Electronic Supplementary Material (ESI) for Materials Advances.

Supporting Information: Mixed-dimensional organic-inorganic metal halide perovskites (OIMHP) based gas sensors with superior stability for NO_2 detection

The Duong[a,†,*], Alishba T. John[b,†], Hongjun Chen[c,*], Huyen Pham[d], Krishnan Murugappan[b], Thanh Tran-Phu[b,e], Antonio Tricoli[b,e], Kylie Catchpole[a]

[a]School of Engineering, The Australian National University, Canberra 2601, Australia

[b]Nanotechnology Research Laboratory, Research School of Chemistry, College of Science, The Australian National University, Canberra 2601, Australia

[c]The University of Sydney Nano Institute (Sydney Nano) and School of Physics, University of Sydney, Sydney 2006, Australia

[d]Department of Electronic Materials Engineering, Research School of Physics, The Australian National University, Canberra 2601, Australia

[e]Nanotechnology Research Laboratory, School of Biomedical Engineering, Faculty of Engineering, the University of Sydney, Sydney 2006, Australia

[†]These authors contribute equally.

[*]**Corresponding Authors**: the.duong@anu.edu.au; hongjun.chen@sydney.edu.au

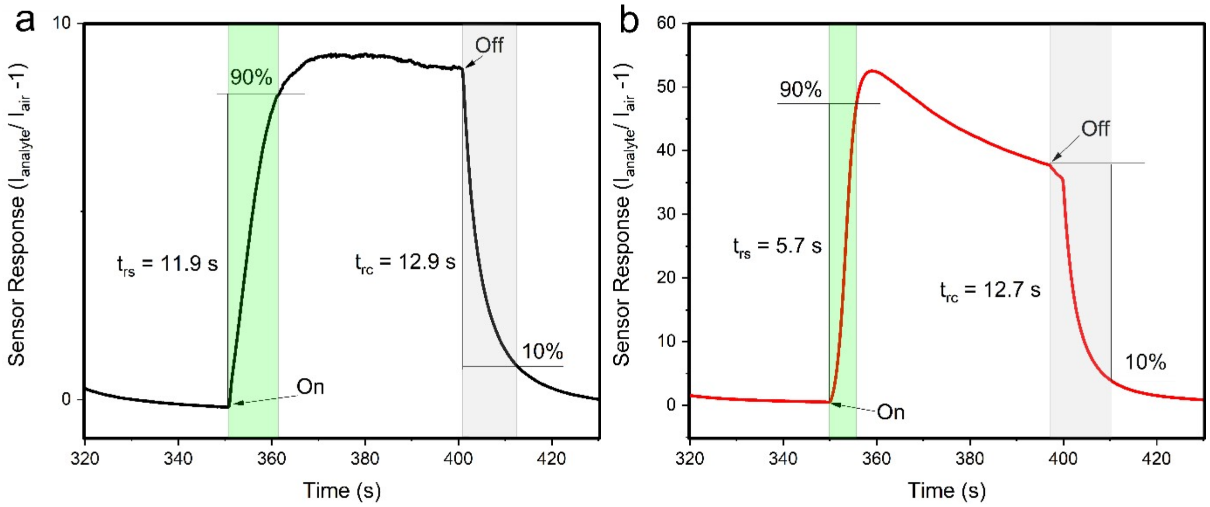


Figure S1. Response and recovery time of **a** – 3D and **b** – 2D/3D perovskite gas sensors for the detection of 8 ppm of NO_2 gas.

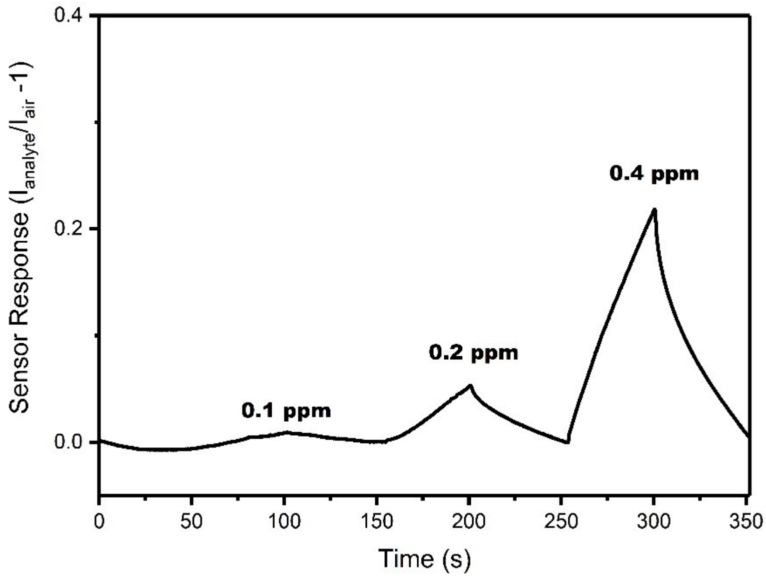


Figure S2. Gas sensing characterization of the 2D/3D perovskite sensor to sub-ppm NO_2 concentrations.

