NRC Publications Archive Archives des publications du CNRC

Synthesis of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ cathode material with eutectic molten salt LiOH-LiNO_3

Chang, Zhao-Rong; Yu, Xu; Tang, Hong-Wei; Yuan, Xiao-Zi; Wang, Haijiang

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1016/j.powtec.2010.11.025>

Powder Technology, 207, 1-3, pp. 396-400, 2010-12-03

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=92ad49c7-0e2e-432b-adb3-5df5f66fdcab>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=92ad49c7-0e2e-432b-adb3-5df5f66fdcab>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

Synthesis of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ cathode material with eutectic molten salt LiOH-LiNO_3

Zhao-Rong Chang^{a,*}, Xu Yu^a, Hong-Wei Tang^a, Xiao-Zi Yuan^b, Haijiang Wang^b

^a College of Chemistry and Environmental Science, Henan Normal University, Xinxiang 453007, P.R. China

^b Institute for Fuel Cell Innovation, National Research Council of Canada, Vancouver, British Columbia, Canada V6T 1W5

ARTICLE INFO

Article history:

Received 12 July 2010

Received in revised form 20 October 2010

Accepted 21 November 2010

Available online 3 December 2010

Keywords:

Cathode materials

Eutectic molten salt

Doping

$\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$

ABSTRACT

A lithium-ion battery cathode material, $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$, with excellent electrochemical properties was prepared by three-phase temperature sintering, using eutectic lithium salts ($0.38\text{LiOH}\cdot\text{H}_2\text{O}$ - 0.62LiNO_3) mixed with the precursor $\text{Ni}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}(\text{OH})_2$. This method was simple and inexpensive, and the materials could be mixed uniformly at the eutectic melting point without any grinding. A well-layered α - NaFeO_2 structure was confirmed by X-ray diffraction (XRD). The ratio of characteristic diffraction peaks $I(003)/I(104)$ reached 1.73. Charge-discharge testing of the synthesized powder showed an initial charge-discharge capacity of $151.5 \text{ mAh}\cdot\text{g}^{-1}$ at a specific current of 0.2 C in the range 2.8 – 4.3 V up to 20 cycles with no noticeable capacity-fading (94.5% of the first discharge capacity), and reversible capacities of 133.7 and $120.9 \text{ mAh}\cdot\text{g}^{-1}$ for specific currents of 1 C and 2 C at room temperature. The discharge capacity and capacity retention at 55°C were substantially better than at room temperature.

© 2010 Published by Elsevier B.V.

1. Introduction

At present, most lithium-ion batteries on the market still use LiCoO_2 as the cathode material; however, cost and unsatisfactory thermal stability seriously limit its use in electric vehicles [1–3]. From the viewpoint of environmental friendliness, finding a non-polluting cathode material with high capacity, good cycling performance, high thermal stability, and low cost has become the keystone in this area of research [4–6]. The Ni-based ternary cathode material $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$ seems promising for use in applications that require a power supply, e.g., electric vehicles, and has become a particular focus of research due to its high discharge capacity, good thermal stability, and low cost [7–13]. Recently, additional reports on Ni-based multi-doped lithium-ion battery cathode materials have been published. Major synthetic methods include the high-temperature solid-phase method, the sol-gel method, the coprecipitation method [14–16], and the molten salt method [17,18]. The main doping elements for improving thermal characteristics and cycling performance include cobalt, aluminum, manganese, titanium, magnesium, and gallium. Most recently, a new layer structure material, $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$, was successfully synthesized by Lin et al. using the water-in-oil micro-emulsion method [19]. Both thermal stability and cycling performance were improved,

and the discharge capacity at high temperatures was better than at room temperature, which is very important for electric vehicles. Unfortunately, that synthesis process is complicated and costly. No other reports on the structure and electrochemical properties of this new material have been found.

Our research team synthesized $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$ and $\text{LiNi}_{0.8}\text{Co}_{0.2}\text{O}_2$ with excellent structure and electrochemical properties using eutectic lithium salts ($0.38\text{LiOH}\cdot\text{H}_2\text{O}$ - 0.62LiNO_3) mixed with a precursor in a controlled ratio of $1.1:1 \text{ Li}/(\text{Ni} + \text{Co} + \text{Al})$. This method enables uniform mixing at the eutectic melting point without any grinding, thereby avoiding a labor-intensive washing process and the waste of eutectic molten salt [17,18]. Based on our previous work [20], the cathode material $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ was prepared in the present study via three-stage heating temperature sintering using eutectic lithium salts, in which the ratio of $\text{Li}/(\text{Ni} + \text{Co} + \text{Al})$ in the raw material $\text{Ni}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}(\text{OH})_2$ and the eutectic molten salt ($0.38\text{LiOH}\cdot\text{H}_2\text{O}$ - 0.62LiNO_3) with a melting point of 175°C was controlled at $1.1:1$. The $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ powder prepared by this method demonstrated excellent electrochemical performance.

