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Waveguide-integrated PdSe₂ photodetector with high responsivity and speed in the near-infrared range across the O+E+S+C bands

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ABSTRACT

Hybrid integration of two-dimensional (2D) materials on a silicon photonic platform enables diverse exploration of novel active functions and significant improvement in device performance for next-generation silicon integrated photonic circuits. 2D transition metal dichalcogenide materials (TMDCs) have attracted extensive attention for photodetectors, but developing high-performance waveguide-integrated photodetectors based on conventionally investigated 2D TMDCs at the telecom C-band is still a big challenge because of their large optical bandgap and slow carrier mobility. Here, we propose PdSe₂, a new type of 2D TMDC, to be integrated with silicon photonic components for on-chip photodetection with high responsivity and speed in the datacom and telecom optical bands ranging from the O-band to the C-band. The obtained waveguide-integrated photodetectors show a high responsivity of 1190.2 mA·W⁻¹ at 1550 nm and a low noise-equivalent power of 4.0 pW·Hz^{-0.5} at 5V. The 3 dB bandwidth reaches up to 1.5 GHz, and the measured data rate is 2.5 Gbit·s⁻¹. The achieved PdSe₂ photodetectors provide new insights to explore the integration of novel 2D TMDCs with silicon photonics and demonstrate the potential of integrated photodetectors for applications in diverse areas, including optical communications, on-chip spectroscopy, and sensing.

INTRODUCTION

Over the past decade, two-dimensional (2D) materials have demonstrated novel and intriguing optoelectronic properties, including ultrafast mobility, broadband absorption, strong nonlinear response and dangling-bond-free surface, exhibiting great potential for both electronic and optoelectronic devices.¹⁻¹⁰ Especially, integrating 2D materials with silicon integrated photonic circuits is a highly promising application. A plethora of waveguide-integrated 2D materials optoelectronic devices, including light sources,^{11,12} switches,¹³ polarizers,¹⁴ modulators^{15,16} and photodetectors,¹⁷⁻¹⁹ have already been realized. Among these prototypical optoelectronic devices, waveguide-integrated photodetectors have attracted considerable attention, essential for multiple applications such as optical communications and interconnects,^{20,21} spectroscopy,²² sensing,²³ imaging,²⁴ and quantum computing.²⁵ Among all 2D materials, graphene has been extensively studied for waveguide-integrated photodetectors, which in some aspects have shown competitive performance to Ge and III-V semiconductor counterparts.²⁶⁻²⁹ However, graphene photodetectors suffer from a large dark current because of a zero bandgap. Nowadays, 2D semiconductors such as black phosphorus (BP), MoTe₂ and Bi₂O₂Se are alternative candidates for waveguide-integrated photodetectors at the current telecommunication bands.³⁰⁻³³ Actually, the low air-stability of BP limits the device fabrication and applications. A large optical bandgap for MoTe₂ (1.04 eV) and Bi₂O₂Se (0.9 eV) prevents it from optical detection at the C-band.

Recently, 2D PdSe₂ flake with great air-stability has been a new candidate for optoelectronic applications at near- and mid-IR wavelengths.³⁴⁻³⁶ PdSe₂ flakes possess a large bandgap tunability, ranging from 0.03 eV (bulk) to ~1.3 eV (monolayer).^{37,38} The experimental effective electron mobility of few-layer PdSe₂ is more than 200 cm²·V⁻¹·s⁻¹.³⁹ Moreover, a wafer-scale PdSe₂ film can be obtained by a simple selenization process of pre-deposited Pd film,^{40,41} and centimeter-scale PdSe₂ film (thinner than 10 nm) can be prepared by Chemical Vapor Deposition method,⁴² which ensures the fabrication of a device array on a large scale. To date, free-space PdSe₂ photodetectors have already been investigated. For example, a PdSe₂ phototransistor showed photoresponse ranging from the visible to mid-infrared wavelengths up to 4.05 μm. The responsivity was 708 A·W⁻¹ under a low incident power at 1064 nm,⁴³ and this high responsivity mainly resulted from the trap state, which brought about a slow dynamic response as well. A photodiode based PdSe₂/Si heterostructure possessed a responsivity of 300.2 mA·W⁻¹ at 780 nm, and a small 3 dB bandwidth

