Supporting Information

Electrically conductive aluminum ion-reinforced MXene films for efficient electromagnetic interference shielding

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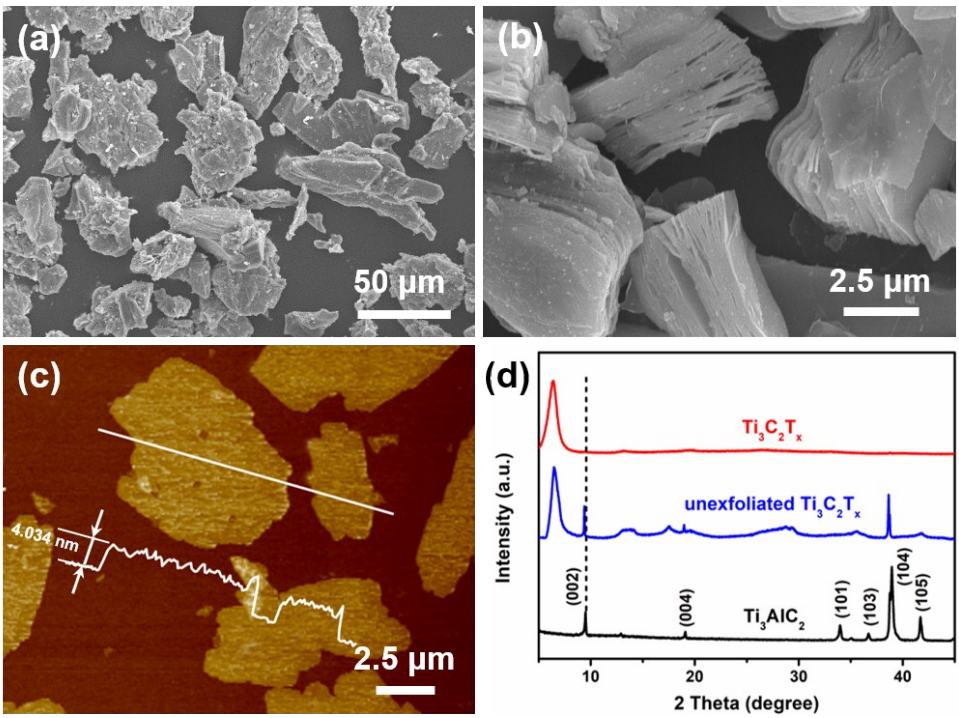

Fig. S1. SEM images of (a) Ti_3AlC_2 and (b) unexfoliated $Ti_3C_2T_x$. (c) AFM image of $Ti_3C_2T_x$ sheets deposited on a silicon wafer. (d) XRD patterns of Ti_3AlC_2, unexfoliated $Ti_3C_2T_x$ and $Ti_3C_2T_x$.

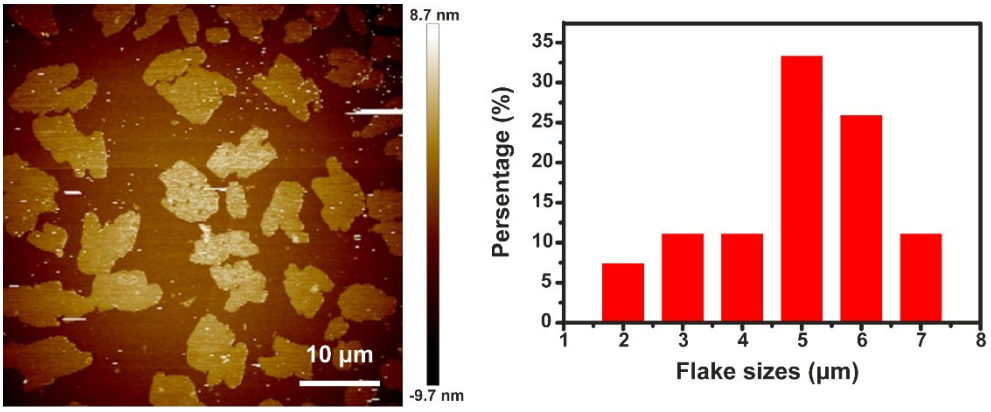

Fig. S2. AFM image and size distribution of MXene sheets.