2. Experimental

The precursor $\text{Ni}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}(\text{OH})_2$ was obtained by dissolving stoichiometric amounts of $\text{NiSO}_4\cdot 6\text{H}_2\text{O}$, $\text{CoSO}_4\cdot 7\text{H}_2\text{O}$, and $\text{Al}_2(\text{SO}_4)_3\cdot 18\text{H}_2\text{O}$ together in distilled water (transition metal ratio of $\text{Ni}:\text{Co}:\text{Al} = 1:1:1$). The aqueous solution was precipitated by adding a NaOH solution of $4 \text{ mol}\cdot\text{L}^{-1}$ with continuous stirring at 50°C under an air atmosphere. Synthesis of non-spherical $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ was carried

* Corresponding author. Tel.: +86 373 3326335; fax: +86 373 3326336.
E-mail address: czzr_56@163.com (Z.-R. Chang).

out using a eutectic molten salt reaction. The lithium salt used was $0.38\text{LiOH}\cdot\text{H}_2\text{O}-0.62\text{LiNO}_3$ (melting point 175.6°C). The $\text{Ni}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}(\text{OH})_2$ precursor was mixed with eutectic lithium molten salt in a molar ratio of 1:1.1. The mixtures were initially heated to 200°C for 3 h and subsequently sintered in an air atmosphere at 600°C for 5 h and 900°C for 10 h. After heating, the resulting powders were cooled to ambient temperature.

To investigate their crystal structures, powders were analyzed by X-ray diffraction (XRD) using a D8 X diffractometer (Bruker, Germany) employing $\text{Cu K}\alpha$ radiation. The scan data were collected in a 2θ range of $15-70^\circ$, with a step size of 0.02° and a counting time of 3 s. The prepared powders were also observed using scanning electron microscopy (SEM) with an SEM-6701 F (JEOL, Japan). The cells were cycled on a Land CT2001A battery tester (Wuhan Jinnuo Electronics Co. Ltd., China).

Coin cells (CR2016) were used to test the electrochemical performance of the samples. Positive electrodes were prepared by mixing the active material, Super S Carbon Black, and polyvinylidene fluoride (PVDF) in a weight ratio of 80:10:10. The solvent N-methyl-2-pyrrolidone (NMP) was added to these active materials, forming a slurry that was then coated on Al foil and dried at 120°C under vacuum for 10 h. The coin cells were assembled in an Ar-filled glove box using metallic Li as the counter electrode, Celgard 2400 as the separator, and $1\text{ mol}\cdot\text{L}^{-1}\text{LiPF}_6$ as the electrolyte. The cells were then removed from the glove box and connected to a computer-controlled charging system by which they were initially charged and discharged at a C/5 rate of 2.8–4.3 V versus Li metal on a Land CT2001A battery tester at room temperature.

3. Results and discussion

3.1. Effects of lithium salts on the crystal structure and morphology of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$

Fig. 1 illustrates the XRD patterns of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ sintered with different lithium salts via three-stage heating temperature control.

As Fig. 1 shows, sintering different lithium salts had a significant impact on the target structure of the cathode materials. In Fig. 1(a), the locations of the diffraction peaks perfectly match the standard $\alpha\text{-NaFeO}_2$ layered structure, and there is no obvious miscellaneous peak. Li locates at the 3a position in $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$, metal elements Ni, Co, and Al at the 3b position, and oxygen atoms at the 6c position. Given the very similar radii of Ni^{2+} (0.069 nm) and Li^+ (0.067 nm), the Li^+ and Ni^{2+} located at the 3a and 3b positions will constantly be shuffling, leading to a decline in these materials' electrochemical properties [21]. According to the literature, the $I(003)/I(104)$ peak value ratio of a six-layered structure of lithium-oxygen-transition metal oxides in the XRD patterns may reflect the degree of cation order [22]: the larger the ratio of $I(003)/I(104)$, the lower the amount of cation shuffling. If the $I(003)/I(104)$ ratio is below 1.2, the increased cation shuffling will interfere with the lithium ions de-embedding from the material. As indicated in Fig. 1, the $I(003)/I(104)$ peak intensity ratios of samples A–D are 1.65, 1.64, 1.70, and 1.73, respectively. Apparently, mixed lithium salts are superior to single lithium salts, and a eutectic mixed lithium salt is superior to simple mixed lithium salts. In addition, the splitting observable in the XRD patterns between the (006) and (102) peaks and the (008) and (110)

