Supplementary Information for: Hot electron engineering in layered heterojunction for efficient infrared detection

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S1. SEM and AFM data of devices D2 and D3

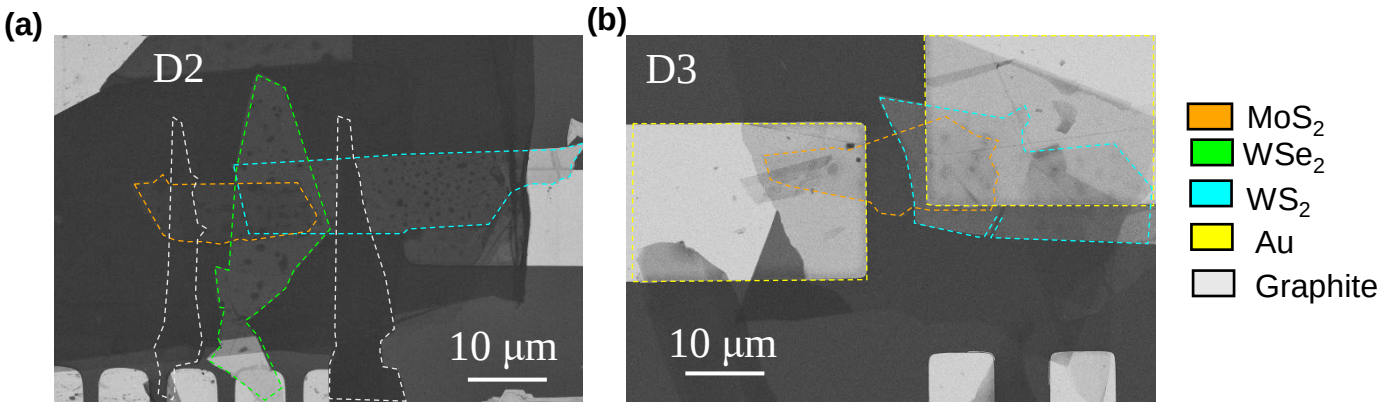

Fig. S1: SEM image of device (a) D2 and (b) D3.

