Electronic Supplementary Information

Unraveling Na-ion storage performance of vertically-aligned interlayer-expanded two-dimensional MoS_2@C@MoS_2 heterostructure

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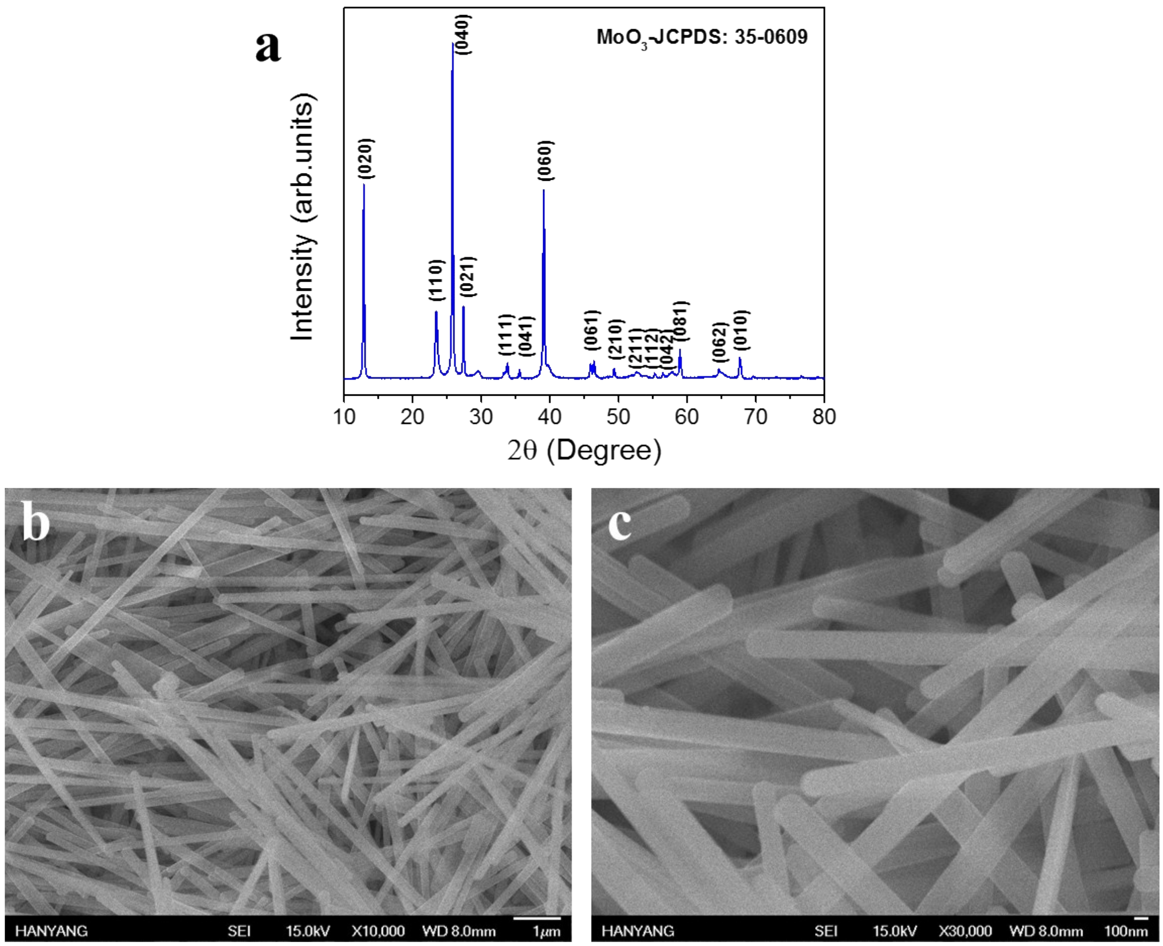

Fig. S1. (a) XRD pattern and (b, c) FE-SEM images at different magnification of MoO_3 NRs.

