Supporting Information

2D WS_2-Edge Functionalized Multi-Channel Carbon Nanofibers: Effect of WS_2 Edge-Abundant Structure on Room-Temperature NO_2 Sensing

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S1. WS_2@CNFs

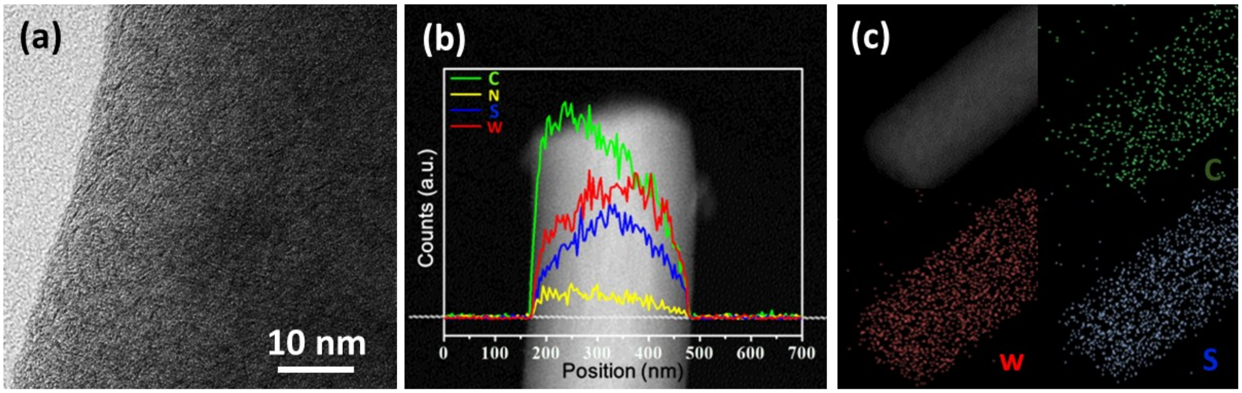

Figure S1. (a) HRTEM image of WS_2@CNFs. (b) STEM image of WS_2@CNFs on which EDS line-scan profile of W,S, N, and C is presented. (c) STEM image and STEM-EDS mapping image of WS_2@CNFs: W (red), S (sky-blue), nad C (green).