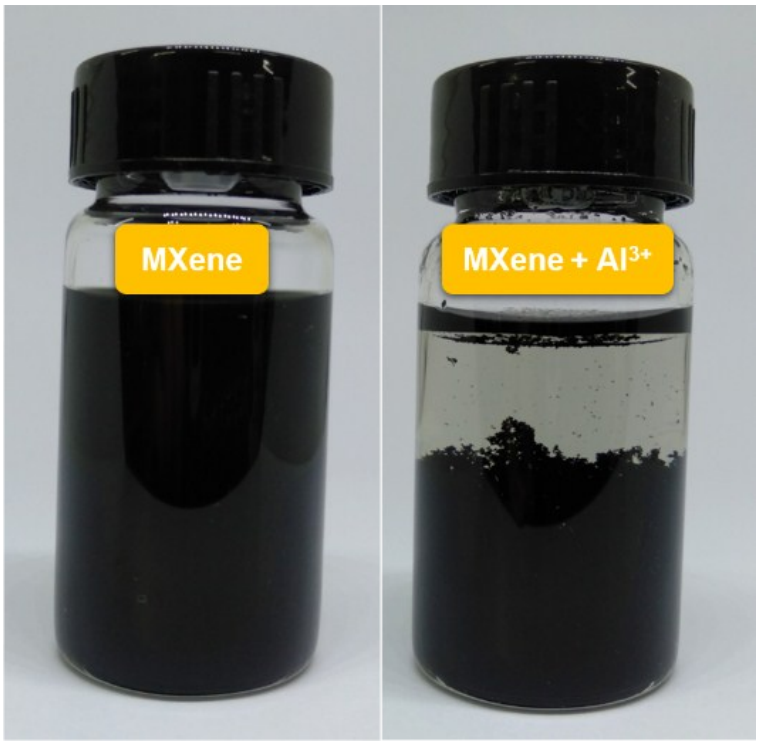

Fig. S3. Digital images of an aqueous mixture of MXene (left) and a suspension of MXene with Al^{3+} (right).

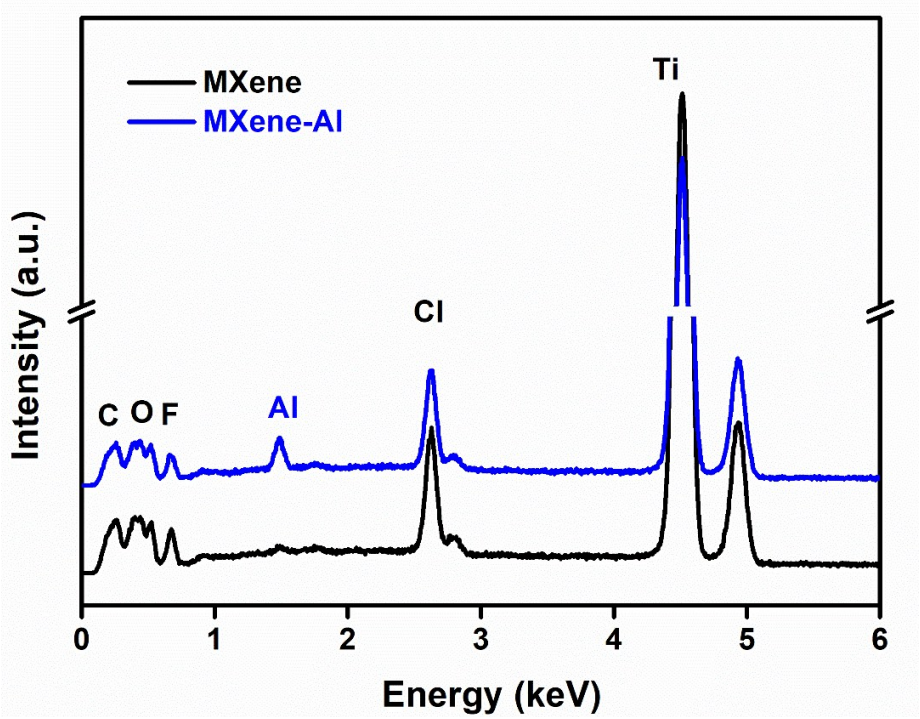

Fig. S4. EDS spectra of MXene and MXene-Al films.