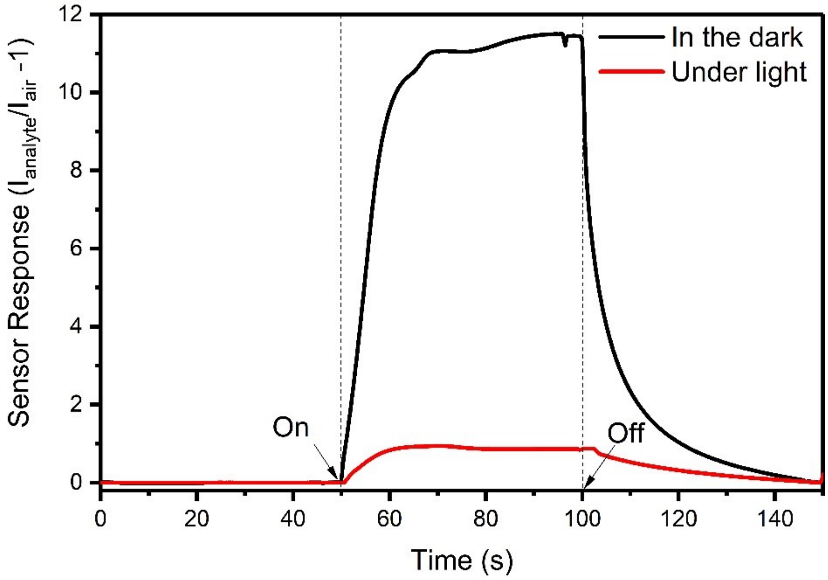


Figure S3. Comparison of the performance of the 3D perovskite-based sensor to 8 ppm NO_2 when operating in the dark and under light with an applied bias of 1 V.

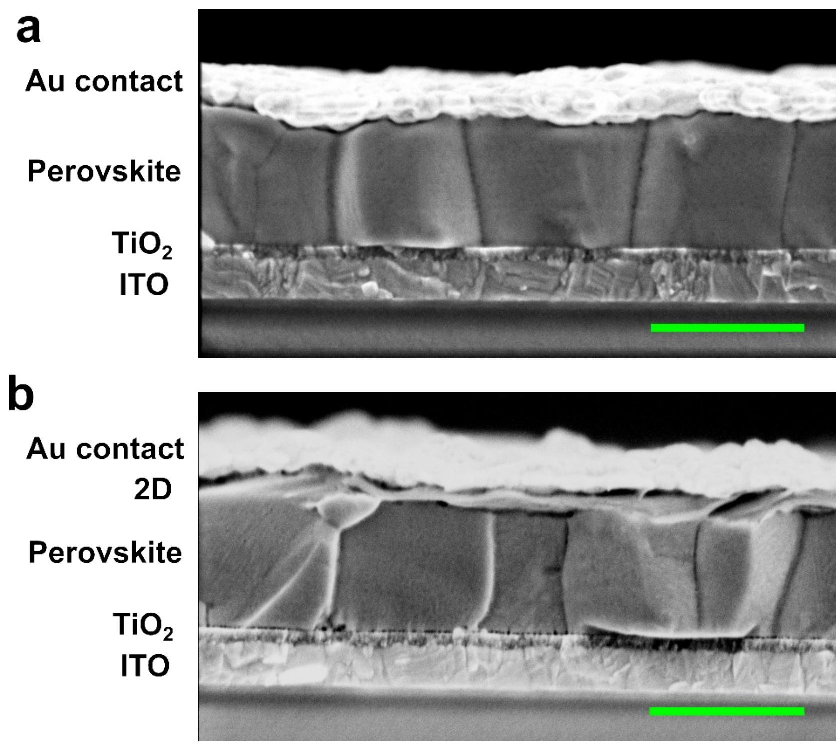


Figure S4. Cross-sectional SEM images of perovskite sensor devices **a** – 3D device, **b** – 2D/3D perovskite device with 10.0 mg/ml of the passivation precursor. The scale bar is 500 nm.