S2. TEM images of WS_2@MTCNFs and CNFs

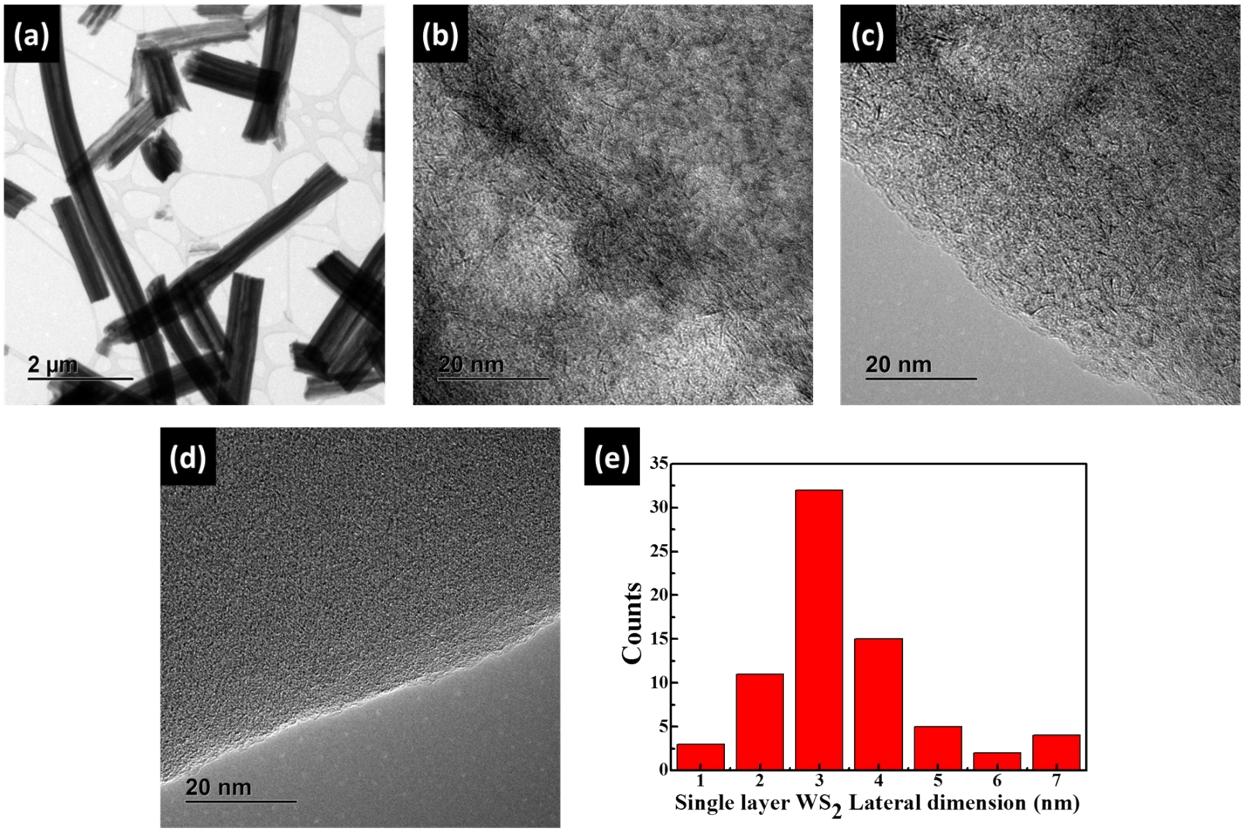

Figure S2. (a) TEM image of WS_2@MTCNFs. HRTEM images of (b-c) WS_2@MTCNFs and (d) CNFs. (e) Lateral dimension size distribution histogram of single layer WS_2 in MTCNFs.

S3. XRD patterns of WS_2@MTCNFs

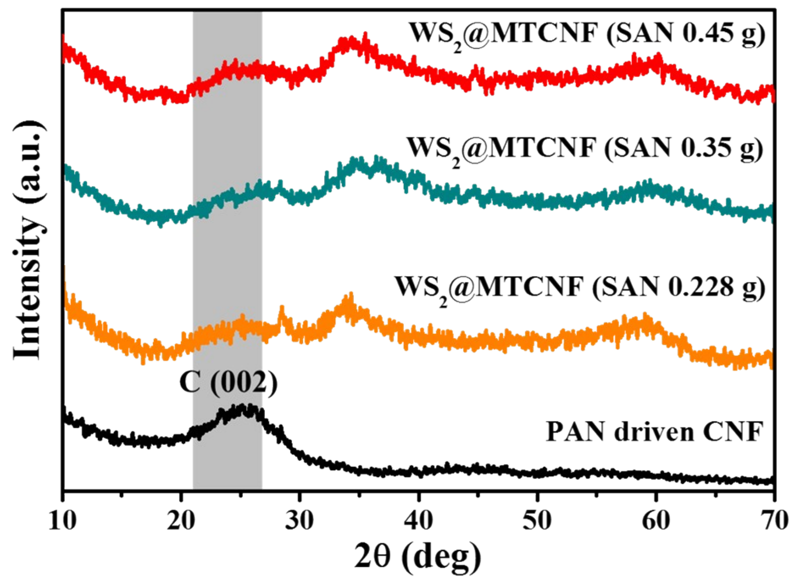

Figure S3. XRD patterns of WS_2@MTCNFs with SAN 0.450 g, SAN 0.350 g, and SAN 0.228 g and PAN-driven CNFs, respectivley.

