WO_3-NPs activated WS_2 layered heterostructures for efficient broadband (254 nm-940 nm) photodetection

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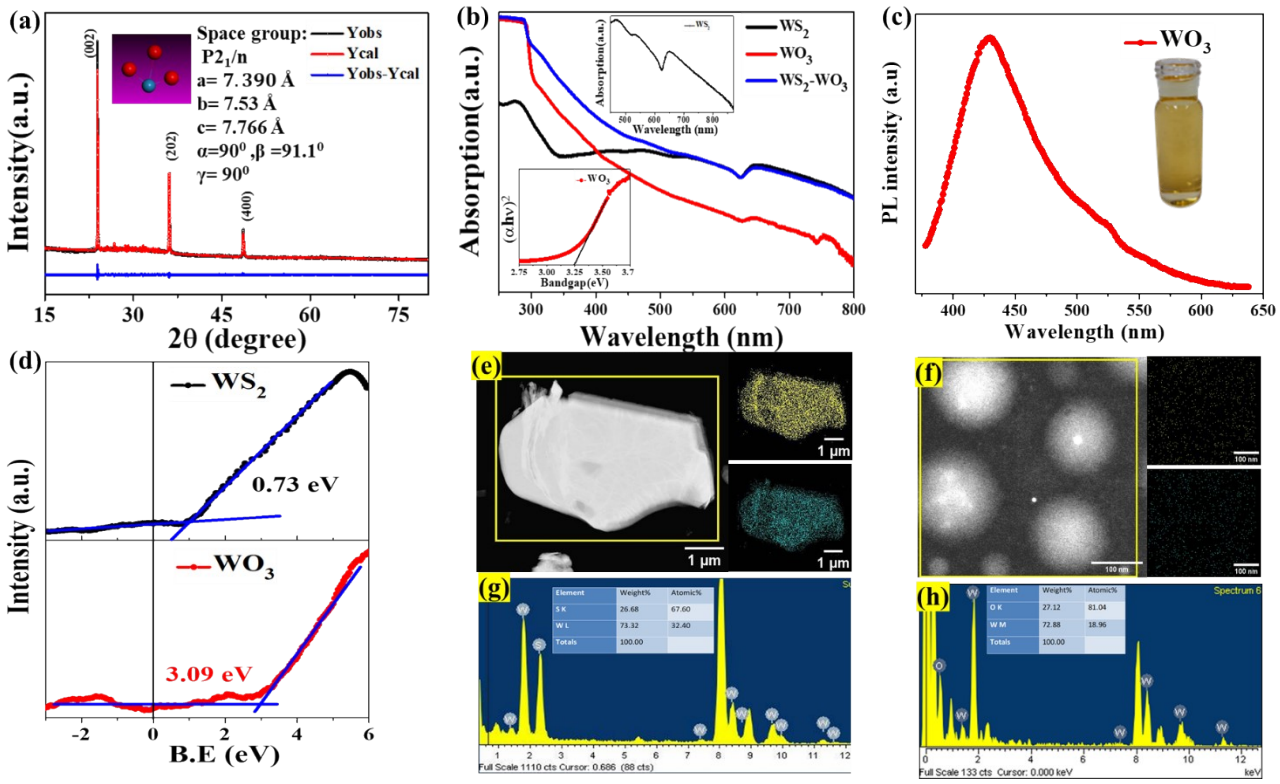

Figure S1. (a) XRD measurements for WO_3 nanoparticle coated thin film, (b) UV-Vis absorption spectra for WS_2, WO_3 and WS_2-WO_3 mixed solution, (c) Photoluminescence spectra for exfoliated WO_3 nanoparticles (d) valence band spectra recorded for WS_2 and WO_3, (e)-(f) HAADF mapping for WS_2 and WO_3, (g)-(h) EDX data for WS_2 and WO_3 respectively.