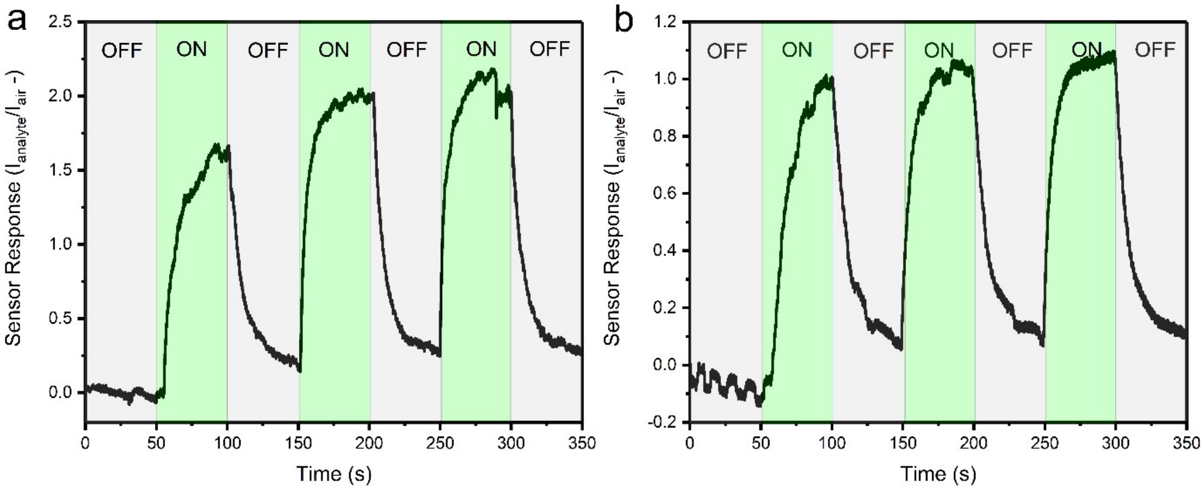


Figure S5. Sessor response of 2D/3D perovskite with different concentrations of the passivation solution for consecutive detection of 8 ppm of NO_2 gas **a** – 5.0 mg/ml and **b** – 10.0 mg/ml.

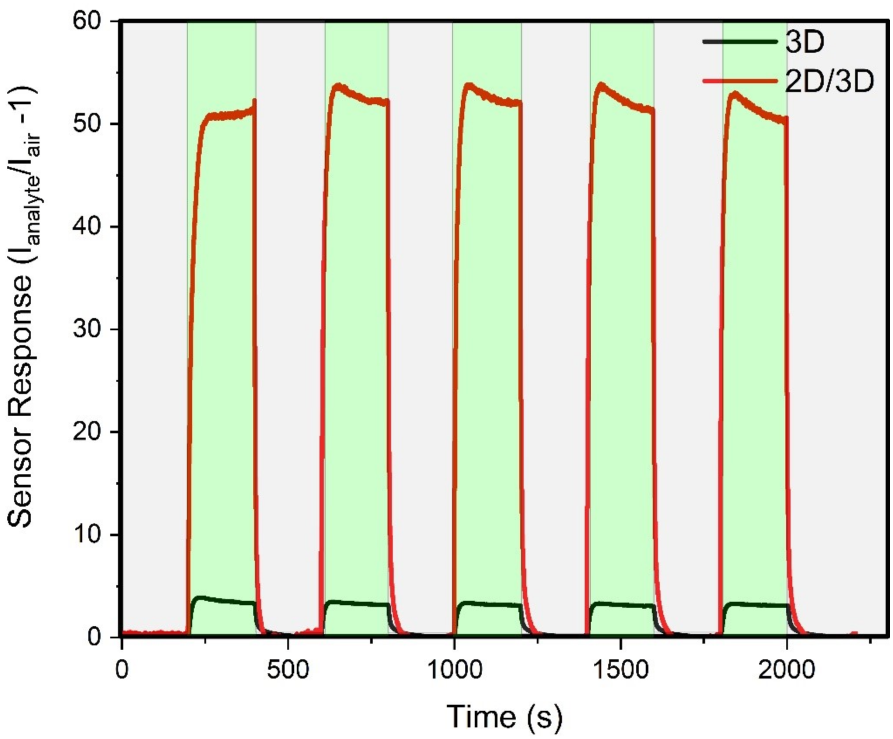


Figure S6. Short-term operation of 3D and 2D/3D perovskite sensors in a 40% RH environment for the consecutive detection of 8 ppm of NO_2 gas.