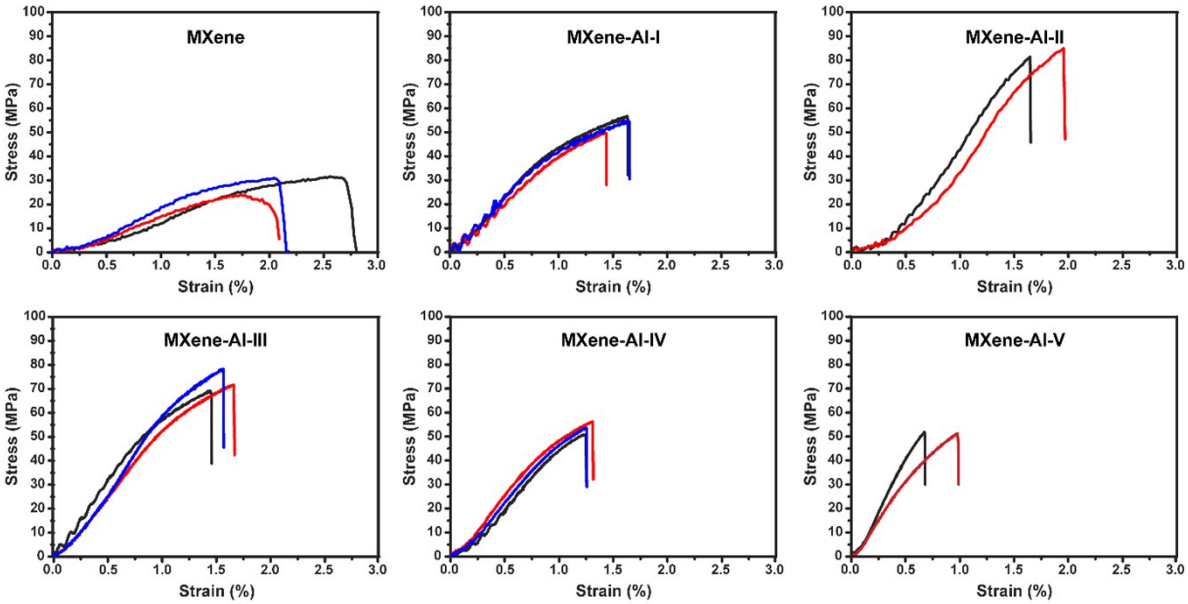

Fig. S5. Tensile stress-strain curves of pristine MXene film, and MXene-Al films.

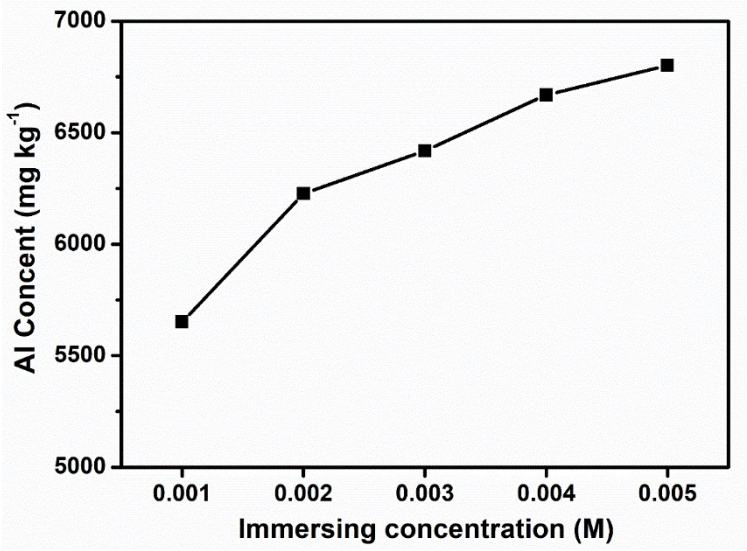

Fig. S6. The concentrations of Al in MXene-Al film.

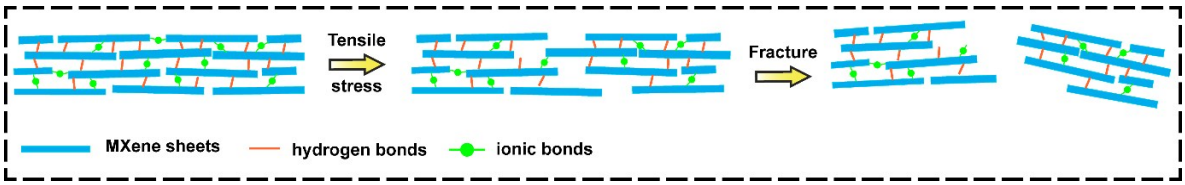

Fig. S7. Schematic illustrating tensile fracture process of the MXene-Al film.

