Near-Infrared Self-Powered Linearly Polarized Photodetection and Digital Incoherent Holography Using WSe₂/ReSe₂ van der Waals Heterostructure

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ABSTRACT: Polarization-sensitive photodetection has attracted considerable attention as an emerging technology for future optoelectronic applications such as three-dimensional (3D) imaging, quantum optics, and encryption. However, traditional photodetectors based on Si or III–V InGaAs semiconductors cannot directly detect polarized light without additional optical components. Herein, we demonstrate a self-powered linear-polarization-sensitive near-infrared (NIR) photodetector using a two-dimensional WSe₂/ReSe₂ van der Waals heterostructure. The WSe₂/ReSe₂ heterojunction photodiode with semivertical geometry exhibits excellent performance: an ideality factor of 1.67, a broad spectral photoresponse of 405–980 nm with a significant photovoltaic effect, outstanding linearity with a linear dynamic range wider than 100 dB, and rapid photoswitching behavior with a cutoff frequency up to 100 kHz. Strongly polarized excitonic transitions around the band edge in ReSe₂ lead to significant 980 nm NIR linear-polarization-dependent photocurrent. This linear polarization sensitivity remains stable even after exposure to air for longer than five months. Furthermore, by leveraging the NIR (980 nm)-selective linear polarization detection of this photodiode under photovoltaic operation, we demonstrate digital incoherent holographic 3D imaging.

KEYWORDS: 2D ReSe₂, 2D WSe₂, heterostructure, linear polarization detection, digital incoherent holography

Photodetectors are essential components in a number of optoelectronic applications both in academic spectroscopy and in daily use appliances.¹ Beyond conventional photodetection, polarized light detection has attracted significant attention as a promising technology to be utilized in such a variety of fields as quantum information, cryptography, and three-dimensional (3D) displays.^{2,3} In particular, linear-polarization (LP)-sensitive photodetectors can be used extensively in emerging imaging systems. Image sensors based on LP-sensitive detectors can remove unwanted glare and reflections, enabling visualization of artificial objects that can otherwise be difficult to identify. Material inspections (stress or scratch) or contrast improvements under low light intensity can be performed by measuring the angle of polarized light. As such, there has been considerable interest in the exploration of low-dimensional semiconductors with asym-

metric crystal structures that possess intrinsic polarization sensitivity.^{4,5}

In this context, two-dimensional (2D) van der Waals (vdW) layered semiconductors with in-plane anisotropic properties are a promising candidate for use in LP-sensitive photodetection.^{5–7} In addition, vdW heterostructures can be readily implemented by simply stacking different 2D materials without the constraint of atomic lattice matching owing to their

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Figure 1. 2D WSe₂/ReSe₂ heterostructure and device schematics. (a) Schematic 3D view, optical microscope (OM) images, and energy band diagram of the 2D WSe₂/ReSe₂ heterojunction photodiode. (b) Atomic force microscopy (AFM) step-height profiles of ReSe₂ and WSe₂ nanoflakes. (c) Microfocused absorption spectra of ReSe₂ and WSe₂ for various LP light angles.

dangling-bond-free nature, which provides a device platform for high-performance optoelectronic applications.^{8,9} For example, black phosphorus (BP) with a puckered in-plane lattice structure has shown anisotropic optoelectronic characteristics.^{5–7,10–13} Through the combination of BP with group VI transition-metal dichalcogenides (TMDs) such as MoS₂ and WSe₂, highly LP-sensitive heterojunction photodetectors with broadband spectral photoresponse in the visible to infrared range have been demonstrated.^{11,12} Despite these significant achievements, the long-term stability of BP still remains a challenging issue that must be addressed for many practical applications. On the one hand, group VII ReX₂ TMDs (X: chalcogen atoms) with in-plane asymmetric crystal structures have recently been introduced. Unlike typical group VI MoX₂ and WX₂ TMDs, ReX₂ TMDs clearly exhibit strongly anisotropic excitonic absorption features.^{14–19} Following these fundamental studies, several optoelectronic devices based on ReX₂ have been demonstrated.^{20–25} However, only a few studies have examined the LP-sensitive characteristics of phototransistors.^{20,21} Except for a preliminary result of an LP-sensitive ReS₂/ReSe₂ heterojunction,²⁶ LP-sensitive heter-

ojunction photodiodes based on ReX₂ combined with typical group VI TMDs have been rarely reported. Above all, any advanced demonstration such as functional imaging, beyond the basic photodetector unit, has hardly been found yet. Such LP-sensitive imaging in practical forms of demonstration would strongly deserve attention.

