frontiers
in Energy Research

ORIGINAL RESEARCH
published: 26 November 2019
doi: 10.3389/fenrg.2019.00125

Synthesis and Characterization of Nano SnO_2 Modification on $LiNi_{0.8}Mn_{0.1}Ni_{0.1}O_2$ Cathode Materials for Lithium Ion Batteries

Chunxiang Wang, Wanwan Peng, Zhifeng Li, Yali Liang, Shengwen Zhong* and Qian Zhang*

Jiangxi Key Laboratory of Power Battery and Material, School of Materials Science and Engineering, Jiangxi University of Science and Technology, Ganzhou, China

OPEN ACCESS

Edited by:
Yutao Li,
University of Texas at Austin,
United States

Reviewed by:
Biyi Xu,
University of Texas at Austin,
United States
Nan Wu,
Beijing Institute of Technology, China
Yijie Liu,
Nanjing University, China

****Correspondence:***
Shengwen Zhong
jxustzsw@126.com
Zhifeng Li
jxlzfeng@163.com

Specialty section:
This article was submitted to
Electrochemical Energy Conversion
and Storage,
a section of the journal
Frontiers in Energy Research

Received: *20 September 2019*
Accepted: *25 October 2019*
Published: *26 November 2019*

Citation:
Wang C, Peng W, Li Z, Liang Y,
Zhong S and Zhang Q (2019)
Synthesis and Characterization of
Nano SnO_2 Modification on
$LiNi_{0.8}Mn_{0.1}Ni_{0.1}O_2$ Cathode Materials
for Lithium Ion Batteries.
Front. Energy Res. 7:125.
doi: 10.3389/fenrg.2019.00125

The precursor material of $Ni_{0.}8Co_{0.1}Mn_{0.1}(OH)_2$ was prepared by a co-precipitation method to obtain the layered cathode materials $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ (811) through roasting with $LiOH{\cdot}H_2O$. Then the SnO_2-modified samples were obtained by adding tin oxide into the ball mill. It was found by XRD characterization of the original and modified samples, that the addition of SnO_2 did not change the layered structure of the raw materials. Microstructure and distribution of the SnO_2 were analyzed with SEM and EDS. Charge/discharge tests indicated that the SnO_2-modified phases improved the cycling stability and rate capability. The results of CV test showed that the polarization of SnO_2 modified electrode was smaller. AC impedance showed that $SnO_2/LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ electrode had smaller R_{ct} and R_f value. The above test results indicate that the modification of SnO_2 improves the electrochemical performance of cathode material $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$.

Keywords: Li-ion battery, Ni-based cathode materials, SnO_2 modification, electrochemical performances, lower electrode polarization

INTRODUCTION

Layered Ni-based cathode materials have attracted more and more attention due to their high energy density and environmental friendliness. Among these materials, $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (811) material has become the focus of many pursuits because of its high specific discharge capacity, low material cost, and environmental protection concept. However, the stability and safety problems of this material are more prominent. Researchers have carried out many modification studies to solve the problems existing in $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (811), in which doping and coating are generally recognized as effective methods. Researchers believe that doping can reduce the probability of phase transition during the cycle, improve the structural stability and contribute to electrochemical performance, doping cations such as Cr^{3+}, Ti^{4+}, Rb^{+}, Al^{3+}, and Mg^{2+} (Li et al., 2010, 2013; Yuan et al., 2014; Du et al., 2015; Dong et al., 2017; Zhang et al., 2017). Semiconductive or insulating materials are usually adopted to coat the $LiMO_2$ phase because it has the functions of protecting active substances from diffusion and dissolution in electrolyte, improving electronic conductivity, ensuring surface structure stability and avoiding corrosion of anode materials. The materials selected for coating are mainly some substances with relatively stable chemical properties, such as oxides, fluorides, salts and polymers. As previously reported, AlF_3, Al_2O_3, TiO_2, ZnO,

Li_4SiO_4, $LiAlO_2$, and SnO_2 (Yang et al., 2012; Lee et al., 2013; Wang et al., 2015; Dai et al., 2016; Lai et al., 2016; He et al., 2017; Srur-Lavi et al., 2017; Liua et al., 2018; Zheng et al., 2018; Xie et al., 2019) were used as effective coating materials for lithium battery cathode materials. The coated materials contribute to more stable SEI film, which can slow down the decomposition of electrolyte and protect bulk materials from corrosion during charging and discharging. For instance, SnO_2 was adopted to improve the electrochemical properties in many cathode materials with better results such as $LiCoO_2$ (Hudaya et al., 2014), $LiFePO_4$ (Ziolkowska et al., 2013), and $LiMn_2O_4$ (Ma et al., 2017), $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ (Luo et al., 2015), $Li_{1.2}Mn_{0.54}Co_{0.13}Ni_{0.13}O_2$ (Li B. et al., 2016), $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (He et al., 2017; Xie et al., 2019). However, the influence of SnO_2 modification on electrochemical properties of $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ cathode materials has rarely been researched.