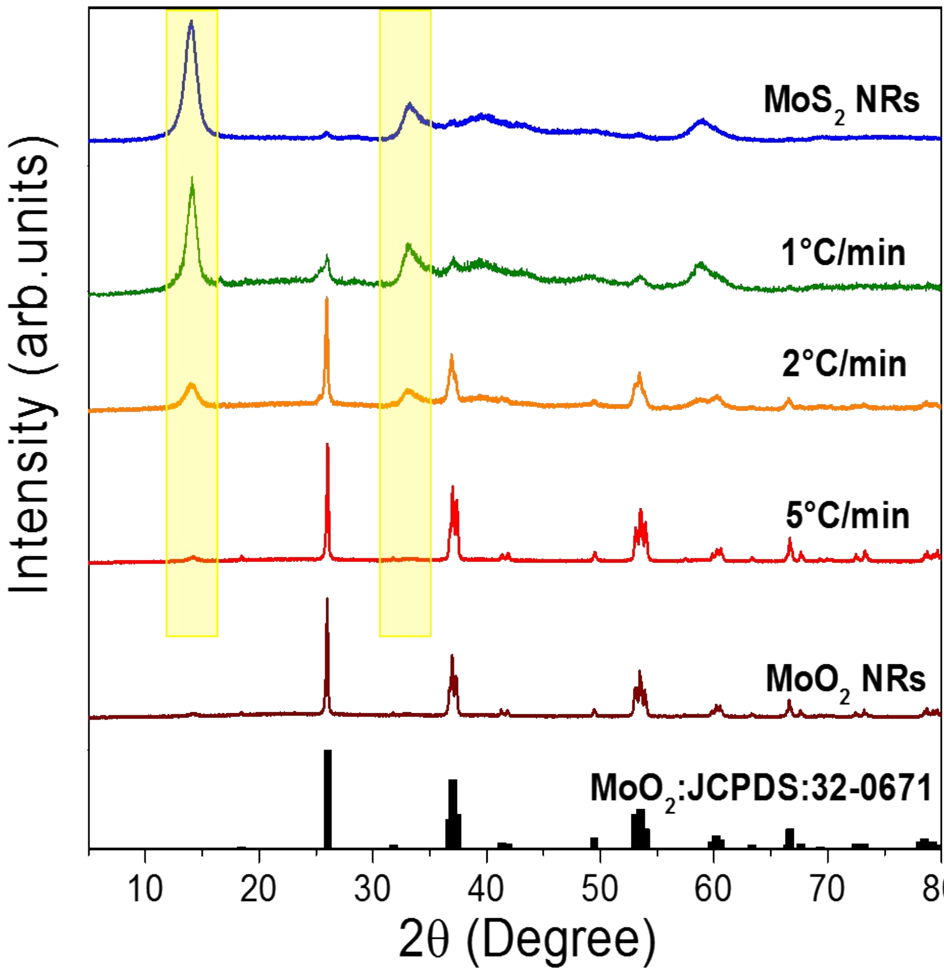

Fig. S2. XRD patterns of various raming rate tuned samples (pristine MoO_2 NRs, 5 °C min^{-1}, 2 °C min^{-1}, 1 °C min^{-1} , pristine MoS_2 NRs).

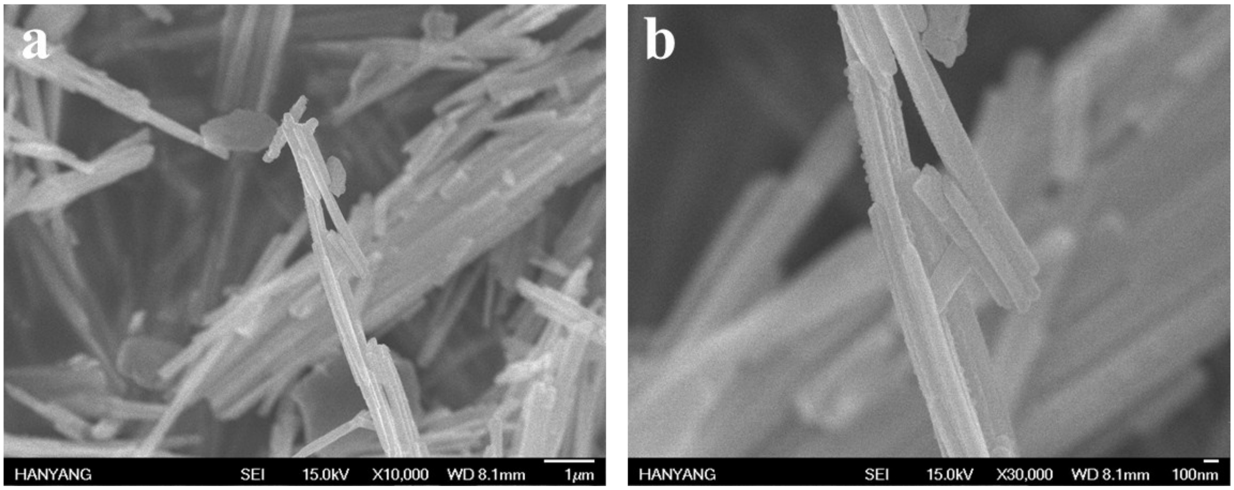

Fig. S3. (a, b) FE-SEM images of MoO_2 NRs at different magnification.

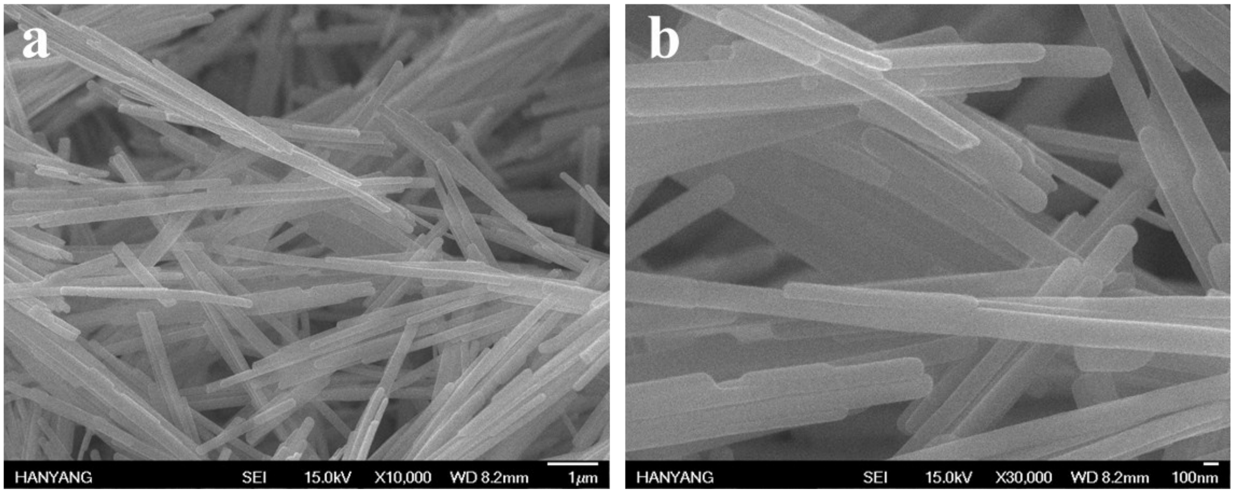

Fig. S4. (a, b) FE-SEM images at different magnification of MoS_2 NRs at ramping rate of 5 °C min^{-1}.

