Supporting Information

Polarization-sensitive and broadband germanium sulfide photodetectors with excellent high-temperature performance

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Discussion

The specific detectivity can be got based on the measured noise power and bandwidth, using $D^* = (A\Delta f)^{1/2}/\text{NEP}$ with $\text{NEP} = i_n/R$, where NEP is noise equivalent power, A the effective area of the detector in cm^2, Δf the electrical bandwidth in Hz, i_n the noise current and D^* the detectivity in Jones.[1,2]

The noise of photodetector can originate from a shot noise of dark current, Johnson noise (thermal noise), and thermal fluctuation "flicker" noise.[1] The Johnson noise arises from the thermal agitation of charge carriers within a conductor; the random nature of this motion results in a fluctuating voltage appearing across the device.[3-5] However, compared to the bias voltage (e.g., V_{ds} = 4 V), the Johnson noise voltage is usually much smaller.[3,4] Furthermore, according to the Nyquist theory, the deviation voltage (V_t) originating from the Johnson noise can be written as $V_t = (4k_B T R_e \Delta f)^{1/2}$, where $k_B = 1.38 \times 10^{-23}$ J/K is the Boltzman's constant, T is the temperature, and R_e is the resistance. Taking the current as 20 pA, R_e is calculated to be about 2×10^{11}.[4,6] Then we can get $V_t = 5.7 \times 10^{-5} \times (\Delta f)^{1/2}$. Assuming we use very high frequency (Δf = 1 MHz), which is higher than the usual testing value, V_t is still as small as 0.057 V, about 1.4% of the adopted bias voltage.[6]

Flicker noise is an electronic device noise that results from the random fluctuation of electrons flow accompanying the direct current, which is highly dependent on the frequency (f) and may be important in the low frequency range. The flicker noise is even smaller than the Johnson noise when the direct current level is low.[5,7] Furthermore, the current power spectral density (S) of Flicker noise can be expressed as $S = k(I_0)^{\alpha}/f^{\beta}$, where k is the constant. The exponents, α and β, are ideally expected to be close to 2 and 1, respectively. Typically, $S/(I_0)^2$ is usually smaller than 10^{-3} in various types of FET devices including 2D layered materials based devices, such as MoS_2 and $TaSe_3$.[7-10] Thus, it is reasonable to assume that the shot noise from the dark current is the major contribution of the noise, whose validity has also been frequently proved by many previous reports about photodetectors.[1,2] Under this assumption, D^* can be expressed as $RA^{1/2}/(2eI_0)^{1/2}$.[1,2] In addition, the dark current in our case is smaller than most of the related reports, and we think that our calculation of specific detectivity is acceptable using the equation of $D^* = RA^{1/2}/(2eI_0)^{1/2}$. This is also supported that the evaluated D^* from $RA^{1/2}/(2eI_0)^{1/2}$ in the commercial reference Si photodiode (Thorlabs, FDS1010) at 500 nm is consistent with its specific detectivity (1.5×10^{12} Jones) in our experimental setup.

Figures

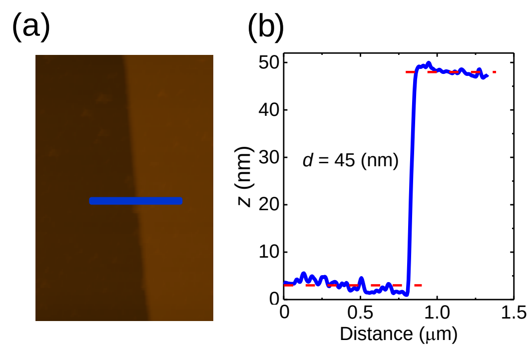

Fig. S1 (a) AFM image of 45-nm-thick GeS multilayer. (b) Height profile.