In this work, $SnO_2/LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ was prepared by facile ball-milling post-treatment. The structure and morphology of $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ with or without SnO_2 modification were investigated and the charge transfer resistance and electrochemical properties of SnO_2 modification on the $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ material were discussed in detail.

MATERIALS AND METHODS

Synthesis and Characterization

The layered Ni-rich material of $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ was prepared by $LiOH{\cdot}H_2O$ and $Ni_{0.8}Co_{0.1}Mn_{0.1}(OH)_2$ precursor formed by a simple continuous co-precipitation method through high temperature solid phase reaction. In this preparation process, excessive lithium hydroxide 5% (Li et al., 2012), 550°C for 6 h, 800°C for 12 h, and oxygen is introduced into the whole process. SnO_2-modified phases were further obtained by mechanical ball milling treatment. The mass percentage of SnO_2 in composites is as follows: 1, 2, 3, and 4 wt%.

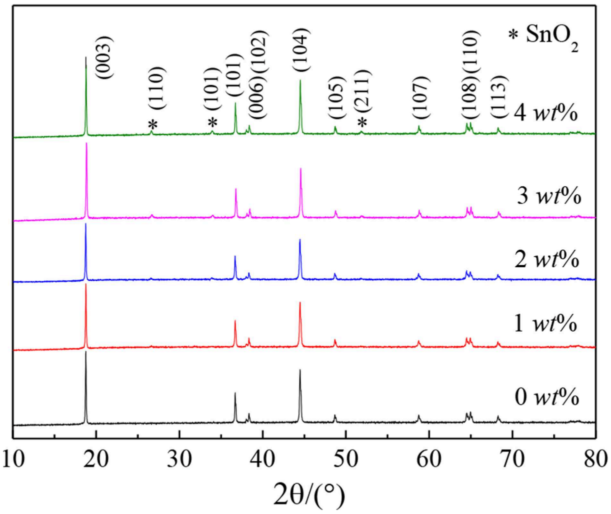

FIGURE 1 | The XRD patterns of the 811 and *x* wt% SnO_2-modified 811 (x = 0, 1, 2, 3, 4) materials.

The X-ray diffraction was measured on Bruker D8 Advance X-ray Diffractometer. The morphology of the material was examined by ZEISS EVO/MA10 electron microscope. Cyclic voltammetry (CV) and EIS measurements of the cells were collected on Ivium-n-Stat electrochemical workstation.

The cathode materials were assembled into CR2032 type button batteries to detect electrochemical performances. The preparation of cathode active materials slurry and the assembly of batteries can be referred to Reference (Li et al., 2018).

RESULTS AND DISCUSSION

XRD Phase

Figure 1 shows the structure of pristine $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ (NCM) materials and its coating process with SnO_2. As shown in the figure, the cathode materials are essentially the same