of 30 kHz limited it for high-speed applications.⁴¹ Moreover, the van der Waals heterostructure such as InSe/PdSe₂ and PdSe₂/MoS₂ heterostructure showed a responsivity of 58.8 A·W⁻¹ at 1650 nm, and 42.1 A·W⁻¹ at 10.6 μm, respectively, but the rise/fall times of these photodetectors were tens of millisecond.^{44,45} Up to now, realizing a PdSe₂ photodetector with high responsivity and large bandwidth is still a challenge and highly desired. Indeed, a waveguide architecture is attractive for designing photodetectors with both high responsivity and large bandwidth. It can simultaneously ensure adequate absorption via evanescent field coupling over a long propagation distance and decrease the transit time of photoinduced carriers with a short channel.

In this work, we propose and demonstrate waveguide-integrated PdSe₂ photodetectors operating in the datacom and telecom optical bands ranging from the O-band to the C-band, for the first time, with both high responsivity and large bandwidth. The significant optoelectronic properties of multilayer PdSe₂ film, including anisotropy and ultrafast carrier dynamics, are characterized. We integrate silicon-on-insulator (SOI) ridge waveguides with the multilayer PdSe₂ flakes, which were exfoliated from bulk materials and transferred by an imprint-transfer process. Such devices ensure sufficient optical absorption for the fundamental mode of TE polarization (TE₀) and a low mode mismatching loss. The present PdSe₂ waveguide-integrated photodetectors possess a broadband spectral operation, a high responsivity of 1190.2 mA·W⁻¹, and a low noise-equivalent power (NEP) of 4.0 pW·Hz^{-0.5} at 5 V at 1550 nm. Additionally, a 3 dB bandwidth reaches up to 1.5 GHz, and the receiver eye diagram indicates PdSe₂ photodetector could realize a data transmission rate being more than 2.5 Gbit·s⁻¹.

Fig. 1 Multilayer PdSe₂ flake characterization. **a** Raman spectra of a multilayer PdSe₂ flake excited by incident light at 532 nm under two different polarization states. **b** Polar plots of the measured and fitted peak intensities of the A_{1g}^1 mode. **c** The energy-dispersive X-ray spectroscopy (EDS) mappings of a multilayer PdSe₂ flake on an SOI ridge waveguide. Scale bar: 5 μm . **d** High-resolution transmission electron microscope (TEM) image of a multilayer PdSe₂ film. The illustration is the corresponding selected area electron diffraction (SAED) pattern. Scale bar: 2 nm. **e** Reflection spectra of a multilayer PdSe₂ flake with a white light source under different polarization states.

RESULTS

PdSe₂ characterization. The lattice structure of the 2D-layer PdSe₂ flake is a puckered pentagon, where the Pd atom is connected with four Se atoms through a covalent bond, constituting an asymmetric lattice structure,³⁷ and the van der Waals force is dominant in the interactions between adjacent layers. Raman spectra of a multilayer PdSe₂ flake (purchased from Taizhou SUNANO New Energy CO., Ltd.) on SiO₂ substrate excited by the 532 nm laser are shown in Fig. 1a, where four distinct Raman peaks at about 145, 208, 223, and 258 cm⁻¹ are observed, which are corresponding to $A_{1g}^1 - B_{1g}^1$, A_{1g}^2 , B_{1g}^1 , and A_{1g}^3 modes, respectively. Furthermore, the measured Raman spectra under different polarization states are shown in Supplementary Fig. 1a, indicating the strong in-plane anisotropic phonon vibration. The polarization-dependent Raman intensity of $A_{1g}^1 - B_{1g}^1$ (Fig.1b) shows clear periodical variations of π . The chemical composition of a multilayer PdSe₂ flake was characterized by X-ray photoelectron spectroscopy (XPS) measurement (Supplementary

Figs. 1b, c) in which four typical peaks at 54.6, 55.4, 336.7, and 342.1 eV are ascribed to Se 3d_{5/2}, 3d_{3/2}, Pd 3d_{5/2}, and 3d_{3/2} orbitals, respectively. The energy-dispersive X-ray spectroscopy (EDS) mappings of a multilayer PdSe₂ flake on an SOI ridge waveguide are shown in Fig. 1c, where Pd and Se elements show a uniform distribution. Moreover, the high-magnification TEM image and SAED pattern in Fig. 1d demonstrates the single-crystal characteristic of the exfoliated multilayer PdSe₂ flake. Additionally, anisotropic optical properties were confirmed by the variation of the reflection spectra under different polarization states (Fig. 1e), and the reflectivity rises gradually when the polarization angle increases from 0° to 90°, which indicates that the crystal orientation has an important impact on photon-to-electron transition.