S4. XPS spectra of the WS_2@MTCNFs : C 1s peaks

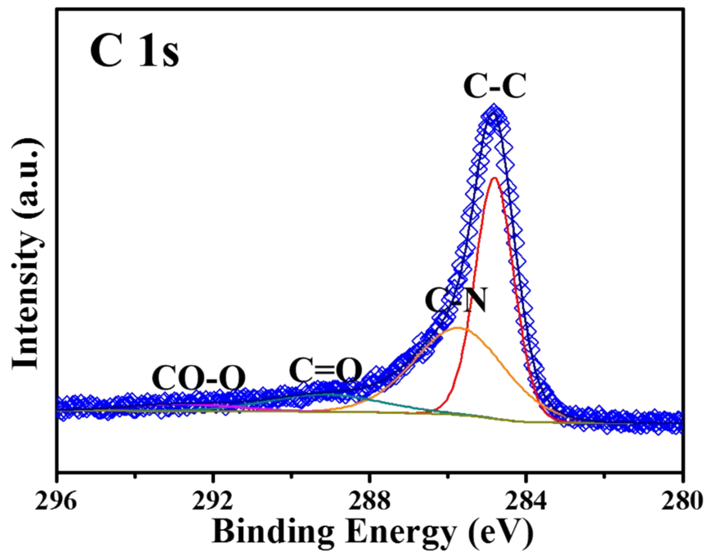

Figure S4. XPS spectra of the WS_2@MTCNFs : C 1s peaks

S5. Ex-situ XPS analysis in humid condition

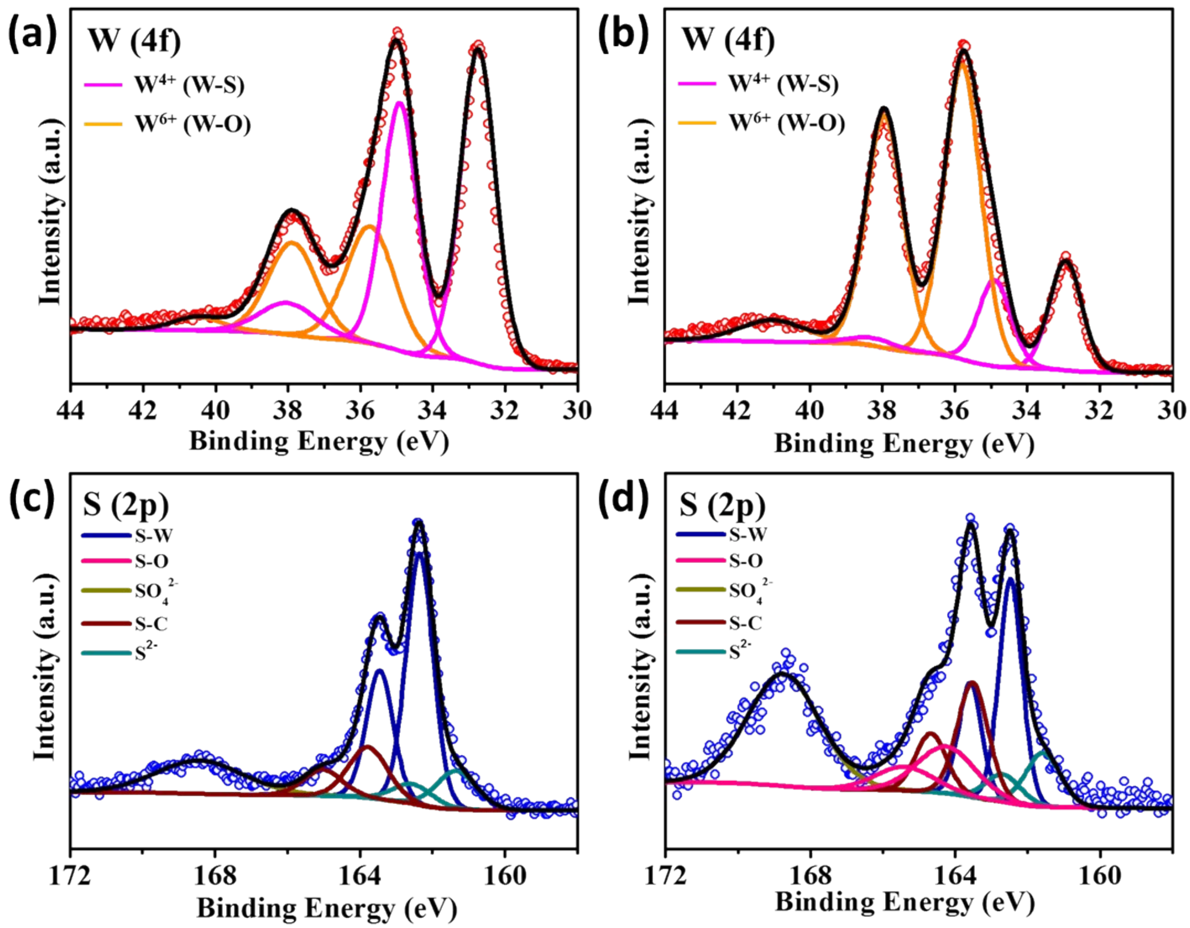

Figure S5. Ex-situ XPS analysis with WS_2@MTCNFs: W 4f spectra (a) before and (b) after exposure to NO_2 in humid condition. S 2p spectra (c) before and (d) after exposure to NO_2 in humid condition.