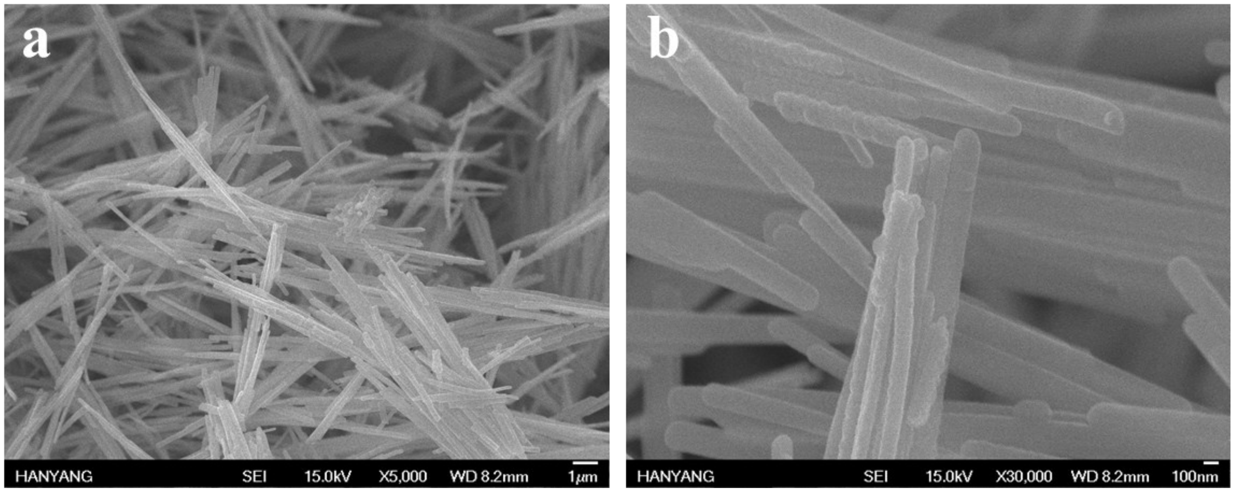

Fig. S5. (a, b) FE-SEM images at different magnification of MoS_2 NRs at ramping rate of 2 °C min^{-1}.

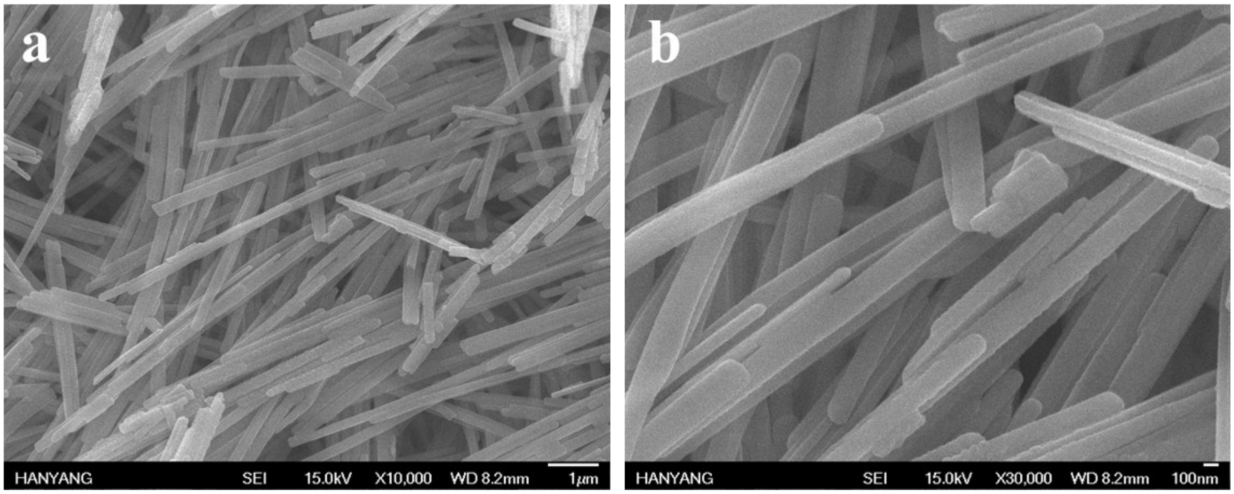

Fig. S6. (a, b) FE-SEM images at different magnification of MoS_2 NRs at ramping rate of 1 °C min^{-1} .