Fig. 2 PdSe₂ photodetector integrated with a silicon photonic circuit. **a** The measured ultrafast transient reflectance of a multilayer PdSe₂ flake (12 nm thick). **b** Three-dimensional illustration of the waveguide-integrated PdSe₂ photodetector. **c** Optical image of a PdSe₂ waveguide-integrated photodetector. Scale bar: 100 μ m. **d** Cross-section scanning electron microscope (SEM) image of a PdSe₂ photodetector. Scale bar: 500 nm. **e** Calculated electric field profiles of the TE₀ mode in the hybrid silicon/PdSe₂ waveguide, the thickness of the PdSe₂ flake is 50 nm. **f** The transmission spectra of the unbalanced MZI with and without a PdSe₂ flake (155 nm thick).

The lifetime of photoinduced carriers was inferred by the ultrafast transient reflectance (TR) spectroscopy. Details of measurement setup could be found in the previous report.⁴⁶ We excited a multilayer PdSe₂ flake with a 2.07 eV pump pulse (50 fs pulse duration) and measured the reflectance change of this PdSe₂ flake using a white-light continuum probe. The TR kinetics (Fig.

2a) indicates that the lifetime of photoinduced carriers of this PdSe₂ flake (12 nm thickness in Supplementary Fig. 1d) is about 68 ps. With the increase in PdSe₂ thickness, a narrowing bandgap induces a shorter lifetime of photoinduced carriers, and the measured lifetime under 1550 nm wavelength illumination is 22 ps for a multilayer PdSe₂ flake (20 nm thick) in a previous report.⁴⁷ The lifetime is longer than that counterpart of graphene,⁴⁸ indicating PdSe₂ photodetectors can not only realize a high photoconductive gain ($G=\tau_{life}/\tau_{tran}$, τ_{tran} is the drift transit time), but also a large 3 dB bandwidth.

Device concept and simulation. Figure 2b shows the schematic configuration of the waveguide-integrated PdSe₂ photodetector, where SOI ridge waveguide (220 nm thick) with an etching height of 150 nm is applied. The silicon waveguide was lightly doped, and the heavily doped area (2×10^{20} cm⁻³) was close to the waveguide at a suitable distance, which can not only suppress unnecessary optical loss induced by the plasma dispersion effect, but also decrease the total resistance to optimize the device performance. A layer of Al₂O₃ (15 nm thick) was deposited by atomic layer deposition to avoid photoinduced carriers transferring between a PdSe₂ flake and the bottom Si waveguide. Two Ti/Au pads (5/100 nm) were deposited, locating around the straight waveguide with a suitable distance, which effectively promoted the collection of photoinduced carriers and significantly avoided an unnecessary optical loss. A PdSe₂ flake was transferred to the top of a waveguide, which connected these two Au pads. Incident light was coupled into/out waveguide by two grating couplers whose SEM images are illustrated in Supplementary Fig. 2. A typical optical image of the waveguide-integrated PdSe₂ photodetector is shown in Fig. 2c, where a PdSe₂ flake is on one arm of an unbalanced Mach-Zehnder interferometer (MZI). We integrated PdSe₂ flakes with straight waveguides as well. The cross-section of a waveguide-integrated PdSe₂ photodetector (Fig. 2d) indicates that an altitude difference remains at the top of the waveguide core, slab and Au pads, and a part of PdSe₂ flake is suspended. The adhesion between a PdSe₂ flake and the waveguide substrate was strong enough, which was approved by the photoresist coating.