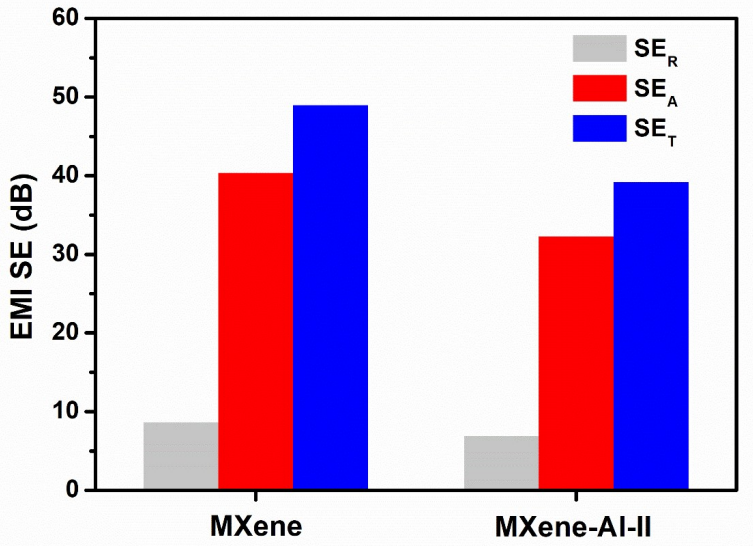

Fig. S8. Total EMI shielding effectiveness (SE_T), absorption (SE_A) and reflection (SE_R) mechanism in pristine MXene and MXene-Al-Ⅱ film.

The total SE (SE_{Total}) and its components of absorption (SE_A) and reflection (SE_R) are determined on the basis of the measured S parameters:

$$R = 10^{(S_{11}/10)} \quad (1)$$

$$T = 10^{(S_{21}/10)} \quad (2)$$

$$A = 1 - R - T \quad (3)$$

Where R is the reflection coefficient, A is the absorption coefficient, and T is the transmission coefficient. The total EMI SE (SE_{Total}) is the sum of reflection (SE_R), absorption (SE_A), and multiple reflections (SE_M), and their relationships are expressed using the following equations:

$$SE_{Total} = SE_R + SE_A + SE_M \quad (4)$$

$$SE_R\,(\mathrm{dB}) = -10\log_{10}(1 - R) \quad (5)$$

$$SE_A\,(\mathrm{dB}) = -10\log_{10}(T/(1 - R)) \quad (6)$$

Table S1. Mechanical properties and conductivities of MXene and MXene-Al films.

Sample	Strength (MPa)	Toughness (MJ m^{-3})	Strain (%)	Young's modulus (GPa)	Conductivity (S cm^{-1})
MXene	28.7 ± 4.3	0.332 ± 0.045	2.2 ± 0.3	2.05 ± 0.12	3143 ± 68
MXene-Al Ⅰ	53.8 ± 2.9	0.496 ± 0.068	1.6 ±0.1	4.50 ± 0.26	2733 ± 37
MXene-Al Ⅱ	83.2± 1.7	0.657 ± 0.076	1.8 ± 0.2	7.42 ± 0.12	2656 ± 48
MXene-Al Ⅲ	73.1± 3.9	0.645 ± 0.033	1.6 ± 0.1	6.24 ±0.16	2059 ± 51
MXene-Al Ⅳ	53.6± 2.3	0.363 ±0.038	1.3 ± 0.0	5.74 ± 0.08	1018 ± 14
MXene-Al Ⅴ	51.7± 0.3	0.230 ± 0.051	0.8 ± 0.2	7.64 ± 1.40	926 ± 40

Table S2. Comparison of EMI shielding performances of the MXene-Al films with those reported in the literature.

Sample	Thickness (mm)	EMI SE (dB)	SE/t (dB cm^{-1})	Strength (MPa)	Conductivity (S m^{-1})	Refs.
CNT sponge/epoxy	2	33	165	79.2	516	1
m-G/IP porous film	0.3	38	1267	1.448	2310	2
Magnetic CNT paper	0.078	37	4744	30	4330	3
rLGO film	0.015	20.2	13467	77.7	24300	4
CNT/NR30 film	0.5	44.7	894	20.6	2243	5
GNs/NFC film	0.013	43	33077	61	98820	6
GNR/PANI	3.4	34	100	56.2	-	7
EG/LGE	0.043	48.3	11233	40.9	146700	8
rGO/PI foam	0.8	21	263	11.4	0.8	9
AgNW/PANI	0.013	51	39231	44	402000	10
$Ti_3C_2T_x$ foam	0.06	70	11667	4	58000	11
87.5wt% $Ti_3C_2T_x$ /PEDOT:PSS	0.011	42.1	38273	13.7	34050	
83.3wt% $Ti_3C_2T_x$ /PEDOT:PSS	0.012	28.2	23500	17.59	18320	12
80wt% $Ti_3C_2T_x$ /PEDOT:PSS	0.013	21.6	16615	24.16	8330	
90wt% d-$Ti_3C_2T_x$/CNFs	0.047	24	5106	44.2	739.4	
80wt% d-$Ti_3C_2T_x$/CNFs	0.074	26	3514	60.2	115.5	13
50wt% d-$Ti_3C_2T_x$/CNFs	0.167	25	1497	135.4	13.44	
MXene/TOCNF	0.038	39.6	10421	212	2837	14
MXene/CNF/silver	0.046	50.7	11022	32.1	588.2	15
CNTs/Ti_3C_2/CNFs	0.038	38.4	10105	97.9	2506.6	16
90wt% d-$Ti_3C_2T_x$/ANFs	0.015	32.84	21893	33.07	62827.2	
50wt% d-$Ti_3C_2T_x$/ANFs	0.020	23.97	11985	83.92	6960.6	17
20wt% d-$Ti_3C_2T_x$/ANFs	0.023	12.74	5539	158.53	981.3	
MXene	0.005	49	98000	28.7	314300	This work
MXene-Al Ⅱ	0.005	45	90000	83.2	265600	
MXene-Al Ⅴ	0.0044	41	93182	69.2	92600	

