is typically attributed to lattice oxygen within the TiO₂ lattice (i.e., lattice oxygen), while the secondary peak at 531.6 eV (O_V) is associated with oxygen species at surface defective sites (such as adsorbed oxygen or oxygen near oxygen vacancies)[25]. The presence of this secondary peak indicates minor surface defects on TiO₂ nanorods. Such surface defects can serve as active sites for photo-generated charge carriers to modulate their trapping and release behaviors, thereby regulating the optoelectronic performance of the device. Figure 1(g) shows the Bi 4f XPS spectrum of BiOI. The characteristic peaks at 159.5 eV and 164.8 eV correspond to the Bi 4f_{7/2} and Bi 4f_{5/2} orbitals, with a spin-orbit splitting gap of 5.3 eV, matching the standard splitting energy of Bi³⁺ in BiOI and verifying the trivalent state of bismuth. Figure 1(h) shows the I 3d XPS spectrum of BiOI film, where peaks at 630.6 eV and 619.2 eV match the binding energies of I 3d_{5/2} and I 3d_{3/2} orbitals, with an energy difference of 11.4 eV between the two peaks, indicating that iodine exists in BiOI film in the form of I⁻[26]. Figure 1(i) shows the O 1s XPS spectrum of BiOI film, which can be deconvoluted into three sub-peaks representing oxygen species in distinct chemical environments. The binding energy of 530.5 eV (O_L) is attributed to lattice oxygen in the BiOI lattice; the binding energy of 531.4 eV (O_V) corresponds to adsorbed oxygen or oxygen near oxygen vacancies at BiOI surface defect sites; and

532.5 eV (O_H) is attributed to surface-adsorbed hydroxyl groups ($-OH$), which mainly originate from water molecules adsorbed from ambient air on the sample surface.

Figure 2(a) shows the valence band (VB) spectra of TiO_2 and BiOI derived from XPS and UPS measurements, which were used to determine the energy offsets between the Fermi level (E_F) and valence band maximum (VBM) for both materials. A tangent line is drawn at the maximum-slope position of each spectrum and extrapolated to intersect the baseline to determine the E_F -VBM energy separations. For TiO_2 , the value is 2.54 eV from XPS VB spectra. For BiOI, the corresponding values are 1.43 eV (XPS) and 0.96 eV (UPS). These data provide important experimental evidence for subsequent analysis of the band alignment of the BiOI/ TiO_2 heterojunction as well as the separation process of photo-generated carriers. The distinct E_F -VBM offset of BiOI is mainly attributed to the porous morphology of BiOI nanosheet arrays. Owing to the different excitation sources of XPS and UPS, UPS is more sensitive to surface-related information, whereas XPS probes a relatively deeper region than UPS. This can be supported by the detectable Ti 2p signal in the XPS spectra of BiOI/ TiO_2 composite films (Figure S2). The larger E_F -VBM value of BiOI acquired by XPS is therefore affected by the underlying TiO_2 substrate. Accordingly, the UPS derived results are utilized for subsequent band-structure analysis.

Figure 2(b) shows the UV-visible transmission and absorption spectra of pristine TiO_2 film and a BiOI/ TiO_2 composite film in the 300-800 nm wavelength range. TiO_2 NRs exhibit strong light absorption in the UV region (300-400 nm) and moderate absorption in the visible region. After BiOI deposition, the absorption edge of the composite film undergoes a significant red shift, accompanied by enhanced absorption in the UV-blue region. The optical photographs of pristine TiO_2 and BiOI/ TiO_2 films are presented in the inset of Figure 2(b). The pristine TiO_2 appears pale white, whereas the BiOI/ TiO_2 composite exhibits an orange-yellow color. This visual observation confirms that the light absorption range has been extended into the visible region, which is consistent with the redshift of the absorption edge observed in the UV-Vis absorption spectra.

Defect states within the bandgap form an Urbach tail in the absorption spectra,

and the Urbach energy (E_U) is a quantitative parameter for evaluating the internal defect density and structural disorder of crystal. A larger E_U value generally corresponds to higher defect density and greater structural disorder inside the crystal. The inset in Figure 2(c) shows the relationship between transmittance and photon energy for TiO_2 film and BiOI/TiO_2 composite film, whose trend is consistent with the absorption spectra in Figure 2(a). When the photon energy is lower than the energy corresponding to the bandgap, the transmittance of the composite film is higher than that of the pristine TiO_2 film. This is because BiOI deposition modifies the surface morphology and light scattering behavior of the film, and it mitigates light absorption loss induced by defect states in TiO_2 , thereby improving light transmittance. As the photon energy gradually approaches the optical band gap of the material, the transmittance of both films drops sharply, consistent with the enhanced absorption observed in the visible region of the absorption spectra. The BiOI/TiO_2 composite film exhibits a distinct absorption edge at approximately 2.14 eV, corresponding to the narrower optical bandgap of BiOI , whereas the absorption edge of the pristine TiO_2 film is located at approximately 3.01 eV. This discrepancy directly enables superior light harvesting of the composite film in the visible region (below 3.01 eV, i.e., wavelengths above ~ 400 nm). The Urbach energy E_U of defect states is a vital parameter affecting the recombination efficiency of photo-generated carriers in semiconductors. Calculations based on Eq. (S1), (S2), and (S3) yield E_U values of 0.58 eV and 0.50 eV for the TiO_2 film and the BiOI/TiO_2 composite film, respectively. The results indicate that a certain number of defect states exist within both materials, with a relatively higher defect density in TiO_2 , which agrees with the oxygen vacancy defects on TiO_2 and BiOI surfaces characterized by XPS in Figure 1(f) and 1(g). A comprehensive analysis of the absorption and transmission spectra reveals that, compared to pristine TiO_2 film, the BiOI/TiO_2 composite film exhibits a significantly reduced absorption intensity within 500-800 nm. After BiOI nanosheets were deposited on TiO_2 , the light absorption range of the film extends to the visible band to realize light absorption in the UV-visible band. Meanwhile, the defect density of the film is lowered, which helps suppress the nonradiative recombination of photo-generated electron-hole pairs, prolong the carrier lifetime, and ultimately boost the photoelectric conversion efficiency of heterojunction devices.

Figure 2(d) shows the Kubelka–Munk function $F(R)$ versus photon energy obtained from UV-visible diffuse reflectance spectra of the two films. The optical bandgap (E_g) of semiconductors can be determined by drawing a tangent at the maximum slope of the spectrum and finding the intersection between the tangent and the extended baseline. There is a significant difference in the absorption edges between pristine TiO_2 and the composite film. From Figure 2(d), the E_g values for the TiO_2 film and the BiOI/TiO_2 composite film are 3.01 and 2.14 eV, respectively.

Figure 2(e) plots the M-S curves for the TiO_2 film and BiOI/TiO_2 composite film. Fitting the slopes of the curves reveals that the M-S curve of TiO_2 has a positive slope, indicating its n-type semiconductor characteristic; the slope of BiOI/TiO_2 M-S curve is negative, proving that BiOI is p-type. Accordingly, a p-n heterojunction is constructed in the BiOI/TiO_2 composite film. Furthermore, flat-band potentials of TiO_2 and BiOI were fitted from M-S slopes to be -0.85 V and 2.34 V, respectively. Using Eq. (S6) and (S7), the E_F relative to the vacuum energy level was further calculated to be -4.26 eV for TiO_2 and -7.45 eV for BiOI . Combining Figure 2(a) and optical bandgap results, the energy level diagram of BiOI and TiO_2 before equilibrium is established, as shown in Figure 2(f). Herein, the conduction band edge (E_C) and valence band edge (E_V) of TiO_2 are 3.79 eV and 6.27 eV, while those of BiOI are 6.80 eV and 8.41 eV, respectively.

Figure 2(g) and 2(h) show the EIS curves of the TiO_2 film and BiOI/TiO_2 composite film under dark conditions and under 385 nm UV illumination, respectively. A smaller curvature radius of EIS arc represents lower interfacial transfer resistance and higher charge transfer efficiency. Under 385 nm UV irradiation, the interfacial transfer resistance (R_{ct}) of both films decreases, indicating that light irradiation promotes interfacial charge transfer. The R_{ct} of TiO_2 film drops significantly from 2.41 k Ω in the dark to 0.26 k Ω under illumination. The photon energy of 385 nm UV light exceeds the bandgap of TiO_2 , which effectively excites valence-band electrons to the conduction band and generates a large number of photo-generated electron-hole pairs. This increases carrier concentration, reduces the interfacial charge transfer barrier, accelerates charge transfer, and thus decreases R_{ct} . For the BiOI/TiO_2 composite film,

its R_{ct} declines from 13.95 k Ω in the dark to 4.03 k Ω under illumination. In addition to the increase in free carrier concentration due to light excitation, the built-in electric field at the p-n heterojunction interface formed between BiOI and TiO₂ promotes the separation of photo-generated carriers and suppresses recombination during illumination, further facilitating interfacial charge transfer and thereby reducing the transfer resistance.