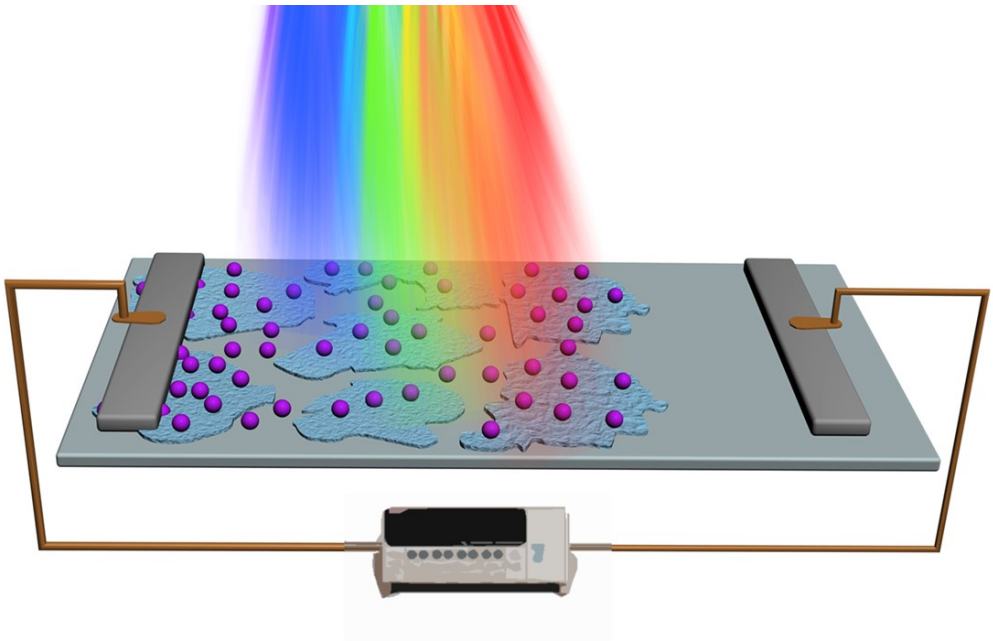

Figure S2. Schematics of fabricated photodetector along with I-V measurement system under a broad spectral response.

