

## Effects of Nitriles additives on performances of SiO<sub>x</sub>/Graphite||NCM811 pouch cell at elevated temperature

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Although fluoroethylene carbonate (FEC) additive has been developed to accelerate the commercial process of SiO<sub>x</sub>/Graphite (SiO<sub>x</sub>/Gr) composite anode for several years, there are still some challenges need to be solved, such as performance deterioration at elevated temperature, gas and HF generation. In this work, two kinds of nitriles additives are reported to optimize performance of SiO<sub>x</sub>/Gr||NCM811 pouch cell at high temperature. The introducing of nitriles additives can not only inhibit the decomposition of FEC additive to release HF, but reduce the dissolution of metal ion coming from NCM811 cathode. As a result, an enhanced charge/discharge capacity and rate capability, a reduced polarization resistance are obtained for the SiO<sub>x</sub>/Gr||NCM811 pouch cell after high temperature storage at 60°C for seven days.

**Keywords:** Lithium-ion battery, SiO<sub>x</sub>/Gr anode, Electrolyte additive, elevated temperature, nitriles

### 1. INTRODUCTION

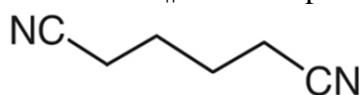
Lithium-ion batteries (LIBs) have launched a revolution in the energy storage field since they became commercialized in the market in the 1990s [1–3]. Currently, LIBs with high nickel (NCM811 or NCA) material as the cathode and SiO<sub>x</sub>/Gr as the anode are not only used in the field of the electric vehicles for cylindrical battery, but also successfully used in small battery market for portable electronic devices [4–6]. With the continuous rising demands of portable electronic devices, anodic material stability is a key factor that needs to be tackled. The performance of anode materials not only determines the charge-discharge capacities, but also the high temperature and cycling performance of the battery [7].

Portable electronic devices have appeared a strong demand for next-generation LIBS with high energy density, fast charge performance and high endurance of working temperature. Although with

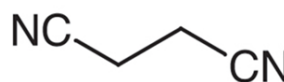
excellent stability and properties, the commercial anode materials graphite has relatively low capacity, which becomes a restricted factor. So the replacement of the traditional graphite with silicon anode has attracted much attention in recent years [8-10]. The super high theoretical capacity (about 4000mAh/g) is the obvious superiority compared with graphite. So silicon has been the preferred anode material for second-generation lithium ion battery. However, its commercial utilization is limited by the multi-volume swelling and shrinkage in the lithium-ion battery charge and discharge process [11-12]. For the past few years, researchers have been studying the silicon oxide-graphite (as SiO<sub>x</sub>/Gr) composite anode and advantages occurs from the equilibrium between reversible capacity and volume swelling [13].

To decrease electrolyte consumption and reduce volume expansion, it is effective to construct stable solid electrolyte interface (SEI) on the surface of SiO<sub>x</sub>/Gr anode [11,14,15]. Vinylene carbonate (VC) and fluoroethylene carbonate (FEC) [16-18], used as the electrolyte additives, have made big contributions for the commercial application of SiO<sub>x</sub>/Gr anode. FEC could increase and improve the cycle life of battery successfully, and is an unique and standard additive to silicon anode [19-21]. However, due to the strong reduction on the anode, FEC could be reduced and induce secondary reaction. Some researchers assumed the mechanism that FEC can form some F-polymer, which promotes the decomposition of LiPF<sub>6</sub> [3, 22, 23]. Through OEMS studies, some researchers found that FEC could bring abundant dissolution of Li<sub>2</sub>CO<sub>3</sub>, and increase the generation of CO<sub>2</sub>, assembling a large amount of gas [24].

In our previous work, systematic discussion was conducted on the effects and attenuation mechanism of FEC on the SiO<sub>x</sub>/Gr||NCM811 pouch cell at high temperature. Results demonstrated that FEC can accelerate the decomposition of LiPF<sub>6</sub> salt to produce more HF, which will destroy SEI eventually and cause performance degradation of pouch cells [25]. Therefore, how to lower the negative influence of FEC and lessen the content of HF impurity will be discussed in this work. Nitrile additives, such as adiponitrile (APN) and succinonitrile (SN), as illustrated in Scheme 1, usually used in HV LCO battery system. Both of them can be mixed with high oxidation Co metal ion to protect the LCO cathode [26,27]. But whether nitriles have the same function on high nickel cathode and silicon anode is unknown. Therefore, both APN and SN electrolyte additives were researched to discuss the effects on the performance of SiO<sub>x</sub>/Gr||NCM811 pouch cells at elevated temperature.