Fig. 1. XRD patterns of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ sintered using different lithium salts: (a) full XRD 2D-diagram; (b) and (c) locally magnified XRD patterns.

peaks enables us to measure the degree to which a layered structure developed: the greater the number of peak splits, the more orderly the layered structure. In Fig. 1(b) and (c), the number of splits between (006)/(102) and (008)/(110) increases gradually from A to D, which indicates that the eutectic mixed lithium salt had a more satisfactory layered structure and better electrochemical performance. The melting point of the eutectic mixed lithium salt $0.38\text{LiOH} \cdot \text{H}_2\text{O} - 0.62\text{LiNO}_3$ is only 175.7°C , which may be the main reason why it can form a complete layered structure with a high degree of crystallinity and low cation shuffling. When it was sintered in the first phase at 200°C for 3 h, the molten liquid lithium salt could easily permeate and infiltrate to the solid precursor $\text{Ni}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}(\text{OH})_2$ particle surface and then inside, resulting in extensive, even mixing and distribution of lithium ions and solid oxide metal ions, which is key for preparing cathode materials with ideal structures.

Fig. 2 shows scanning electron micrographs of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ samples prepared with eutectic lithium salts. A and B are the SEM images for $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ from single lithium salts of $\text{LiOH} \cdot \text{H}_2\text{O}$ and LiNO_3 , respectively, while C and D show different magnifications of SEM images for the same sample synthesized using a eutectic mixture of $0.38\text{LiOH} \cdot \text{H}_2\text{O} - 0.62\text{LiNO}_3$.

As can be seen in Fig. 2, samples synthesized using a single lithium salt had larger particle sizes (about $2\text{ }\mu\text{m}$) and a varied size distribution (about $2\text{--}0.2\text{ }\mu\text{m}$). The sample prepared using a eutectic mixed lithium salt had a more regular particle morphology with a more uniform particle size (about $1\text{--}0.5\text{ }\mu\text{m}$). This is consistent with the XRD results above.

3.2. Effects of crystallization temperature on the crystal structure of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$

In this study, a three-stage heating temperature sintering process was adopted. The first phase was to melt the eutectic lithium salts above their melting point and evenly mix them with the solid transition metal oxide particles. In the second stage (at a constant temperature of 600°C) the lithium salts and solid oxide reacted to generate $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$. According to our previous study, although $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ with a certain stoichiometric ratio can be produced in this temperature range, its crystal structure is not completely developed. Further crystallization at a certain temperature is required to adjust the atomic arrangement in the crystal structure. Fig. 3(a) illustrates the XRD patterns of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ heated at (E) 850°C , (F) 900°C , and (G) 950°C .

It has been demonstrated that crystallization temperature has a significant effect on crystal structure development. The ratios of the characteristic diffraction peaks $I(003)/I(104)$ are 1.43, 1.73, and 1.40 at crystallization temperatures of 850°C , 900°C , and 950°C , respectively. Raising the crystallization temperature to 900°C yielded the highest ratio, indicating the smallest cation shuffling effect and the highest degree of crystallinity. As is evident in the magnified XRD pattern (Fig. 3(b)), in all cases there is not much difference in the split level of the (108) and (110) peaks. However, a clear split occurs in the (113) peak when the crystallization temperature is 900°C , indicating that this sample has the most complete layered structure.

Fig. 2. SEM images of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ samples synthesized using different lithium salts. (a) $\text{LiOH} \cdot \text{H}_2\text{O}$; (b) LiNO_3 ; (c and d) $0.38\text{LiOH} \cdot \text{H}_2\text{O} - 0.62\text{LiNO}_3$. (a), (b), (d) $\times 20,000$; (c) $\times 6000$.

Fig. 3. XRD patterns of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ sintered using $0.38\text{LiOH} \cdot \text{H}_2\text{O} \cdot 0.62\text{LiNO}_3$ at different temperatures. (a) full XRD 3D-diagram; (b) locally magnified XRD patterns (E) 850 °C; (F) 900 °C; (G) 950 °C.

3.3. Electrochemical characterization

The electrode was cycled over 2.8–4.3 V at a constant current density of $0.2 \text{ mA} \cdot \text{cm}^{-2}$. The first discharge curves and the discharge curves after 20 cycles of the $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ samples synthesized with different lithium salts are shown in Fig. 4(a) and (b), respectively.