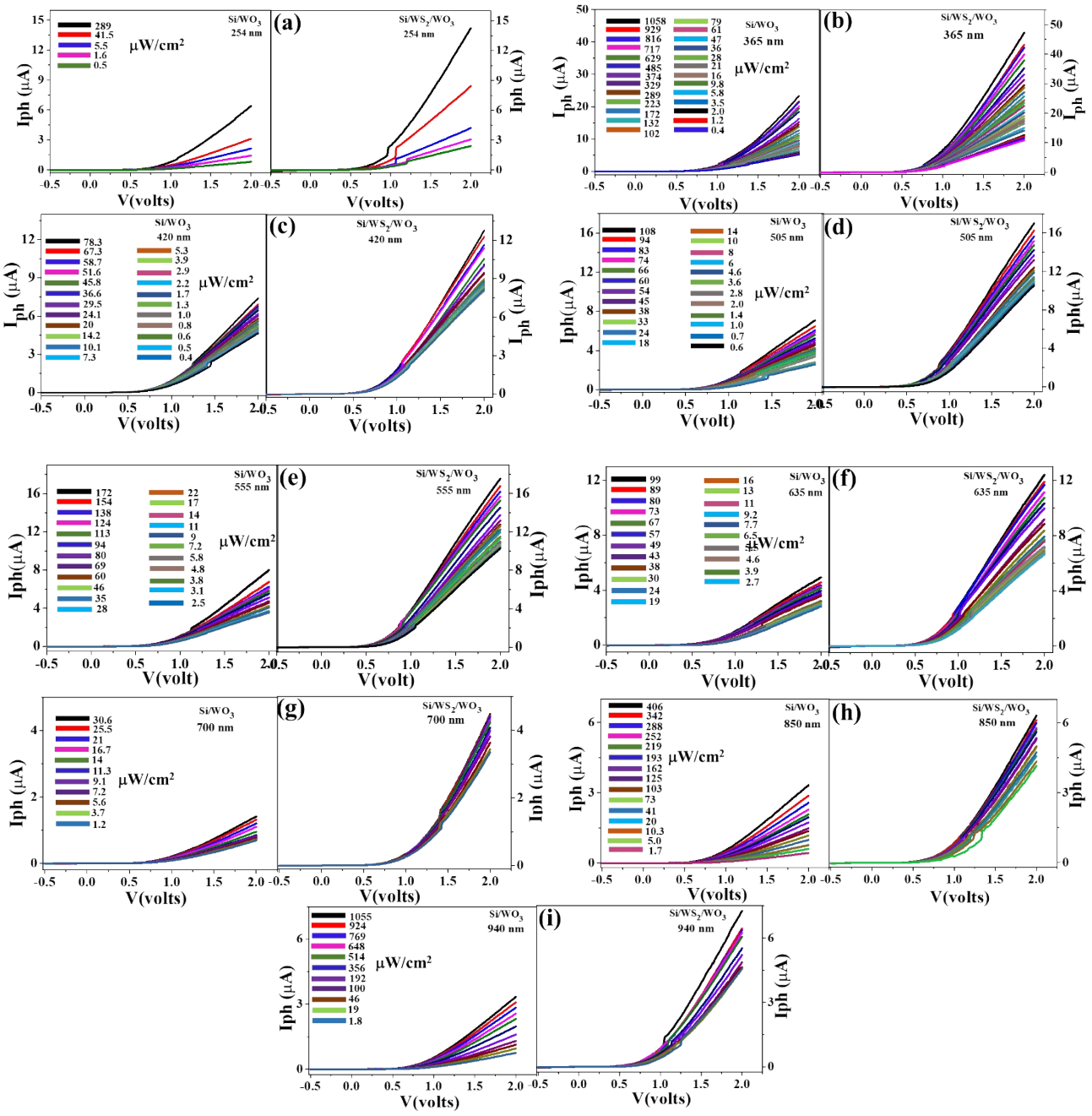

Figure S3. Optoelectronic characteristics of fabricated photodetectors (a)-(i) I-V curve of D_1abd D_2 under various light intensities from 254 nm to 940 nm.