Optical absorption of a PdSe₂ flake is a significant factor for the photon-to-electron transition, thereby the simulated electric field profiles of the TE₀ mode is illustrated (Fig. 2e). The simulation result indicates that a part of the electric field profiles of the TE₀ mode is in the PdSe₂ flake in a PdSe₂/Si hybrid waveguide. The measured optical absorption of a PdSe₂ flake was characterized by comparing the transmission spectra of an unbalanced MZI (Fig. 2f) with/without a PdSe₂ flake. In

this unbalanced MZI, beam splitter and combiner are realized by two 1×2 MMIs. The detailed performance of a 1×2 MMI is characterized by the serially cascaded MMIs, and the transmission spectra indicate a 1×2 MMI in our design could split incident light power equally (Supplementary Fig. 3). According to the change of extinction ratio (ER), the absorption coefficient of the PdSe₂ (155 nm thick)/Si hybrid waveguide is calculated to be 0.14 dB/ μm . We also demonstrated the transmission spectra variation of a straight waveguide with/without a PdSe₂ flake (Supplementary Fig. 7a). Actually, the slight difference of grating coupler during different operations remains, leading to an experimental error of absorption coefficient of PdSe₂/Si hybrid waveguide, which could be avoided by measuring from an MZI.

Fig. 3 Electronic characteristics of PdSe₂ photodetector. **a** Kelvin probe force microscopy (KPFM) image of the Au-PdSe₂ contact on a Si/SiO₂ substrate. Scale bar: 1 μm . **b** KPFM profile along with the red dashed line in Fig. a. **c** The energy band diagram of Au-PdSe₂-Au junction at equilibrium, under illumination, at a bias voltage, and corresponding equivalent circuit. **d** Current-voltage (IV) curves a waveguide-integrated PdSe₂ photodetector (Sample 1, S1) in the dark and under illumination with different optical power at 1550 nm. **e** Photocurrent versus incident optical power at 2 V.

Electrical characterization. Next, we measured the contact potential difference (V_{CPD}) between an Au electrode and a PdSe₂ flake by Kelvin probe force microscopy (KPFM). The V_{CPD} is defined as

the difference of the work function between the probe tip and the measured sample, which can be expressed as $V_{CPD} = (W_{tip} - W_{sample}) / -e$, where W_{tip} and W_{sample} are the work function of the probe tip and the sample, respectively. The KPFM image of a PdSe₂-Au junction (Fig. 3a) indicates the different work functions for an Au electrode and a PdSe₂ flake, where the green dot line is the edge of the PdSe₂ flake and Au electrode. The detailed surface potential profile along the red dot line is illustrated in Fig. 3b, in which we can observe that the work function difference between the Au electrode and PdSe₂ flake is about 90 meV. The smaller work function results in electron transferring from PdSe₂ flake to Au electrode, the energy band sloping upward, and a built-in electric field coming into being at the contact interface (Fig. 3c). Therefore, the equivalent circuit of a realized PdSe₂ photodetector can be regarded as a back-to-back Schottky junction (Fig. 3c) which brings about a small dark current. The photovoltaic effect (PVE) is usually dominant for free-space photodetectors based on Au-semiconductor-Au structure, and photocurrent can be generated at the junction without an external bias voltage.⁴⁹ However, the optical absorption of a PdSe₂ flake in our photodetector is mainly located on top of a waveguide surface (Fig. 2e), and the distance between the Au electrode and optical absorption area (the edge of the waveguide) is larger than the width of depletion area, thereby PVE is not the dominant mechanism for the present photodetector. Moreover, the photo-thermoelectric effect (PTE) probably contributes to the total photocurrent in a suspended device structure, but photocurrent is extremely weak at zero bias voltage. Thereby, PTE effect does not contribute to a photon-to-electron transition in the obtained PdSe₂ photodetectors.

The static characteristics of a PdSe₂ photodetector (Sample1) were measured, and IV curves in the dark and under illumination at 1550 nm were demonstrated (Fig. 3d). The nonlinear property of IV curves is attributed to a Schottky barrier at the contact interface between Au and PdSe₂. Two primary aspects resulted in the Schottky contact. On the one hand, a low background doping level of the multilayer PdSe₂ flake⁵⁰ brings about a large depletion layer width and small thermionic and tunneling currents. On the other hand, a multilayer PdSe₂ flake was transferred onto the Au electrode, avoiding unnecessary chemical disorder and Fermi-level pinning, leading to a better Schottky junction.⁵¹ The dark currents are -38 μ A at -5 V, and the thickness of this PdSe₂ flake is 171 nm (Supplementary Fig. 4), respectively. Moreover, a smaller dark current can be obtained by decreasing the thickness of the PdSe₂ flake because of the increase of resistance.⁵² Furthermore, aligning the crystal orientation has an impact on total resistance.⁵³ The anisotropic electronic