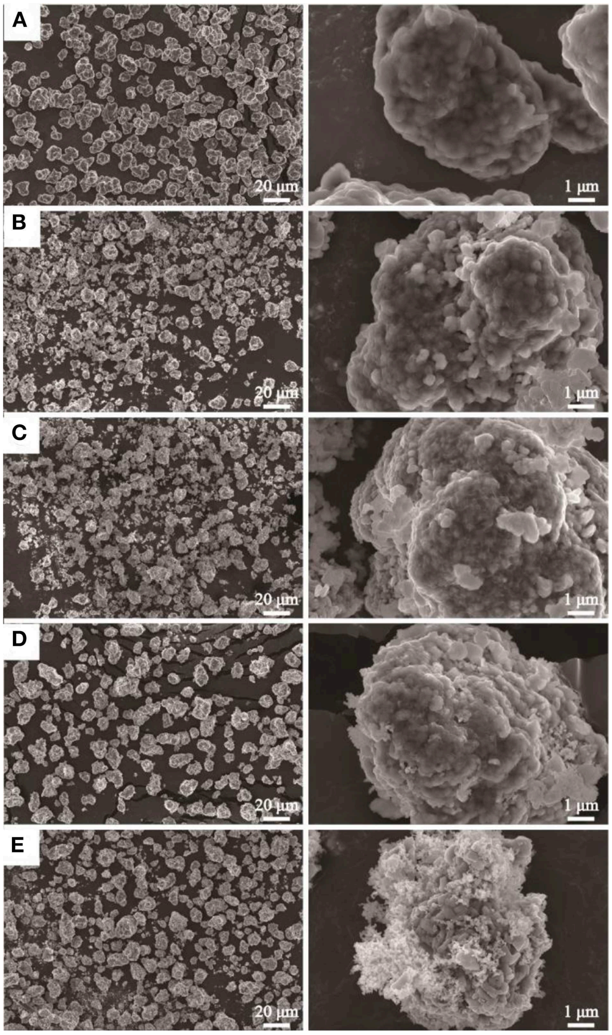

FIGURE 2 | SEM images of 811 **(A)** and nano SnO_2-modified samples (**B**: 1 wt%; **C**: 2 wt%; **D**: 3 wt%; **E**: 4 wt%).

and belong to a hexagonal α-NaFeO$_2$ structure with a space group of R$\bar{3}$m, the lattice constant are very close which means that the crystal structure of NCM is not affected by coating with nano SnO$_2$. Moreover, the distinct splitting of (006)/(102) and (108)/(110) indicates the products possess well-developed layered structure (Li G. Y. et al., 2016). The XRD plots of SnO$_2$ modification samples also show the diffraction peak at about 27 degree representing for the plane (110) of SnO$_2$, which becomes obvious with the increase of the concentration of SnO$_2$.

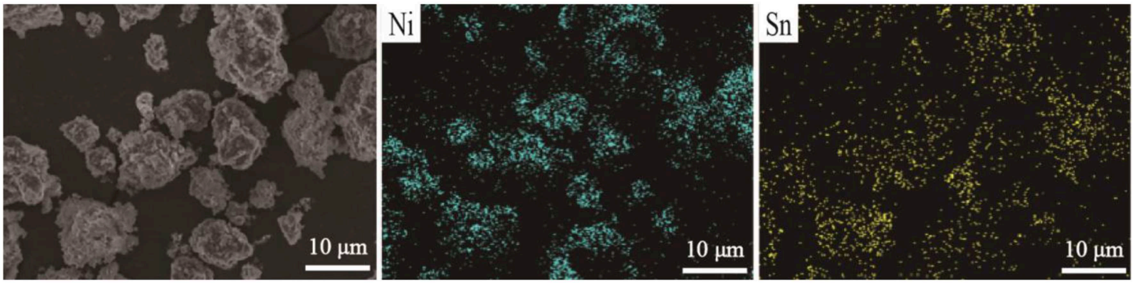

FIGURE 3 | EDS maps of the 3 wt % SnO$_2$-modified 811 material.