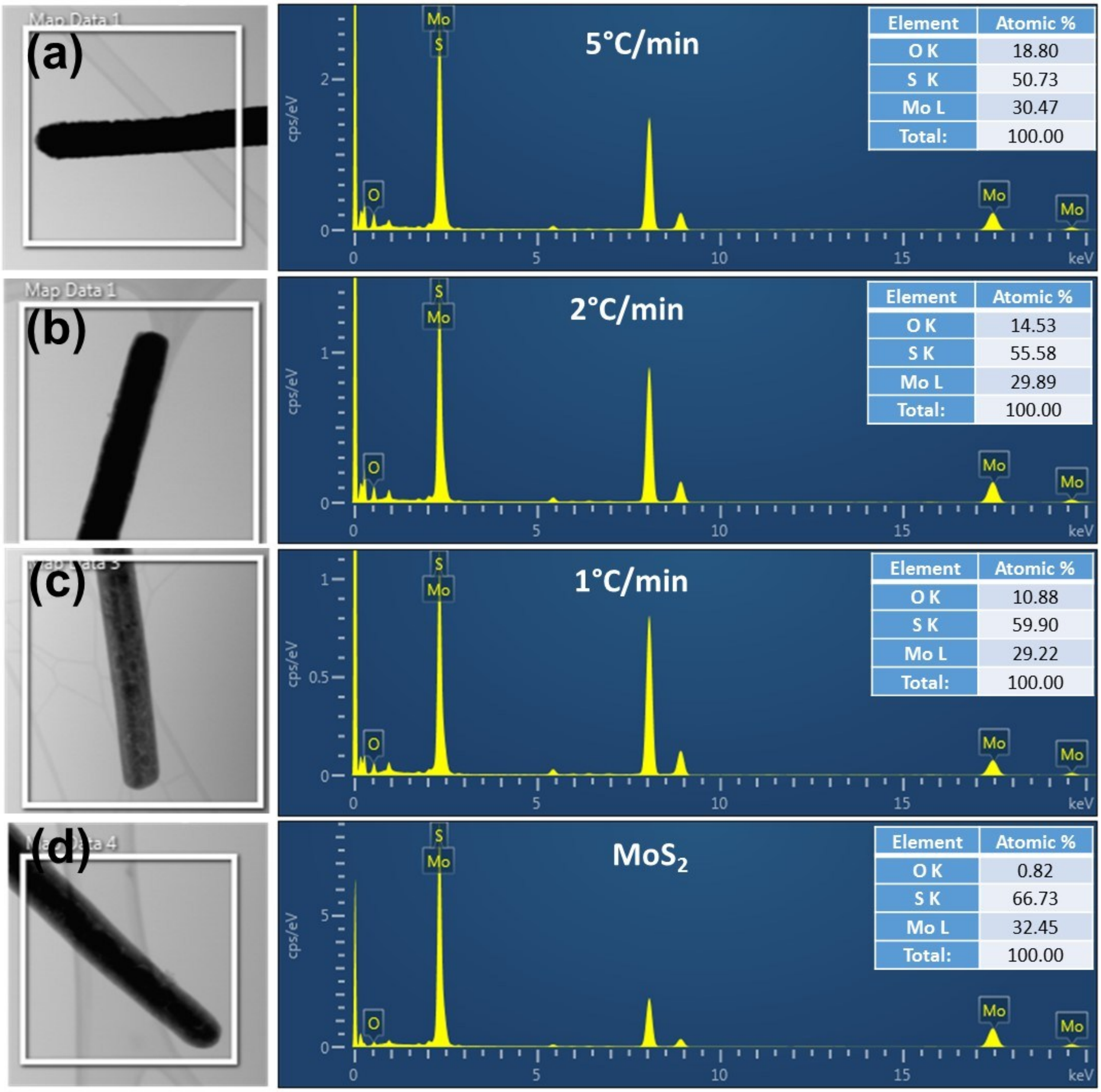

Fig. S7. EDS spectra of various sulfurized samples obtained at ramping rate of (a) 5 °C min^{-1}, (b) 2 °C min^{-1}, (c) 1 °C min^{-1} and (d) full MoS_2 NRs.

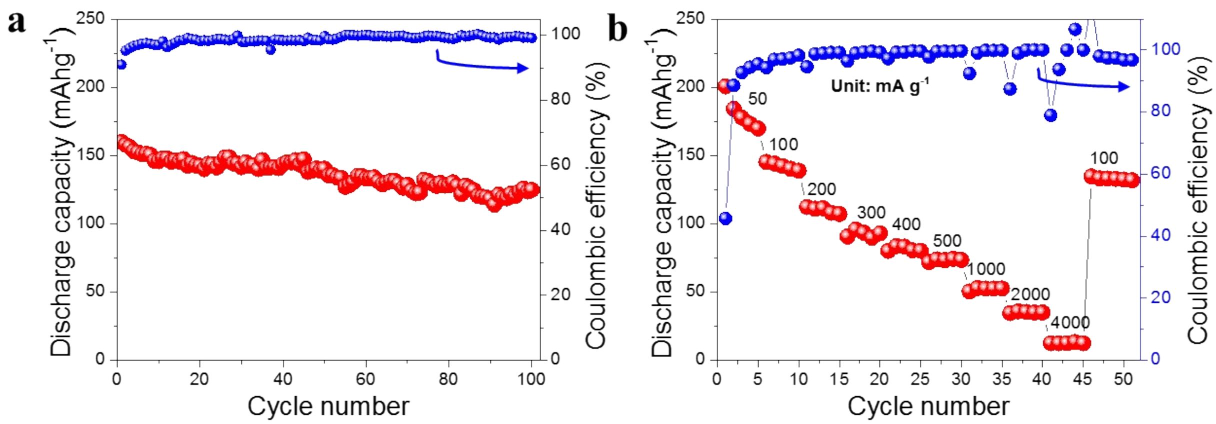

Fig. S8. (a) Cycling stability and (b) rate capabiilty of MoO_3 NRs.