S6. Sensing characteristics of CNFs and WS_2@MTCNFs

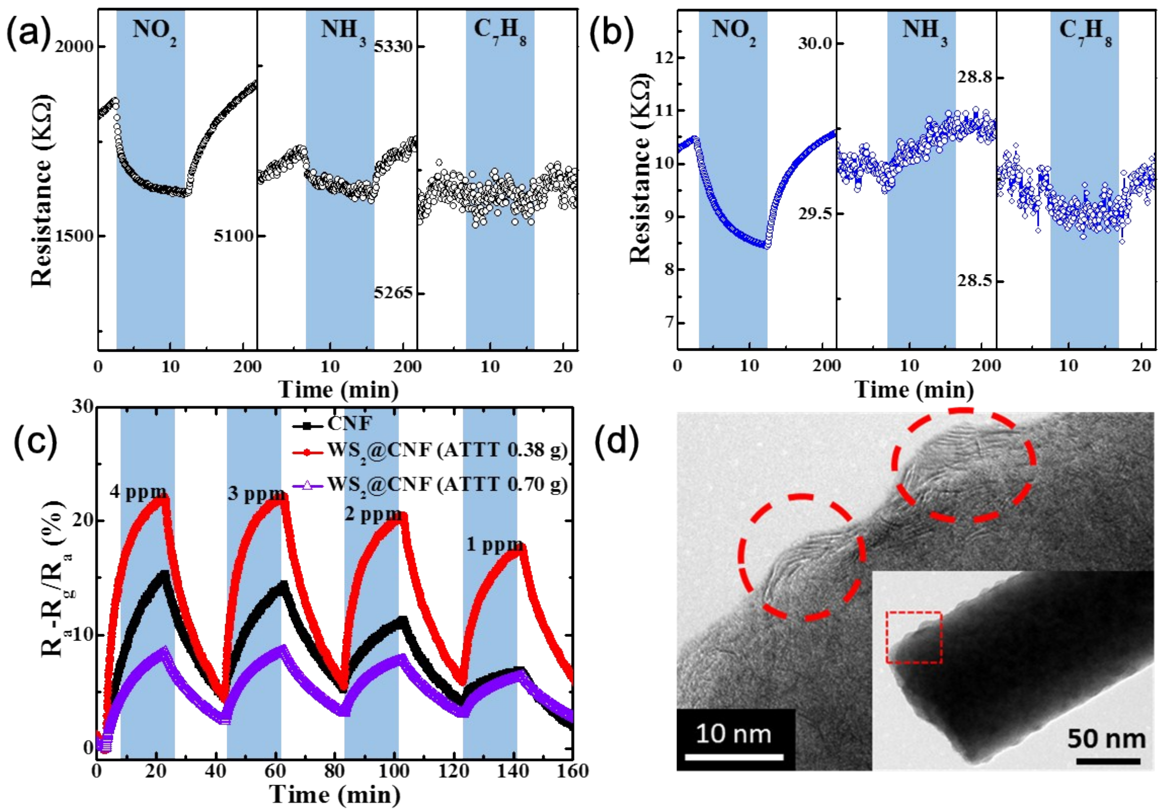

Figure S6. (a) Dynamic resistance transition characteristics of CNFs toward 5 ppm of NO_2, NH_3, and C_7H_8. (b) Dynamic resistance transition characteristics of WS_2@MTCNFs toward 5 ppm of NO_2, NH_3, and C_7H_8. (c) Dynamic response transients of CNFs, WS_2@CNFs (ATTT 0.38 g), and WS_2@CNFs (ATTT 0.7 g) toward NO_2 in the concentration range of 4-1 ppm at room temperature. (d) TEM image and HRTEM image of WS_2@CNFs (ATTT 0.7 g)

The sensing tendency of the dense CNFs and WS_2@MTCNFs toward NH_3 based on resistance might be further supported by edge effects exerted by WS_2 nanoflakes distributed on the surface. During exposure to NH_3, the resistance of the dense CNFs decreases due to the electron donating property of NH_3 molecules. According to previous studies, carbon-based gas sensors such as carbon nanotubes and graphene exhibiting n-type sensing behavior against reducing gases even though carbon nanofibers exhibit a p-type response in oxidizing gases.[1-2] In the present study, the resistance of WS_2-edge functionalized CNFs (WS_2@MTCNFs) is increased with no recovery when NH_3 gas was injected, which is identical in sensing tendency toward NH_3 of layered MoS_2.[3-4]