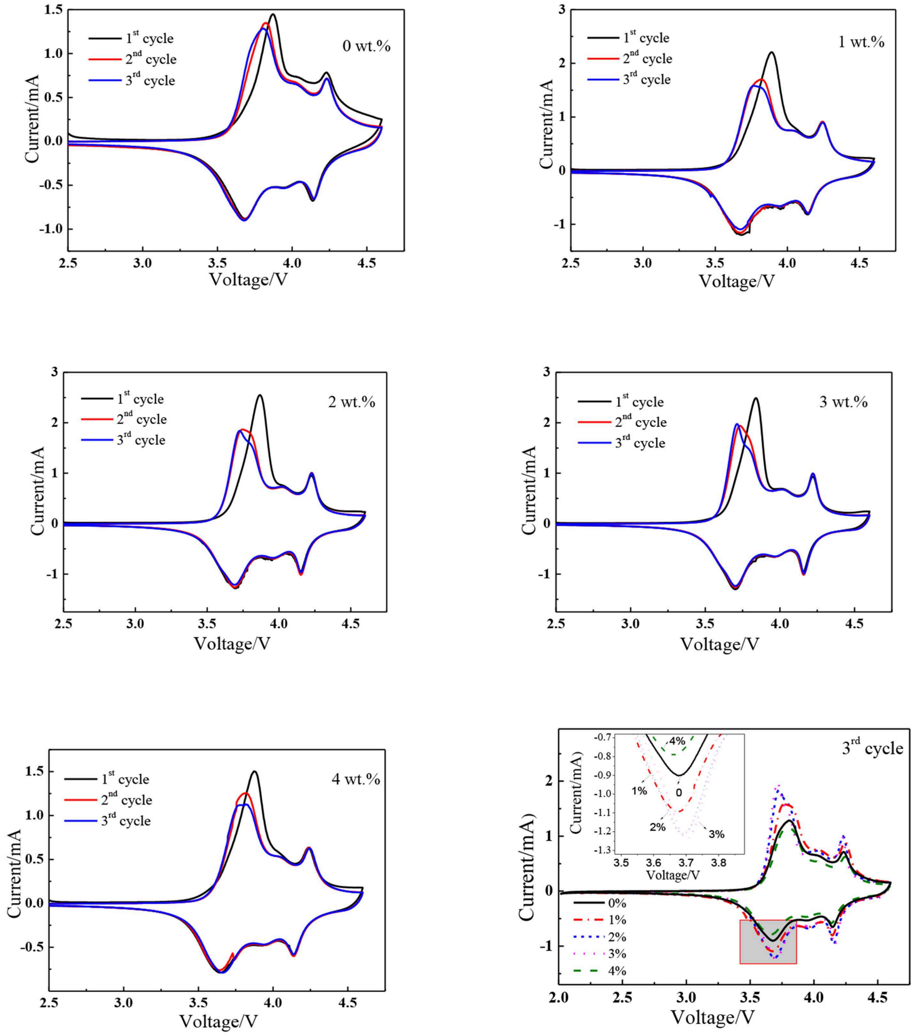

FIGURE 4 | Cyclic voltammograms of pristine and SnO$_2$-modified materials.

Microtopography

The SEM images of pristine and nano SnO$_2$-modified samples are shown in **Figure 2**. It is clearly seen that the second particles of pristine samples (the diameter is about 10 μm) are made of abundant primary nanoparticles which the surface is smooth. Compared with the pristine sample, the surface of the sample modified by SnO$_2$ appears rough, and some bright white spots can be seen because the nano tin dioxide particles partially cover it. However, when the mass percentage of SnO$_2$ is 4 wt%, the SnO$_2$ nanoparticles begin to aggregate and distribute unevenly on the surface of the original particles which will reduce the electro-chemical performance. The EDS spectra of 3 wt% SnO$_2$ modified specimen are shown in **Figure 3** which is also used to confirm the distribution of SnO$_2$ particles on the surface of LiNi$_{0.8}$Co$_{0.1}$Mn$_{0.1}$O$_2$ cathode materials. As can be seen from the figure, the tin element covers the surface of the cathode material relatively evenly.

Electrochemical Performance

The cyclic voltammograms for the first, second, and third cycle were tested in the range of 2.5–4.6 V with a scanning rate of 0.1 mV s^{-1} to clearly obtain the different redox behaviors of pristine and nano SnO$_2$-modified samples. As shown in **Figure 4**, there are three redox couples in the cyclic voltammogram curves of 2.5–4.3 V voltage range (Abraham et al., 2003; Belharouak et al., 2006), indicating the polyphase transition from hexagonal to monoclinic (H1/M), monoclinic to hexagonal (M/H2), hexagonal to hexagonal (H2/H3). The major anodic peak of the first cycle is different from the second and third cycle which may be partially attributed to the formation of solid electrolyte inter-phase (Zhong et al., 2015, 2016) or the cation mixing (Zhong et al., 2015) in the first cycle. There is only small shift of the major anodic peak in the second and third cycle. This means that the material has good intercalation and deintercalation reversibility of lithium ions which facilitates the good electrochemical properties. As shown in **Table 1**, nano SnO$_2$-modified samples exhibit smaller potential difference between anodic peak and cathodic peak ($\Delta\psi$V) compared to the pristine sample. The value of $\Delta\psi$V is only 20 mV when the tin oxide content is 3 wt%. It can be seen from the above data that nano SnO$_2$-modification can reduce electrode polarization.

Figures 5A,B are cycling performance curves of pristine and SnO$_2$-modified materials between the voltage of 2.8–4.35 V at 0.2C and 1C rate. The initial specific capacities of pristine and SnO$_2$-modified samples at 0.2C rate (1, 2, 3, and 4 wt%) were, respectively, 185.7, 181.3, 183.375, 187.5, and 179.9 mAh/g. The corresponding capacity was maintained with 85.25%, 90.40%, 91.88%, 90.77%, and 88.72 wt% after 50 cycles. The capacity of each material decreases rapidly at 1C rate, however, compare to the pristine, the capacity retention rate increased from 74.23 to 87.43% when the SnO$_2$ content is 3 wt%. All these results attributed to the fact that the proper addition of SnO$_2$ not only improves the conductivity of the material, but also reduces the

TABLE 1 | Values of CV peaks for pristine and SnO$_2$-modified materials in the third cycle.