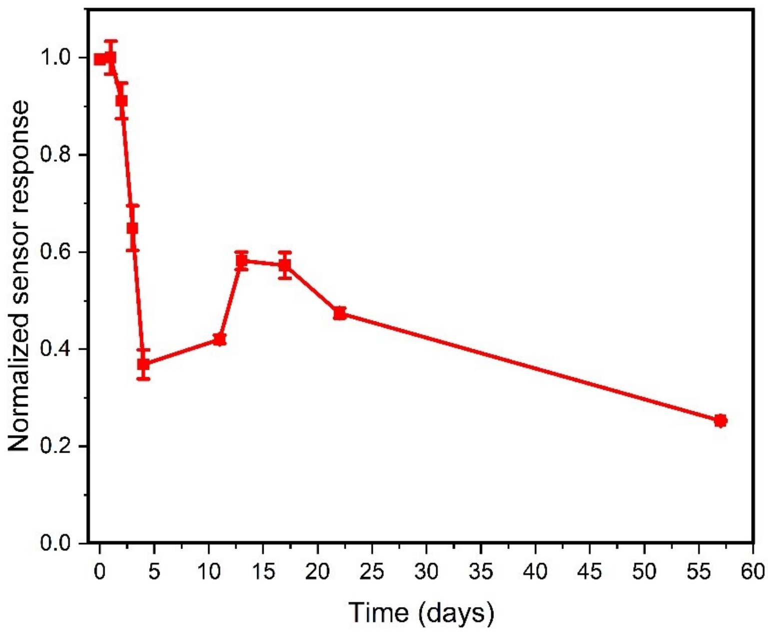


Figure S7. Normalized sensor response of the 2D/3D perovskite sensor device with ambient stability over almost 2 months.

Table S1. Summary of recent reports on state-of-the-art room-temperature operating metal oxide - based NO_2 gas sensors and comparison with this work.

Materials	Required activation	Sensor response $\left(\frac{I_{analyte}}{I_{air}} - 1\right)$ (NO_2 concentration)	Limit of Detection (LOD)	Response / Recovery Time	Reference, year
Mixed 2D/3D perovskite	No	45.2 (8 ppm)	0.2 ppm	5.7 s / 12.7 s	This work
SnO2-boron nitride nanotubes	No	119.6 (250 ppm)	250 ppb	51 s/ 42 s	[1], 2021
CuO/rGO	No	~4 (5 ppm)	50 ppb	6.8 s / not mentioned	[2], 2021
MoS2/ZnO	Light	0.91 (5 ppb)	0.2 ppb*	Not mentioned	[3], 2021
ZnO/TiO_2/Au nps	Light	7.5 (50 ppm)	Not mentioned	43 s / 50 s	[4], 2021

Fe_2O_3 NRs/rGO	No	23.8 (5 ppm)	1 ppm	15 s / not mentioned	[5], 2021
macro-/mesoporous ZnO	Light	13.1 (400 ppb)	0.2 ppb	19 s / 32 s	[6], 2020
ZnO/TiO_2	Light	1.05 (5 ppm)	Not mentioned	26 s / 224 s	[7], 2020
SnO_2@SnS_2 nano structures	Light	4 – 6.5 (0.2 ppm)	Not mentioned	950 s / 1160 s	[8], 2020
ZnO/polypeptides	Light	4 – 13 (25 ppm)	Not mentioned	11 – 19 s / 25 – 31 s	[9], 2020
ZnO nanoparticles	Light	0.2 (25 ppb)	1 ppb*	>5 minutes / not mentioned	[10], 2019
rGO/CO_3O_4	No	0.268 (5 ppm)	0.05 ppm*	1.5 minutes / 40 minutes	[11], 2018
CuO/rGO	No	14 (1 ppm)	60 ppb	66 s / 34 s	[12], 2018
rGO/ZnO	No	0.484 (40 ppm)	Not mentioned	Not mentioned	[13], 2018
CuO platelets	No	5737.7 (40 ppm)	Not mentioned	34 s / not mentioned	[14], 2018
CuO-ZnO/rGO	No	0.629 (40 ppm)	Not mentioned	40 s / not mentioned	[15], 2018

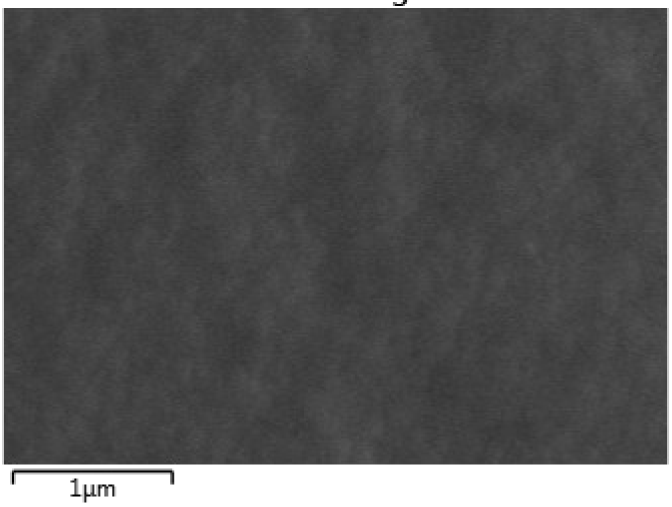
* theoretical calculation based on signal to noise ratio.