The initial maximum discharge capacities of samples A, B, C, and D were $131.9 \text{ mAh} \cdot \text{g}^{-1}$, $136 \text{ mAh} \cdot \text{g}^{-1}$, $146.2 \text{ mAh} \cdot \text{g}^{-1}$, and $151.5 \text{ mAh} \cdot \text{g}^{-1}$, respectively. The reversible capacities of samples A, B, C, and D after 20 cycles were $109.1 \text{ mAh} \cdot \text{g}^{-1}$ (82.7% of the maximum discharge capacity), $117.6 \text{ mAh} \cdot \text{g}^{-1}$ (86.4%), $133 \text{ mAh} \cdot \text{g}^{-1}$ (90.9%), and $143.2 \text{ mAh} \cdot \text{g}^{-1}$ (94.5%), respectively. This result indicates that the eutectic mixture of lithium salts $0.38\text{LiOH} \cdot \text{H}_2\text{O} \cdot 0.62\text{LiNO}_3$ was superior to both the simple mixture of lithium salts and the single lithium salt, which agrees very well with the XRD analysis. Furthermore, the discharge capacity of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ sintered with the eutectic mixture $0.38\text{LiOH} \cdot \text{H}_2\text{O} \cdot 0.62\text{LiNO}_3$ exceeded the $130.7 \text{ mAh} \cdot \text{g}^{-1}$ capacity reported in the literature [19], with a higher discharge platform and better cycling performance.

Fig. 5 shows the discharge curves, at different discharge rates, of the $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ sample synthesized using eutectic mixed lithium salts ($0.38\text{LiOH} \cdot \text{H}_2\text{O} \cdot 0.62\text{LiNO}_3$) and sintered at a crystallization temperature of 900 °C.

The test batteries were charged to 4.3 V at a constant current of 0.2 C, then discharged to 2.8 V at constant currents of 0.2 C, 0.5 C, 1 C, and 2 C. The theoretical capacity of the cathode material $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ for a lithium-ion battery was calculated to be $205 \text{ mAh} \cdot \text{g}^{-1}$. As indicated in Fig. 5, the discharge capacities were $151.5 \text{ mAh} \cdot \text{g}^{-1}$, $144.7 \text{ mAh} \cdot \text{g}^{-1}$,

Fig. 4. Discharge curves of samples A, B, C, and D: (a) initial and (b) after 20 cycles.

$133.7 \text{ mAh} \cdot \text{g}^{-1}$, and $120.9 \text{ mAh} \cdot \text{g}^{-1}$ at the respective discharge rates. Compared with the discharge capacity at 0.2 C, the retention rates at 0.5 C, 1 C, and 2 C were 94.5%, 88.3%, and 79.8%, respectively, indicating improved rate performance. As the discharge rate increased, the downward trend of the material's discharge capacity gradually increased and the discharge platform gradually decreased. This result stemmed primarily from the polarization caused by the high discharge rate. Effective methods of improving the material's magnification performance might be to reduce its average particle size or increase its electrical conductivity.

Fig. 5. Discharge curves of sample D at different rates: 0.2 C, 0.5 C, 1 C, 2 C.

Fig. 6. Discharge curves: at 55 °C initially (A) and after 20 cycles (C); at room temperature initially (B) and after 20 cycles (D).

As sample D had best electrochemical properties and an even particle size distribution, we compared its performance at 55 °C. Fig. 6 shows the discharge curves of $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ initially and after 20 cycles at room temperature and 55 °C, respectively.

The initial discharge capacities at room temperature and 55 °C were 151.5 mAh.g^{-1} and 156.4 mAh.g^{-1} , respectively. After 20 cycles, the discharge capacity retention rates at room temperature and 55 °C were 94.5% and 95.3%, respectively. Clearly, the discharge capacity and capacity retention at 55 °C were better than at room temperature when the batteries were cycled between 2.8 V and 4.3 V. Owing to this perfect layer structure, the products by eutectic molten salt are not only beneficial to extraction and insertion of Li^+ ion but also improve thermal stability of materials. In addition, the discharge curve at 55 °C indicates that the discharge platform increased with a longer discharge. This is a very important observation for batteries used in applications such as electric vehicles.

4. Conclusion

A lithium-ion battery cathode material, $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$, with excellent electrochemical properties was prepared via three-phase temperature sintering (200 °C for 3 h, 600 °C for 5 h, and 900 °C for 10 h) using eutectic lithium salt ($0.38\text{LiOH.H}_2\text{O}-0.62\text{LiNO}_3$) mixed with the precursor $\text{Ni}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}(\text{OH})_2$. This method is procedurally simple and inexpensive, and the materials can be uniformly mixed at the eutectic melting point without grinding. The synthesized material, $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$, demonstrated better performance than samples synthesized using a single lithium salt (LiOH or LiNO_3) or a 1:1 mixture of lithium salts with a typical $\alpha\text{-NaFeO}_2$ layered structure.