SnO$_2$ content (wt%)	ψ1/V	ψ2/V	$\Delta\psi$12/mV
0	3.806	3.674	132
1	3.776	3.668	108
2	3.727	3.688	39
3	3.718	3.698	20
4	3.769	3.659	137

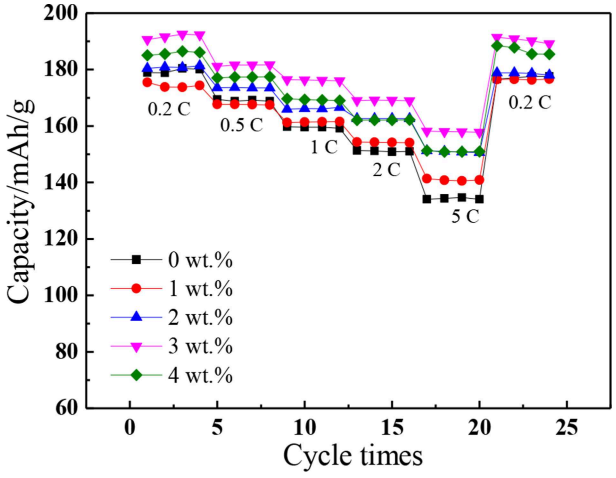

FIGURE 6 | Rate performance of the samples from 2.75 to 4.35 V.

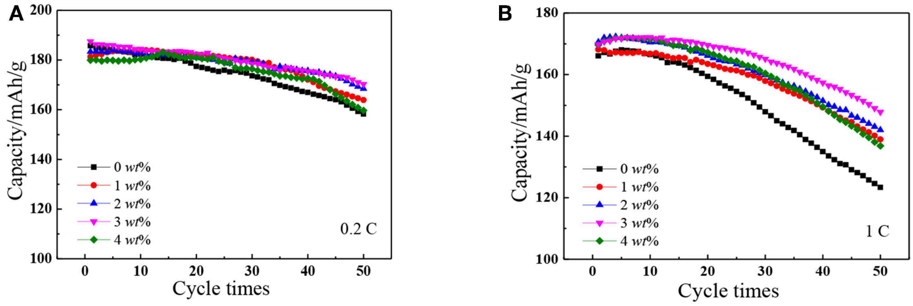

FIGURE 5 | Cyclic performance of all samples at 0.2C rate **(A)** or 1C rate **(B)**.

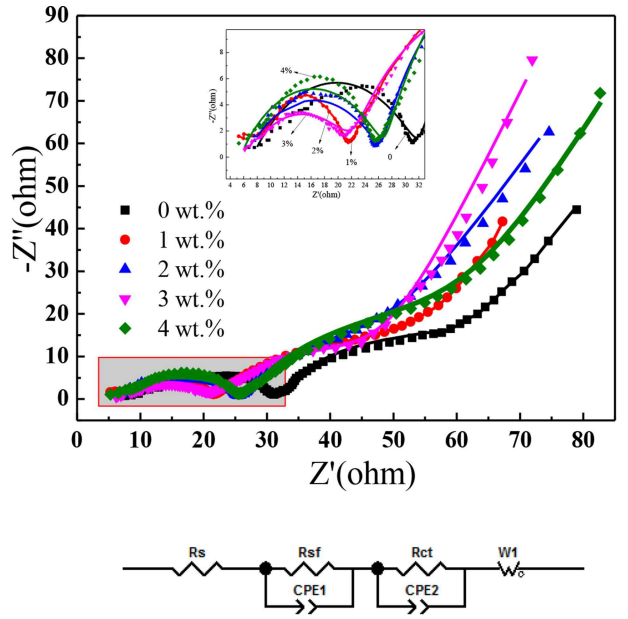

FIGURE 7 | Nyquist plots and equivalent circuit for *x* wt% SnO$_2$-modified NCM ($x = 0, 1, 2, 3, 4$) positive electrode materials.

TABLE 2 | The fitting results of EIS after the 5th cycle.

x wt% SnO$_2$	R$_s$(Ω)	R$_{sf}$(Ω)	R$_{ct}$(Ω)
0	7.305	25.03	35.87
1	5.645	17.34	31.11
2	6.200	20.45	23.51
3	5.741	16.23	25.28
4	5.462	21.65	31.02

corrosion of the electrolyte. However, when the SnO$_2$ content is 4 wt%, the capacity and recyclability of cathode materials will be reduced due to the uneven distribution of SnO$_2$ in the surface of NCM and hinder the migration of lithium ions.