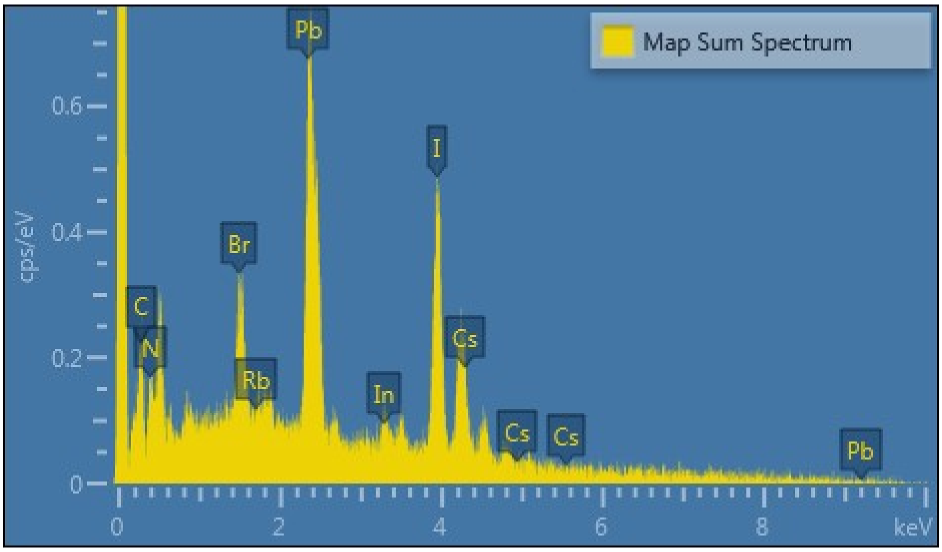
Note S1. Energy dispersive X-ray spectroscopy (EDS) measurements and analysis of 3D and 2D/3D perovskite films.

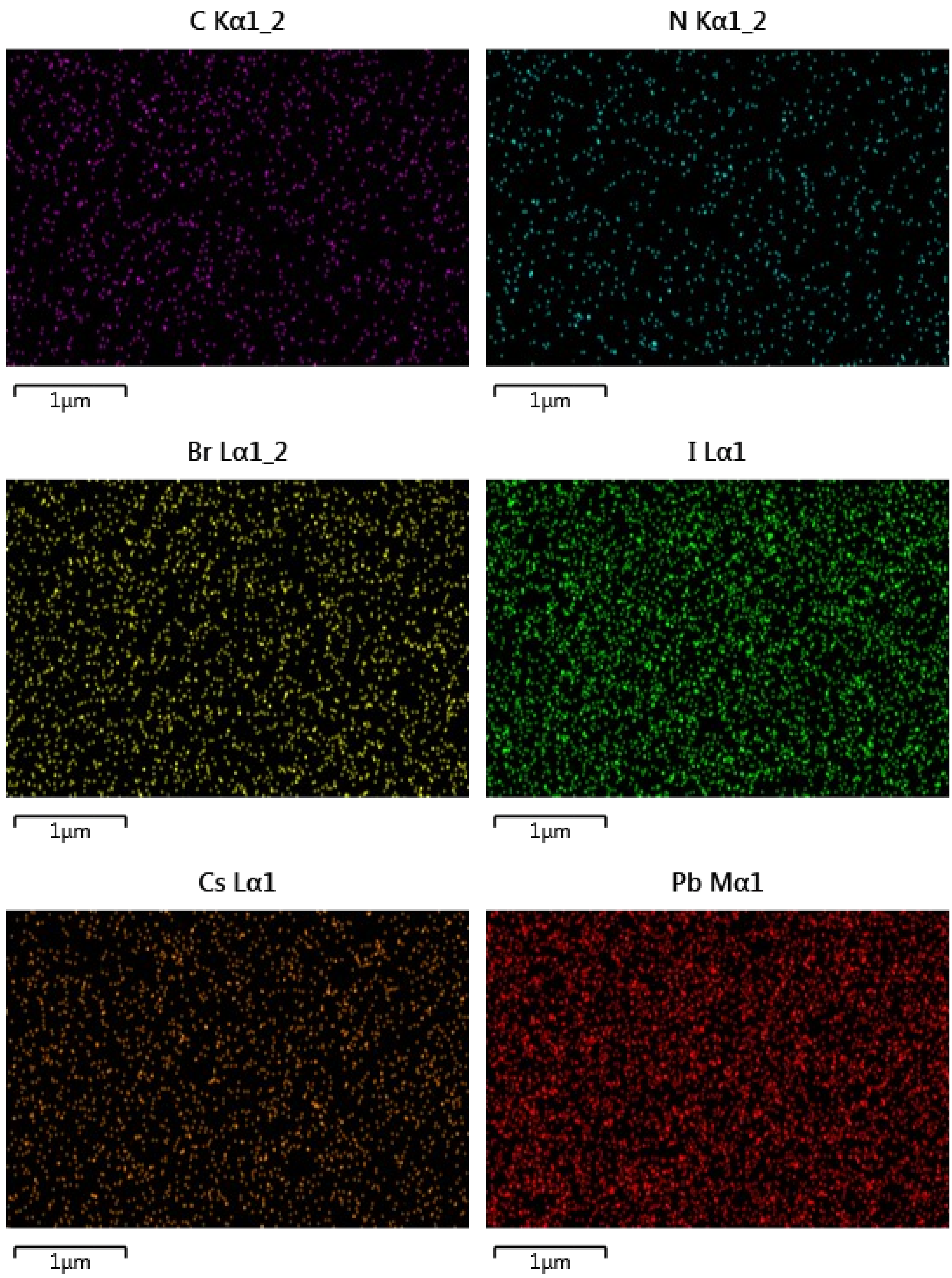
Element	3D perovskite Atomic %	2D/3D perovskite Atomic %
C	23.82	26.81
N	18.89	19.54
Br	3.98	3.78
In	2.80	3.43
I	34.18	32.72
Cs	1.65	0.56
Pb	14.33	13.16
Total:	100.00	100.00