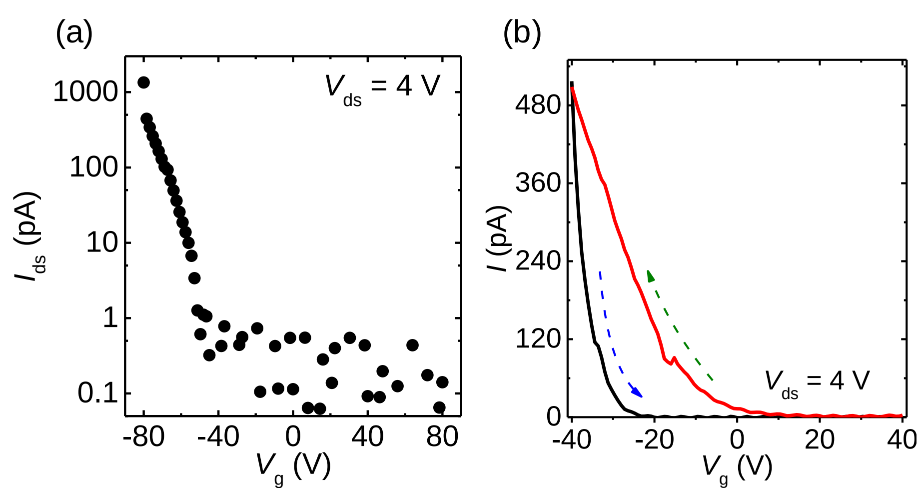

Fig. S2 (a) Gate dependent transfer characteristics of GeS FET under air and room temperature conditions by sweeping from −80 to 80 V on semi-log scale. (b) Gate-dependent transfer characteristic of GeS transistor under vacuum conditions. The black (red) line corresponds to the data by sweeping from −40 to 40 V (40 to −40 V) and the sweep directions are indicated by the dashed lines.

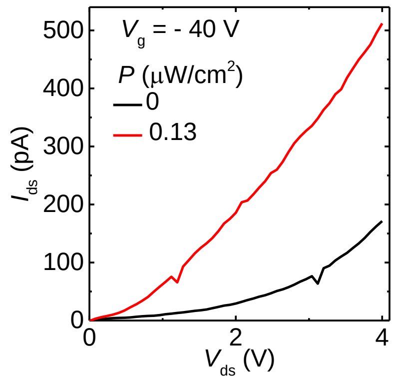

Fig. S3 Drain-source current of the GeS photodetector at V_g = -40 V without and with 500 nm light irradiation. In this case, *R*, *EQE* and *D** is determined to be about 2.3 $\times 10^4$ A/W, 5.8 $\times$ 10^6 % and 1.1 $\times$ 10^{15} Jones, respectively.

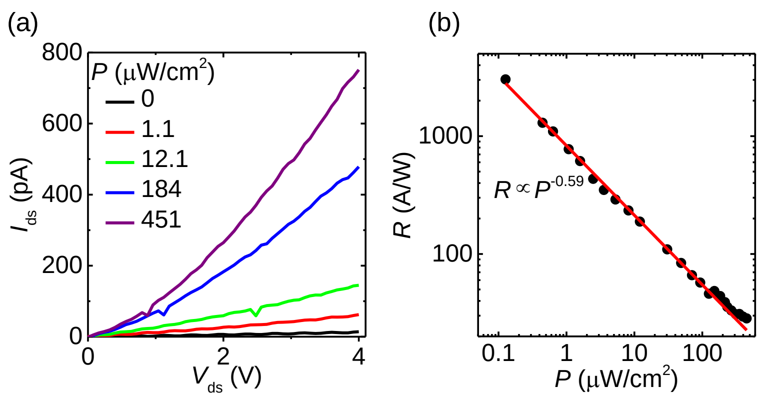

Fig. S4 (a) Current of the 45-nm GeS photodetector as a function of drain-source voltage (V_{ds}) under various light irradiation conditions (λ = 500 nm, V_g = 0 V) from 0 to 451 μW/cm^2. (b) Power dependence of *R*.

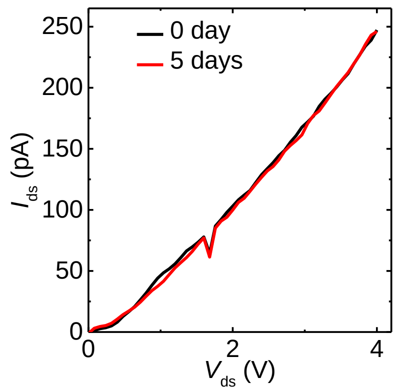

Fig. S5 Photocurrent for GeS photodetector under initial condition (0 day) and that after working for 5 days under light illumination (λ= 500 nm) in air.