As shown in **Figure 6**, the rate performances for the pristine and SnO$_2$-modified materials were tested at 0.2C, 0.5C, 1C, 2C, and 5C, respectively. The average discharge specify capacity of pristine and SnO$_2$-NCM (the SnO$_2$ is 1, 2, 3, and 4 wt%) at 0.2C rate are, respectively, 179.6, 174.4, 180.8, 191.8, and 185.8 mAh/g, which, respectively, decreased to 134.3, 141.0, 150.9, 158.2, and 151.1 mAh/g when the current rate raised to 5C rate with the capacity retentions of 74.8, 68.6, 80.8, 83.5, 82.5, and 81.3%. And the discharge capacities almost restored from decay when the rate returned to 0.2C. The results showed that the existence of SnO$_2$ improved the rate performance of the cathode material electrode. The reason may be that the existence of SnO$_2$ in the electrode passivates the reaction between the cathode and the electrolyte which contributes to forming a more stable interface.

Electrochemical impedance spectroscopy measurement (EIS) technology was applied to study the internal resistance change of the five electrodes. The EIS profiles of the 5th cycled electrodes are demonstrated in **Figure 7**. R_s, R_{sf}, and R_{ct} calculated from EIS results are tabulated in **Table 2**. All of the EIS profiles are similar and consist of two semicircles and a line, according to the reported references (Noh et al., 2013), the high-frequency semicircle represent the resistance of Li$^+$ diffusion in the surface layer (R_{sf}), the mid-frequency semicircle and the low-frequency line should be, respectively, ascribed to the charge transfer resistance (R_{ct}) and the Warburg impedance of solid phase diffusion (Z_w). Compared with the original electrode, the SEI film resistance (R_{sf}) and charge transfer resistance (R_{ct}) of SnO$_2$ modified electrodes are slightly smaller in which the SEI film resistance of 3 wt% SnO$_2$ modified electrode is the smallest. Therefore, the modification of SnO$_2$ greatly improves the ionic conductivity, which improves the electrochemical performance of the material.

CONCLUSION

In this paper, the precursor material of Ni$_{0.8}$Co$_{0.1}$Mn$_{0.1}$(OH)$_2$ was prepared by a co-precipitation method then roasted with LiOH·H$_2$O to obtain the layered cathode materials LiNi$_{0.8}$Co$_{0.1}$Mn$_{0.1}$O$_2$. SnO$_2$-modified phases were further obtained by mechanical ball milling treatment. The effect of SnO$_2$ modification on the structure, morphology and electrochemical properties of LiNi$_{0.8}$Co$_{0.1}$Mn$_{0.1}$O$_2$ was mainly studied. Duo to the existence of SnO$_2$ in the surface of LiMO$_2$ active materials, the cycling stability and rate capability are greatly improved. The results of cyclic voltammetry (CV) show that the existence of SnO$_2$ can reduce the polarization of the electrode. When the content of SnO$_2$ is 3 wt%, the sample has the lowest SEI film resistance (R_{sf}) and best cycling performance performed 0.2C or 1C under the potential of 2.75–4.35 V. In conclusion, this study has potential significance for improving the cyclic and rate properties of nickel-based cathode materials.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

CW: experimental design, data analysis and discussion, and article writing. WP: battery preparation, electrochemical performance testing, and data discussion. ZL: experimental design, electrochemical performance analysis, and discussion. YL: synthesis of cathode compounds and SnO$_2$ doped modification experiment. SZ: experimental design. QZ: CV performance test, results analysis, and discussion.

FUNDING

The project was supported by National Natural Science Fund of China (No. 51874151), Jiangxi Province Science and Technology Plan Project (No. 20151BBE50106), and Jiangxi Provincial Education Office Natural Science Fund Project (No. GJJ160202).

REFERENCES

Abraham, D. P., Twesten, R. D., Balasubramanian, M., Kropf, J., Fischer, D., McBreen, J., et al. (2003). Microscopy and spectroscopy of lithium nickel oxide-based particles used in high power lithium-ion cells. *J. Electrochem. Soc.* 150, A1450–A1456. doi: 10.1149/1.1613291

Belharouak, I., Lu, W., Vissers, D., and Amine, K. (2006). Safety characteristics of $Li(Ni_{0.8}Co_{0.15}Al_{0.05})O_2$ and $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$. *Electrochem. Commun.* 8, 329–335. doi: 10.1016/j.elecom.2005.12.007

Dai, G., Du, H., Wang, S., Cao, J., Yu, M., Chen, Y., et al. (2016). Improved electrochemical performance of $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ with ultrathin and thickness controlled TiO_2 shell via atomic layer deposition technology. *RSC Adv*. 6, 100841–100848. doi: 10.1039/C6RA21903A