Adiponitrile (APN)



Succinonitrile (SN)

**Scheme 1.** Chemical structure of APN and SN electrolyte additive

## 2. EXPERIMENTAL SECTION

### 2.1 Preparation of electrolytes and cells

Solvents: EC (Ethylene Carbonate, Purity>99.95%) and DEC (Diethyl Carbonate, purity>99.98%), offered by Shenzhen Capchem Chemicals Co., Ltd., both will be dried by 4A molecular sieves before usage. Electrolyte were made in an argon-filled glove box (Braun, Germany, H<sub>2</sub>O< 0.1ppm, O<sub>2</sub><0.1ppm ). Two blank electrolytes were selected in this experiment, with the formulation 1

mol/L LiPF<sub>6</sub> in EC/DEC=3:7 (wt.%) as blank1 electrolyte (noted as Blank1), and the formulation of 1 mol/L LiPF<sub>6</sub> in EC/DEC=3:7 (wt.%) with 10%FEC as blank2 electrolyte (noted as Blank2). In order to guarantee the quality of electrolyte, both HF and moisture will be controlled below 20 ppm by Karl-Fisher and NaOH titration. The experimental group of electrolytes were made by adding various kinds of additive and formulations are listed in Table 1&Table 2.

**Table 1.** Formulations of electrolytes used in SiO<sub>x</sub>/Gr||Li coin half cell

Electrolyte	Components
Blank 1(B1)	1 mol/L LiPF <sub>6</sub> in EC/DEC=3:7 (wt.%)
B1-APN	Blank 1 electrolyte + APN
B1-SN	Blank 1 electrolyte + SN

**Table 2.** Formulations of electrolytes used in SiO<sub>x</sub>/Gr||NCM811 pouch cell

Electrolyte	Components
Blank 2 (B2)	1 mol/L LiPF <sub>6</sub> in EC/DEC=3:7 (wt.%) with 10%FEC
B2-APN	Blank 2 electrolyte + 1%APN
B2-SN	Blank 2 electrolyte + 2%SN

Li-fun Technology (HuNan, China) supplied the pouch cells without any electrolyte. With the capacity of 1.8Ah, the cells are composed of high nickel NCM811 cathode and SiO<sub>x</sub>/Gr anode (10 wt.% SiO<sub>x</sub>). Steps are listed below: Firstly, the dry pouch cells will be cut a small opening along the air trap side to be dried in vacuum oven to dry the water, with the temperature of 85°C for 24 h. Secondly, the experimental electrolyte will be injected into the sealed pouch cell to achieve full electrolyte wetting at 45°C for about 48 h. Thirdly, after being charged to 3.7 V at 0.05 C, the cells will be placed in an oven of high temperature for about 48 h at 45°C. In this step, aging is finished. At last, the pouch cells were resealed by vacuum sealing machine. Formation steps were finished by charging the cells to 4.2V at 0.05C and discharging them to 3.0V.

The basic function of various additive is evaluated by CR2032 half coin cells composed in an argon-filled glove box with the active material of SiO<sub>x</sub>/Gr (cutting from the NCM811/SiO-C pouch cells). The physical separator is PE membrane and the counter electrode is Li wafer. The diameters of Li wafer and SiO<sub>x</sub>/Gr electrode are both 12 mm, and that of the separator is 17 mm.

## 2.2 Measurements

**Pouch cell formation:** After electrolyte injection, the pouch cells as-prepared were rest for 24 h at RT (Room Temperature) before being charged at 0.05 C for 3 h, 0.1 C for 3 h, 0.2 C for 2 h, with 5 mins rest between each step. The pouch cells were degassed and vacuum sealed at 180°C for 4 s after aging for 24h@45 ° C. After that, with the 0.05C as the cutting current, they were charged to 4.2V at 0.1C, then discharged to 3.0V at 0.2C.

**Pouch cell electrochemical test:** discharge/charge cycling performances were evaluated in Land C2000 battery test system. Before the test, the cells were put into the oven of 25°C to rest for 0.5 h. After that, with 20 mA as the cutting current in each cycle, they were charged to 4.2 V at 0.5 C and then discharged to 3.0V at 0.5 C.

Pouch cell rate capability test : the test was also carried out in the same system(Wu han, China). 100% SOC pouch cell was discharged with 0.2C, 1C and 2C in sequence after formation.