Figure 2(i) displays the LSV curves for the TiO₂ film and BiOI/TiO₂ composite film. Fitting according to Eq. (S8) yields a carrier mobility of 2.39 cm²·V⁻¹·s⁻¹ for the TiO₂ film, which falls within the range of 0.75-38.88 cm²·V⁻¹·s⁻¹ reported in previous literature[27, 28]. The mobility of the BiOI/TiO₂ film is 1.07 cm²·V⁻¹·s⁻¹, lower than the theoretical value of 3.58 cm²·V⁻¹·s⁻¹ calculated for pristine BiOI[29].

Figure 3(a) presents the I-V curves of BiOI/TiO₂ heterojunction device under dark conditions and monochromatic illumination with UV (330, 365, and 385 nm) and visible (405, 420, and 475 nm) light, with an irradiance of 2 mW/cm². Under dark conditions, the device exhibits distinct rectification behavior over a voltage scan range of -2 V to 2 V, with a rectification ratio of 10 at ± 2 V, indicating the formation of a p-n heterojunction interface between BiOI and TiO₂. The dark current of the device at 0 V is 1.77 nA. linear fitting of the I-V curve near 0 V yields a series resistance (R_{sh}) of 5.2 M Ω . Under illumination, the device current increases, exhibiting good photosensitivity to both UV and visible light. When the incident light energy is significantly higher than the optical bandgap of BiOI (particularly under 385 nm UV illumination), the device exhibits a negative differential resistance (NDR) phenomenon in the 0.8 V-1.2 V range, meaning that as the forward bias increases, the photocurrent first increases and then decreases. This is due to a reversible redox reaction occurring at the interface between the Pt electrode and BiOI under photoexcitation with photon energy exceeding the BiOI bandgap[30, 31]. Such redox reaction alters the charge distribution at the interface, which in turn affects the charge transfer barrier at the interface, causing the photocurrent to decrease as the bias voltage increases. The inset of Figure 3(a) is a magnified view of the I-V curve near 0 V. It can be seen that under UV and visible light irradiation, the device exhibits a

short-circuit current and an open-circuit voltage. Spontaneous photovoltage can be established under illumination, endowing the device with self-powered photodetection capability. The short-circuit current of the device first increases and then decreases with increasing wavelength, reaching its maximum at 385 nm. Except for illumination at 385 nm, the open-circuit voltage first increases and then decreases with increasing wavelength. The relatively low open-circuit voltage under 385 nm illumination may be related to redox reactions between oxygen adsorbed on the BiOI surface and the Pt electrode. Interfacial redox reactions consume a portion of the photo-generated charge carriers and weaken the built-in electric field at the heterojunction interface, thereby reducing the open-circuit voltage. To understand the dark current transport mechanism of the BiOI/TiO₂ device, double-logarithmic fitting analysis was performed on the dark I-V characteristics in Figure 3(b). Based on the slope variations of the double-logarithmic I-V curve, the charge transport behavior can be divided into four distinct regions. In the low bias region (0.2-0.4 V), the fitted slope is approximately 2.01, exhibiting typical space-charge-limited current (SCLC) characteristics. The current in this region is dominated by carrier injection from the electrodes. A small number of shallow traps in the functional layer are rapidly filled, and the current increases approximately quadratically with voltage. In the transition region (0.4-1.0 V), the fitted slope drops to 0.95, exhibiting ohmic conduction behavior. As the bias voltage increases, thermally excited carriers originating from intrinsic defects and impurities inside the device gradually dominate charge transport, leading to a linear correlation between current and voltage. In the medium bias region (1.0-1.5 V), the fitted slope increases to 2.31, returning to the SCLC transport mode, consistent with the characteristics of Child's law. At this stage, the injected carrier density exceeds the intrinsic carrier density, and the space-charge effect once again dominates current transport. In the high bias region (1.5-2.0 V), the fitted slope further increases to 3.29, exhibiting typical trap-filling-limited current (TFL) behavior. The applied electric field drives massive carrier injection to fill deep-level defect traps. Once all traps are fully filled, the charge transport reverts to ideal SCLC behavior.

Figure 3(c) plots the photocurrent response of the BiOI/TiO₂ heterojunction device as a function of incident light wavelength under zero bias, measured over the wavelength range of 300–800 nm at a light intensity of 0.034 mW/cm². The device exhibits distinct spectral selectivity in the 300–475 nm UV-blue light band. The photocurrent increases initially and then decreases as the incident wavelength increases, with the strongest photoresponse peak occurring at 375 nm, corresponding to a photocurrent of 717 nA. This peak position matches the strong absorption region of the composite film, because photons at this wavelength can efficiently excite both TiO₂ and BiOI to generate photogenerated carriers simultaneously. Figures 3(d)–(f) display the wavelength-dependent curves of responsivity (R), detection efficiency (D^*), and external quantum efficiency (EQE) of the device under self-powered operation, calculated using Eq. (S9), (S10), and (S11), respectively. In the 300–800 nm range, the trends of R , D^* , and EQE as a function of incident wavelength are essentially consistent with those of the photocurrent, all exhibiting a pattern of first increasing and then decreasing, and reaching their maximum values in the 375 nm UV band at 0.68 A/W, 7.0×10^{11} Jones (1 Jones = 1 cm·Hz^{1/2}·W⁻¹), and 225%, respectively. Notably, the EQE value exceeds 100%, indicating the presence of a photo-generated carrier multiplication effect in the device. The high EQE primarily arises from the synergy of the Z-scheme heterojunction and the built-in electric field. Under the Z-scheme charge-transfer mechanism, specific carrier recombination pathways allow more high-energy carriers for charge transport. Upon absorption of high-energy photons, the generated "hot carriers" may produce additional electron-hole pairs via impact ionization during the relaxation process, leading to a gain effect where one incident photon generates multiple charge carriers. Meanwhile, the robust built in electric field established at the BiOI/TiO₂ p-n heterojunction interface facilitates efficient spatial separation of photogenerated electrons and holes toward opposite directions, which greatly mitigates carrier recombination. Furthermore, interfacial defect states or trap levels can selectively trap one type of carrier (e.g., holes) and prolong the lifetime of the counter-type carriers (e.g., electrons). Such prolonged

carrier lifetime enables repeated carrier circulation across the external circuit and thus produces considerable photoconductive gain.

Figure 3(g) presents the I-t curves of BiOI/TiO₂ heterojunction devices at zero bias upon pulsed monochromatic illumination of UV (330, 365, 385 nm) and visible (405, 420, 475 nm) light with an optical power density $P = 2 \text{ mW/cm}^2$. Under both UV and visible light irradiation, the device current rapidly rises to a peak upon light switching on, then decays quickly and stabilizes at a steady-state value. After light is turned off, the current rapidly recovers to the dark current value, demonstrating favorable photoresponsive switching characteristics. After eight illumination cycles, both the peak and steady-state photocurrent remain stable, indicating good response stability and reproducibility of the device toward UV-visible pulsed light. A transient spike current occurs at the moment illumination begins, gradually decaying over time to reach a steady-state value. Under monochromatic UV and visible light irradiation, the photocurrent of the device first increases and then decreases with longer incident wavelength, reaching a maximum at 385 nm. Figures 3(h) and (i) show the I-t curves of the device under 385 nm UV light and 420 nm blue light with varying optical power densities at zero bias. Under irradiation with monochromatic light, the steady-state photocurrent of the device rises with increasing optical power density. The photocurrent obtained under UV light is higher than that under blue light illumination. At high optical power densities, both the transient spike current and steady-state photocurrent of the device decay to a certain extent as the number of periodic light on-off cycles increases. This can be attributed to two factors. First, the dynamic equilibrium of carrier trapping and release at intrinsic defect states within BiOI and TiO₂ is disrupted. Second, high-energy photoexcitation induces irreversible modifications to interfacial defect states, which deteriorate the carrier transfer and transport properties at the interface.