3D perovskite

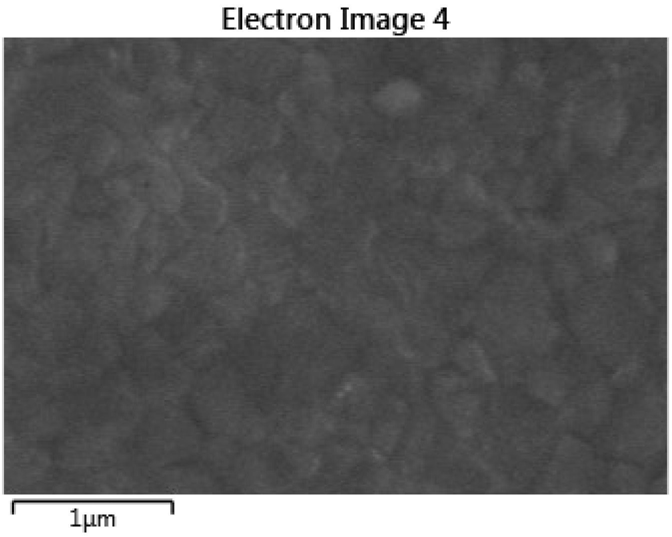
Electron Image 3

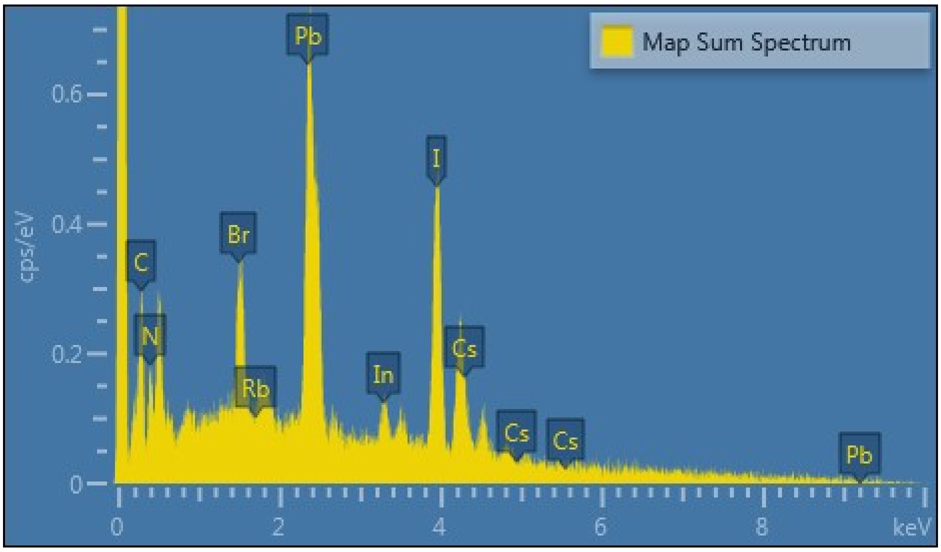


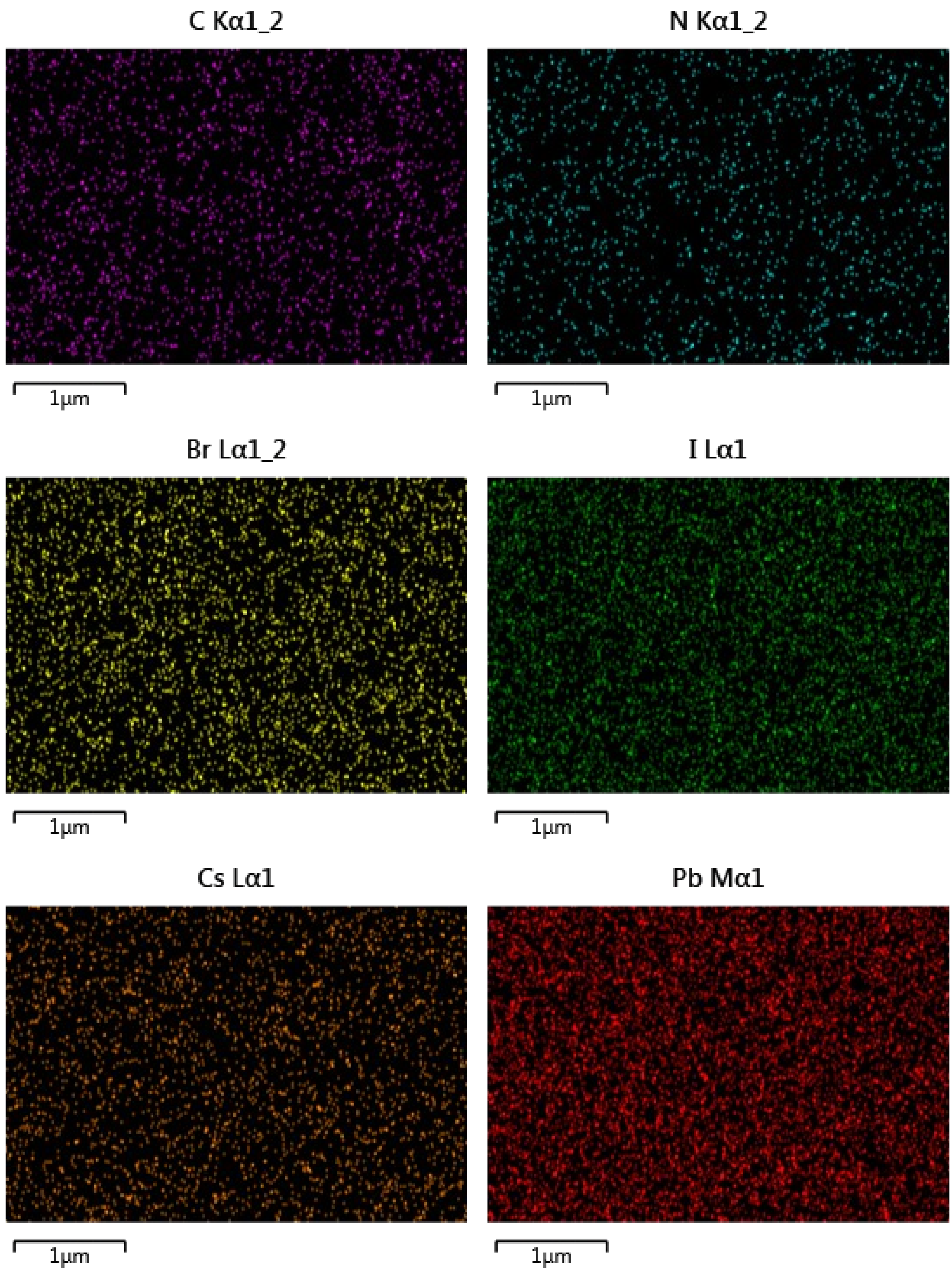




2D/3D perovskite (5.0 mg/ml)


Electron Image 4
1μm


Map Sum Spectrum
cps/eV
0.6
0.4
0.2
0
0
2
4
6
8
keV
C
N
Br
Rb
Pb
In
I
Cs
Cs
Cs
Pb