Pouch cell high temperature storage test: with 0.05C as the cutting current, the cells were firstly charged to 4.2 V at 0.05C after formation and then discharged to 3.0V or 2.75V at 1 C at 25 °C. with the discharge capacity marked as C1 accordingly. Then the cell was charged again to 4.2 V at 0.5 C, and reserved for a couple of days in the oven at 60 °C. After that, it was discharged to 3.0 V or 2.75V at 1 C at 25 °C with discharge capacity noted as C2 accordingly. Afterwards, a new charge/discharge cycle was conducted at 25 °C with the discharge capacity recorded as C3 accordingly. At last, evaluation can be carried out in the the capacity recovery (C3/C1) and capacity retention (C2/C1). On the basis of the Archimedes principle, before and after 60 °C storage, the thickness of swelling can be calculated by weighing the pouch cell in ultrapure water .

DQ/DV curves were tested to evaluate the reduction potential of various additives by Maccor battery test system[28].

Microstructure and morphology of SiO/Gr anode were profiled by the scanning of electron microscope (SEM, Hitachi S-4800) at 15KV.

Transition metal ion dissolution of cathode was evaluated by ICP measurement. After the formation, the concentration of Transition metal ion (Ni<sup>2+</sup>, Co<sup>2+</sup>, Mn<sup>2+</sup>) in electrolyte was analyzed by separating the pouch cell.

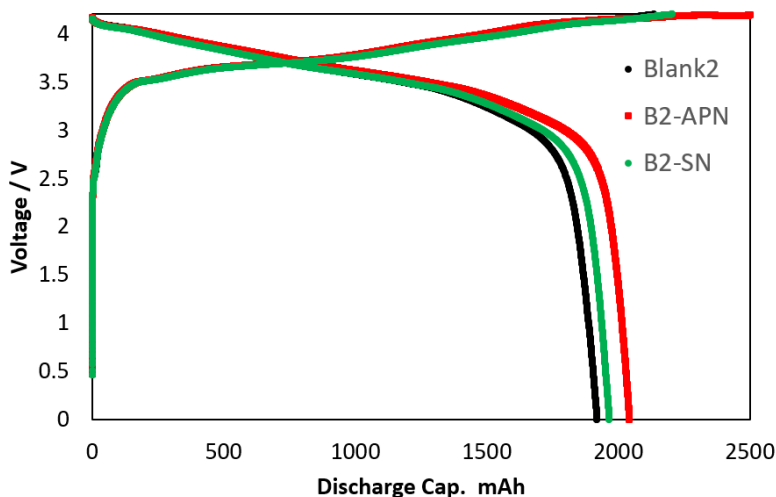
Additive consumption was tested by GC (gas chromatography) to analyze the residual contents of each additive in the charging step of 3.2V, 4.2V after capacity check.

### 3. RESULTS AND DISCUSSION

**Table 3.** HF of electrolytes before and after storage @ 60°C 7days

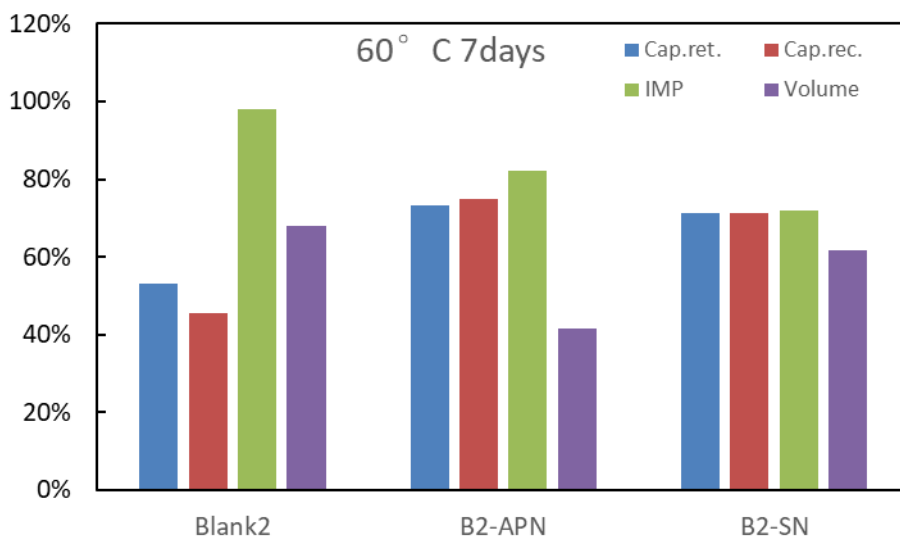
Electrolyte	HF content (ppm)	
	before Storage	after Storage
<b>Blank 2</b>	18	48
<b>B2-APN</b>	14	20
<b>B2-SN</b>	15	22

In order to evaluate the thermal instability of FEC in the electrolyte, the electrolyte of 1 mol/L LiPF<sub>6</sub> in EC/DEC=3:7 (wt.%) with 10%FEC (Blank2) with different kinds of nitriles were stored at 60°C for 7days, which is showed in Table 3. An obvious HF rising occurred in Blank2, which was about 160% from 18 to 48ppm. While electrolytes with nitriles of B2-APN and B2-SN has increased by about 40~50% for HF. The results indicate that many acidic compounds are produced in FEC electrolyte during HT storage. The reason has been discussed at last paper. With the strong electronegativity of FEC, it could initiate the decomposition of LiPF<sub>6</sub>, and the latter will produce PF<sub>5</sub> and HF. But obviously, we can observe from Table 3 that the addition of nitriles in the electrolyte has the ability to decelerate the formation of HF.