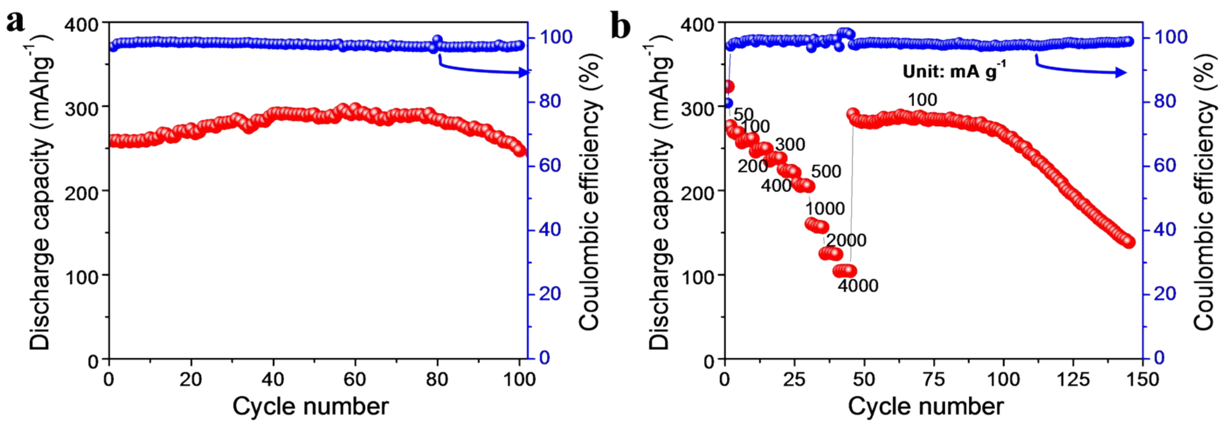

Fig. S9. (a) Cycling stability and (b) rate capabiilty of MoS_2 NRs at ramping rate of 5 °C min^{-1}.

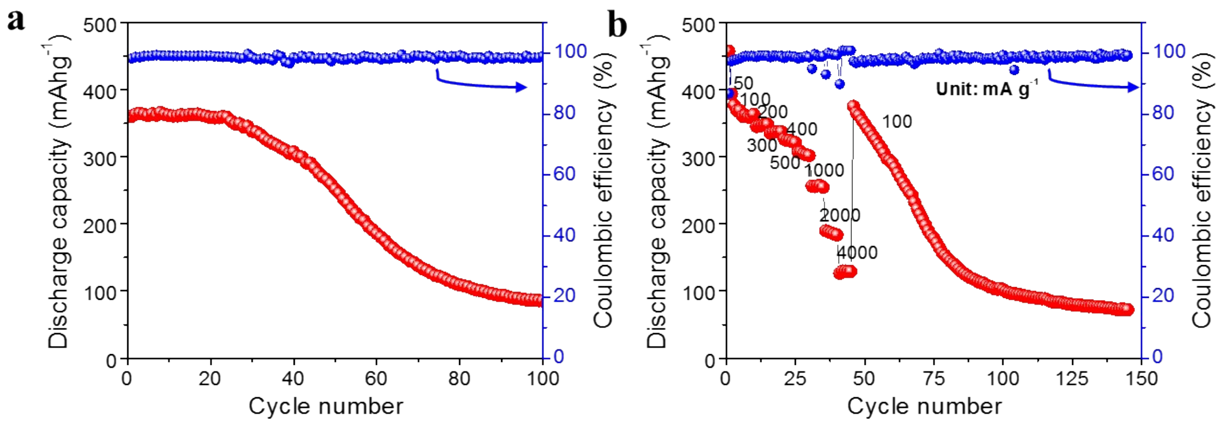

Fig. S10. (a) Cycling stability and (b) rate capabiilty of MoS_2 NRs at ramping rate of 2 °C min^{-1}.

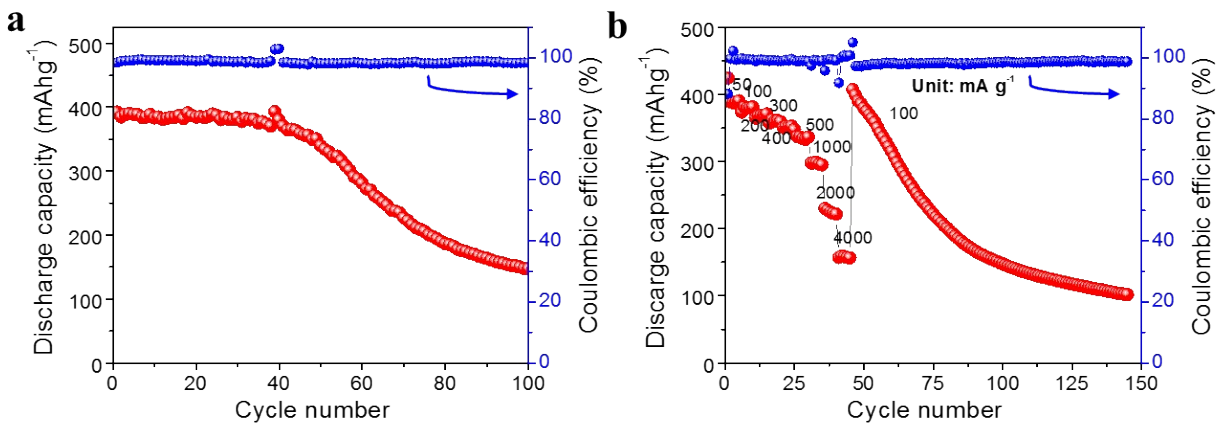

Fig. S11. (a) Cycling stability and (b) rate capabiilty of MoS_2 NRs at ramping rate of 1 °C min^{-1}.