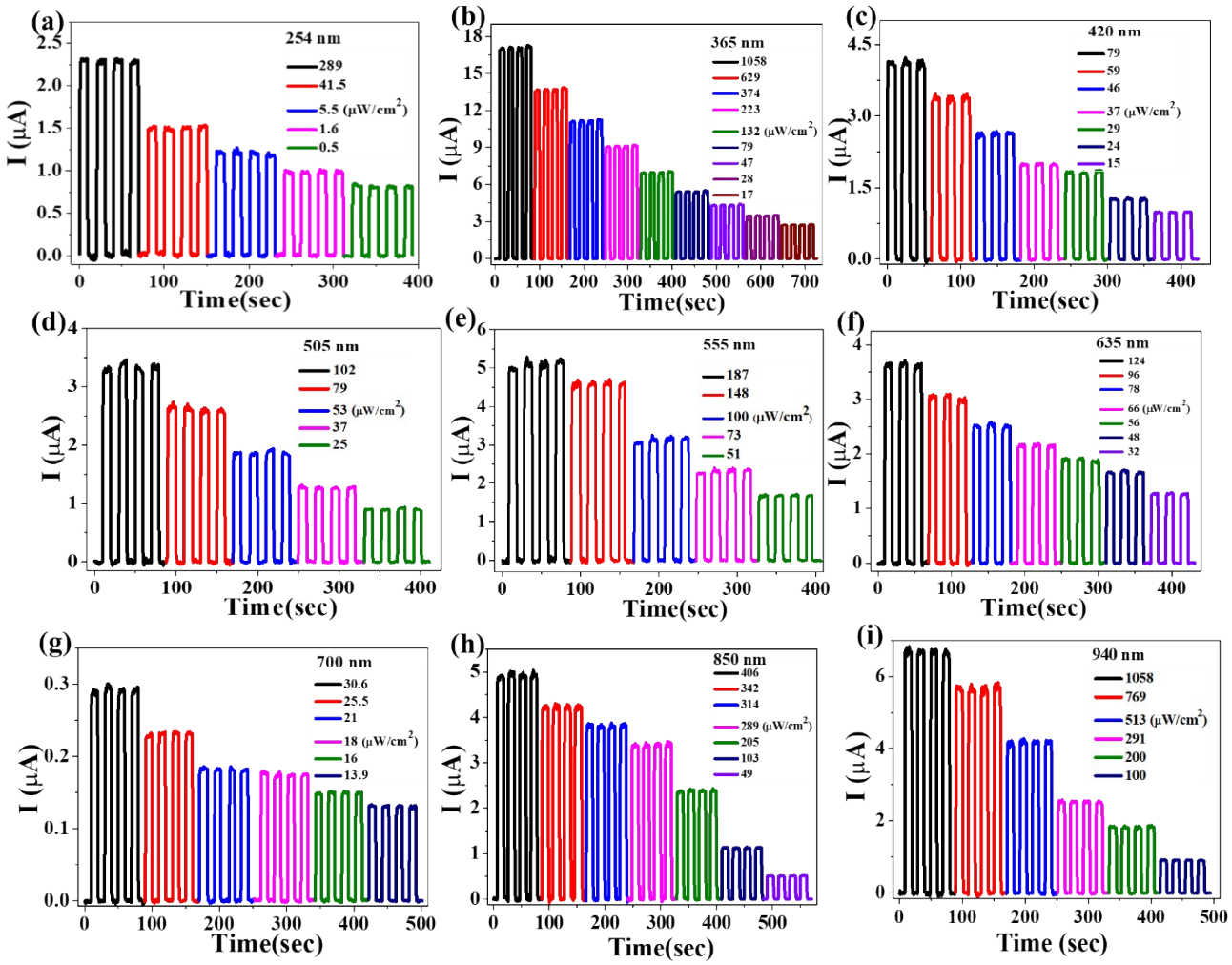

Figure S4. (a)-(i) Intensity dependent photoswitching of D_2 under a fixed bias 2 volt from 254 nm to 940 nm.