The amplitude, frequency dependence, and characteristic shape of the noise current power density spectra can reflect the intrinsic physical properties of the device. Device noise current primarily consists of shot noise (i_{sh}), thermal noise (i_{th}) and $1/f$

flicker noise ($i_{1/f}$). Under dark conditions without illumination, shot noise is mainly contributed by dark current, and the total noise can be expressed by Eq. (1).

$$i_n^2 = [i_{sh}^2 + i_{th}^2 + i_{1/f}^2(f)]\Delta f = \left[2eI_d + \frac{4k_b T}{R_{sh}} + i_{1/f}^2(f) \right] \Delta f \quad (1)$$

Where I_d and Δf represent dark current (1.77 nA) and standard operating bandwidth (1 Hz), f is the device operating frequency, k_b is the Boltzmann constant, T is the device operating temperature (298 K), R_{sh} is the shunt resistance of the PD, and e is the elementary charge. Figure 4(a) shows the noise current power density spectra of the BiOI/TiO₂ heterojunction device in the dark state. In the low-frequency region, the noise current power density decreases sharply with increasing frequency and gradually levels off when the frequency exceeds 860 Hz. The device exhibits distinct 1/f noise characteristics in the low-frequency range, whereas white noise including shot noise and thermal noise dominates at high frequencies. Based on Eq. (1), the total white noise current of the device was calculated to be 1.87×10^{-11} A. Converting to the standard 1 Hz operating bandwidth, the white noise current density is 5.95×10^{-14} A/Hz^{1/2} for the BiOI/TiO₂ heterojunction device in the dark state (see Eq. (S12-S15) in the supplementary materials for calculation details). Given that the 1/f noise current is smaller than the white noise current, the white noise current density approximates the total noise current density. The total noise current density of the BiOI/TiO₂ PD is on the same order of magnitude as reported high-performance PDs based on perovskite (1.6×10^{-14} A/Hz^{1/2})[32] and PbS quantum dot (4.85×10^{-14} A/Hz^{1/2})[33]. Low noise effectively suppresses signal interference and improves the weak-light detection capability of the device.

Figure 4(b) shows the steady-state photocurrent of the PD at different optical power densities. To eliminate interference of transient spike current on test results, all steady-state photocurrent values are uniformly extracted at an illumination duration of 5 s. Under UV and blue light illumination, the steady-state photocurrent rises with increasing light power density, while the growth rate slows down gradually at high power densities, showing a saturation trend. Under 420 nm illumination, the

photocurrent reaches saturation more readily at relatively low optical power densities.

A nonlinear model ($I \propto P^\theta$, $0 < \theta < 1$, where I is photocurrent and P is optical power density) is adopted to fit the dependence of photocurrent on optical power density. The fitted θ value is 0.84 under 385 nm illumination and 0.85 under 420 nm illumination. The close θ values for the two wavelengths indicate that comparable light absorption capacity and photoelectric conversion efficiency in the UV and visible regions. Using Eq. (S16), the noise-equivalent power (NEP) of the BiOI/TiO₂ heterojunction device is calculated to be 9.56×10^{-14} and 5.90×10^{-13} W/Hz^{1/2} under 385 nm and 420 nm illumination, respectively, corresponding to a noise current of 5.95×10^{-14} A at a standard bandwidth of 1 Hz. Taking the NEP value at 1 Hz standard operating bandwidth as the minimum detectable power of the device, the linear dynamic range (LDR) calculated via Eq. (S17) reaches 99 dB and 88 dB when the maximum optical power densities are 20 and 10 mW/cm² under 385 nm and 420 nm illumination, respectively. The device achieves a linear dynamic range of 99 dB under 385 nm ultraviolet light, combined with a NEP as low as 9.56×10^{-14} W/Hz^{1/2}, demonstrating its ability to maintain linear response across a wide power range from extremely weak light to strong light (20 mW/cm²), thus exhibiting excellent capability in detecting weak optical signals. Under 420 nm visible light, the device still retains an 88 dB linear dynamic range and a NEP of 5.90×10^{-13} W/Hz^{1/2}, achieving both high sensitivity and broad linearity in the visible spectrum, confirming its advantages in self-driven detection across a wide spectral range (ultraviolet to visible).

Figure 4(c) displays the transient I-t curves of the BiOI/TiO₂ PD under zero bias when irradiated with 385 nm UV light and 420 nm visible light, with a light power density of 2 mW/cm². As illustrated, the rise times of the device are 26 ms and 57 ms, respectively, while the decay times are 168 ms and 258 ms, respectively. The device exhibits a faster response under UV light, indicating that the rates of photo-generated carrier separation and transport are higher at this wavelength. Furthermore, the decay time of photoresponse is nearly one order of magnitude longer than the rise time.

Figure 4(d) schematically illustrates the dynamics of photo-generated carriers in a BiOI/TiO₂ heterojunction device under UV excitation without an applied bias. Since the E_F of TiO₂ is higher than that of BiOI, majority carriers (electrons) in TiO₂ diffuse toward BiOI, and majority carriers (holes) in BiOI diffuse toward TiO₂, until thermodynamic equilibrium is reached. After equilibrium, a stable built-in electric field forms at the heterojunction interface, pointing from n-type TiO₂ toward p-type BiOI. Since both the conduction band edge (E_C) and valence band edge (E_V) of TiO₂ are higher than those of BiOI, which generates conduction band offset and valence band offset at the interface. The upward-bent valence band on the TiO₂ side forms a potential well for holes, while the downward-bent conduction band on the BiOI side forms a potential well for electrons, constructing a typical Z-scheme band alignment. Upon UV excitation (e.g., 385 nm), electrons in the TiO₂ valence band jump to the conduction band (Process ①). Since the photon energy far exceeds BiOI bandgap, electrons in the BiOI valence band are excited to energy levels above the CBM, forming high-energy hot electrons (Process ②). In accordance with energy matching principles, high-energy hot electrons are more susceptible to being captured by deep level traps. Within an extremely short time after light switching on, photo-generated holes from the TiO₂ valence band (Process ③) and high-energy hot electrons above the BiOI conduction band migrate directionally toward the interface driven by the built-in electric field (Process ④) and get trapped by deep levels at the interface. A small fraction of the high-energy hot electrons relax to the CBM and then participate in Process ④. With prolonged illumination, trapped electrons and holes at the interface overcome the interfacial potential barrier and undergo non-radiative recombination (Process ⑤). The resultant non-equilibrium electrons in the TiO₂ conduction band and non-equilibrium holes in the BiOI valence band diffuse to the FTO and Pt electrodes, respectively, generating a transient spike current in the external circuit. When recombination and diffusion reach dynamic equilibrium, the current rapidly decays from the spike to a steady-state value.

Figure 4(e) illustrates the dynamics of photo-generated carriers in a BiOI/TiO₂ heterojunction device under visible light excitation (e.g., 420 nm) without an applied

bias. Since the incident photon energy is lower than the band gap of TiO_2 but higher than that of BiOI , interband transitions in TiO_2 cannot be triggered; instead, electrons are excited to donor levels below the conduction band (Process ①). Electrons at donor levels can be thermally excited to the conduction band at a certain probability, while electrons in the conduction band can also relax back to donor levels, establishing a dynamic equilibrium. Meanwhile, electrons in the valence band of BiOI are excited to levels above the conduction band, forming medium-energy hot electrons (Process ②). Driven by the built-in electric field in the Z-scheme heterojunction, the migration and recombination processes of photo-generated holes from TiO_2 and medium-energy hot electrons from BiOI (Processes ③, ④, and ⑤) are similar to the carrier dynamics under UV excitation (Processes ③, ④, and ⑤). These medium-energy hot electrons have a lower probability of being captured by deep interfacial traps compared with high-energy hot electrons, which explains the distinct spike current and larger photocurrent under UV irradiation at identical optical power. Furthermore, the recombination probability rises with increasing incident photon flux (i.e., the excitation optical power density). Therefore, under low-power-density 420 nm illumination, fewer photo-generated electrons are captured at the interface and interfacial recombination is negligible, leading to an indistinct transient spike current upon light switching on. In contrast, an obvious spike current emerges immediately after high-power light is turned on, consistent with the phenomena in Figure 4(e). Besides the interface potential well and defect states, bulk defects within BiOI and TiO_2 nanomaterials also perturb the dynamics of photogenerated carriers and consequently modify the sharp peak feature of transient photocurrent.

In the fields of urban low-altitude security and unmanned aerial vehicle (UAV) trajectory supervision, there is an urgent need for continuous, low-power, and traceable recording of dynamic UAV trajectories. This technology not only enables precise tracking of flight paths and directions in complex urban environments and timely early warning of violations, but also fundamentally eliminates regulatory blind

spots caused by trajectory gaps or data loss. It holds significant practical value in scenarios including urban low-altitude security, low-altitude logistics management, and security for large-scale events. Figure 5(a) illustrates a scenario where a PD is used to monitor UAV flight trajectories in real time. As shown in Figure 5(b), the photocurrent of a BiOI/TiO₂ PD under UV illumination exhibits a nonlinear time-domain characteristic of “instantaneous peak, exponential decay and slow stabilization”. This characteristic renders it suitable for directional dynamic target trajectory monitoring systems. To validate this concept, a simulated array consisting of 60×60 PD pixels is constructed, with each pixel corresponding to an independent detection unit. An optical lens projects the scene onto the detector array, where each pixel independently responds to the local light intensity to capture a complete two-dimensional image at a single moment. In the 60×60 spatial image, the grayscale value of each pixel is mapped from the instantaneous photocurrent of the corresponding detection unit: higher photocurrent corresponds to a larger grayscale value (dark purple). The UAV target occupies 12×8 pixels in the image. Pixels corresponding to its instantaneous spatial position of the UAV exhibit the maximum grayscale value (mapped from the current at the moment of light turn-on), while the pixels along the trajectory record decaying current signals after illumination activation (decreasing grayscale values). As shown in Figure 5(c), image grayscale mapping based on steady-state current yields identical grayscale values for all points on the trajectory, making it impossible to judge the UAV’s moving direction. In contrast, Figure 5(d) adopts spike current with nonlinear time-domain features for grayscale mapping and the direction along which the grayscale deepens on the trajectory reveals the travel direction of UAV. By analyzing the spatial distribution of pixel grayscale values (i.e., mapped photocurrent), directional trajectory monitoring of UAVs can be realized. In the simulated scenario, the photodetection module remains deactivated under normal conditions. When a moving target enters the detection area, the detector automatically switches on and maintains operation for 10 s. If no UAV passes through that position again, the PD shuts down automatically after 10 s. If another UAV traverses the same spot, the timing counter for the PD at that position resets. Figures

5(e)-(h) simulate UAV flight trajectories including straight-line, rectangle, arc shaped, and serpentine paths, where the trajectories and motion directions in each frame are clearly distinguishable. The orientation of these gradients directly indicates the target's motion direction, eliminating the requirement for post-processing algorithms. Such a function is unattainable in conventional PDs that produce steady-state photocurrent under light illumination.