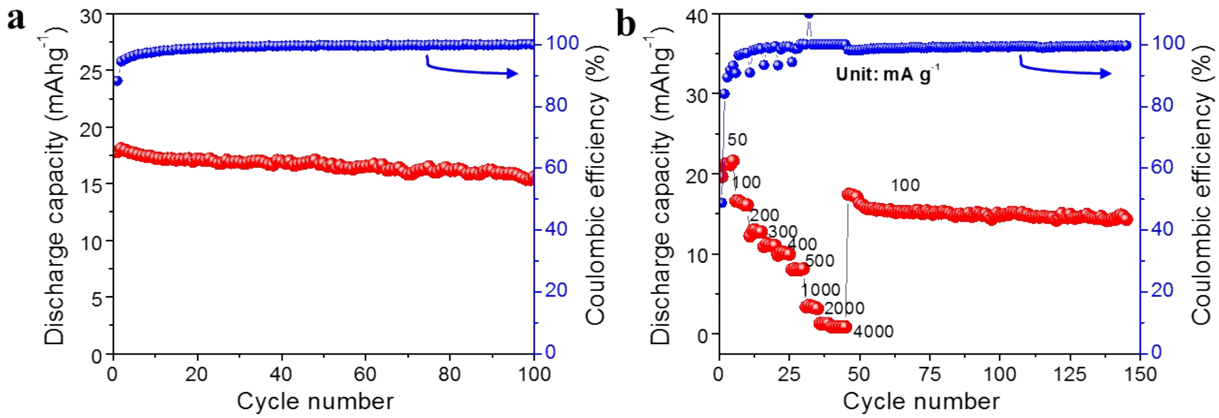

Fig. S12. (a) Cycling stability and (b) rate capabiilty of MoO_2 NRs.

Table S1. Comparison of $MoS_2@C@MoS_2$ performance with other MoS_2 based anodes.

Electrode Material	Initial Coulombic efficiency (%)	Cycling stability	Rate capability	References
HMF-MoS_2	60.2	384 mAh g^{-1} at 100 mA g^{-1} (After 100 cycles)	226 mAh g^{-1} at 5 A g^{-1}	[1]
BD-MoS_2	<75	354 mAh g^{-1} at 500 mA g^{-1} (After 1000 cycles)	262 mAh g^{-1} at 5 A g^{-1}	[2]
Expanded MoS_2@ Carbon fiber	65.1	241 mAh g^{-1} at 1000 mA g^{-1} (After 700 cycles)	109 mAh g^{-1} at 10 A g^{-1}	[3]
MoS_2@C paper	79.5	268 mAh g^{-1} at 0.08 A g^{-1} (after 100 cycles)	205 mAh g^{-1} at 1 A g^{-1}	[4]
1T-MoS_2	64	313 mAh g^{-1} at 50 mA g^{-1} (After 200 cycles)	175 mAh g^{-1} at 2 A g^{-1}	[5]
MoS_2 Nanoflowers	-	350 mAh g^{-1} at 50 mA g^{-1}	300 mAh g^{-1} at 1 A g^{-1}	[6]
$MoS_{2-x}Se_x$ /GF	55	208 mAh g^{-1} at 0.2 A g^{-1} (78.6% after 500 cycles)	~115 mAh g^{-1} at 5 A g^{-1}	[7]
MoS_2 /RGO Sponge	67.4	372 mAh g^{-1} at 0.1 A g^{-1} (after 50 cycles)	192 mAh g^{-1} at 1 A g^{-1}	[8]
MoS_2 /RGO Sponge	64	420 mAh g^{-1} at 0.1 A g^{-1} (after 160 cycles)	284 mAh g^{-1} at 1 A g^{-1}	[9]
S/MoS_2	78.6	413.2 mAh g^{-1} at 0.1 A g^{-1} (after 100 cycles)	358.8 mAh g^{-1} at 0.5 A g^{-1}	[10]
$MoS_2@C@MoS_2$	86.3	434 mAh g^{-1} at 100 mA g^{-1} (After 100 cycles)	365 mAh g^{-1} at 4000 mA g^{-1}	*This work*

Table S2. Comparison of $MoS_2@C@MoS_2$ performance with other metal sulfides/selenides based anodes.

Electrode Material	Initial Coulombic efficiency (%)	Cycling stability	Rate capability	Reference
NiS_2-rGO	65	313 mAh g^{-1} at 100 mA g^{-1} (after 200 cycles)	168 mAh g^{-1} at 2C rate	[11]
VS_4-rGO	75.1	240.8 mAh g^{-1} at 100 mA g^{-1} (after 50 cycles)	192.2 mAh g^{-1} at 800 mA g^{-1}	[12]
SnS-C	79	260 mAh g^{-1} at 100 mA g^{-1} (after 300 cycles)	145 mAh g^{-1} at 1000 mA g^{-1}	[13]
SnS-MWCNT	73.3	391 mAh g^{-1} at 100 mA g^{-1} (after 50 cycles)	410 mAh g^{-1} at 500 mA g^{-1}	[14]
$CoMoS_3$	77.7	411 mAh g^{-1} at 2 A g^{-1} (after 300 cycles)	349 mAh g^{-1} at 10 A g^{-1}	[15]
$CoSe_2$@N-PGC/CNTs	75.6	424 mAh g^{-1} at 0.1 A g^{-1} (after 100 cycles)	368 mAh g^{-1} at 5 A g^{-1}	[16]
Fe_7Se_8@NC	78.7	367 mAh g^{-1} at 0.5 A g^{-1} (after 100 cycles)	251 mAh g^{-1} at 2 A g^{-1}	[17]
FeS/N-C	51.5	511 mAh g^{-1} at 0.2 A g^{-1} (after 100 cycles)	260 mAh g^{-1} at 4 A g^{-1}	[18]
CoS_2@N,S-doped carbon	70	510 mAh g^{-1} at 0.1 A g^{-1} (after 100 cycles)	288 mAh g^{-1} at 2 A g^{-1}	[19]
$MoSe_2$/N,P-doped rGO	69.6	337 mAh g^{-1} at 0.1 A g^{-1} (after 100 cycles)	244.4 mAh g^{-1} at 1 A g^{-1}	[20]
$MoS_2@C@MoS_2$	86.3	434 mAh g^{-1} at 100 mA g^{-1} (after 100 cycles)	365 mAh g^{-1} at 4000 mA g^{-1}	*This work*