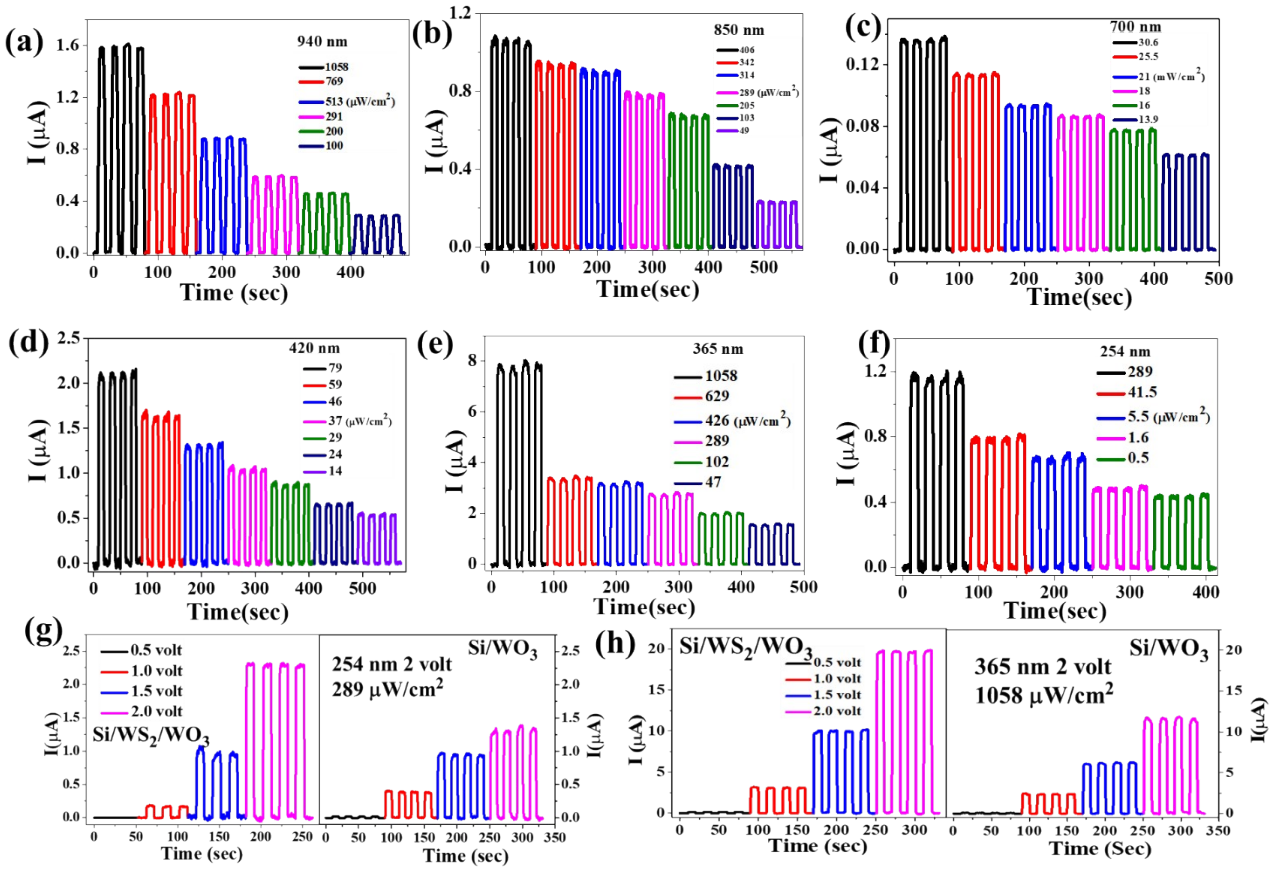

Figure S5. (a)-(f) Intensity dependent photoswitching of D_1 under a fixed bias 2 volt from 254 nm to 940 nm, (g) Bias dependent photoswitching of D_1 and D_2 under a fixed intensity 289 μW/cm² for 254 nm, (h) Bias dependent photoswitching of D_1 and D_2 under a fixed intensity 1058 μW/cm² for 365 nm.