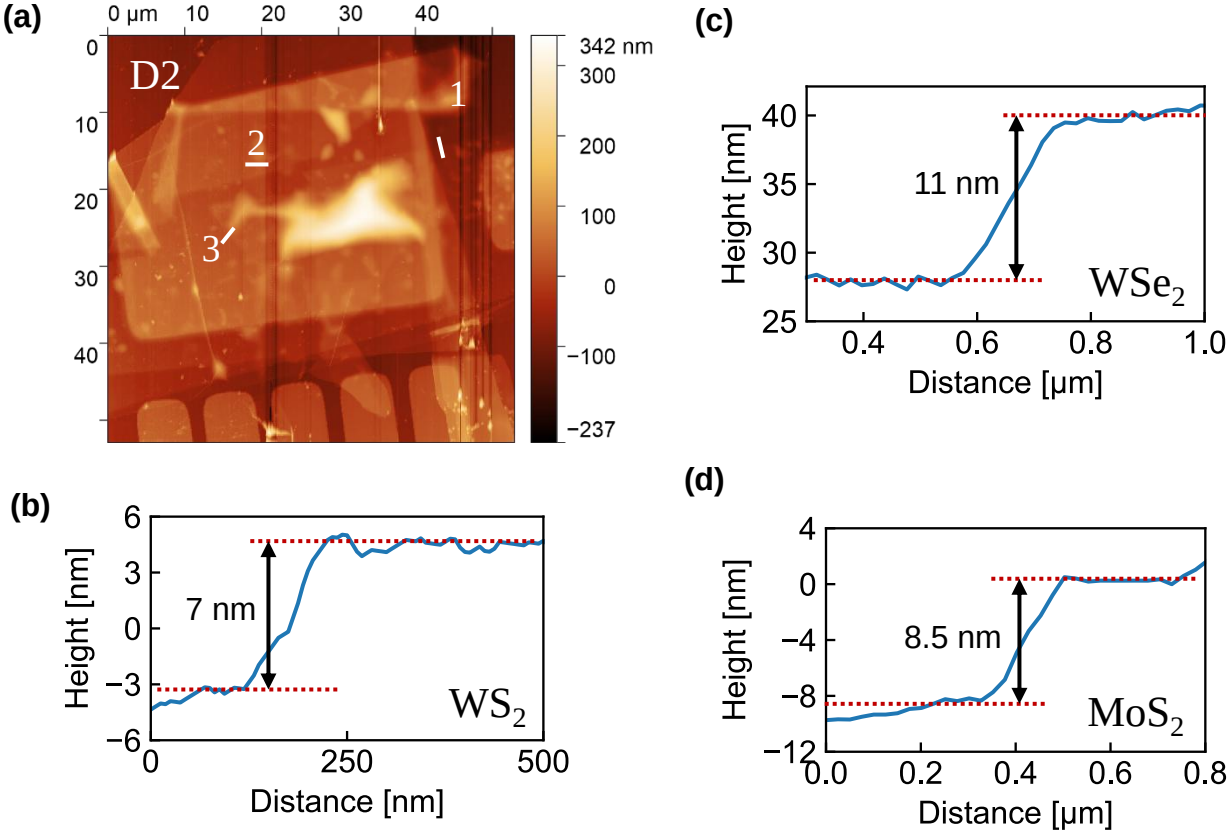

Fig. S2: (a) AFM image of Device D2. Thickness profile along line marked (b) 1, (c) 2 and (d) 3 in (a). These profiles correspond to WS_2 , WSe_2 and MoS_2 layers, respectively.

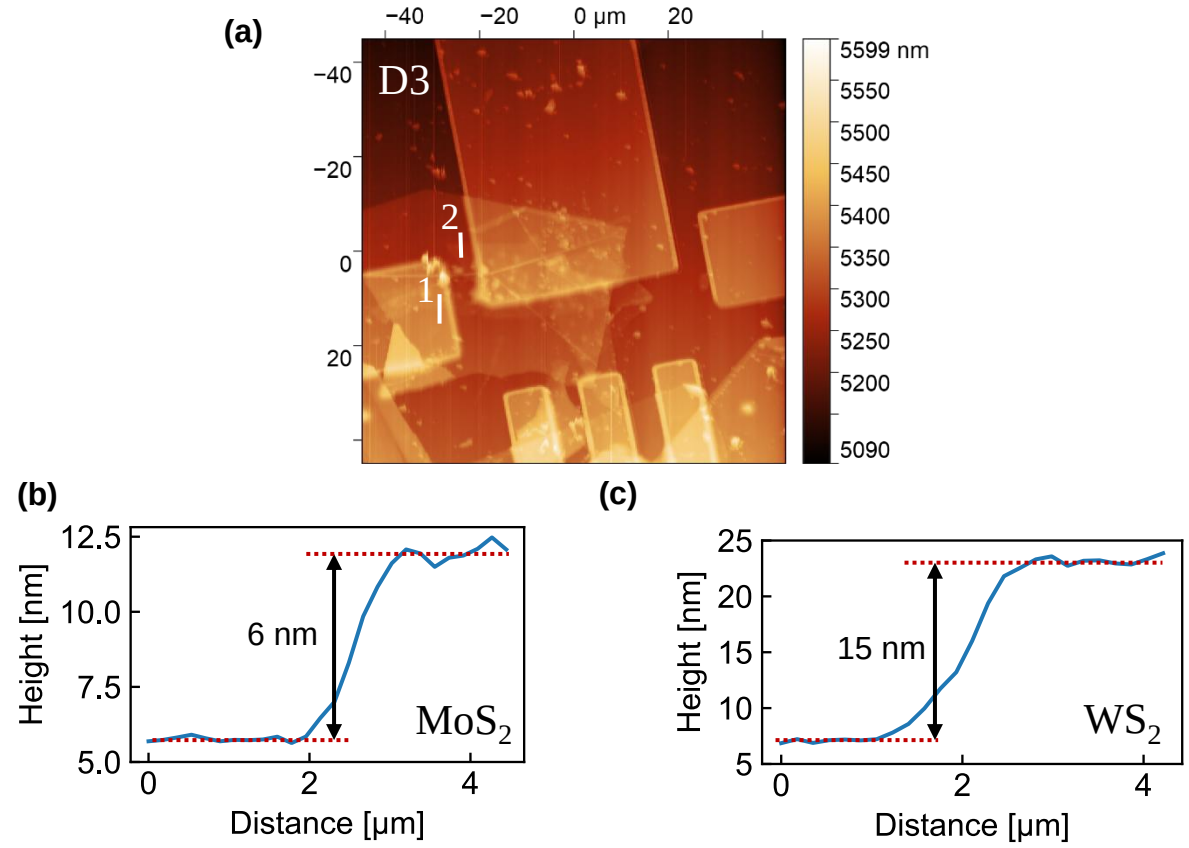

Fig. S3: (a) AFM image of Device D3. Thickness profile along line marked (b) 1 and (c) 2 in (a). These profiles correspond to MoS_2 and WS_2 layers, respectively.