Herein, we propose a WSe₂/ReSe₂ heterostructure for a high-performance photodiode with LP photodetection that enables 3D imaging application. A semivertical geometry is adopted to reduce the parasitic resistance, expecting a significant photovoltaic effect.^{27,28} This photodiode exhibits an ideality factor of 1.67, a broadband photodetection capability from visible (405 nm) to near-infrared (NIR; 980 nm). A wide linear dynamic range (LDR) greater than 100 dB with a linearity parameter of 0.99 is observed. In addition to this superior static performance, the device exhibits rapid photoswitching behavior with a cutoff (3 dB loss) frequency between 30 kHz (980 nm) and 100 kHz (638 nm). Beyond the typical photodetection characteristics, a significant LP-dependent photocurrent only under 980 nm NIR illumination is clearly observed, which is attributed to strongly polarized

Figure 2. WSe₂/ReSe₂ photodiode characteristics. (a) Dark and photoinduced I – V characteristics of the WSe₂/ReSe₂ heterojunction photodiode under near-infrared (NIR; 980, 850, and 808 nm) and visible (638, 532, 450, and 405 nm) illumination. (b) Fill factor and power conversion efficiency as a function of illumination wavelength. (c) Spectral photoresponsivity under photovoltaic ($V = 0$ V) and photoconductive modes ($V = -1$ V). (d) Photocurrent distribution as a function of applied voltage and 980 nm NIR-illumination power density. Open-circuit voltage and short-circuit current are indicated by dotted lines. (e) Photocurrent versus illumination power density. (f) Normalized photoresponse as a function of frequency.

excitonic transitions around the band edge in ReSe₂. This LP sensitivity remains very visible even after five months of exposure in ambient air. Finally, we demonstrate self-powered phase-shifting holography as a 3D imaging application utilizing the 980 nm NIR LP-sensitive characteristics of the proposed WSe₂/ReSe₂ photodiode under photovoltaic operation.

RESULTS AND DISCUSSION

The energy band diagram of the WSe₂/ReSe₂ heterostructure, as shown in Figure 1a, is estimated from ultraviolet (UV) and microfocused X-ray photoemission spectroscopy results (see Figure S1 in the Supporting Information (SI)) combined with an optical bandgap (obtained from absorption in Figure 1c). The proposed WSe₂/ReSe₂ heterostructure is a staggered (type II) heterojunction, with potential for high photodiode performance. In addition, the large effective bandgap in excess of 1 eV (energetic difference between the electron affinity of ReSe₂ and the ionization energy of WSe₂) could lead to considerable open-circuit voltage in the photovoltaic behavior. A 3D schematic and an optical microscopy (OM) image of the WSe₂/ReSe₂ heterojunction photodiode are also shown in Figure 1a. In the semivertical structure, the Pt bottom electrode overlaps with the WSe₂/ReSe₂ heterojunction, reducing the quasi-neutral region that acts as parasitic resistance. As a result, a significant photovoltaic effect and high photodetection performance can be achieved. The superiority of this semivertical geometry has also been verified in our previous works.^{27,28} While WSe₂ possesses a symmetric hexagonal honeycomb crystal structure, ReSe₂ has a distorted 1T' structure with Re chains arranged in one dimension, leading to a long tearing feature along the Re chain (b axis) in exfoliated flakes.²⁰ The b axis of ReSe₂ is indicated in the OM image of the device. To confirm the direction of the b axis of