Dong, M. X., Li, X. Q., Li, X. H., Guo, H. J., and Huang, Z. J. (2017). Enhanced cycling stability of La modified $LiNi_{0.8-x}Co_{0.1}Mn_{0.1}La_xO_2$ for Li-ion battery $LiNi_{0.8-x}Co_{0.1}Mn_{0.1}La_xO_2$. *Trans. Nonferrous Met. Soc. China* 27, 1134–1142. doi: 10.1016/S1003-6326(17)60132-8

Du, R., Bi, Y. J., Yang, W. C., Peng, Z., Liu, M., Liu, Y., et al. (2015). Improved cyclic stability of $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ via Ti substitution with a cut-off potential of 4.5V. *Ceram. Int.* 41, 7133–7139. doi: 10.1016/j.ceramint.2015.02.026

He, X., Du, C., Shen, B., Chen, C., Xu, X., Wang, Y., et al. (2017). Electronically conductive Sb-doped SnO_2 nanoparticles coated $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ cathode material with enhanced electrochemical properties for Li-ion batteries. *Electrochim. Acta* 236, 273–279. doi: 10.1016/j.electacta.2017.03.215

Hudaya, C., Park, J. H., Lee, J. K., and Choi, W. (2014). SnO_2-coated $LiCoO_2$ cathode material for high-voltage applications in lithium-ion batteries. *Solid State Ionics* 256, 89–92. doi: 10.1016/j.ssi.2014.01.016

Lai, Y. Q., Xu, M., Zhang, Z., Gao, C., Wang, P., and Yu, Z. (2016). Optimized structure stability and electrochemical performance of $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ by sputtering nanoscale ZnO film. *J. Power Sources* 309, 20–26. doi: 10.1016/j.jpowsour.2016.01.079

Lee, S. H., Yoon, C. S., Amine, K., and Sun, Y. K. (2013). Improvement of long-term cycling performance of $Li[Ni_{0.8}Co_{0.15}Al_{0.05}]\ O_2$ by AlF_3 coating. *J. Power Sources* 234, 201–207. doi: 10.1016/j.jpowsour.2013.01.045

Li, B., Wang, J., Cao, Z. L., Zhang, P., and Zhao, J. B. (2016). The role of SnO_2 surface coating in the electrochemical performance of $Li_{1.2}Mn_{0.54}Co_{0.13}Ni_{0.13}O_2$ cathode materials. *J. Power Sources* 325, 84–90. doi: 10.1016/j.jpowsour.2016.06.027

Li, G. Y., Zhang, Z. J., Wang, R. N., Huang, Z. L., Zuo, Z. C., and Zhou, H. H. (2016). Effect of trace Al surface doping on the structure, surface chemistry and low temperature performance of $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ cathode. *Electrochim. Acta* 212, 399–407. doi: 10.1016/j.electacta.2016.07.033

Li, L. J., Chen, Z. Y., Long, X. B., Jin, W. F., and Xia, Q. (2013). Synthesis of cation-substituted $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ from laterite. *Ionics* 19, 1215–1222. doi: 10.1007/s11581-013-0957-3

Li, L. J., Li, X. H., Wang, Z. X., Guo, H. J., Yue, P., Chen, W., et al. (2010). Synthesis, structural and electrochemical properties of $LiNi_{0.79}Co_{0.1}Mn_{0.1}Cr_{0.01}O_2$ via fast co-precipitation. *J. Alloy Comp.* 507, 172–177. doi: 10.1016/j.jallcom.2010.07.148

Li, Z., Chernova, N. A., Feng, J., Upreti, S., Omenya, F., and Whittingham, M. S. (2012). Stability and rate capability of Al substituted lithium-rich high-manganese content oxide materials for Li-ion batteries. *J. Electrochem. Soc.* 159, A116–A120. doi: 10.1149/2.044202jes

Li, Z. F., Luo, C. Y., Wang, C. X., Jiang, G. X., Chen, J., Zhong, S. W., et al. (2018). Effects of Nb substitution on structure and electrochemical properties of $LiNi_{0.7}Mn_{0.3}O_2$ cathode materials. *J. Solid State Electr.* 22, 2811–2820. doi: 10.1007/s10008-018-3975-2

Liua, W., Lia, X., Xiong, D., Hao, Y., Li, J., Kou, H., et al. (2018). Significantly improving cycling performance of cathodes in lithium ion batteries: the effect of Al_2O_3 and $LiAlO_2$ coatings on $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$. *Nano Energy* 44, 111–120. doi: 10.1016/j.nanoen.2017.11.010