transport (Supplementary Fig. 5) indicates resistance variation remains in multilayer PdSe₂ flakes, which provides flexibility to device design. Current rises gradually (Fig. 3d) with the improving incident power, indicating that PdSe₂ could be used for optical detection at C-band. Such a positive relationship between photocurrent and bias voltage is observed, and photocurrent at zero bias voltage is weak, illustrating photoconductive effect is the dominant mechanism for photocurrent. The photocurrent-incident optical power curve (Fig. 3e) at 2 V indicates the PdSe₂ photodetector possesses a great linear relationship.

Responsivity varies as a function of bias voltage (Fig. 4a), because the higher efficiency of the generation-separation-collection process of photoinduced carriers can be realized at a larger bias voltage. The measured external responsivity ($R = I_p/P_{in}$) is 1190.2, 285.7, and 191.2 mA·W⁻¹ at 5 V and 1550 nm for S1, S2, and S3, respectively, and the external quantum efficiency ($EQE = 1.24 \times R/\lambda$) is 95.2%, 22.9%, and 15.3% at 5 V for S1, S2, and S3, respectively, where λ is the wavelength of incident light. Such an external responsivity and EQE are higher than the counterparts based on graphene,^{54,55} BP,³² and MoTe₂.⁵⁶ The variation of responsivity for these three samples (S1, S2, and S3) is mainly attributed to the thickness, length, and optical anisotropy of the multilayer PdSe₂ flakes. The thickness of PdSe₂ flakes in these three samples is 171, 186 and 284 nm, respectively, which is characterized by the atomic force microscope (Supplementary Fig. 4). Moreover, the reflectivity varies under different polarization states (Fig. 1e), illustrating that optical anisotropy has a severe impact on optical absorption and photo-to-electron transition, which is consistent with previous reports.^{57,58}

We then measured the channel current in the dark and under illumination with a back-gate voltage (Fig. 4b). I_d - V_g curve in the dark shows a small on-off ratio of about 3 for a PdSe₂ photodetector (S1), indicating that the PdSe₂ flake in our experiment is p-doped, which is consistent with previous reports.⁵⁰ The thickness of the PdSe₂ flake (171 nm thick) in our device is significantly greater than the Debye screening length, resulting in the device not being fully turned off, and a moderate gate-dependent transport. Two PdSe₂ field-effect transistors (FET) on a SiO₂/Si substrate also verify the gate-dependent transport, one PdSe₂ FET (about 25 nm thick) demonstrates an ambipolar transport with an on-off ratio of about 11, and another PdSe₂ FET (about 120 nm thick) shows the unipolar transport (Supplementary Fig. 6). The transport indicates that multilayer PdSe₂ flake possesses a low background doping, because the onset of different doping locates about $V_g=0$

V. Moreover, the slight gate-dependent photocurrent is observed as well (Fig. 4b), which could be primarily attributed to the variation of optical absorption of PdSe₂ flakes, but not the larger thermionic and tunneling currents,⁵⁹ being similar with photodetectors based on graphene.⁶⁰ As shown in Fig. 2d, carrier variation induced by a back-gate voltage mainly concentrates on the area at the top surface of a waveguide, thereby a back-gate voltage has little impact on the PdSe₂-Au Schottky barriers, as well as thermionic and tunneling currents. Similar results, including the unipolar dark current and maximal photocurrent at $V_g=0$ V were observed in another waveguide-integrated photodetector as well (Supplementary Fig. 7).

Fig. 4 Static performance of PdSe₂ photodetectors. **a** Responsivity and EQE for S1, S2 and S3 at different bias voltage under the illustration of 1550 nm. **b** Gate-tunable transport and photoresponse of a PdSe₂ photodetector (S1). **c** Spectral response of PdSe₂ photodetectors, the measured results at O-band are obtained by S4 and others are gotten by S1. **d** 1/f noise spectra of a waveguide-integrated PdSe₂ photodetector (S1) under different applied voltages.