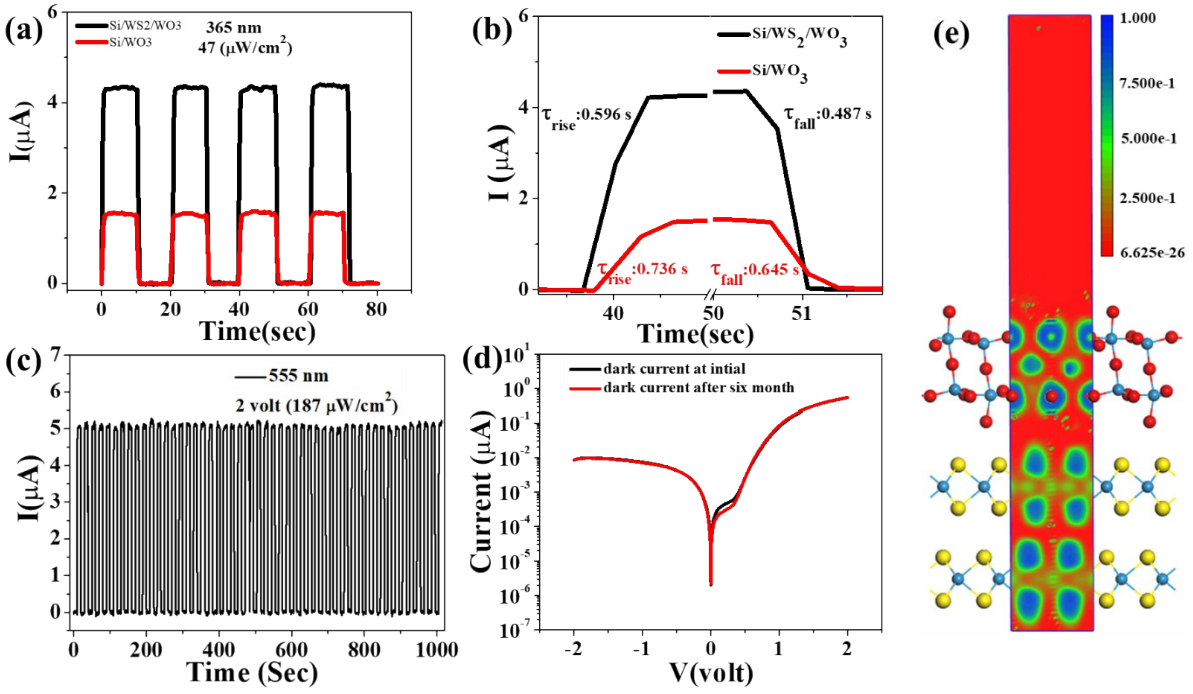

Figure S6. (a) Intensity dependent photoswitching of D_1 and D_2 under a fixed bias 2 volt under 365 nm with a fixed intensity 47 μW/cm², (b) rise time and fall time of device D_1 and D_2, (c) multiple photoswitching of device D_2 under a fixed bias 2 volt under 555 nm with a fixed intensity 187 μW/cm², (d) dark current measurements of device D_2 with a time interval of six months, (e) electron localization function for WS_2/WO_3 heterostructures.

Table S1. Parameters to calculate the average photoluminescence lifetime of carriers

$T= A+B_1*\exp(-i/T_1) + B_2*\exp(i/T_2)$

Device Configuration	Excitation (nm)	Emission (nm)	Average Life time(ns)	T_1 (ns)	T_2 (ns)	B_1	B_2
WO_3	**375**	**430**	1.3822	1.03352	4.16676	66.45	**33.55**
WS_2/WO_3			**1.016485**	**0.907484**	**4.50884**	**86.57**	**13.43**

Table S2. Parameters to calculate the average photoluminescence lifetime of carriers

$T= A+B_1*\exp(-i/T_1) + B_2*\exp(-i/T_2) + B_3*\exp(-i/T_3)$

Sample	Excitation (nm)	Emission (nm)	Average Life time(ns)	T_1 (ns)	T_2 (ns)	T_3 (ns)	B_1	B_2	B_3
Si/WO_3	**375**	**430**	0.527	1.29646	5.8678	0.22844	30.13	33.13	36.74
$Si/WS_2/WO_3$			**0.298**	**1.35534**	**6.23679**	**0.13845**	**21.62**	**35.03**	**43.35**

Table S3. The highest recorded responsivity and EQE (%) values for D1 and D2 device configuration.

Figure	Wavelength (nm)	Intensity ($\mu W/cm^2$)	R (D_1) in A/W	EQE (D_1) (%)	R (D_2) in A/W	EQE (D2) (%)
5 (a)	365	0.43	121.1	41×10^3	**251.4**	**85** $\times 10^3$
	850	1.79	2.39	0.34×10^3	**23.1**	**3.3** $\times 10^3$
	940	1.81	1.8	0.23×10^3	**25.14**	**3.3** $\times 10^3$
5 (b)	254	0.5	16.3	7.9×10^3	**47.9**	**23** $\times 10^3$
	505	0.58	43.8	10×10^3	**179.9**	**43** $\times 10^3$
	555	2.57	14.07	3.1×10^3	**39.97**	**8.9** $\times 10^3$
5 (c)	420	0.42	109.2	32×10^3	**192.7**	**56** $\times 10^3$
	635	2.78	10.09	1.9×10^3	**23.89**	**4.7** $\times 10^3$
	700	1.26	5.47	0.96×10^3	**26.57**	**4.7** $\times 10^3$

Table S4. Performance comparison of our fabricated device with other reported work.