ReSe₂, we conducted polarization resolved Raman spectroscopy (see Figure S2 in the SI). In the parallel to b axis, the scattering peak at 174 cm⁻¹ is the highest. On the other hand, the highest scattering peak in the perpendicular direction is located at 160 cm⁻¹. These features match those reported in the literature.²⁹ According to atomic force microscopy (AFM) profiles, as shown in Figure 1b, the thicknesses of ReSe₂ and WSe₂ are estimated to be 50 and 6 nm, respectively. To attain sufficient LP-dependent absorbance in the heterojunction photodiode, we use a significantly thicker layer of ReSe₂ compared with WSe₂. The absorption spectrum is an important factor, which can directly be correlated with optoelectronic properties of the photodiode. Figure 1c shows the microfocused absorption spectra of ReSe₂ and WSe₂ at various LP light angles (at intervals of 30°). The LP light in the direction parallel to the b axis of ReSe₂ is set to an angle of 0°. In the ReSe₂ layer, strongly LP-dependent excitonic transitions induced by in-plane asymmetry are clearly observed. The excitonic peak at approximately 980 nm under 0° LP light is fully blue-shifted at approximately 960 nm under 90° LP light and returns to its original position under 180° LP light, which is consistent with the LP-dependent feature reported in the literature.¹⁷ In contrast, the WSe₂ layer with in-plane symmetry shows LP-independent excitonic transitions. It is worth noting that the first excitonic peaks of ReSe₂ and WSe₂ are different. The LP-independent absorption behavior of WSe₂ can bleach the LP-dependent characteristics of ReSe₂ in the spectral range below approximately 800 nm, indicating that NIR (approximately 980 nm) LP-selective detection is feasible using the proposed WSe₂/ReSe₂ heterojunction.

Prior to LP-sensitive characterization of the WSe₂/ReSe₂ photodiode, its general photodetection properties are extensively examined. For spectral photoresponse measurement,

Figure 3. Linear-polarization (LP)-sensitive characteristics. (a) Dark and photoinduced I – V characteristics with various 980 nm NIR LP light angles. (b) Normalized photocurrent plot in polar coordinates. (c and d) LP-dependent photocurrent mapping of the photodiode.

NIR (980, 850, and 808 nm) and visible (638, 532, 450, and 405 nm) laser diodes (LDs) combined with an optical-fiber coupling system are used as light sources. Their illumination power densities are set to 100 mW/cm² for accurate comparison. As shown in Figure 2a, the WSe₂/ReSe₂ photodiode exhibits typical type II heterojunction p – n diode behaviors, with a relatively good electrical performance (an ideality factor of 1.67 and rectification ratio of over 10⁴) and a broad photoresponse in the measured spectral range from 405 nm visible to 980 nm NIR light. A significant photovoltaic effect was observed (Figure S3 in the SI): open-circuit voltages of 0.3 V (980 nm) to 0.5 V (405–850 nm), short-circuit currents on the order of 10^{−9} A (980 nm) to 10^{−8} A (405–850 nm), and a maximum electrical power of 18 nW (638 nm). Fill factor and power conversion efficiency (PCE) as a function of illumination wavelength are shown in Figure 2b; the highest PCE of 9.77% is achieved under 638 nm illumination, which is comparable to those of state-of-the-art 2D photovoltaic devices.^{30–33} Such outstanding photovoltaic behaviors are attributed to the synergetic effect of the higher effective bandgap of the WSe₂/ReSe₂ heterojunction (larger open-circuit voltage) and the semivertical device geometry (reduced parasitic resistance). The spectral photoresponsivities are also directly extracted from the photoinduced current–voltage (I – V) curves at $V = 0$ V (photovoltaic mode) and $V = -1$ V (photoconductive mode), as shown in Figure 2c. For each mode, identical spectral behaviors were observed with peak responsivity values of 0.57 A/W (photoconductive mode) and 0.48 A/W (photovoltaic mode) under red 638 nm illumination. Several factors, such as the absorbance of photoactive material, penetration depth of light, and charge collection efficiency, affect the spectral responsivity.^{27,34,35}

There is a trade-off relationship between the absorbance of the WSe₂/ReSe₂ heterojunction and the penetration depth of light in the measured spectral range; consequently, the highest value under red illumination is likely to indicate the optimum point.