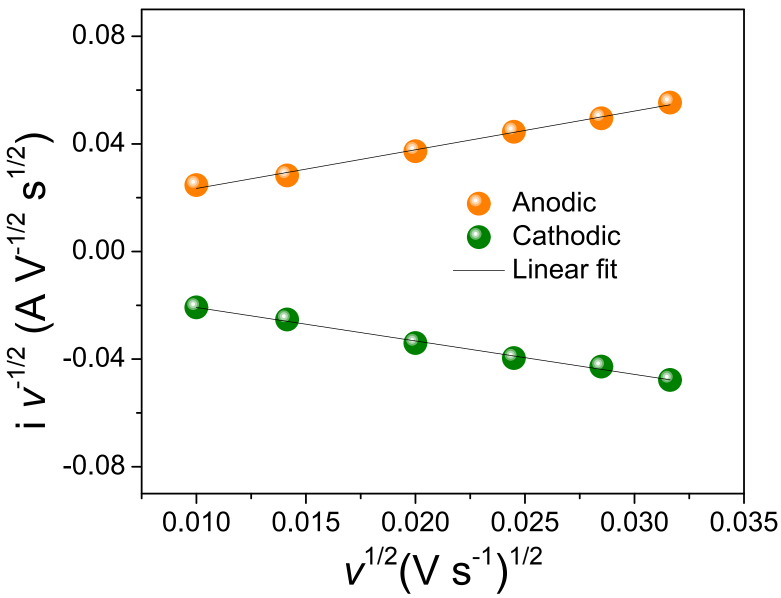

Fig. S13. Linear fit curve for peak current vs square root of scan rates for MoS_2@C@MoS_2 electrode.

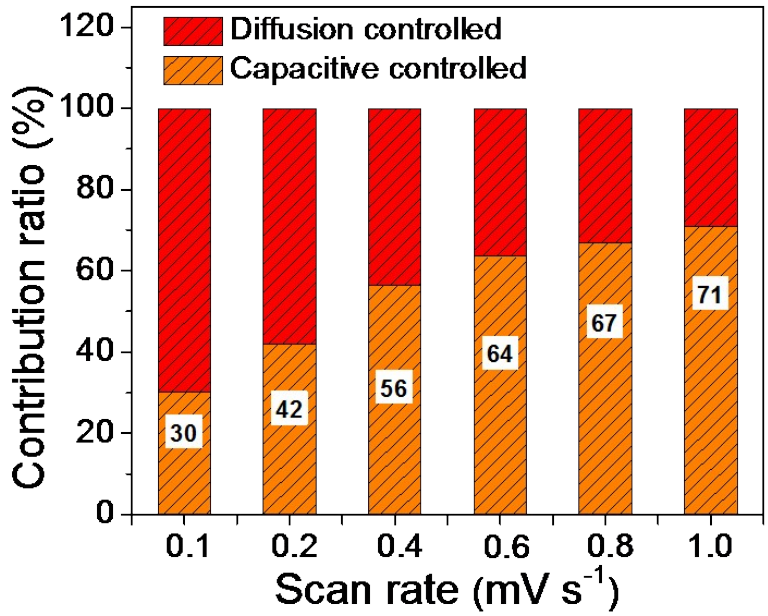

Fig. S14. Contribution of capacitive and diffsuion controlled reaction for pristine MoS_2 NRs.