S7. Ex-situ XPS analysis in dry condition

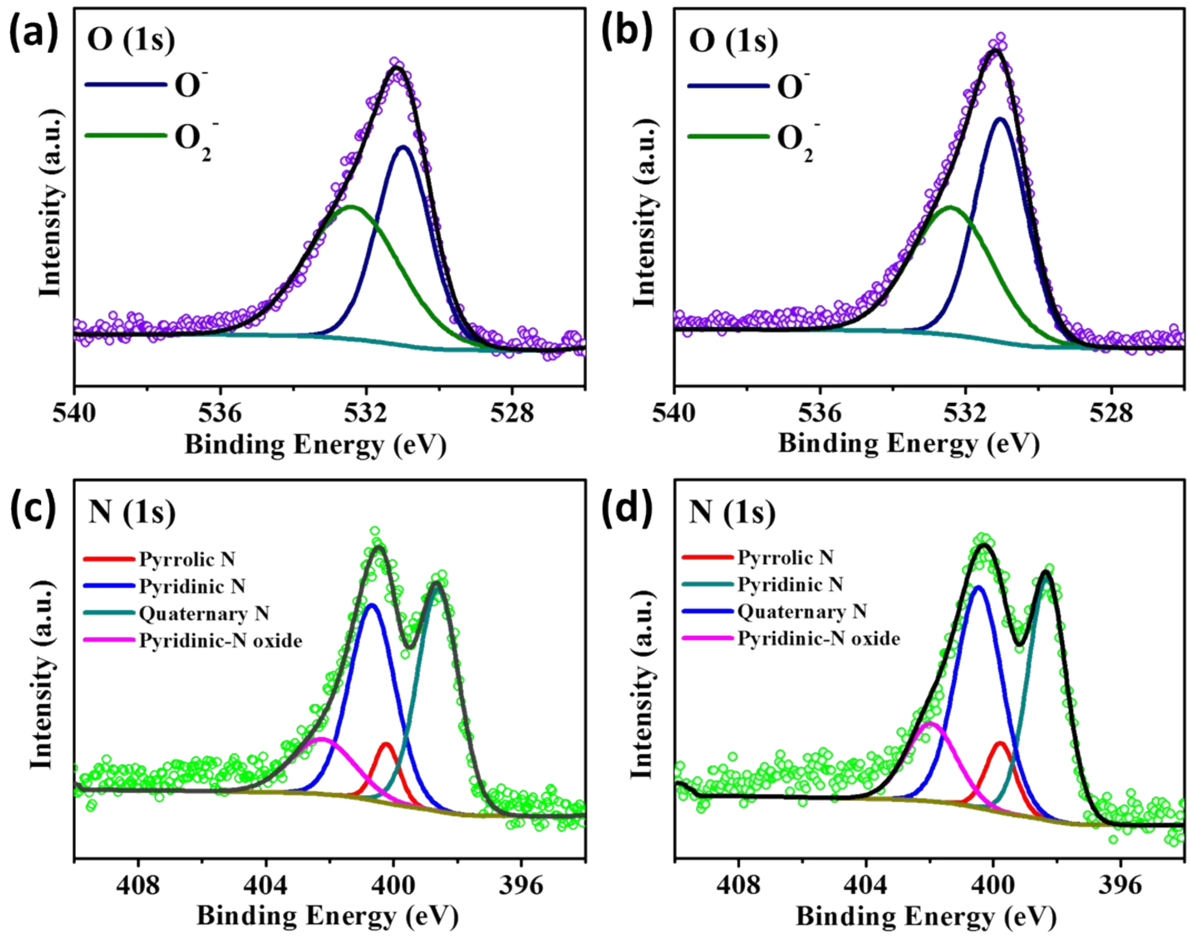

Figure S7. Ex-situ XPS analysis with WS_2@MTCNFs: O 1s spectra (a) before and (b) after exposure to NO_2 in dry air. N 1s spectra (c) before and (d) after exposure to NO_2 in dry air.

S8. Temperature dependency of sensing characteristics of WS_2@MTCNFs

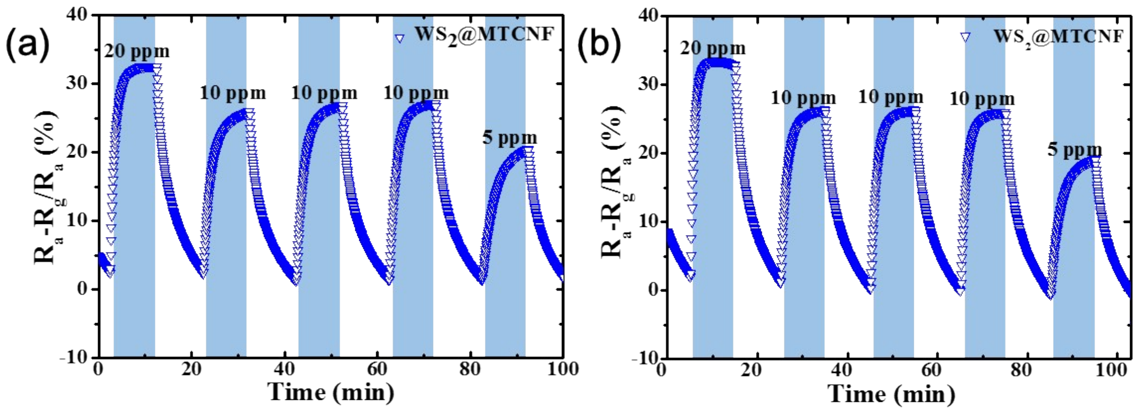

Figure S8. Dynamic response transients of WS_2@MTCNFs toward NO_2 in the concentration rage of 20-5 ppm at (a) 25 °C and (b) 80 °C.

For analysis regarding temperature dependency of the sensing materials, the sensing performance of WS_2@MTNCFs was characterized at 80 °C in the concentrations of 20, 10, and 5 ppm. As a result, any enhancement in response of the WS_2@MTNCFs was not observed, showing that the sensing material are not affected much by temperature.