In the simulated scenario, it is essential to distinguish two distinct photocurrent relaxation regimes in the BiOI/TiO₂ PD. During the light-on window, the photocurrent exhibits an instantaneous spike followed by a slow, exponential relaxation toward a steady state over several seconds when a pixel remains continuously illuminated by the optical footprint of a moving target. This slow decay arises from the trapping-release equilibrium at interfacial deep-level traps, which effectively encodes the illumination history and generates spatially distributed grayscale gradients within a single readout frame, enabling motion-direction discrimination. As illustrated in Figure 5(e)-(h), each subplot represents a direct, single-frame readout of the detector array at successive time instants, rather than a post-processing superposition of multiple short-exposure frames. Unlike conventional vision systems that rely on off-chip transmission and inter-frame feature matching across multiple raw frames, our approach embeds temporal historical information at the pixel level during optical sensing. Consequently, only lightweight spatial-gradient analysis is required after readout. Conversely, when the target completely exits the pixel's field of view, the device enters the light-off window. In this regime, the photocurrent rapidly decays back to the dark level within a timescale of hundreds of milliseconds, causing trajectory-related signals to vanish promptly. Therefore, reliable trajectory recognition is confined to the continuous-illumination window. This operating principle imposes an inherent application constraint: the target must maintain sufficient overlap with adjacent pixels over the several-second timescale of the light-on slow decay. For fast-moving targets that traverse a single pixel within hundreds of milliseconds, the necessary grayscale gradient cannot be established, leading to failure in directional trajectory judgment. Consequently, this strategy is well-suited for relatively

slow-moving objects but is not applicable to general-purpose, high-speed target tracking.

The field of dynamic image encryption requires encrypted information to be controllably displayed within a specific time window and automatically hidden after expiration, so as to guarantee the security of information transmission and storage and prevent unauthorized personnel from accessing sensitive data. This requirement holds vital application value in confidential communication, military reconnaissance, safety patrol inspection and other scenarios[34]. The security of this solution does not depend on algorithmic complexity, but rather on the irreversibility and time-dependent characteristics of physical processes. It is adaptable to read and destroy application scenarios such as security inspection. When inspectors arrive at designated locations, they obtain temporary passwords or commands through handheld devices. Upon access, the information vanishes instantaneously to avoid interception by subsequent operators or surveillance cameras. This work envisions an information-transmission scenario within an authorized time window. Consider a secure communication system consisting of a transmitter and a receiver. The transmitter is a controllable ultraviolet light source (e.g., UV LED array or DMD projection system) that projects encrypted image information (e.g., the characters “TJUT”). The receiver is a BiOI/TiO₂ PD array connected to a signal-processing unit. As shown in Figure 6(a), for safety patrol scenarios, information acquirers need to rapidly read encrypted data before patrol staff arrive while avoiding information leakage. The figure captures the instant right after the acquirer completes reading, when the encrypted information is clearly recognizable. As displayed in Figure 6(b), the encrypted content vanishes entirely once patrol personnel approach the acquirer, preventing monitors from capturing any confidential data and achieving the encryption goal of exclusive authorized access. The transient peak current behavior of BiOI/TiO₂ heterojunction devices under UV illumination can meet the above demands for dynamic image encryption. The instantaneous current peak can render encrypted information clearly visible; the current decay process gradually while conceals the data, and the eventual steady-state current fully hides all encrypted content. To

implement dynamic encrypted imaging, a simulated 770×916 array is constructed using BiOI/TiO₂ self-powered PDs, with a current threshold $I_{th} = 2.98 \mu\text{A}$. When the instantaneous current detected by a pixel exceeds this threshold, the detector array receives a photocurrent signal and generates image pixels with different grayscale values proportional to the instantaneous current magnitude, and larger current corresponds to higher pixel grayscale and clearer images. If the instantaneous current falls below the threshold, the array cannot form a valid image, and the encrypted information is concealed.

Figure 6 (d)-(i) intuitively demonstrates the dynamic imaging evolution of the encrypted text “TJUT” captured by the detector array under 385 nm UV light as illumination time elapses. The variations of grayscale values (color depth) perfectly match the current decay trend in the I-t curve. Detailed descriptions are as follows: At $t = 0$, the transmitter projects an encrypted UV image onto the PD array at the receiver end. At the instant the illumination is turned on ($t = 0.1\text{s}$), each pixel of the detector array generates a large transient spike current. At this moment, the system reads the current values of all pixels. Since the current is far larger than the preset threshold (I_{th}), the encrypted image “TJUT” is clearly reconstructed and displayed on the authorized user’s screen. At $t = 0.5\text{ s}$ and $t = 1\text{ s}$, the current decays rapidly following an exponential law yet remains above the threshold, and the purple shade of “TJUT” continuously fades and image definition declines gradually. At $t = 3\text{ s}$ and $t = 5\text{ s}$, the photocurrent enters a slow decay plateau and approaches the threshold, and only faint traces of “TJUT” remain, barely recognizable. If an attacker attempts to intercept the signal during information projection (e.g., $t = 3\text{ s}$), only a blurry, incomplete image with an extremely low signal-to-noise ratio can be obtained, and no complete information can be acquired. At $t = 5.5\text{ s}$, the instantaneous current values of all pixels decay below the threshold I_{th} . At this point, even if an attacker intercepts the output signals of the detector array, no valid image can be reconstructed and the information is physically “erased”. Moreover, this spike current profile can be reproduced repeatedly through multiple cycles of light switching, and such repeatability ensures stable transmission of encrypted information. This work envisions an

information-transmission scenario within an authorized time window. The proposed “dynamic image encryption” is adaptable to read and destroy application scenarios such as security inspection. When inspectors arrive at designated locations, they obtain temporary passwords or commands through handheld devices. Upon access, the information vanishes instantaneously to avoid interception by subsequent operators or surveillance cameras.

4 Conclusions

In this work, BiOI/TiO₂ heterojunction thin films were successfully synthesized using a two-step hydrothermal method, and self-powered Pt/BiOI/TiO₂/FTO PDs were fabricated. At zero bias, the device exhibits distinct photoresponse characteristics to UV-blue light in the 300-475 nm range, achieving a maximum R of 0.68 A/W, a D^* of 7.0×10^{11} Jones, an EQE of 225%, and a LDR of 99 dB at 385 nm. Benefiting from the synergistic effect of the Z-scheme band structure, built-in heterojunction electric field and interfacial potential wells, the device delivers distinctive transient spike current under UV irradiation. Combining the nonlinear time-domain evolution characteristics of photocurrent, including instantaneous spike generation, exponential decay, and slow current stabilization, numerical simulations verify the capability of the proposed device for directional dynamic trajectory monitoring and UV image encryption applications. Notably, the BiOI/TiO₂ self-powered PD realizes the integration of optical sensing and in-situ computation. It can directly implement feature extraction and signal encoding at the sensing terminal, which eliminates the transmission of massive raw data to rear-end systems, effectively reduces device power consumption, and alleviates the inherent “memory wall” limitation of traditional optoelectronic devices. The proposed self-powered PD possesses promising application prospects in intelligent perception, secure optical communication, and dynamic UV imaging fields.

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.

Acknowledgments

This study was partially supported by the National Natural Science Foundation of China (Grant Nos. 52271187, 62375205, 51871167, 5197115).

Declaration of competing interest

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

Author contribution statement

Yuxi Jiang: Led conceptualization, Data curation, Formal analysis, Investigation, Validation, Visualization, Drafted the original manuscript, and Reviewed/edited it. Jianping Xu: review & editing, Investigation, Formal analysis, Data curation, Conceptualization, Funding acquisition. Shaobo Shi: Investigation, Formal analysis, Data curation. Jing Chen: Investigation, Formal analysis, Data curation. Lina Kong: Investigation, Formal analysis. Xiaosong Zhang: Investigation, Formal analysis. Lan Li: Supervision, Resources, Funding acquisition.