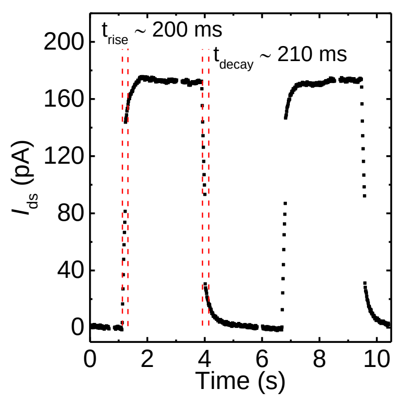

Fig. S6 Time-resolved photoresponse of GeS photodetector measured in response to two on–off cycles of illumination.

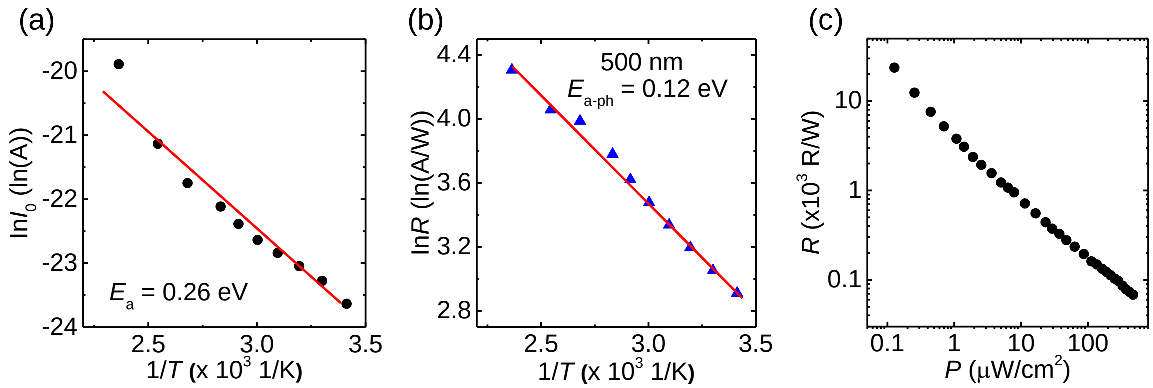

Fig. S7 The results here were obtained from a GeS photodetector with Pd/Au electrods. (a) Temperature dependent dark current on $\ln I_0 - 1/T$ scale. (b) R at different temperatures on $\ln R - 1/T$ scale under 500 nm illumination (P = 1.6 mW/cm^2). The solid lines correspond to the fitted results of Arrhenius plots. (c) Power dependence of R at 373 K.

Table S1. Performances summary of 2D materials based photodetectors

Photodetectors	R (A/W)	*D** (Jones)	EQE (%)	λ (nm)	Ref.
GeS	6800	5.6×10^{14}	1700000	300-800	This work
BP	0.1-15		149~3000	> 400	11
GaSe	2.8		1367	254-620	12
GaS	19.2	10^{13}	9371	254-520	13
GeS	173	1.7×10^{13}	53200	405	14
GeS	206	2.35×10^{13}	40000	400-800	15
G/Bi_2Te_3	35		8300	532-1550	16
HfS_2	890			473,633	17
ReS_2	604		1.5×10^5	532	18
$ReSe_2$	2.98		458	532	19
SnS_2	100		33000	473	20
$MoTe_2$	6			685	21
MoS_2	880			400-680	22
MoS_2	342.6			532	23
P(VDF-TrFE)/MoS_2	2570	2.2×10^{12}		500-1550	24
WS_2/Au NPs	1090	3.5×10^{11}		520	25
MoS_2/h-BN/G	180	2.6×10^{13}		400-800	26

Table Footnote, λ: demonstrated detecting range, BP: black phosphorus; G: graphene; QDs: quantum dots; P(VDF-TrFE): poly(vinylidene fluoride-trifl uoroethylene); NPs: nanoparticles.

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