Table 1: Summary of thicknesses of various layers in D2

Layer	Thickness
MoS_2	8.5 nm
WSe_2	11 nm
WS_2	7 nm

Table 2: Summary of thicknesses of various layers in D3

Layer	Thickness
MoS_2	6 nm
WS_2	15 nm

S2. Electrical characteristics of Device D1 under dark conditions

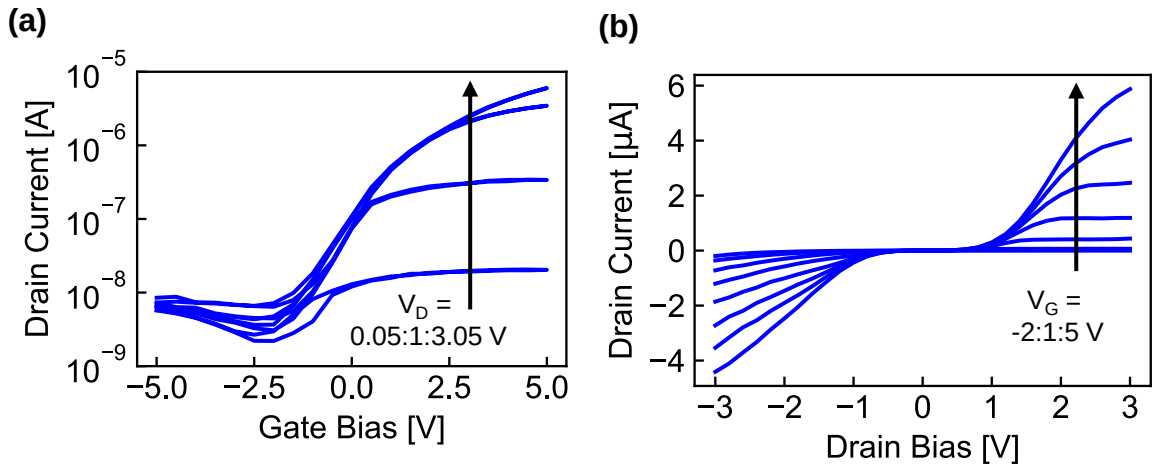

Fig. S4: (a) Transfer characteristics and (b) Output characteristics of device D1.

S3. Hot-electron photocurrent model

The structure used in the physical model for the device is shown in the figure below. The emitter, barrier and collector layers are considered thin, separated by a physical distance t. This distance is typically the van der Waal gap between the materials.

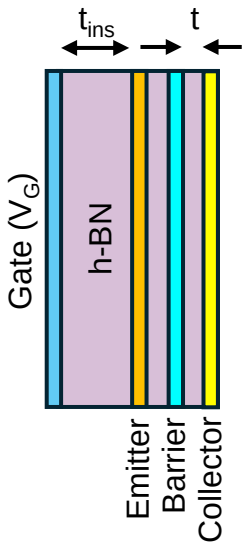

Fig. S5: Device structure considered for simulation

Since the layers are assumed thin, they are equipotential with the electrostatic potential of the three layers denoted by ϕ_E, ϕ_B and ϕ_C. The system of equations that govern the system are:

$$\begin{aligned}
\epsilon\frac{\phi_E - V_G}{t_{ins}} + \epsilon\frac{\phi_E - \phi_B}{t} &= e(N_{DE} - n_E) \\
\epsilon\frac{\phi_B - \phi_E}{t} + \epsilon\frac{\phi_B - \phi_C}{t} &= e(N_{DB} - n_B) \\
\epsilon\frac{\phi_C - \phi_B}{t} &= e(N_{DC} - n_C)
\end{aligned}$$

where N_{Di} and n_i represent the fixed doping concentration and electron concentration inside the i^{th} layer ($i : E, B, C$). e is the absolute charge of an electron, and ϵ is the effective dielectric constant (assumed to be uniform in the device). The carrier concentration is

related to the electrostatic potential of the layer by:

$$n(\phi, T, E_F) = \frac{g_s g_v m^* k_B T}{\pi \hbar^2} \log\left(1 + \exp\left(\frac{e(E_F - D + \phi)}{k_B T}\right)\right)$$

where g_s and g_v are spin and valley degeneracies, respectively. E_F is the Fermi level, m^* is the effective mass, and k_B is the Boltzmann constant. Under dark conditions, we take $E_F = 0$. D is the position of the conduction band with respect to Fermi level $E_F = 0$ at $\phi = 0$. This parameter represents the doping of the layer.