**Figure 1.** Initial charge-discharge curve of SiOx/Gr||NCM811 pouch cells in Blank2 electrolyte with different additives

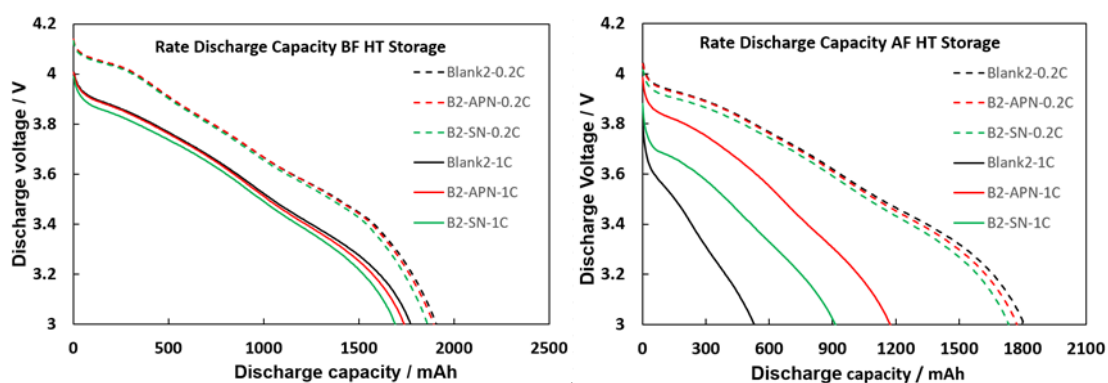
Fig. 1 presents the initial charge-discharge of SiOx/Gr||NCM811 pouch cells, 1 mol/L LiPF<sub>6</sub> in EC/DEC=3:7 (wt.%) with 10%FEC as based. Compared with nitriles electrolyte, a reduced discharge capacity of 1900 mAh is delivered by the FEC-based electrolyte without nitriles. While for nitriles electrolyte, the discharge capacity is 1965 mAh and 2040 mAh for SN and APN respectively. These results come from the electrochemical reduction of FEC, showing that the voltage for pouch cells with FEC is about 2.5 V with Li<sup>+</sup> intercalation. However, there is no extra reduction peaks in the initial charge curves after adding nitriles additives, indicating that the nitrile additives will not be reduced at the SiOx/Gr anode. It could suppress the consumption of FEC while increase the initial discharge capacity [1, 22].



**Figure 2.** High-temperature storage properties of SiOx/Gr||NCM811 pouch cells after stored at 60°C for 7 days with 100% SOC state

The inferior performance of FEC emerges in the volume expansion and gas generation during high temperature storage. Nitriles additives are used for improving high temperature performance for commercial LCO cells [4, 29]. To test whether nitriles additive still has the same advantages at high nickel –silicon system, tests were carried out on SiO<sub>x</sub>/Gr||NCM811 based pouch cells.