The variation in performance parameters as a function of illumination power is also a very important characteristic for evaluating photodetectors. Two different light wavelengths of NIR 980 nm and red 638 nm are selected, because 980 nm NIR light is related to LP characteristics and 638 nm red light affords the maximum photocurrent (and responsivity). As the illumination light power increases, both the photocurrent and open-circuit voltage increase, as shown in Figure 2d and e and Figures S4a,b and S5a–d in the SI. The relation between illumination power density and photocurrent is expressed as $I_{ph} = BP^\alpha$, where I_{ph} denotes the photocurrent, B is a constant, P is the optical power density, and α is a fitting parameter representing the degree of linearity of the photodetector. The WSe₂/ReSe₂ photodiode shows outstanding α values of 0.99 (photovoltaic mode) and 0.93 (photoconductive mode) under 980 nm NIR illumination and 0.99 (both photovoltaic and photoconductive modes) under 638 nm red illumination. Dark leakage current under photovoltaic mode is lower than that under photoconductive mode, leading to a low noise condition (better signal-to-noise ratio condition). As a result, a larger α value (better linearity performance) can be achieved under photovoltaic mode. The LDR is also a figure of merit to examine the linearity.²⁷ In the measured illumination power densities, excellent LDR values of 105 dB (980 nm) and 108 dB (638 nm) are estimated. It is worth noting that photocurrent is linearly proportional to illumination power with no indication of saturation within the measured range, indicating that the photogenerated carriers in the WSe₂/ReSe₂

photodiode are efficiently collected at the electrode without significant degradation. This strong photocurrent linearity leads to an almost constant responsivity as a function of illumination power, as shown in Figures S4c and S5e in the SI. The change in open-circuit voltage as a function of illumination power provides the physical information on interlayer recombination in the vdW heterojunction. In the WSe₂/ReSe₂ devices, the β values as a fitting parameter for the interlayer recombination are calculated to be 2.0 under both 980 and 638 nm illumination, indicating that Shockley–Read–Hall (SRH) recombination is the dominant process.³⁶

The specific detectivity (D^*) is also investigated. On the basis of the noise power spectral densities (Figure S6a in the SI), spectral responsivities, and device area ($1.86 \times 10^{-6} \text{ cm}^2$), the spectral D^* values are estimated to be 10^7 to 10^9 Jones ($\text{cm Hz}^{1/2} \text{ W}^{-1}$), as shown in Figure S6b in the SI. The variation in D^* as a function of illumination power (980 and 638 nm) is not significant (Figure S6c and d in the SI). The theoretical D^* values dominated by the shot noise limit can be calculated. Higher theoretical D^* values of 10^9 to 10^{10} Jones ($\text{cm Hz}^{1/2} \text{ W}^{-1}$) are estimated, indicating that further enhancement is feasible by the reduction of the background noise.

In addition to the static characteristics of the WSe₂/ReSe₂ photodiode, its dynamic behaviors are investigated, which are also critical to the evaluation of photodetectors. Compared with phototransistors, which show high responsivity as photodetectors owing to their photoconductive gain, the great advantage of photodiodes is their faster operation speed. The WSe₂/ReSe₂ photodiode exhibits clear dynamic photocurrent-switching characteristics without any reduction at modulation frequencies of 10 and 100 Hz (Figure S7a and b in the SI). As the modulation increases in frequency up to 20 kHz, rising and falling times were found to be 2 and 2.5 μs , respectively (see Figure S7c in the SI). With a photoelectrical bandwidth system employed (Figure S7d in the SI), the cutoff frequencies (3 dB) of the device under photovoltaic mode operation are estimated to be 30 kHz (980 nm) and 100 kHz (638 nm), as shown in Figure 2f and Figure S4f in the SI. These fast dynamic responses are superior to those of ReS₂- or ReSe₂-based phototransistors.^{20,21}