Luo, Z. M., Sun, Y. G., and Liu, H. Y. (2015). Electrochemical performance of a nano SnO_2-modified $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ cathode material. *Chin. Chem. Lett.* 26, 1403–1408. doi: 10.1016/j.cclet.2015.06.007

Ma, F., Geng, F., Yuan, A., and Xu, J. Q. (2017). Facile synthesis and characterization of a SnO_2-modified $LiNi_{0.5}Mn_{1.5}O_4$ high-voltage cathode material with superior electrochemical performance for lithium ion batteries. *Phys. Chem. Chem. Phys.* 19, 9983–9991. doi: 10.1039/C7CP00943G

Noh, H. J., Youn, S., Yoon, C. S., and Sun, Y. K. (2013). Comparison of the structural and electrochemical properties of layered $Li[Ni_xCo_yMn_z]O_2$ ($x =$ 1/3, 0.5, 0.6, 0.7, 0.8 and 0.85) cathode material for lithium-ion batteries. *J. Power Sources* 233, 121–130. doi: 10.1016/j.jpowsour.2013.01.063

Srur-Lavi, O., Miikkulainen, V., Markovsky, B., Grinblat, J., Talianker, M., Fleger, Y., et al. (2017). Studies of the electrochemical behavior of $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ electrodes coated with $LiAlO_2$. *J. Electrochem. Soc.* 164, A3266–A3275. doi: 10.1149/2.1631713jes

Wang, J., Du, C., Yan, C., He, X., Song, B., Yin, G., et al. (2015) Al_2O_3 Coated concentration-gradient $Li[Ni_{0.73}Co_{0.12}Mn_{0.15}]O_2$ cathode material by freeze drying for long-life lithium ion batteries. *Electrochim. Acta* 174, 1185–1191. doi: 10.1016/j.electacta.2015.06.112

Xie, Z. C., Zhang, Y. Y., Yuan, A. B., and Xu, J. Q. (2019). Effects of lithium excess and SnO_2 surface coating on the electrochemical performance of $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ cathode material for Li-ion batteries. *J. Alloy Comp.* 787, 429–439. doi: 10.1016/j.jallcom.2019.02.127

Yang, K., Fan, L. Z., Guo, J., and Qu, X. H. (2012). Significant improvement of electrochemical properties of AlF_3-coated $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ cathode materials. *Electrochim. Acta* 63, 363–368. doi: 10.1016/j.electacta.2011.12.121

Yuan, S., Liu, L. B., Tang, Y. P., Wang, J. H., and Guo, Y. Z. (2014). Synthesis and electrochemical properties of cathode material $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ via Li, Mg, Al doping. *Adv. Mater. Res.* 1058, 302–306. doi: 10.4028/www.scientific.net/AMR.1058.302

Zhang, Z. L., Chen, D. H., and Chang, C. (2017). Improved electrochemical performance of $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ cathode materials via incorporation of rubidium cations into the original Li sites. *Rsc Adv.* 7, 51721–51728. doi: 10.1039/C7RA10053A

Zheng, J., Yang, Z., He, Z., Tong, H., Yu, W., and Zhang, J. (2018). *In situ* formed $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2@Li_4SiO_4$ composite cathode material with high rate capability and long cycling stability for lithium-ion batteries. *Nano Energy* 53, 613–621. doi: 10.1016/j.nanoen.2018.09.014

Zhong, S., Chen, P., and Yao, W. (2015). Ni-rich layered oxide $Li_{1.05}(Ni_{0.7}Mn_{0.3})O_2$ as a highly reversible cathode material for lithium-ion batteries. *ECS Electrochem. Lett.* 4, A45–A48. doi: 10.1149/2.0041506eel

Zhong, S. W., Lai, M. Z., Yao, W. L., Li,. Z., and Li, Z. C. (2016). Synthesis and electrochemical properties of $LiNi_{0.8}Co_xMn_{0.2-x}O_2$ positive-electrode material for lithium-ion batteries. *Electrochim Acta* 212, 343–351. doi: 10.1016/j.electacta.2016.07.040

Ziolkowska, D., Korona, K. P., Hamankiewicz, B., Wu, S.-H., Chen, M.-S., Jasinskid, J. B., et al. (2013). The role of SnO_2 surface coating on the electrochemical performance of $LiFePO_4$ cathode materials. *Electrochim. Acta* 108, 532–539. doi: 10.1016/j.electacta.2013.06.075

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.