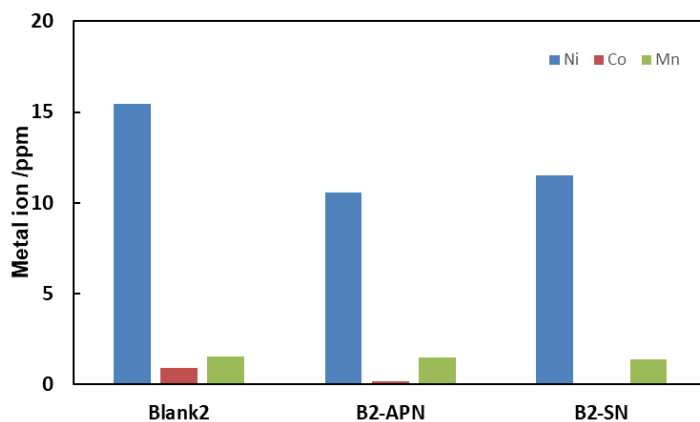
For commercial pouch batteries, one of the most important evaluation index is the high temperature storage performance. Fig. 2 demonstrates how did the SiO<sub>x</sub>/Gr||NCM811 pouch cells perform in high temperature storage with and without nitrile additive after stored at 60 °C for 7 days with 100% SOC state. At first, all cells were discharged to 3.0 V and then charged to 4.2V with 0.5 C at room temperature after storage. Fig. 2 collected and compared the capacity recovery (Rec.), performances of capacity retention (Ret.), swelling and impedance (IMP) growth respectively. Taking pouch cells with blank2 electrolyte as comparison, part of the results can be realized. Firstly, pouch cells without any nitriles(Blank2) appear highest IMP growth after being reserved at 60 °C for 7 days. The IMP growth is about 100% and volume increase by almost 70% for blank2. While for nitriles electrolyte, the IMP growth is about ~70% and ~80% , and volume growth is ~60% and ~40% for B2-SN and B2-APN. At the same time, both nitriles could improve the capacity Ret. and capacity Rec. after storage prominently. These results indicate that nitriles could also enhance the high temperature performance for SiO<sub>x</sub>/Gr||NCM811 pouch cells, showing the same trend with high voltage LCO cells. We can draw the conclusions that the deterioration of elevated temperature performance of SiO<sub>x</sub>/Gr||NCM811 pouch cells is more related with cathode materials. Therefore, the selection of the additives which could protect the cathode materials is an effective method to inhibit high temperature performance failure.



**Figure 3.** Rate discharge capacity of SiO<sub>x</sub>/Gr||NCM811 pouch cells after stored at 60°C for 7 days

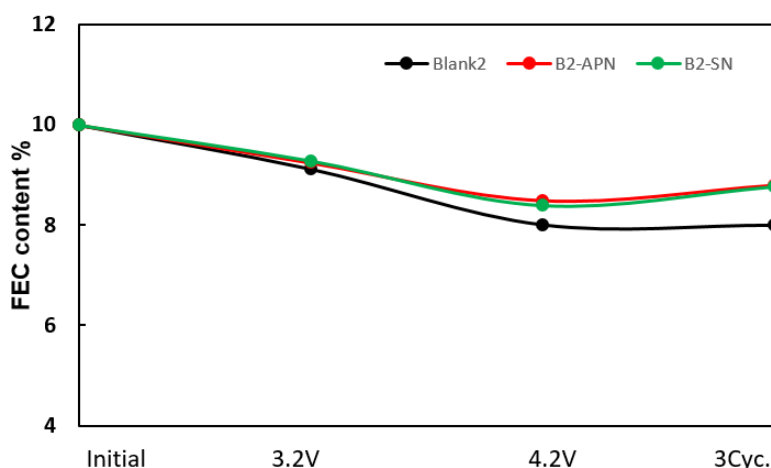
Except for high temperature storage performance, rate performance is also an important thing that needs special attention. Generally speaking, nitriles will increase the impedance and influence the rate performance in the high voltage LCO cell. **Fig. 3** displays rate discharge capacity of SiO<sub>x</sub>/Gr||NCM811 pouch cells with and without nitriles before and after the storage in high temperature. Firstly, pouch cell with and without nitriles showed no big difference of rate performance in high temperature, whether at 0.2C or 1.0C. Secondly, after HT storage, still no obvious difference occurs on discharge capacity for pouch cells with and without nitriles at 0.2C. However, at a big current of 1.0C,

a noticeable distinction emerges with, the pouch cell discharge capacity of 1169 (with APN), 912 (with SN) and 527mAh(without nitriles) respectively. The results showed that in the system of SiO<sub>x</sub>/Gr||NCM811, nitriles are in favor of rate current discharge, especially for high rate current. The reason is the FEC high temperature failure mechanism which leads to the deterioration of rate discharge performance without nitriles. While the electrolyte with nitriles could protect cathode and reduce the failure of FEC.



**Figure 4.** ICP results showing the amounts of the transition metal (Co, Mn, Ni) in SiO/Gr anodes retrieved from NCM811-SiO/Gr full cells after storage for 7 days at 60°C

We have discussed the effective influence of nitriles in FEC electrolyte at NCM811-SiO/Gr, nitrile which can improve elevated temperature performance and high rate discharge obviously. Some mechanism is discussed as following.