Use of AI statement

None

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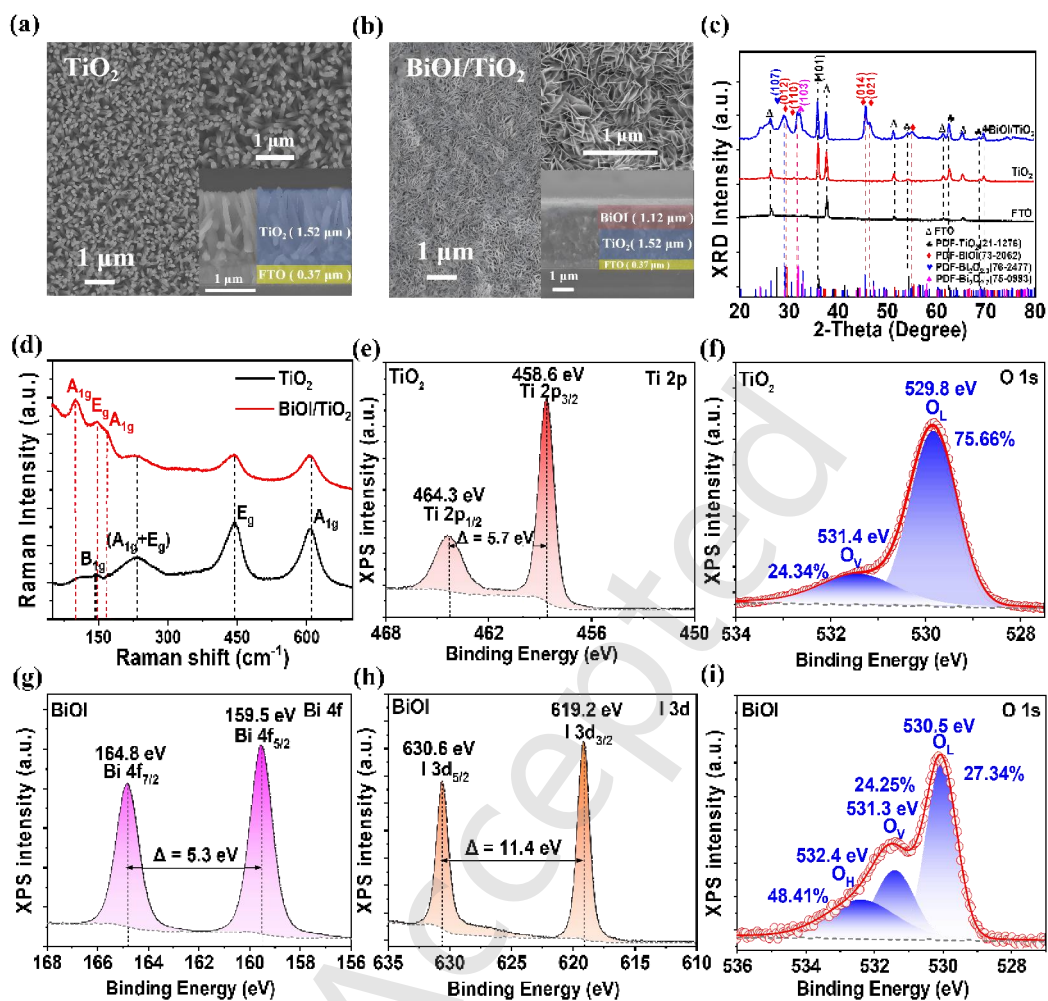


Figure 1 Top-view and cross-sectional SEM images of (a) TiO_2 NRs and (b) BiOI/TiO_2 film. (c) XRD patterns and (d) Raman spectra of TiO_2 NRs and BiOI/TiO_2 films. (e) Ti 2p and (f) O 1s XPS spectra of TiO_2 NRs and (g) Bi 4f, (h) I 3d and (i) O 1s XPS spectra of TiO_2 NRs and BiOI/TiO_2 films.

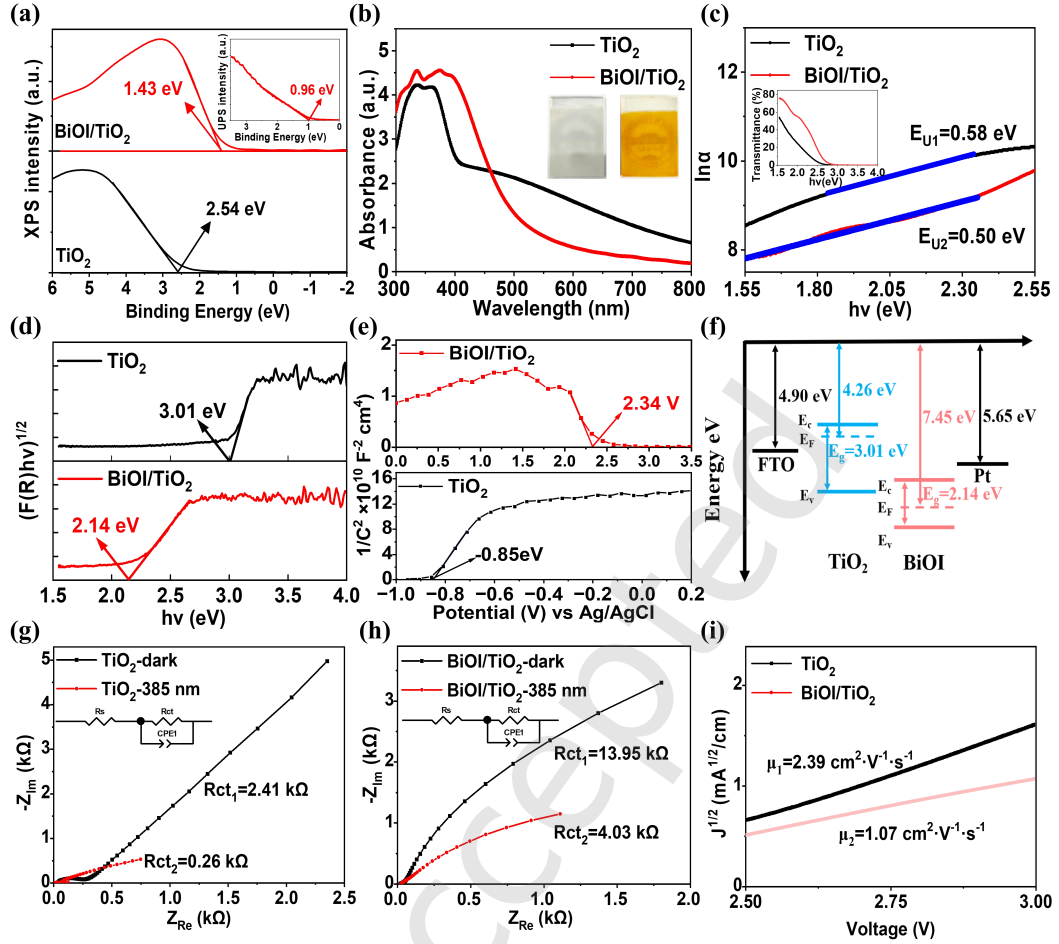


Figure 2 (a) VB spectra derived from XPS and UPS measurements, (b) UV-vis absorption spectra and corresponding optical photographs, (c) semi-logarithmic plots of $\ln \alpha$ versus $h\nu$, (d) optical bandgap, and (e) M - S curves of TiO₂ NRs and BiOI/TiO₂ films. (f) Energy level structure diagram of BiOI and TiO₂ before heterojunction contact. EIS curves of (g) TiO₂ films and (h) BiOI/TiO₂ films. (i) LSV curves of TiO₂ films and BiOI/TiO₂ films