Under illumination, we assume the temperature of the electrons to be $T_e > T$ in both collector and emitter layers. Unlike an inter-band photo-excitation, the number of carriers in the conduction band will remain constant. Also, since the carrier concentration does not change, we do not expect the electrostatic potentials to change either. Using these constraints, we can calculate the new quasi-Fermi level, E_{Fe} using the relation:

$$n(\phi, T, E_F = 0) = n(\phi, T_e, E_{Fe})$$

The new quasi-Fermi level and the higher temperature define the distribution of electrons in the conduction band under illumination.

Once the distribution is obtained, the number of carriers in the emitter layer with energy higher than the conduction band edge of the barrier layer is calculated $[n_E(T_e^E)]$. Similarly, the number of carriers in the collector layer with energy greater than the barrier layer conduction band edge is calculated $[n_C(T_e^C)]$. The photocurrent, then, is proportional to the difference between the two.

$$I_{ph} \propto n_E(T_e^E) - n_C(T_e^C)$$

S4. Response of structure D2 to various wavelengths

D2 exhibits a similar wavelength response to various radiation of the SWIR spectrum as D3.

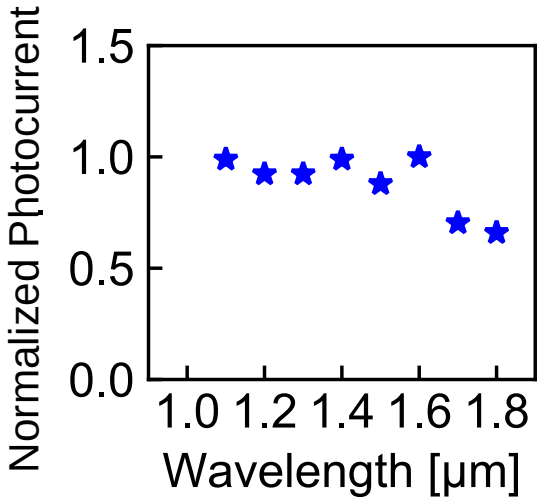

Fig. S6: Response of D2 to infrared radiation from 1.1 μm to 1.8 μm.

S5. Characterization of additional D3 device

The results of the characterization of device D3 from another fabrication run are shown in the figure below. The device shows qualitatively similar behaviour as the device presented in the main text. The device shows a peak responsivity of 12.5 mA/W.