The characteristic peak ratio of $I(003)/I(104)$ reached 1.73, indicating high crystallinity and small cationic shuffling. The obvious splits in the characteristic diffraction peak pairs $(006)/(102)$ and $(008)/(110)$ and in the (113) peak demonstrated the material's well-developed layer structure. As a result, the synthesized $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Al}_{1/3}\text{O}_2$ had an excellent discharge capacity of 151.5 mAh.g^{-1} (at 0.2 C) for the first cycle and a very fine capacity retention rate of more than 94.5% after 20 cycles at room temperature. The reversible capacity reached 133.7 mAh.g^{-1} and 120.9 mAh.g^{-1} at charge–discharge rates of 1 C and 2 C, respectively. At 55 °C, the initial capacity of the material was 154.9 mAh.g^{-1} (at 0.2 C) with a capacity retention rate more than 95.3% after 20 cycles, which was better than at room temperature. These results show that the material has good discharge performance, cycling reversibility, and rate performance, making it promising for future lithium-ion battery applications.

Acknowledgements

This work is financially supported by the Natural Science Foundation of China under approval No. 21071046, and by Henan Provincial Department of Science and Technology Key Research Project under approval No. 080102270013.

References

- [1] Z.S. Peng, C.R. Wan, C.Y. Jiang, J. Power Sources 72 (1998) 215.
- [2] S. Bruno, Electrochim. Acta 45 (2000) 2461.
- [3] E. Antolini, Solid State Ionics 170 (2004) 159.
- [4] G.X. Wang, M.J. Lindsay, M. Ionescu, D.H. Bradhurst, S.X. Dou, H.K. Liu, J. Power Sources 97–98 (2001) 211.
- [5] H.M. Wu, J.P. Tu, X.T. Chen, Y.F. Yuan, Y. Li, X.B. Zhao, G.S. Cao, J. Power Sources 586 (2006) 180.
- [6] W.B. Luo, J.R. Dahna, Electrochim. Acta 54 (2009) 4655.
- [7] H. Joachin, J. Prakash, J. Liu, K. Amine, J. Power Sources 163 (2007) 1074.
- [8] X.Y. Han, Q.F. Meng, T.L. Sun, J.T. Sun, J. Power Sources 195 (2010) 3047.
- [9] T.H. Cho, S.M. Park, M. Yoshio, T. Hirai, Y. Hideshima, J. Power Sources 142 (2005) 306.
- [10] J.H. Yoon, H.J. Bang, J. Prakash, Y.K. Sun, Mater. Chem. Phys. 110 (2008) 222.
- [11] S. Zhang, C. Deng, B.L. Fu, et al., Powder Technol. 198 (2010) 373.
- [12] P.S. Whitfield, I.J. Davidson, L.M.D. Cranswick, I.P. Swainson, P.W. Stephens, Solid State Ionics 176 (2005) 463.
- [13] S.B. Jang, S.H. Kang, K. Amine, Y.C. Bae, Y.K. Sun, Electrochim. Acta 50 (2005) 4168.
- [14] S.H. Kang, J. Kim, M.E. Stoll, et al., J. Power Sources 112 (2002) 41.
- [15] Z.R. Chang, X. Qi, F. Wu, H.W. Tang, J.L. Wang, Chem. Eng. 34 (2006) 50.
- [16] R. Santhanam, B. Rambabu, J. Power Sources 195 (2010) 4313.
- [17] Z.R. Chang, Z.J. Chen, F. Wu, H.W. Tang, Z.H. Zhu, Acta Phys. Chim. Sin. 24 (2008) 513.
- [18] Z.R. Chang, Z.J. Chen, F. Wu, X.Z. Yuan, H.J. Wang, Electrochim. Acta 54 (2009) 6529.
- [19] Y.K. Lin, et al., J. Power Sources 146 (2005) 594.
- [20] H.W. Tang, Z.H. Zhu, Z.R. Chang, Z.J. Chen, Acta Phys. Chim. Sin. 23 (2007) 1265.
- [21] T. Ohzuku, A. Ueda, M. Kouguchi, J. Electrochem. Soc. 142 (1995) 4033.
- [22] Y. Gao, M.V. Yakovleva, W.B. Ebner, Solid State Ionics 1 (1998) 117.