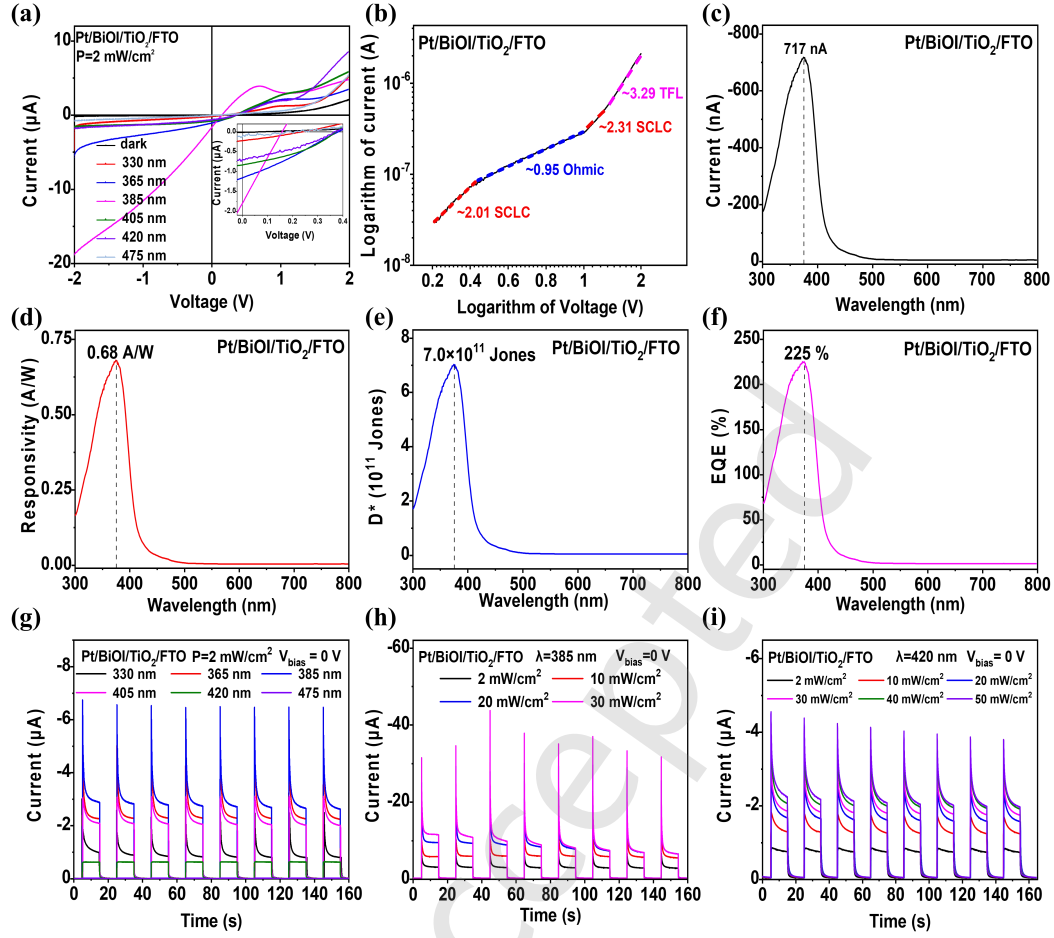


Figure 3 (a) I-V curves under dark and light states. (b) I-V curve under dark fitting across different voltage ranges. Wavelength-dependent (c) photocurrent, (d) responsivity, (e) detectivity, and (f) *EQE* curves without external bias. (g) I-t cycle curves under UV and visible light without external bias. (h) I-t cycle curves under 385 nm and (i) 420 nm light with different optical power density without external bias for BiOI/TiO₂ PD.

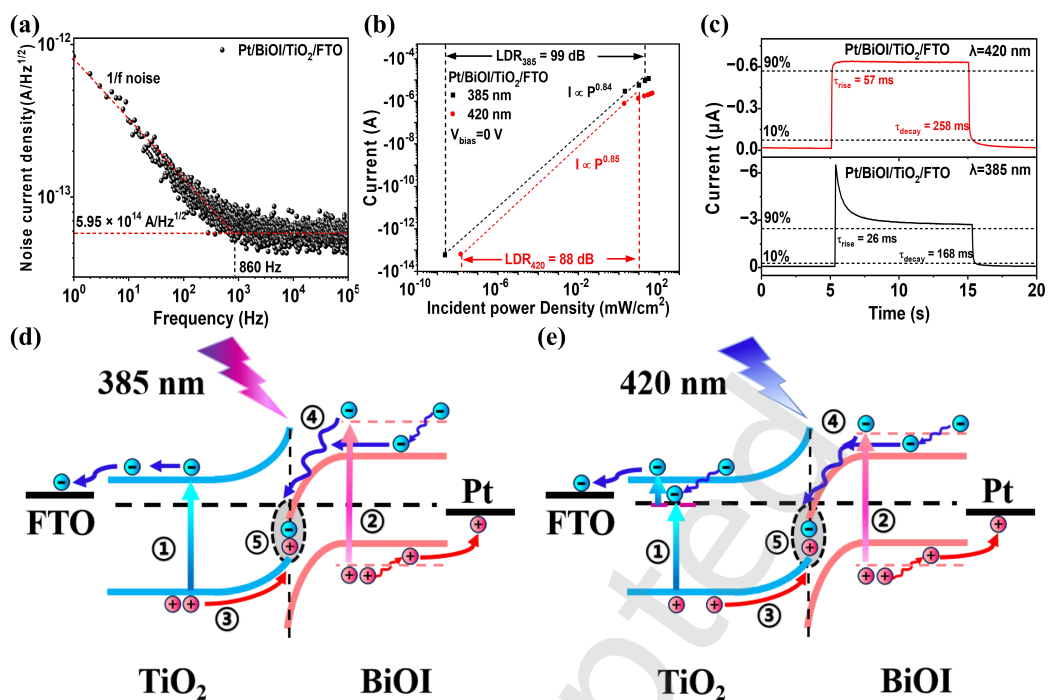


Figure 4 (a) Noise current spectral density of BiOI/TiO₂ PDs. (b) *LDR*, (c) transient current curves, and the dynamic processes of generation, recombination, and transfer for photogenerated carriers in BiOI/TiO₂ PDs under (d) 385 nm and (e) 420 nm light without external bias.

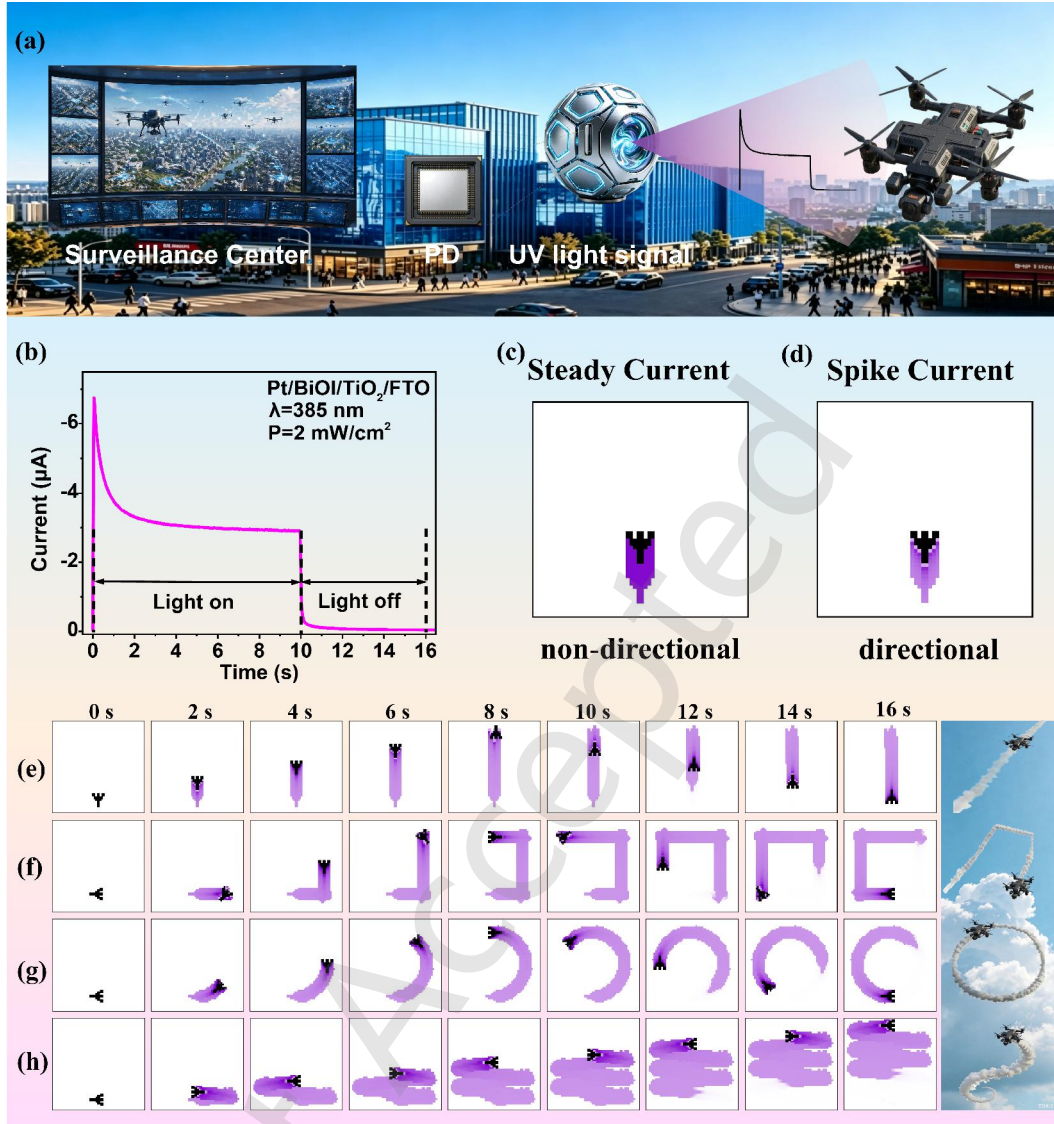


Figure 5 (a) Schematic diagram of the scenario for detecting UAV trajectory and movement direction using a PD. (b) The photocurrent under UV light shows a nonlinear transient response comprising an instantaneous peak, exponential decay, and slow stabilization for the PD. (c) Grayscale mapping of steady-state photocurrent: uniform grayscale values along the trajectory prevent the determination of the UAV trajectory's forward direction. By utilizing the spike current with nonlinear temporal characteristics for image grayscale mapping, the forward direction of the UAV trajectory can be determined based on the direction in which the grayscale values along the trajectory change from light to dark: (d) linear, (e) rectangular, (f) arc, and (g) serpentine flight