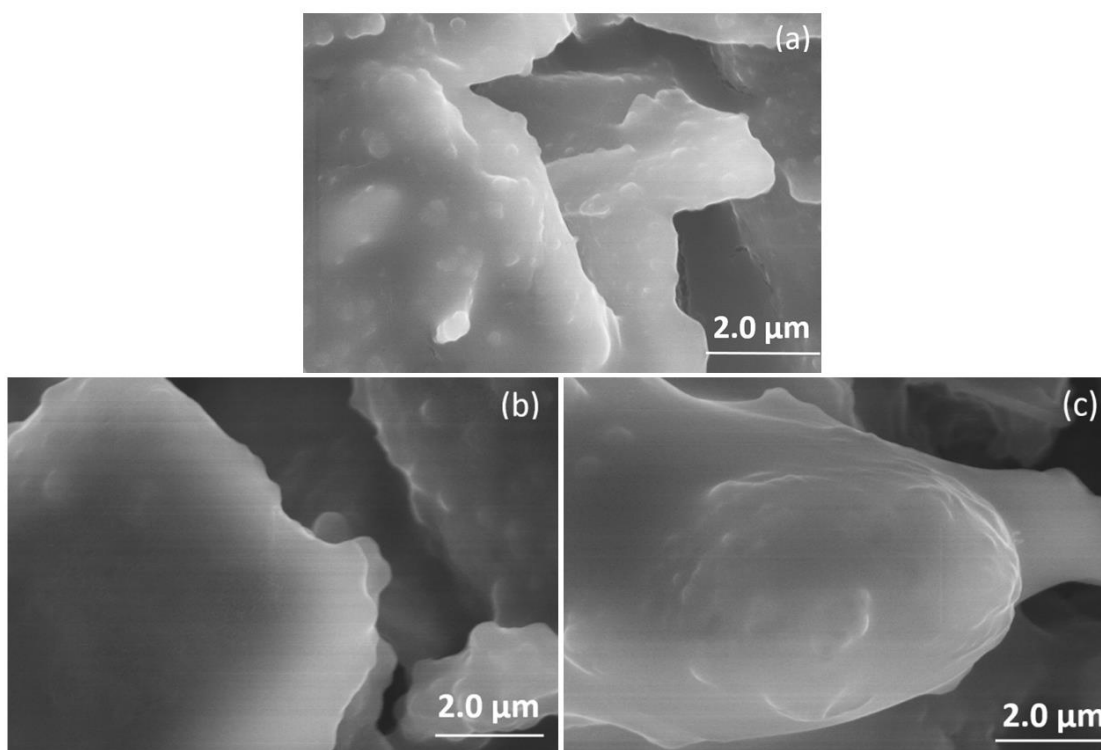


**Figure 5.** residue contents of FEC during initial, 3.2V, 4.2V and after 3 cycles from NCM811-SiO/Gr full cells

In the author’s last paper, attenuation mechanism of FEC has been discussed. We found that metal ion will be dissolved out of cathode, then deposited on anode. In this paper, deposition of transition metal ion (Ni, Co, Mn) on the anode was also confirmed by ICP. The anode of SiO/Gr was retrieved from full cells after stored for 7 days at 60°C. The data was listed in Fig.4. Firstly, nitriles additives could reduce metal ion dissolution, especially for Co ion. Almost no Co ion was observed at anode for

SN additive and APN has the priority of inhibiting Ni ion dissolution. Secondly, the quantities of transition metal Ni ion in the silicon anode was much higher compared to Co and Mn ion. Similarly, nitriles could also decrease Ni ion dissolution. We estimate that transition metal ions are more severely dissolved in the FEC electrolyte on the basis of these results. APN and SN could form the protecting CEI film on cathode and reduce the content of metal ion dissolution from cathode.

For the further exploration of the mechanism of nitriles additives in the FEC electrolyte, the consumption of FEC at different stage is tested. Fig. 5 shows the residue contents of FEC from NCM811-SiO/Gr full cells. In the four charge procedures: initial, charge to 3.2V, charge to 4.2V in 3 cycles. Usually, we assume that the consumption before 3.2V comes from anode and the consumption from 3.2 to 4.2V comes from cathode. So it can be concluded that FEC could be consumed both at anode and cathode [30,31]. From the data, the contents of FEC reduce from 10% to 8% in blank2, and the consumption of FEC is 2%. While the electrolyte with nitrile has the obvious lower FEC consumption compared with blank2, from 10% to ~8.8% for APN and SN within electrolyte. It indicates that the consumption of FEC is reduced by adding nitriles additive, and it could explain the former high temperature performance. For the electrolytes containing nitriles, gassing problems arising from reduction of FEC are inhibited in some extent.