To precisely examine the LP-sensitive characteristics of the WSe₂/ReSe₂ photodiode, we construct an experimental setup (schematic in Figure S8 in the SI) and confirm that the 980 nm NIR illumination power is approximately constant regardless of LP angle; its variation is less than 0.5%, as shown in Figure S9 in the SI. Figure 3a shows the I – V characteristics corresponding to various LP light angles. The maximum photocurrent is achieved under an LP angle of 0° (parallel to the b axis). As the LP angle is increased, the photocurrent gradually decreases and its minimum value is observed under an LP angle of 90° (perpendicular to the b axis). In the short-circuit condition (photovoltaic mode), the ratio of maximum/minimum photocurrent (polarization sensitivity) is estimated to be approximately 2. The dynamic photocurrent change (photovoltaic mode) as a function of LP angle is monitored and found to be similar to a cosine waveform (Figure S10a in the SI). The corresponding normalized photocurrent change is shown in the polar plot of Figure 3b. This LP-dependent photocurrent can be directly correlated with the LP-dependent excitonic transitions of ReSe₂. The strongly LP-dependent absorption spectra correspond very closely with the change in photocurrent as a function of LP angle. In addition, as previously mentioned in the discussion regarding optical

properties, the LP-independent absorption of WSe₂ could affect the LP-dependent photocurrent behaviors under different illumination wavelengths. Under 850 and 808 nm LP light illumination, LP-dependent photocurrent changes were significantly reduced, as shown in Figure S10b and c in the SI. It is worth noting that the WSe₂/ReSe₂ photodiode is capable of selective detection of 980 nm NIR LP light involved in strongly polarized excitonic transitions around the band edge in ReSe₂.

To further investigate the effect of the semivertical device geometry, photocurrent mapping measurements are performed under different LP angles. As expected, a higher-photocurrent image is observed under 0° LP light than that under 90° LP light. Interestingly, the photocurrents in cases are strongly generated on the only heterojunction area at the top of the bottom Pt electrode, as shown in Figure 3c and d. These results demonstrate the superiority of the semivertical device geometry. The bottom Pt electrode underneath the WSe₂/ReSe₂ junction region is able to reduce the parasitic resistive quasi-neutral region and to induce the strong electric field. As a result, the exciton separation and charge collection efficiencies can be enhanced. In addition, more excitons can be generated by reabsorption of the reflected light from the Pt electrode. On the other hand, the other WSe₂/ReSe₂ junction area without a Pt electrode makes a relatively low contribution to photocurrent generation. Hence, much higher and LP-dependent photocurrents were clearly observed in the WSe₂/ReSe₂/Pt overlap region. Furthermore, a significant photovoltaic effect and fast photoswitching speed can be realized in our semivertical device.

The environmental stability and batch-to-batch reproducibility of the device are critical to its wider practical applicability. The device is exposed to ambient air for more than five months, after which the LP-dependent photocurrent is measured. Notably, the device clearly exhibits LP-dependent characteristics, and LP sensitivity changes are negligible (Figure S11 in the SI). Next, to examine the reproducibility of WSe₂/ReSe₂ devices, we fabricate two more batches and characterize their LP-dependent properties (Figures S12 and S13 in the SI), which exhibit distinct LP-sensitive photocurrent with a significant photovoltaic effect in the I – V characteristics. Similar maximum/minimum photocurrent ratios of approximately 2 were achieved.

The above-mentioned results reveal that the WSe₂/ReSe₂ heterojunction photodiode with semivertical geometry shows excellent overall photodetection performance with a function of NIR-selective LP detection: significant photovoltaic effect (with a maximum PCE of 9.77% under 638 nm illumination), relatively good responsivities of 0.57 A/W (photoconductive mode) and 0.48 A/W (photovoltaic mode) under 638 nm illumination, outstanding linearity (α values of 0.99 and LDRs of 105 and 108 dB under 980 and 638 nm illumination, respectively), and rapid switching behaviors at 30 kHz (980 nm) and 100 kHz (638 nm). Furthermore, the self-powered LP photodetection property remains even after exposure to ambient air for more than five months and batch-to-batch reproducibility is confirmed. The performance parameters of our photodiode and several LP-sensitive 2D photodetectors previously reported in the literature^{11,12,20,21,26,37,38} are summarized in Table S1 in the SI. The 2D BP/MoS₂ heterojunction photodiode demonstrates the highest LP-sensitive characteristics,¹¹ but the air stability of BP-based devices remains a challenging issue. In addition, as compared with phototransistors based on single vdW materials (ReSe₂,

Figure 4. Digital incoherent holography. (a) Schematic of holographic recording system based on FINCH consisting of a rotating linear polarizer, geometric-phase (GP) lens, and NIR LP-sensitive photodetector. The insets show two metal transmissive negative targets. The green and violet beams after the GP lens indicate the converging and diverging beams, respectively. BC, beam combiner; LP, rotatable front linear polarizer; L, objective lens. (b) Holographic recording results. Four phase-shifted holograms, complex hologram, and focused reconstruction of the “ReSe₂” letter target and the “WSe₂” letter target, illustrating reconstructions of different focused depths.