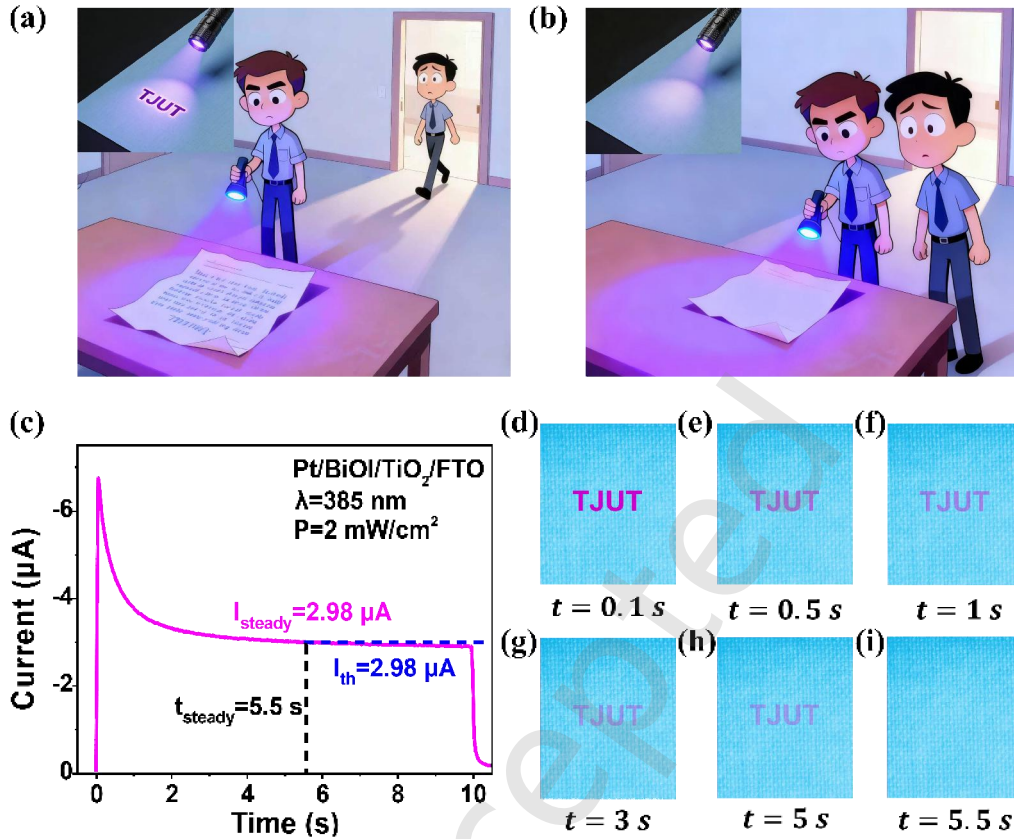


Figure 6 (a)-(b) Schematic of dynamic image encryption based on the transient spike current. The instantaneous peak allows for clear information display, followed by gradual fading during current decay, and final complete concealment upon stabilization. (c) Device transient photocurrent: With a threshold $I_{\text{th}} = 2.98 \mu\text{A}$, instantaneous currents above this level generate grayscale pixels, whereas sub-threshold currents conceal the encrypted information. (d)-(i) Dynamic imaging process of the encrypted content “TJUT” captured by a PD array under varying UV light illumination durations.

Electronic Supplementary Material

Self-powered in-sensor computing photodetector based on BiOI/TiO₂ for motion trajectory

recognition and dynamic image encryption

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Supporting information to <https://doi.org/10.26599/NR.2026.94909168>

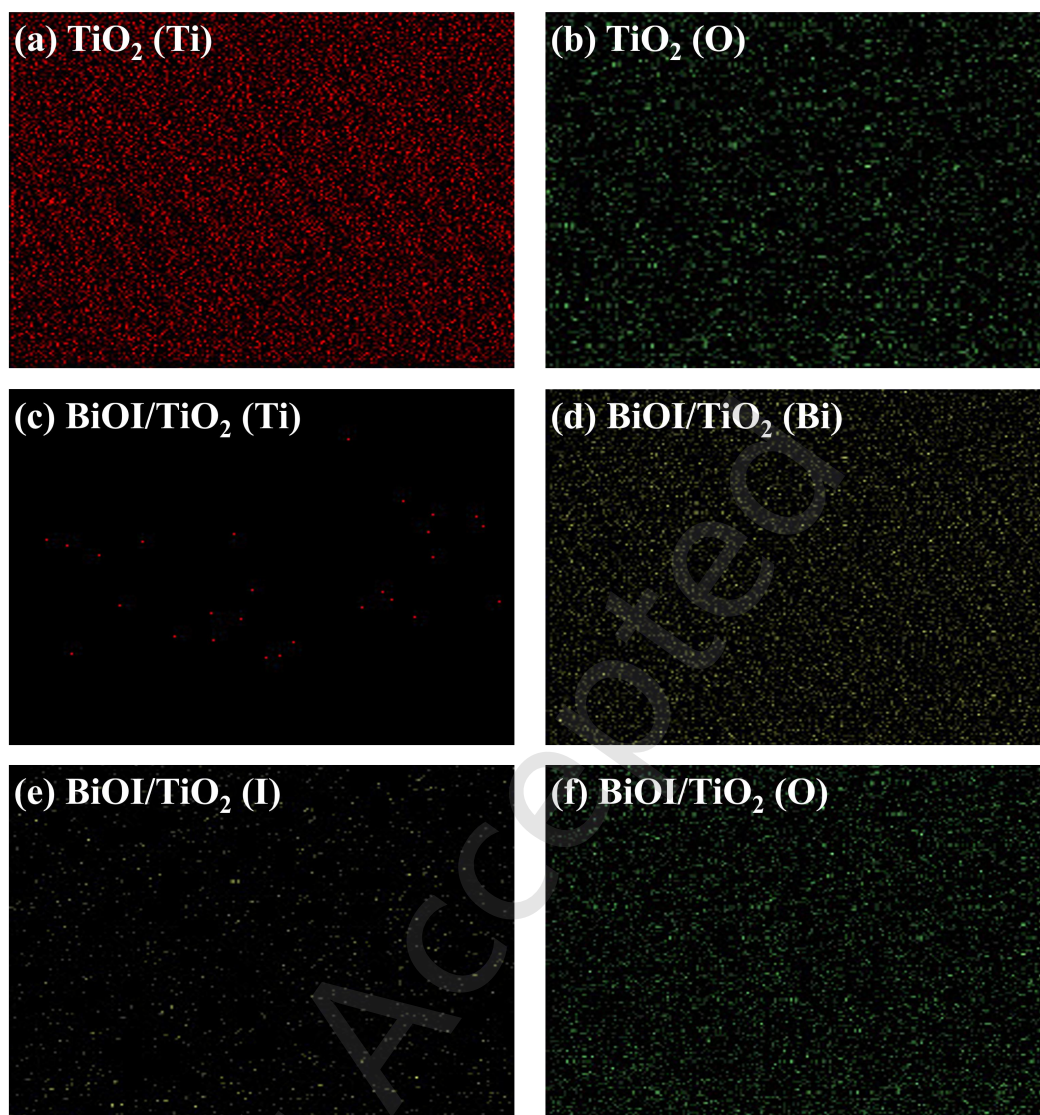


Figure S1.EDS mapping for (a) Ti and (b) O in the TiO_2 NRs film, (c) Ti, (d) Bi, (e) I, and (f) O in the BiOI/TiO_2 film