Spectral response. The spectral photoresponse for PdSe₂ photodetectors at the current optical communication wavelengths was characterized in Fig. 4c, in which PdSe₂ photodetectors demonstrated the broadband operation, and the responsivity was more than 500 mA·W⁻¹ with input optical power being larger than 200 μW at 5V. Limited by a finite optical bandwidth of grating couplers, we fabricated two photodetectors (S1 and S4) to show this broadband spectral

photoresponse. One photodetector (S4) works at O-band, corresponding to the responsivity at wavelengths from 1260 nm to 1320 nm (Fig. 4c), and the detailed characteristics of S4 are illustrated (Supplementary Fig. 8). Another photodetector (S1) works at wavelengths from 1485 nm to 1565 nm (Fig. 4c). The fluctuating responsivity at different wavelengths could be attributed to incident power variation at different wavelengths. During this measurement, the output power of the laser at different wavelengths was fixed up, so the practical incident power passing through the waveguide at different wavelengths was different induced by the various grating coupling efficiency. A smaller incident power usually brings about a large photocurrent gain and responsivity, which accounts for responsivity at the wavelengths with weak coupling efficiency is higher in Fig. 4c.

Noise analysis. Moreover, we analyzed noise-equivalent power ($NEP = i_n/R$) of the PdSe₂ photodetectors, where i_n is the noise current which mainly results from 1/f noise, shot noise, and thermal noise. The measured 1/f noise spectral density in Fig. 4d indicated that PdSe₂ photodetectors possess typical characteristics of 1/f noise, which can be determined by the Hooge's empirical relationship ($S_i = A \cdot i^\alpha / f^\beta$),^{61,62} where i , f , A are the channel current, the frequency, and noise amplitude, respectively. Current noise induced by 1/f noise decreases gradually with the increasing applied frequency. When photodetectors work at a high frequency, shot noise and thermal noise are dominant, which is little influenced by the applied frequency.^{62,63} Current noise induced by shot noise is determined by dark current (i_d), and the measured shot noise is $1.21 \times 10^{-23} \text{ A}^2 \cdot \text{Hz}^{-1}$ at -5 V. Additionally, the thermal noise is evaluated to be $1.25 \times 10^{-25} \text{ A}^2 \cdot \text{Hz}^{-1}$ by $S_t = 4k \cdot T \cdot \Delta f / R_s$ at -5 V, where k , t , R_s are the Boltzmann constant, the temperature (about 300 K in our experiment), and the device's resistance. Therefore, NEP is mainly decided by shot noise at a high frequency, and is estimated to be $4.0 \text{ pW} \cdot \text{Hz}^{-0.5}$ at -5 V. Moreover, current noise for a PdSe₂ photodetector increases with the applied voltage, but a smaller NEP is obtained at the larger bias voltage (Fig. 5a). This phenomenon is attributed to the fact that a larger bias voltage brings about a higher efficiency of the separation-collection process of photogenerated carriers and a larger responsivity.

High-speed photoresponse. The frequency responses for PdSe₂ photodetectors were characterized as well. The measurement setup is shown (Supplementary Fig. 9a), and the measured 3dB bandwidths for S1, S2, and S3 are about 0.2, 0.9 and 1.5 GHz, respectively (Fig. 5b). The total response time for the proposed PdSe₂ photodetector is determined by the carrier a transit time (τ_{tr}),

charge/discharge time of the junction capacitance (τ_{RC}). The τ_{tr} can be written as $\tau_{tr} = \frac{l^2}{2\mu V_{DS}}$, where l , μ , V_{DS} are the length a PdSe₂ photodetector, mobility of a PdSe₂ flake, and bias voltage, respectively, which is negatively correlated as the bias voltage. The measured 3 dB bandwidths kept almost at the same value for S3 (Supplementary Fig. 10), indicating that total response time (τ) is determined by τ_{RC} . Impedance matching in measurement is necessary for a PdSe₂ photodetector with larger bandwidth in the future. Furthermore, decreasing channel length and shortening transit time³¹ promote obtaining an even larger bandwidth. Additionally, we performed an eye-diagram measurement to illustrate the feasibility of PdSe₂ photodetectors for receiving high bit-rate data in high-speed optical communication. The measurement setup is shown (Supplementary Fig. 9b), and the experimental results in Fig. 5c demonstrate a completely open eye at 3 V with a data rate of 2.5 Gbit·s⁻¹. An improved eye diagram could be obtained when increasing the applied bias voltage because of the increase of the signal-to-noise ratio.