Device configuration	Process	Wavelength nm	Bias (volt)	Responsivity (A/W)	Detectivity (Jones)	EQE	Ref
Si/WO_3/Graphene	**radio-frequency (RF) magnetron sputtering**	**UV**	**3**	**0.253**	**5.7136×10^{11}**	**…..**	[1]
Si/WS_2/Graphene	**chemical vapor deposition (CVD)**	**550**	**Vg= 0 Vds= 5**	**8.05**	**2.8×10^{10}**	**…..**	[2]
WS_2/Graphene	**Electrophoresis**	**670**	**10**	**0.439**	**1.41×10^{10}**	**81.39**	[3]
Si/WO_{3-X}	**Atomic layer deposition**	**405**	**-5**	**72.8**	**3.96×10^{11}**		[4]
WS_2/Graphene	chemical vapor deposition (CVD)	480	3	1.15	2.06×10^{9}	…….	[5]
Cr: Au /WS_2/Cr: Au	CVD	240	10	0.261	7.72×10^{11}	1.24	[6]
Si/WO_3	Glancing Angle Deposition	360	3	9.66	5.94×10^{12}	3330	[7]
Ti: Au /WO_3/ Ti: Au	Vapor cooling condensation	350	-5	0.0207	1.34×10^{9}	…….	[8]
ZnO-WS2/Si	Liquid phase exfoliation and microwave assisted	670	-2	9.48	6.39×10^{11}	1758	[9]
WS_2/Graphene/n-Si	Thermal evaporation	800	-0.3	54.5	5.77×10^{13}	…..	[10]
WS_2/Si	magnetron sputtering and post chalcogenation	514	-3	4.3	4.0×10^{12}	1100	[11]
Ti /WO_3/ Ti	magnetron sputtering	382	3	0.94	1.97×10^{12}	304.2	[12]
p-Si/WS_2/WO_3	**Solvothermal & spray coating**	**365 (254-940)**	**2**	**251.4**	**1.892×10^{14}**	**85×10^{3}**	**This work**

References:

1 P. V. K. Yadav, B. Ajitha, Y. A. Kumar Reddy and V. R. Minnam Reddy, *ACS Appl. Electron. Mater.*, 2021, **3**, 2056–2066.

2 M. Alamri, M. Gong, B. Cook, R. Goul and J. Z. Wu, *ACS Appl. Mater. Interfaces*, 2019, **11**, 33390–33398.

3 P. M. Pataniya and C. K. Sumesh, *ACS Appl. Nano Mater.*, 2020, **3**, 6935–6944.

4 X. Zhang, Y. Su, Z. Tang, D. Hu, Z. Wang, Y. Hou and X. Wang, *Scr. Mater.*, 2020, **189**, 89–94.

5 F. I. Alzakia, B. Tang, S. J. Pennycook and S. C. Tan, *Mater. Horizons*, 2020, **7**, 3325–3338.

6 P. Aggarwal, S. Kaushik, P. Bisht, M. Sharma, A. Singh, B. R. Mehta and R. Singh, *Cryst. Growth Des.*, 2022, **22**, 3206–3217.

7 R. Rajkumari and N. K. Singh, *IEEE Trans. Nanotechnol.*, 2019, **18**, 676–683.

8 H.-Y. Lee, T.-S. Lin and C.-T. Lee, *ECS J. Solid State Sci. Technol.*, 2018, **7**, Q85–Q87.

9 M. Patel, P. M. Pataniya, V. Patel, C. K. Sumesh and D. J. Late, *Sol. Energy*, 2020, **206**, 974–982.

10 R. Xiao, C. Lan, Y. Li, C. Zeng, T. He, S. Wang, C. Li, Y. Yin and Y. Liu, *Adv. Mater. Interfaces*, 2019, **6**, 19011304–1901310.

11 S. Pal, S. Mukherjee, R. Jangir, M. Nand, D. Jana, S. K. Mandal, S. Bhunia, C. Mukherjee, S. N. Jha and S. K. Ray, *ACS Appl. Nano Mater.*, 2021, **4**, 3241–3251.

12 P. V. Karthik Yadav, B. Ajitha, Y. A. K. Reddy, V. R. Minnam Reddy, M. Reddeppa and M. D. Kim, *Appl. Surf. Sci.*, 2021, **536**, 147947.