References:

1. Y. Chen, H.-B. Zhang, Y. Yang, M. Wang, A. Cao and Z.-Z. Yu, *Adv. Funct. Mater.*, 2016, **26**, 447-455.

2. J. Liu, H.-B. Zhang, Y. Liu, Q. Wang, Z. Liu, Y.-W. Mai and Z.-Z. Yu, *Compos. Sci.*

Technol., 2017, **151**, 71-78.

3. G.-H. Lim, S. Woo, H. Lee, K.-S. Moon, H. Sohn, S.-E. Lee and B. Lim, *ACS Appl. Mater. Interfaces*, 2017, **9**, 40628-40637.
4. P. Kumar, F. Shahzad, S. Yu, S. M. Hong, Y.-H. Kim and C. M. Koo, *Carbon*, 2015, **94**, 494-500.
5. L.-C. Jia, M.-Z. Li, D.-X. Yan, C.-H. Cui, H.-Y. Wu and Z.-M. Li, *J. Mater. Chem. C*, 2017, **5**, 8944-8951.
6. W. Yang, Y. Zhang, T. Liu, R. Huang, S. Chai, F. Chen and Q. Fu, *ACS Sustainable Chem. Eng.*, 2017, **5**, 9102-9113.
7. A. Joshi, A. Bajaj, R. Singh, A. Anand, P. S. Alegaonkar and S. Datar, *Composites, Part B*, 2015, **69**, 472-477.
8. Y. Liu, J. Zeng, D. Han, K. Wu, B. Yu, S. Chai, F. Chen and Q. Fu, *Carbon*, 2018, **133**, 435-445.
9. Y. Li, X. Pei, B. Shen, W. Zhai, L. Zhang and W. Zheng, *RSC Adv.*, 2015, **5**, 24342-24351.
10. F. Fang, Y.-Q. Li, H.-M. Xiao, N. Hu and S.-Y. Fu, *J. Mater. Chem. C*, 2016, **4**, 4193-4203.
11. J. Liu, H.-B. Zhang, R. Sun, Y. Liu, Z. Liu, A. Zhou and Z.-Z. Yu, *Adv. Mater.*, 2017, **29**, 1702367.
12. R. Liu, M. Miao, Y. Li, J. Zhang, S. Cao and X. Feng, *ACS Appl. Mater. Interfaces*, 2018, **10**, 44787-44795.
13. W.-T. Cao, F.-F. Chen, Y.-J. Zhu, Y.-G. Zhang, Y.-Y. Jiang, M.-G. Ma and F. Chen, *ACS Nano*, 2018, **12**, 4583-4593.

14. Z. Y. Zhan, Q. C. Song, Z. H. Zhou and C. H. Lu, *J. Mater. Chem. C*, 2019, **7**, 9820-9829.

15. W. Xin, G.-Q. Xi, W.-T. Cao, C. Ma, T. Liu, M.-G. Ma and J. Bian, *RSC Adv.*, 2019, **9**, 29636-29644.

16. W. Cao, C. Ma, S. Tan, M. Ma, P. Wan and F. Chen, *Nano-Micro Lett.*, 2019, **11**, 72.

17. F. Xie, F. Jia, L. Zhuo, Z. Lu, L. Si, J. Huang, M. Zhang and Q. Ma, *Nanoscale*, 2019, **11**, 23382-23391.