Fig. 5 Dynamic performance of PdSe₂ photodetectors. **a** NEP and noise current induced by shot noise at different bias voltage. **b** Measured frequency response of three PdSe₂ photodetectors (S1, S2 and S3) at 3V. **c** Receiver eye diagram at a data rate of 2.0 and 2.5 Gbit s⁻¹ measured with a PdSe₂ photodetector (S3). Scale bar: 200 ps. **d** Summary of the performance for waveguide-integrated photodetectors (circular shapes) based on 2D semiconductor materials and free-space

photodetectors (rectangular shapes) based on PdSe₂ flakes. Three five-pointed stars represent waveguide-integrated photodetectors (S1, S2, and S3). The green arrow indicates the direction of device development with improved performance.

Discussion

To compare with currently reported photodetectors operating in the current telecommunication bands, the responsivity and 3 dB bandwidth of some obtained PdSe₂ photodetectors and waveguide-integrated photodetectors based on 2D semiconductor materials are listed in Fig. 5d.^{19,32,41,56,64-70} On the one hand, these achieved PdSe₂ photodetectors possess apparent advantages such as high responsivity and broadband spectral operation, but 3 dB bandwidths of these PdSe₂ photodetectors are smaller than 30 kHz, which limits them to high-speed applications. The waveguide-integrated PdSe₂ photodetector in this work possesses a 3 dB bandwidth of about 1.5 GHz, which is five orders of magnitude larger than these PdSe₂ photodetectors. On the other hand, waveguide-integrated photodetectors based on 2D semiconductor materials possess a small dark current, compared with the counterparts based on 2D semimetal such as graphene. A large optical bandgap of MoTe₂ (1.04 eV) prevents it from detection at C band,⁵⁶ and a strain-reduced bandgap allows MoTe₂ to detect incident light at C-band with a 3-dB bandwidth of 35 MHz that is not enough for some high-speed applications.¹⁹ Moreover, vertical MoTe₂/graphene heterostructure showed a large bandwidth of 50 GHz at O-band by shortening the transit time.³¹ Therefore, heterostructure photodetectors such as PdSe₂/graphene and PdSe₂/ITO probably bring about a larger bandwidth at O- to C-band in the future. Additionally, BP photodetectors possess a bandwidth more than 1 GHz at C-band, but the air-unstability leads to a complex experiment condition and performance degradation in air. Overall, the proposed PdSe₂ photodetectors possess a low dark current, high responsivity from O- to C-band, large 3 dB bandwidth, and air stability. Therefore, a PdSe₂ flake provides a new alternative to design a high-performance waveguide-integrated photodetector at current telecommunication bands even mid-infrared (MIR) regions, promoting the development of various applications of waveguide-integrated photodetectors such as on-chip spectroscopy, sensing, and optical communications.

In conclusion, we have proposed and realized integrated photodetectors based on SOI ridge waveguides and multilayer PdSe₂ flakes covering the entire datacom and telecom wavelength range (1260 nm-1565 nm), for the first time, with both high responsivity and speed. In this work, we have demonstrated four waveguide-integrated PdSe₂ photodetectors (S1, S2, S3, S4) whose detailed

performance was listed in Supplementary Table 1. The obtained photodetectors possessed a broadband spectral response ranging from the O- to the C-band, and the highest responsivity (S_1) was up to $1190.2 \text{ mA}\cdot\text{W}^{-1}$ at 5 V at 1550 nm. The 3 dB bandwidth was about 1.5 GHz, and the eye diagram measurement indicated the PdSe_2 photodetectors could be used for receiving data transmission with a data rate being more than $2.5 \text{ Gbit}\cdot\text{s}^{-1}$. Furthermore, noise characteristics including low-frequency noise, shot noise and thermal noise were analyzed, and shot noise was the dominant noise region at high frequency, leading to a NEP of about $4.0 \text{ pW}\cdot\text{Hz}^{-0.5}$ at 5 V. In the future, the operational wavelengths can be extended to MIR because of the narrow bandgap of multilayer PdSe_2 . The 3 dB bandwidth can be optimized by both reducing the contact resistance between PdSe_2 flakes and metal electrodes and shortening the channel length. Overall, these results pave the way for integrating PdSe_2 flake onto a silicon photonic platform and provide a new route to integrated photodetectors for applications in diverse areas, including optical communications, on-chip spectroscopy, and sensing.