S9. SEM images

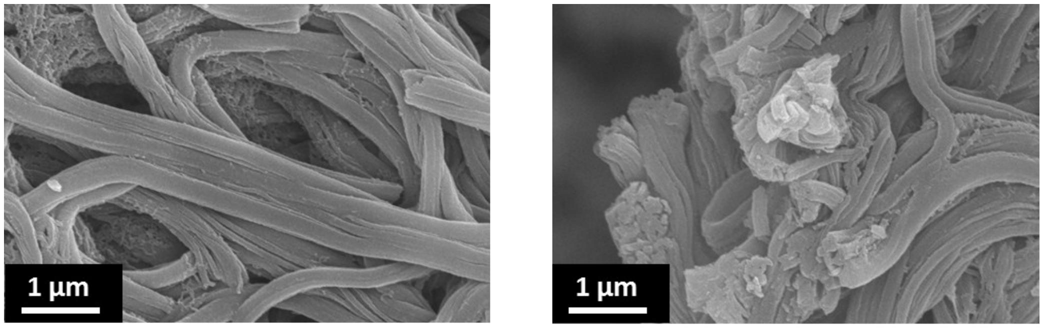

Figure S9. SEM images of CNFs obtained from combination of PAN and SAN without ATTT, followed by heat treatment. It shows that the morphology of synthesized products is much different from that of WS_2@MTCNFs.

S10. Comparison with other WS_2 gas sensors

Table S1. Recent publications on a variety of WS_2 based gas sensors.

Gas species	Materials	Working temperature	Balance gas	Measurement	Response	Exposure time	Detection limit	reference
Various gases	Multilayer WS_2 nanoflakes	Room temp.	Dry	Source drain current	–	~25 s	–	5
Humidity	WS_2 Nanoparticles	Room temp.	Air	Current	–	~200 s	–	6
Methanol	Metallic 1T WS_2	Room temp.	Humid air	Impedance	–	–	–	7
H_2	WS_2-Pd composite film	Room temp.	Dry N_2	Resistance	380% at 1000 ppm	30 min	10 ppm	8
NH_3	2nm-WS_2 film	Room temp.	Dry N_2	Resistance	0.2% at 60 ppm	2 min	1.2 ppm	9
NH_3	Fluorinated 1L WS_2	Room temp.	Dry air	PL intensity	–	2 min	–	10
NO_2	Ag-NW@WS_2 nanosheets	100 °C	Dry air	Current	60% at 25 ppm	5 min	–	11
NO_2	WS_2@MTCNFs	Room temp.	Dry air	Resistance	15% at 1 ppm	20 min	10 ppb	This work

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S11. Comparison with other TMD gas sensors for NO_2 sensing

Table S2. Recent publications on TMD based gas sensors toward NO_2 sensing.

Gas species	Materials	Working temperature	Balance gas	Measurement	Response	Exposure time	Detection limit	reference
NO_2	Thin-layered MoS_2	Room temp.	Dry N_2	Source drain current	1372% at 1000 ppm	~300 s	–	3
	Atomic-layer MoS_2	Room temp.	Dry air	Resistance	27% at 20 ppm	2 min	–	4
	CVD Atomic-layer MoS_2	Room temp.	Dry N_2	Resistance	150% at 1200 ppb	5 min	120 ppb	12
	Graphene/MoS_2	100 °C	Dry N_2	Resistance	3% at 1.2 ppm	5 min	–	13
	Graphene/MoS_2	150 °C	Dry air	Resistance	3% at 5 ppm	5 min	–	14
	MoS_2/SnO_2	Room temp.	Dry air	Conductance	0.6% at 0.5 ppm	~750 s	0.5 ppm	15
	Exfoliated MoS_2 flakes	200 °C	Dry air	Resistance	1.6 at 1 ppm	120 min	20 ppb	16
	Vertically aligned MoS_2	Room temp.	Dry N_2	Resistance	4% at 100 ppm	10 min	–	17
	MoS_2/Graphene hybrid aerogel	200 °C	Dry N_2	Resistance	9% at 0.5 ppm	10 min	14 ppb	18
	Ag-NW@WS_2 nanosheets	100 °C	Dry air	Current	60% at 25 ppm	5 min	–	11
	WS_2@MTCNFs	Room temp.	Dry air	Resistance	15% at 1 ppm	20 min	10 ppb	This work

Note and References

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