ReS₂, PdSe₂, and GeAs), the photodiode based on the WSe₂/ReSe₂ heterostructure shows two distinct advantages: (1) faster dynamic speed and (2) self-powered operation due to a significant photovoltaic effect. Therefore, it is noteworthy that our device may be a promising candidate for a more advanced optoelectronic system with LP-sensitive functionality.

Beyond the basic photodetector unit, we finally leverage the NIR (980 nm)-selective LP detection and significant photovoltaic effect of this photodiode to demonstrate self-powered digital incoherent holographic 3D imaging. The schematic view of our holography recording system is shown in Figure 4a; this system is employed as a Fresnel incoherent correlation holography (FINCH) system^{39–41} by the combination of a rotating linear polarizer, geometric-phase (GP) lens,⁴² and LP-sensitive photodetector. Two different metal transmissive negative targets (“WSe₂” and “ReSe₂” letter targets) are used to mimic the volumetric layer for verifying the capability of holographic 3D imaging. More details on the digital incoherent holographic recording system and data acquisition are presented in Figure S14 in the SI. Figure 4b shows the output results of two targets using the holographic recording system. Through the use of the LP-sensitive photodetection capability of the WSe₂/ReSe₂ device, four phase-shifted holograms are acquired. A complex hologram (CH) without bias and twin images is derived from the equation^{43,44}

$$\text{CH}(x, y) = (I_3(x, y) - I_1(x, y)) - j(I_4(x, y) - I_2(x, y))$$

where I_k denotes the four phase-shifted holograms corresponding to the linear polarizer’s polarization direction of 0°, 45°, 90°, and 135°, respectively. Moreover, x and y are the pixel

coordinates of the hologram. Subsequently, numerical reconstructions (R) are retrieved by calculating the Fresnel backpropagation formula according to the equation⁴⁴

$$R(x, y) = \text{CH}(x, y) * \exp\left[-\frac{j\pi}{\lambda z_{\text{rec}}}(x^2 + y^2)\right]$$

where $*$ denotes a convolution operation in two dimensions, λ is the central wavelength of light, and z_{rec} is the reconstruction distance. As a result of the reconstruction, holographic 3D imaging is successfully realized; “ReSe₂” and “WSe₂” focused images are clearly shown. In addition, a very clear image of a National Bureau of Standards 1963A resolution target is holographically reconstructed, as shown in Figure S15 in the SI.

Recently, much effort has been devoted to developing wafer-scale uniform 2D atomic layer films. By combining the preparation of wafer-scale 2D films and the development of uniform transfer techniques, an integrated complementary metal–oxide–semiconductor polarized image sensor without a polarizer filter can be implemented in principle.

CONCLUSION

We have fabricated a self-powered LP-sensitive NIR photodetector based on a WSe₂/ReSe₂ vdW heterojunction. This device with semivertical geometry shows excellent photodetection performance with a broad spectral photoresponse, significant photovoltaic effect, outstanding linearity, and rapid photoswitching behavior. Strongly polarized excitonic transitions around the band edge in ReSe₂ lead to significant LP-dependent characteristics in the photodiode. This LP

sensitivity is retained even after air exposure for more than five months. Finally, we utilize the LP detection and significant photovoltaic effect of this $\text{WSe}_2/\text{ReSe}_2$ photodiode to demonstrate NIR digital incoherent holographic recordings.

EXPERIMENTAL METHODS

Device Fabrication. The 2D $\text{WSe}_2/\text{ReSe}_2$ heterojunction photodiodes were fabricated on SiO_2 (285 nm)/Si or glass (Eagle XG) substrates. Commercial WSe_2 and ReSe_2 2D single crystals were used. Ti/Pt (5/10 nm) and the Ti (25 nm)/Au (25 nm) were used as bottom and top electrodes, respectively, which were patterned via the conventional photolithographic lift-off process. WSe_2 and ReSe_2 layers were prepared by mechanical exfoliation and a transfer method using a polydimethylsiloxane stamp. In the semivertical geometry, the photoactive region was used to be the only heterojunction area at the top of the bottom Pt electrode, which was estimated to be $1.86 \times 10^{-6} \text{ cm}^2$. The devices were annealed at 250 °C for 5 min in ambient air to enhance the p-type characteristics of WSe_2 for the performance optimization.