METHODS

Device fabrication. The detailed fabrication processes are shown in Supplementary Fig. 11. Optical devices were fabricated on 220 nm SOI wafers with a 2 μm -thick SiO_2 box layer with multi-project wafer (MPW) processes in IMECAS. First, optical devices including grating, waveguide and MMI were patterned by deep ultra-violet (DUV) photolithography and inductive coupling plasma (ICP) etching process. Second, phosphorus ion implantation was carried out to form the lightly doped regions with a doping concentration of $5\times 10^{17} \text{ cm}^{-3}$ and the heavily doped doping regions with a doping concentration of $1.7\times 10^{20} \text{ cm}^{-3}$. Third, a thin Al_2O_3 layer of about 15 nm was deposited onto the prepared wafer by an Atomic Layer Deposition System (Sentech Instruments GmbH, SI ALD). Fourth, a part of the Al_2O_3 layer (the heavily doped region) was exposed by photolithography, etched by HF, and followed with depositing Ti/Au (5/100 nm) by electron-beam evaporation (ULvac vacuum technology (Suzhou) Co., Ltd, Ei-5Z) and a standard lift-off process. Next, source and drain electrodes were defined by electron-beam lithography (Raith, Voyager), followed by depositing Ti/Au (5/100 nm) by electron-beam evaporation and a standard lift-off process. Finally, the multilayer PdSe_2 flakes were exfoliated from bulk PdSe_2 crystal by Scotch tape, aligned and transferred onto the prepared devices with the assist of polydimethylsiloxane under a

microscope.

Device measurement. Raman spectra (WITec, Alpha300R), reflection spectra (WITec, Alpha300R), SEM (Hitachi, Regulus 8230), TEM (Thermo Fisher Scientific, Talos F200X G2), femtosecond TR spectroscopy (mFemto-TR100, Time-Tech Spectra LLC) and XPS (Thermo Fisher, ESCALAB Xi+) were applied to analyze the characteristics of the exfoliated PdSe₂ flakes. The thickness of PdSe₂ flakes was measured by Digital Holographic Microscopy (Lyncee tec, R2014) and AFM (Oxford Instruments, Cypher ES). The cross-section of the device configuration was characterized by a focused Helium/Neon/Gallium ion microscopy (Carl Zeiss, ORION NanoFab). Electrical measurements were collected by a semiconductor analyzer (PDA, FS-Pro), and the static optoelectronic measurements were under the excitation of a tunable semiconductor laser (Santec Corporation, TSL-550) with tunable wavelength ranging from 1260 to 1620 nm. The setups for 3 dB bandwidth characterization are shown (Supplementary Fig. 9a). The RF signal was generated by a vector network analyzer (Agilent Technologies, E5071B, Bandwidth: 300 kHz to 8.5 GHz), driving an optical modulator (Lucent Technologies, 2623NA, Bandwidth: <20 GHz) at 1550 nm. The modulated optical was amplified by EDFA (MC Fiber Optics, MCEYDFA-HP-1550-33-1-1-FA-T2), passing through a polarization controller, and then coupling into a waveguide by a grating coupler. The photodetector was driven by a sourcemeter (Keithley 2400), and the generated AC photocurrent was then extracted by using a bias-tee (Anritsu, G3N46, Bandwidth: 8 kHz–20 GHz). Eventually, the AC photocurrent was received by VNA. The setups for eye diagram measurements are shown (Supplementary Fig. 9b). The RF signal driving an optical modulator was generated by a signal quality analyzer (Agilent Technologies, N4906B: up to 12.5 Gbit·s⁻¹), and the AC photocurrent extracted by a bias-tee was received by an oscilloscope (Agilent Technologies, DSO9404A, Bandwidth: <4 GHz).

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Author Contributions

L.L, H. L., and J. W. conceived the project. J. W., H. M., C. Z., M. W., Y. Y., Y. X., B. T, Y. L., B. S., J. J. and H. D. fabricated these devices. J. W., M. W., and C. S. designed the passive optical devices. J. W. performed optical and optoelectronic measurements. L.L, H. L., and J. W. analyzed the data and wrote the manuscript. All authors commented on the manuscript.

Competing interests

The authors declare no competing financial interest.

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