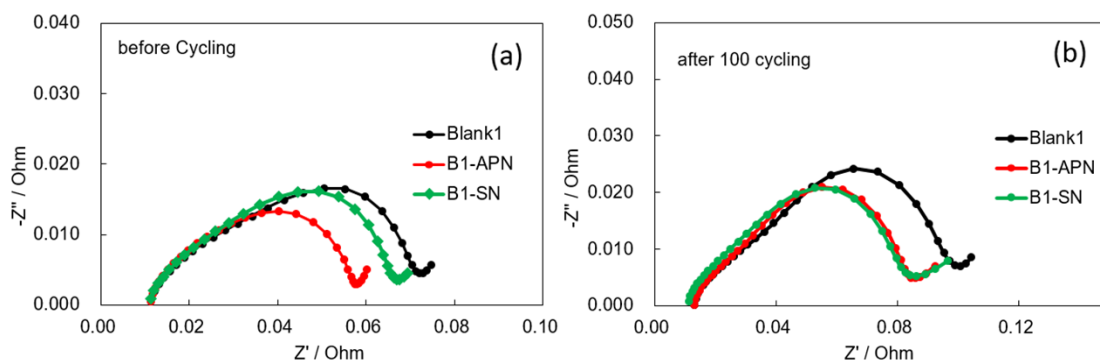


**Figure 6.** SEM images of SiOx/Gr anode after stored at 60°C for 7 days with 100% SOC state (a) Blank2; (b) B2-APN; (c) B2-SN

With the help of SEM, Microstructure were detected to evaluate their morphology of SiOx/Gr anode. Fig. 6 (a), (b) and (c) show SEM profiles of SiOx/Gr anode pouch cells without nitriles with APN



and with SN respectively. Without nitriles, it shows that the surface of SiO/Gr anode was rough covered with many microgroove, which is derived from the decomposition by-products of electrolyte. In the contrast, the surface of SiO/Gr anode were both smooth with nitriles additive utilization. Especially for the electrolyte which contain APN, there is not any cracking at the surface of SiO/Gr anode. The contrast represents that the nitriles additive is beneficial to the stable and smooth SEI forming in FEC electrolyte system.



**Figure 7.** Electrochemical impedance spectroscopy (EIS) of SiO/Gr|Li half cells in Blank1 based electrolyte (a) before cycling; (b) after 100 cycling.

Fig. 7 (a) shows the electrochemical impedance spectroscopy (EIS) of SiO/Gr|Li based on Blank1 electrolyte with half cells measured at 50% SOC before cycling. The high-frequency semicircle can be corresponding to the interface resistance between SEI and both electrodes, and the intermediate-frequency semicircle are related to the charge-transfer resistance ( $R_{ct}$ ) in the interface of electrode and electrolyte [32]. The Warburg impedance at low frequency arises from the  $\text{Li}^+$  ion diffusion process in the interface of electrolyte/SiO/Gr anode. In comparison to Blank1 half coin cell, nitriles additive usage can reduce the polarization resistance. Meanwhile, we found APN has smaller resistance than SN additive. EIS results after 100 cycles are presented in Fig. 7 (b) with almost no big difference between APN and SN additive. Both of them could decrease the impedance of SiO/Gr anode compared with blank1. The results attributed to the excellent SEI decoration function of nitriles.

#### 4. CONCLUSION

In summary, two kinds of nitriles were used as NCM811-SiO/Gr pouch cells electrolyte additive. Both APN and SN could decrease HF of the electrolyte from the decomposition of FEC, and can also help to produce stable SEI, restrict the decomposition of FEC additive and improve the high temperature performance of pouch cell, especially for the performance of high temperature storage and rate discharge after HT. In the aspect of SiO/Gr anode, through SEM images, nitriles could improve the morphology of SiO<sub>x</sub>/Gr anode and decrease the impedance after cycle. In the aspect of NCM811 cathode, nitriles could reduce the dissolution of metal ion of cathode. In brief, for high nickel-silicon pouch cell, since

FEC is an indispensable additive, nitriles could help to reduce the side reaction from FEC and the battery electrochemical performance is improved in this way.