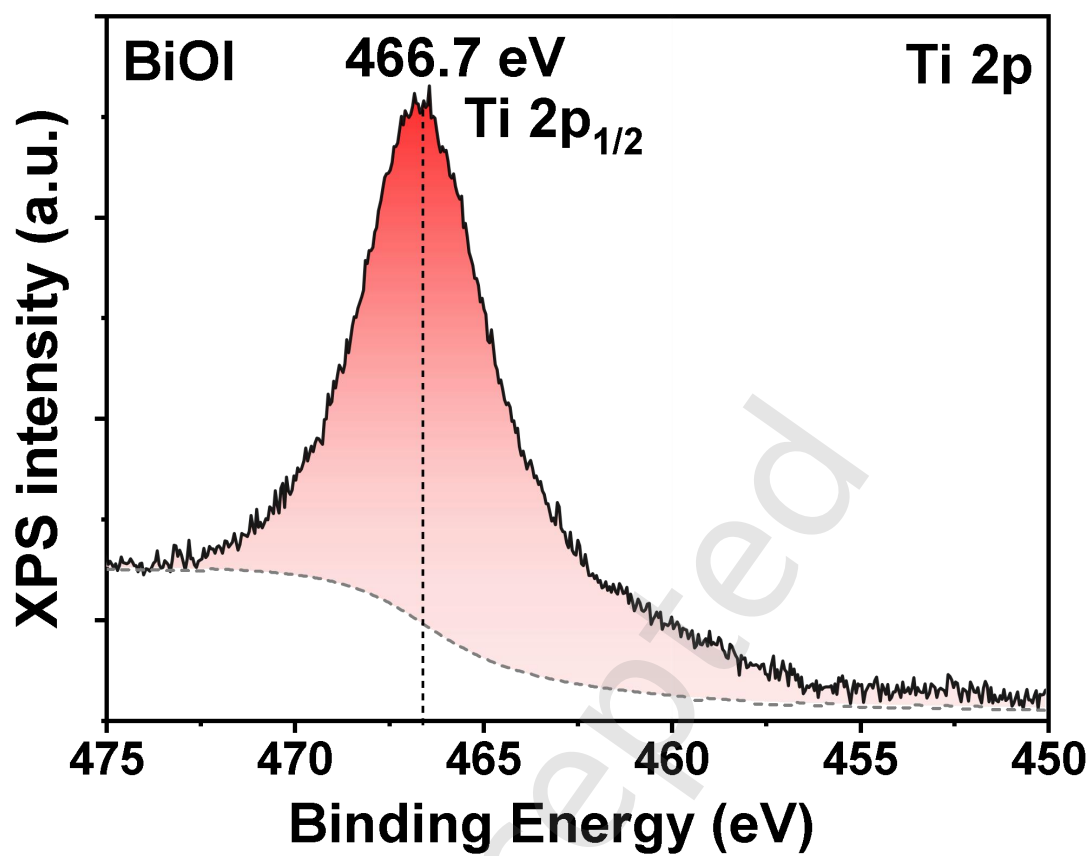


Figure S2 Ti 2p XPS spectra of BiOI/TiO₂ films.

According to Urbach's empirical Eq. (S1), E_U can be obtained by extracting the slope of the absorption coefficient curve in the region bordering the $(\ln\alpha \sim h\nu)$ band in a semi-logarithmic coordinate system.

$$\alpha = \alpha_0 \exp\left(\frac{h\nu - E_g}{E_U}\right) \quad (S1)$$

In particular, the absorption coefficient α is calculated using Eq. (S2):

$$\alpha = \frac{\ln(T^{-1})}{d} \quad (S2)$$

In Eq. (S1), α_0 is the tail parameter (a constant), and $h\nu$ is the energy of the incident photon. In Eq. (S2), T is the transmittance of the thin film, and d is the thickness of the absorption layer. Taking the natural logarithm ($\ln$) of both sides of Eq. (1) yields Eq. (S3):

$$\ln\alpha = \frac{1}{E_U} \cdot (h\nu - E_g) + \ln\alpha_0 = \frac{1}{E_U} \cdot h\nu + \ln C \quad (S3)$$

In Eq. (S3), $\ln C = \ln\alpha_0 - E_g/E_U$ is a constant; therefore, the reciprocal of the slope in the linear region near the edge of the $\ln\alpha \sim h\nu$ band is the Urbach energy E_U .

Using the Kubelka-Munk function S4 and the Tauc relation S5, the optical bandgap values for each sample can be obtained by drawing a tangent at the point of maximum slope on the $(F(R)h\nu)^{1/2}$ curve and extrapolating it until it intersects the photon energy ($h\nu$) axis

$$F(R) = \frac{(1-R)^2}{2R} \quad (S4)$$

$$(\alpha h\nu)^{\frac{1}{n}} = A(h\nu - E_g) \quad (S5)$$

In the above Eq., R represents the reflectance of the material measured from the diffuse reflectance spectrum; α represents the corresponding optical absorption coefficient at different wavelengths; $h\nu$ represents the energy of the incident photon; A is a constant related to the material's intrinsic properties; and E_g is the optical bandgap of the semiconductor. α is directly proportional to the Kubelka-Munk function $F(R)$. Both TiO_2 and BiOI primarily involve indirect transitions; therefore, the transition index n in the Tauc relation is taken as 2.

$$E(RHE) = E(Ag/AgCl) + 0.0591 \times PH + 0.197 \quad (S6)$$

$$E_F = -4.5 - E(RHE) \quad (S7)$$

In the above calculation Eq., $E(Ag/AgCl)$ represents the open-circuit potential. The test electrolyte used in this experiment is a 1 M aqueous solution of Na_2SO_4 with a pH of 7.

$$\mu = \frac{8k^2L^3}{9\varepsilon_r\varepsilon_r} \quad (S8)$$

In the above Eq., μ is the carrier mobility, k is the slope of the fitted straight line, and L is the thickness of the thin film layer.

$$R = \frac{I_{ph} - I_d}{PA} \quad (\text{S9})$$

$$D^* = \frac{R \cdot \sqrt{A \cdot \Delta f}}{i_n} \quad (\text{S10})$$

$$EQE = \frac{Rh\nu}{e} \quad (\text{S11})$$

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Based on the calculation of noise current, the detailed procedure is as follows:

We first determined that the cutoff frequency of the 1/f noise in Figure 3(b) is 860 Hz. We then calculated a fitted curve based on the method for handling 1/f noise in the RMS operational amplifier noise domain. The Eq. (S12) is as follows:

$$i_{1/f}^2(f) = k \log \frac{f}{f_0} \quad (\text{S12})$$

Here, f is the current operating frequency, which is also the cutoff frequency of the noise spectrum; f_0 is fixed at 0.1 Hz. Since Eq. (S1) contains a single constant k , we determined $k = 9.3095 \times 10^{-14}$ by calculating the device's noise current density at an operating frequency of 1 Hz, yielding the relationship between the 1/f noise current density and the operating frequency as shown in Eq. (S13).

$$i_{1/f}^2(f) = 9.3095 \times 10^{-14} \left(\log \frac{f}{f_0} \right) \quad (\text{S13})$$

Then, by substituting the cutoff frequency $f = 860$ Hz into S12, the 1/f current in the range of 0.1 Hz to 860 Hz was calculated to be 2.7984×10^{-13} A. At the same time, using Eq. (S13), the white noise over the actual bandwidth Δf ranging from 860 Hz to 100,000 Hz was calculated to be 1.87×10^{-11} A. Using Eq. (1), the total noise current in was calculated to be 1.8805×10^{-11} A.

$$i_{sh}^2 + i_{th}^2 = \left[2eI_d + \frac{4k_b T}{R_{sh}} \right] \Delta f, \quad (\text{S14})$$

Eq. (S15) expresses the relationship between noise current and noise current density.

$$I_n = \frac{i_n}{\sqrt{\Delta f}}, \quad (\text{S15})$$

Here, I_n represents the noise current density, and i_n represents the noise current within the corresponding range (standard 1 Hz bandwidth). Since the noise ranges Δf calculated in S12 and S13 are 0.1 Hz-860 Hz and 860 Hz-100,000 Hz, respectively, it is necessary to average the data across the bandwidth to achieve 1 Hz normalization (primarily to facilitate the averaging of 1/f noise; whereas the average value of white noise across the entire bandwidth is equivalent to the value at any frequency within

that bandwidth). The resulting noise current density for 1/f noise is 9.6561×10^{-15} A/Hz^{1/2}, the noise current density of white noise was 5.9459×10^{-14} A/Hz^{1/2}, and the noise current density of total noise was 5.9466×10^{-14} A/Hz^{1/2}. Based on the above data, the noise current densities of white noise and total noise are similar; therefore, this paper directly uses the noise current density of white noise.

Noise-equivalent power (*NEP*) is a parameter that characterizes the ultimate sensitivity of a photodetector. It is defined as the incident light power required to achieve a signal-to-noise ratio (*SNR*) of 1 at a standard operating bandwidth of 1 Hz. It reflects the limitation imposed by detector noise on the smallest detectable light signal and is a key metric for evaluating low-light detection capability. The calculation Eq. is:

$$NEP = \frac{I_n}{R} \quad (S16)$$

R represents the light sensitivity, and the noise current density *I_n* is calculated using Eq. (S15).

Eq. (S17), which calculates the linear dynamic range based on noise, is as follows:

$$LDR = 10 \log\left(\frac{P_{\max}}{P_{\min}}\right) \quad (S17)$$

Here, *P_{min}* represents the noise equivalent power (*NEP*) at a bandwidth of 1 Hz; the larger the *LDR*, the wider the range of light intensities the device can detect.