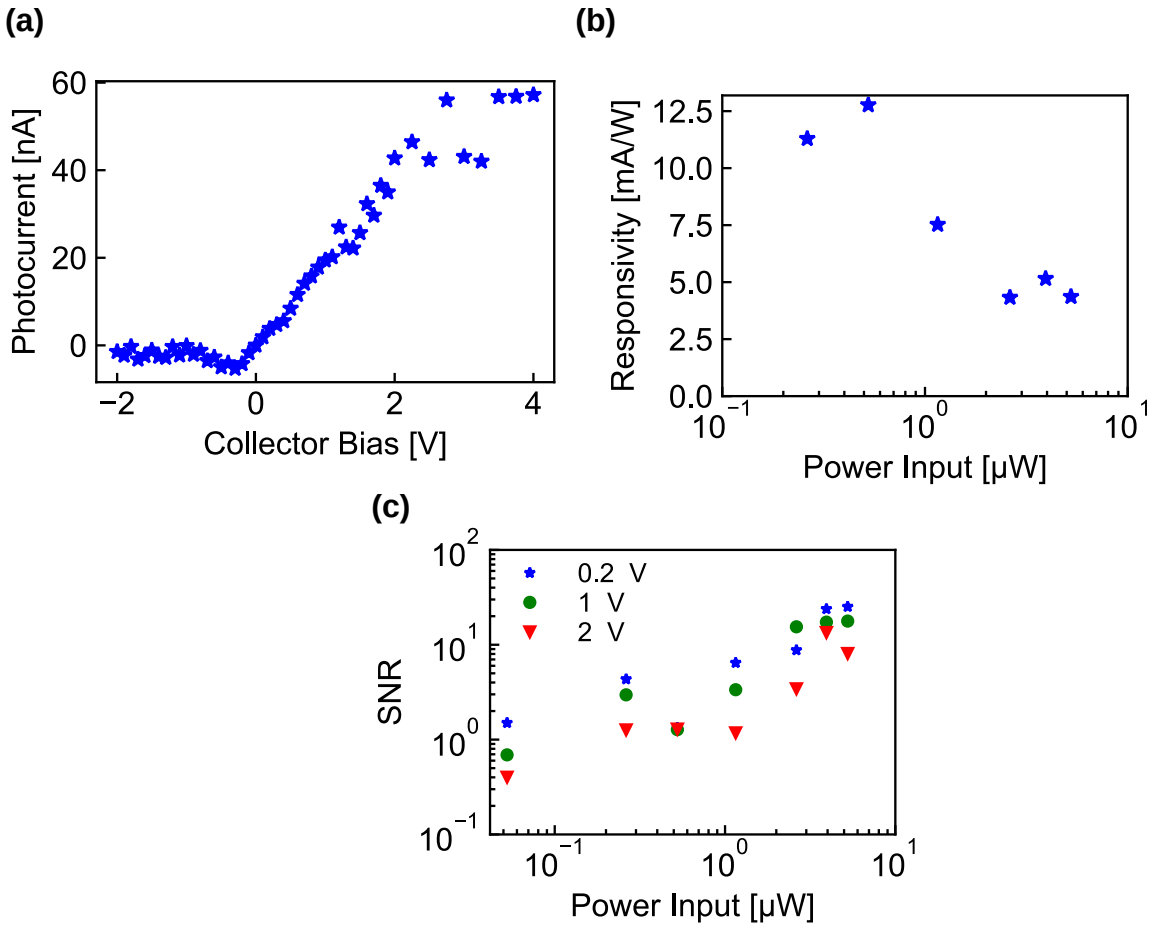

Fig. S7: (a) Dependence of photocurrent on collector bias. (b) Responsivity as a function of input power. (c) SNR for various collector biases as a function of input power.

S6. MoS_2 thickness dependent photoresponse of D3

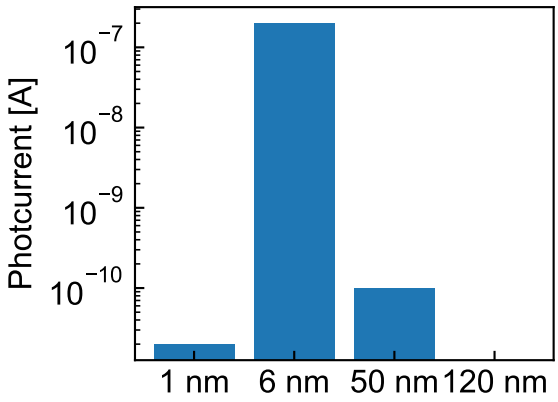

Fig. S8: Comparison of photoresponse of four D3 devices with varying thicknesses of MoS_2 - monolayer, 6 nm, 50 nm, and 120 nm. The device with 6 nm thick MoS_2 showed significantly high photoresponse compared to the other three devices.

S7. Frequency response of D3 for excitation with 633 nm radiation

With 633 nm radiation, we can detect signals up to 100 kHz with the same device.