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#### References

1. E. Markevich, G. Salitra, D. Aurbach, *ACS Energy Lett.*, 2 (2017) 1337–1345.
2. K. Chayambuka, G. Mulder, D.L. Danilov, P.H.L. Notten, *Adv. Energy Mater.*, 10 (2020) 1–11.
3. N. Paul, J. Wandt, S. Seidlmayer, S. Schebesta, M.J. Mühlbauer, O. Dolotko, H.A. Gasteiger, R. Gilles, *J. Power Sources*, 345 (2017) 85–96.
4. B. Deng, D. Sun, Q. Wan, H. Wang, T. Chen, X. Li, M. Qu, G. Peng, *Acta Chim. Sinica*, 76 (2018) 259.
5. S.S. Zhang, *J. Power Sources*, 162 (2006) 1379–1394.
6. J. Zhao, X. Zhang, Y. Liang, Z. Han, S. Liu, W. Chu, H. Yu, *ACS Energy Lett.* (2021) 2552–2564.
7. X. Wu, K. Song, X. Zhang, N. Hu, L. Li, W. Li, L. Zhang, H. Zhang, *Front. Energy Res.*, 7 (2019) 1–17.
8. K. Clemens, *Design News* (2019).
9. S. Zhang, M. He, C.-C. Su, Z. Zhang, *Current Opinion in Chemical Engineering*, 13 (2016) 24–35.
10. S. Dalavi, P. Guduru, B.L. Lucht, *J. Electrochem. Soc.*, 159 (2012) A642–A646.
11. K. Wang, L. Xing, Y. Zhu, X. Zheng, D. Cai, W. Li, *J. Power Sources*, 342 (2017) 677–684.
12. J. Xia, J.E. Harlow, R. Petibon, J.C. Burns, L.P. Chen, J.R. Dahn, *J. Electrochem. Soc.*, 161 (2014) A547–A553.
13. F. An, H. Zhao, W. Zhou, Y. Ma, P. Li, *Sci Rep*, 9 (2019) 14108.
14. B. Han, C. Liao, F. Dogan, S.E. Trask, S.H. Lapidus, J.T. Vaughey, B. Key, *ACS Appl. Mater. Interfaces*, 11 (2019) 29780–29790.
15. X. Li, Z. Yin, X. Li, C. Wang, *Ionics*, 20 (2014) 795–801.
16. K. Schroder, J. Alvarado, T.A. Yersak, J. Li, N. Dudney, L.J. Webb, Y.S. Meng, K.J. Stevenson, *Chem. Mater.*, 27 (2015) 5531–5542.
17. L. Chen, K. Wang, X. Xie, J. Xie, *J. Power Sources*, 174 (2007) 538–543.
18. D. Xu, Y. Kang, J. Wang, S. Hu, Q. Shi, Z. Lu, D. He, Y. Zhao, Y. Qian, H. Lou, Y. Deng, *J. Power Sources*, 437 (2019) 226929.
19. J.-G. Han, M.-Y. Jeong, K. Kim, C. Park, C.H. Sung, D.W. Bak, K.H. Kim, K.-M. Jeong, N.-S. Choi, *J. Power Sources*, 446 (2020) 227366.
20. T. Hou, G. Yang, N.N. Rajput, J. Self, S.-W. Park, J. Nanda, K.A. Persson, *Nano Energy*, 64 (2019) 103881.
21. M.A. Philip, R.T. Haasch, J. Kim, J. Yang, R. Yang, I.R. Kochetkov, L.F. Nazar, A.A. Gewirth, *Batteries & Supercaps* (2020) batt.202000192.
22. K. Kim, I. Park, S.-Y. Ha, Y. Kim, M.-H. Woo, M.-H. Jeong, W.C. Shin, M. Ue, S.Y. Hong, N.-S. Choi, *Electrochim. Acta*, 225 (2017) 358–368.
23. J. Xu, W.-H. Yao, Y.-W. Yao, Z. Wang, *ACTA PHYSICO-CHIMICA SINICA*, 25 (2009).
24. Fangrong Hu, M.Z. *Chin. Phys. B*, 30 (2021) 68202–068202.
25. Y. Abu-Lebdeh, I. Davidson, *J. Electrochem. Soc.*, 156 (2009) A60.
26. S. Li, D. Zhao, P. Wang, X. Cui, F. Tang, *Electrochim. Acta*, 222 (2016) 668–677.

27. N. Ehteshami, A. Eguia-Barrio, I. de Meatza, W. Porcher, E. Paillard, *J. Power Sources*, 397 (2018) 52–58.
28. H.M. Dahn, A.J. Smith, J.C. Burns, D.A. Stevens, J.R. Dahn, *J. Electrochem. Soc.*, 159 (2012) A1405–A1409.
29. X. Wang, W. Xue, K. Hu, Y. Li, Y. Li, R. Huang, *ACS Appl. Energy Mater.* (2018) acsaem.8b00968.
30. N.E. Galushkin, N.N. Yazvinskaya, D.N. Galushkin, *J. Electrochem. Soc.*, 166 (2019) A897.
31. Y. Kim, *J Mater Sci*, 48 (2013) 8547–8551.
32. W. Zhao, B. Zheng, H. Liu, F. Ren, J. Zhu, G. Zheng, S. Chen, R. Liu, X. Yang, Y. Yang, *Nano Energy*, 63 (2019) 103815

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