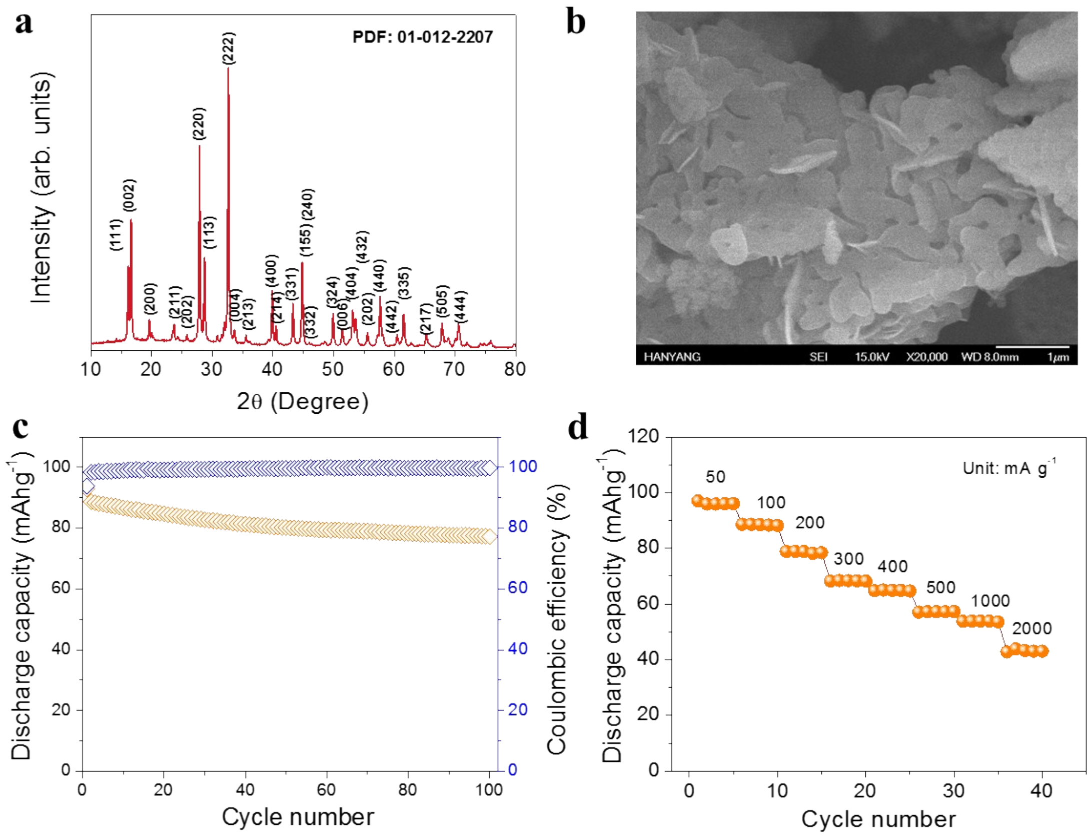

Fig. S15. (a) XRD pattern, (b) FE-SEM image, (c) cycling stability and (d) rate capability of NVPF cathode.

References

[1] Y. Li, R. Zhang, W. Zhou, X. Wu, H. Zhang and J. Zhang, *ACS Nano* 2019, **15**, 5533.

[2] K. Yao, J. Huang, M. Ma, L. Fu, X. Shen, J. Li and M. Fu, *Small* 2019, **15**, 1805405

[3] C. Zhao, C. Yu, M. Zhang, Q. Sun, S. Li, M.N. Banis, X. Han, Q. Dong, J. Yang, G. Wang, X. Sun and J. Qiu, *Nano Energy* 2017, **41**, 66.

[4] X. Xie, T. Makaryan, M. Zhao, K.L. Van Aken, Y. Gogotsi and G. Wang, *Adv Energy Mater*. 2016, **6**, 1502161.

[5] X. Geng, Y. Jiao, Y. Han, A. Mukhopadhyay, L. Yang and H. Zhu, *Adv. Funct. Mater*. 2017, **27**, 1702998.

[6] Z. He, L. Wang, K. Zhang, J. Wang, F. Cheng, Z. Tao and J. Chen, *Angew. Chem*. 2014, **126**, 130088.

[7] G. Jia, D. Chao, N.H. Tiep, Z. Zhang and H.J. Fan, *Energy Storage Materials* 2018, **14**, 136.

[8] J. Li, W. Qin, J. Xie, R. Lin, Z. Wang, L. Pan and W. Mai, *Chem. Eng. J.* 2018, **332**, 260.

[9] Z. Che, Y. Li, K. Chen and M. Wei, *J. Power Sources* 2016, **331**, 50.

[10] Z. Xu, K. Yao, Z. Li, L. Fu, H. Fu, J. Li, L. Cao and J. Huang, *J. Mater. Chem. A* 2018, **6**, 10535

[11] T. Wang, P. Hu, C. Zhang, H. Du, Z. Zhang, X. Wang, S. Chen, J. Xiong and G. Cui, *ACS Appl. Mater. Interfaces* 2016, **8**, 7811.

[12] R. Sun, Q. Wei, Q. Li, W. Luo, Q. An, J. Sheng, D. Wang, W. Chen and L. Mai, *ACS Appl. Mater. Interfaces* 2015, **7**, 20902.

[13] C. Zhu, P. Kopold, W. Li, P.A. Aken, J. Maier and Y. Yu, *Adv. Sci.* 2015, **2**, 1500200.

[14] W. Wang, L. Shi, D. Lan and Q. Li, *J. Power Sources* 2018, **377**, 1.

[15] S.H. Yang, S.-K. Park, J.K. Kim and Y.C. Kang, *J. Mater. Chem. A* 2019, **7**, 13751.

[16] S.K. Park, J.K. Kim and Y.C. Kang, *Chem. Eng. J.* 2017, **328**, 546.

[17] M. Wan, R. Zeng, K. Chen, G. Liu, W. Chen, L. Wang, N. Zhang, L. Xue, W. Zhang and Y. Huang, *Energy Storage Materials* 2018, **10**, 114.

[18] Y. Liu, W. Zhong, C. Yang, Q. Pan, Y. Li, G. Wang, F. Zheng, X. Xiong, M. Liu and Q. Zhang, *J. Mater. Chem. A* 2018, **6**, 24702.

[19] F. Han, T. Lv, B. Sun, W. Tang, C. Zhang and X. Li, *RSC Adv*. 2017, **7**, 30699.

[20] A. Roy, A. Ghosh, A. Kumar and S. Mitra.,*Inorg. Chem. Front*. 2018, **5**, 2189.