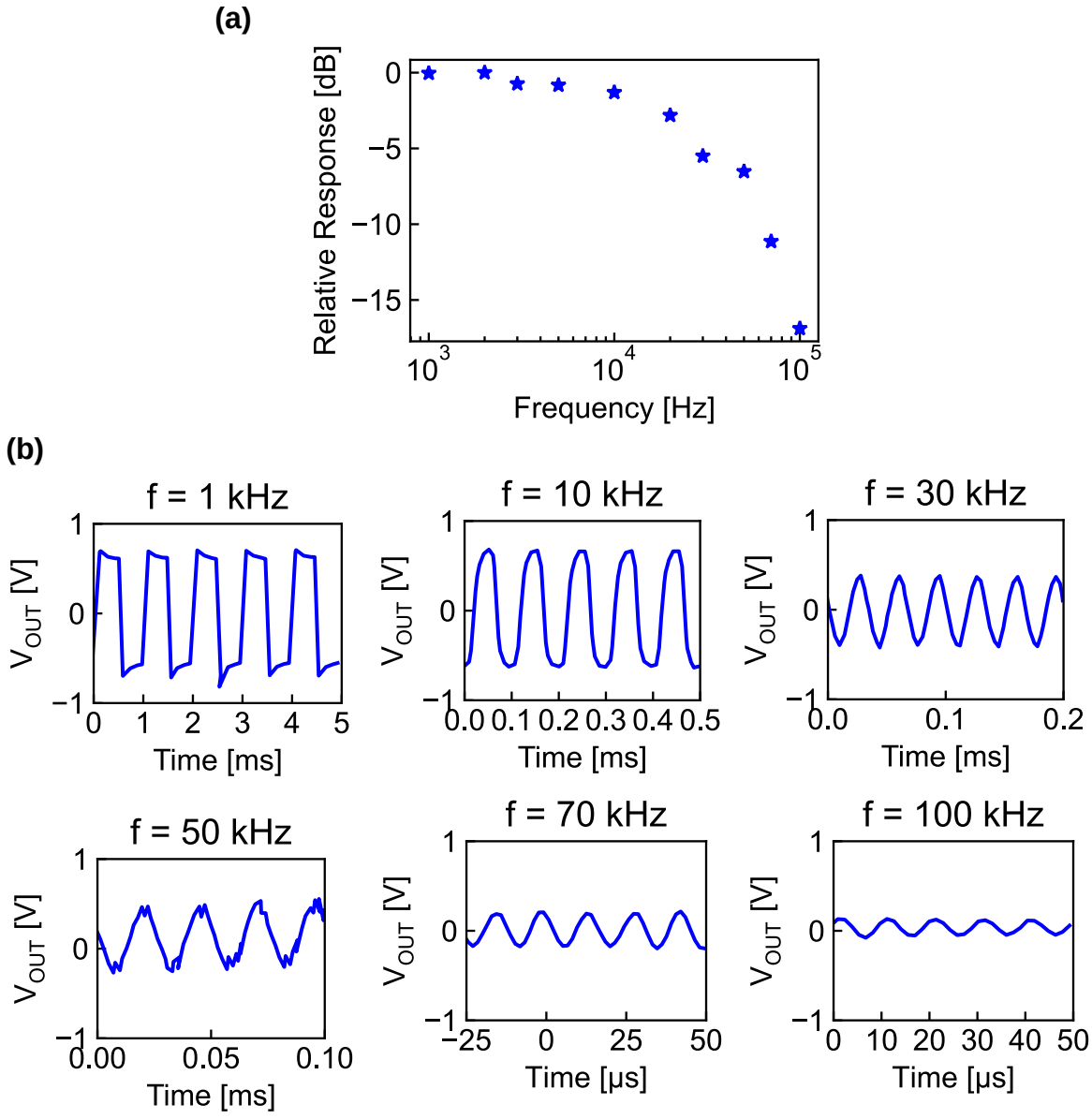

Fig. S9: (a) Frequency response to excitation with 633 nm radiation. (b) Time response of D3 from excitation of 633 nm radiation from 1 kHz to 100 kHz.

S8. Performance benchmarking

Device	Wavelength [nm]	Responsivity [AW^{-1}]	Response time [s]	Circuit (PCB) integration
MoS_2-WS_2 [18] (Interband)	400-800	1.8×10^{-7}	16	No
MoS_2-WS_2 [19] (Interband)	450	2.3	-	No
MoS_2-WS_2 [20] (Interband)	405	298	-	No
Graphene [25] (Interband)	1550	6.1×10^{-3}	6.25×10^{-11}	No
Graphene-Si [37] (Plasmonic hot electron)	1550	0.37	-	No
Graphene-Si [38] (Hot electron)	1550	9.9×10^{-3}	-	No
MoS_2-Au [40] (Hot electron)	1550	17×10^{-3}	1.5×10^{-4}	-
$PtSe_2$ [22] (Interband)	200-2000	0.5	1×10^{-5}	No
Te [23] (Interband)	1550	13	1×10^{-3}	No
Graphene [50] (Gr-hBN tunnel barrier)	8600	8.6×10^{-4}	-	No
This work (Hot electron)	633-1800	42×10^{-3} (@ 1550 nm) 150×10^{-3} (@ 633 nm)	4×10^{-4} (@ 1550 nm) 1×10^{-4} (@ 633 nm)	Yes