Materials and Device Characterization. The thicknesses of the WSe_2 and ReSe_2 nanoflakes were measured using atomic force microscopy (Park Systems, NX10). Our customized microfocused absorption measurements²⁷ were carried out. Micro-X-ray and UV photoelectron spectroscopy (μ -XPS and UPS) were performed to obtain the energy band alignment of the $\text{WSe}_2/\text{ReSe}_2$ interface using a PHI VersaProbe. All static behaviors of the photodiode were characterized by a semiconductor parameter analyzer (Keithley 2636B and Agilent 4156C) in the dark and under illumination by LEDs (Thorlabs, Inc.): NIR (980, 850, and 808 nm), red (638 nm), green (532 nm), blue (450 nm), and violet (405 nm). The details of measurement setups for dynamic properties including photoelectrical bandwidth are described in our previous work.²⁷ A linear polarizer (Thorlabs, LPVIS050) and half-wave plate (Newport, 10RP52-2) were used to measure LP-dependent characteristics.

NIR Digital Incoherent Holography. The holography used in the experiment is self-interference digital holography using incoherent light. A hologram is generated by creating the interference pattern employing a GP lens whose focal length varies depending on right-hand and left-hand circular polarization. Since it is a simple configuration to obtain the hologram, it was chosen as an application system for the NIR LP-sensitive photodetector. The holographic recording system consisted of a linear polarizer (Thorlabs, LPNIRB100-MP2) fixed to a rotatable thread, a general objective lens (Thorlabs, LA1509-B) with a focal length of 100 mm, an off-the-shelf model GP lens (Edmund Optics, #34-466) with a focal length of 100 mm, a fixed focal 50 mm f/1.8 lens (Computar, M5018-SW) as a relay lens, our single-pixel LP-sensitive photodetector, a combination of two linear stages (Physik Instrument, Q-545.240) to form an x - y planar linear stage, and a photocurrent measurement unit (Keysight Technologies, B2901A). LEDs (Thorlabs, M970L4) with a bandpass filter of 980 nm central wavelength and a collimator were used as NIR-range light sources. The two targets used in the experiment are negative patterns with characters that are punctuated on a metal plate. The diffuser sheets are attached on the characters to generate the diffuse light. The total length of the characters in each target is about 10 mm. The targets are located at 200 mm (ReSe_2) and 400 mm (WSe_2) from the objective lens, respectively. For single-pixel recording, as the x - y planar linear stage moved along the x -axis and y -axis in 10 μm increments corresponding to the single-pixel pitch, the photocurrent corresponding to each position of the single pixel was obtained by the measurement unit and recorded as a pixel value of the output phase-shifted intensity image with a pixel size of 800 on both axes. We measured a photocurrent value 20 times and averaged them to obtain a stable photocurrent value corresponding to one pixel value. It took about 10 ms to measure the value. The four-step phase shifting method, which is widely used to eliminate the zeroth order light and twin image, needs the four holograms with the different phase shift between the object wave and reference wave. Since each hologram is 800 by 800 pixels in size, the total time to

obtain the hologram is approximately 7 h. The contrast and histogram of the result images were handled to enhance visibility.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsnano.1c06234>.

Photoemission spectroscopy of the $\text{WSe}_2/\text{ReSe}_2$ heterostructure, photovoltaic effect of the $\text{WSe}_2/\text{ReSe}_2$ diode, variations of the $\text{WSe}_2/\text{ReSe}_2$ photodiode as a function of the illumination power density, noise and specific detectivity, dynamic behaviors, linear polarization experimental setup, wavelength dependence of linear polarization sensitivity and air stability, device reproducibility, comparison of figures of merit for linear-polarization-sensitive photodetectors, and digital incoherent holography (PDF)

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