References

1. Sharma, B.; Sharma, A.; Myung, J.-h., Selective ppb-level NO2 gas sensor based on SnO2-boron nitride nanotubes. *Sensors and Actuators B: Chemical* **2021,** *331*, 129464.
2. Bai, H.; Guo, H.; Wang, J.; Dong, Y.; Liu, B.; Xie, Z.; Guo, F.; Chen, D.; Zhang, R.; Zheng, Y., A room-temperature NO2 gas sensor based on CuO nanoflakes modified with rGO nanosheets. *Sensors and Actuators B: Chemical* **2021,** *337*, 129783.
3. Kumar, R. R.; Murugesan, T.; Dash, A.; Hsu, C.-H.; Gupta, S.; Manikandan, A.; Anbalagan, A. k.; Lee, C.-H.; Tai, N.-H.; Chueh, Y.-L.; Lin, H.-N., Ultrasensitive and light-activated NO2 gas sensor based on networked MoS2/ZnO nanohybrid with adsorption/desorption kinetics study. *Appl. Surf. Sci.* **2021,** *536*, 147933.
4. Kwon, S.-H.; Kim, T.-H.; Kim, S.-M.; Oh, S.; Kim, K.-K., Ultraviolet light-emitting diode-assisted highly sensitive room temperature NO2 gas sensors based on low-temperature solution-processed ZnO/TiO2 nanorods decorated with plasmonic Au nanoparticles. *Nanoscale* **2021,** *13* (28), 12177-12184.
5. Tang, X.; Tian, C.; Zou, C., Highly sensitive and selective room-temperature NO2 gas sensor based on novel Fe2O3 nanorings/reduced graphene oxide heterojunction nanocomposites. *Optik* **2021,** *241*, 166951.
6. Xia, Y.; Zhou, L.; Yang, J.; Du, P.; Xu, L.; Wang, J., Highly Sensitive and Fast Optoelectronic Room-Temperature NO2 Gas Sensor Based on ZnO Nanorod-Assembled Macro-/Mesoporous Film. *ACS Applied Electronic Materials* **2020,** *2* (2), 580-589.
7. Choi, H.-J.; Kwon, S.-H.; Lee, W.-S.; Im, K.-G.; Kim, T.-H.; Noh, B.-R.; Park, S.; Oh, S.; Kim, K.-K., Ultraviolet Photoactivated Room Temperature NO2 Gas Sensor of ZnO Hemitubes and Nanotubes Covered with TiO2 Nanoparticles. **2020,** *10* (3), 462.
8. Liu, D.; Tang, Z.; Zhang, Z., Visible light assisted room-temperature NO2 gas sensor based on hollow SnO2@SnS2 nanostructures. *Sensors and Actuators B: Chemical* **2020,** *324*, 128754.
9. Feng, C.; Wen, F.; Ying, Z.; Li, L.; Zheng, X.; Zheng, P.; Wang, G., Polypeptide-assisted hydrothermal synthesis of ZnO for room temperature NO2 gas sensor under UV illumination. *Chem. Phys. Lett.* **2020,** *754*, 137745.
10. Casals, O.; Markiewicz, N.; Fabrega, C.; Gràcia, I.; Cané, C.; Wasisto, H. S.; Waag, A.; Prades, J. D., A Parts Per Billion (ppb) Sensor for NO2 with Microwatt (μW) Power Requirements Based on Micro Light Plates. *ACS Sensors* **2019,** *4* (4), 822-826.
11. Zhang, B.; Cheng, M.; Liu, G.; Gao, Y.; Zhao, L.; Li, S.; Wang, Y.; Liu, F.; Liang, X.; Zhang, T.; Lu, G., Room temperature NO2 gas sensor based on porous Co3O4 slices/reduced graphene oxide hybrid. *Sensors and Actuators B: Chemical* **2018,** *263*, 387-399.
12. Li, Z.; Liu, Y.; Guo, D.; Guo, J.; Su, Y., Room-temperature synthesis of CuO/reduced graphene oxide nanohybrids for high-performance NO2 gas sensor. *Sensors and Actuators B: Chemical* **2018,** *271*, 306-310.
13. Jyoti; Kanaujiya, N.; Varma, G. D., Highly selective room temperature NO2 gas sensor based on rGO-ZnO composite. **2018,** *1953* (1), 030039.
14. Oosthuizen, D. N.; Motaung, D. E.; Swart, H. C., In depth study on the notable room-temperature NO2 gas sensor based on CuO nanoplatelets prepared by sonochemical method: Comparison of various bases. *Sensors and Actuators B: Chemical* **2018,** *266*, 761-772.
15. Jyoti; Varma, G. D., Synthesis of CuO-ZnO/rGO ternary composites for superior NO2 gas sensor at room temperature. *Materials Research Express* **2018,** *6* (3), 035011.