Silicon-carbon composite dispersed in a carbon paper substrate for solid polymer lithium-ion batteries

Q. Si^{a,*}, M. Kawakubo^a, M. Matsui^a, T. Horiba^a, O. Yamamoto^a, Y. Takeda^a, N. Seki^b,

N. Imanishi^a

^a Department of Chemistry for Materials, Graduate School of Engineering,

Mie University, 1577 Kurimamachiya-cho, Tsu, Mie 514-8507, Japan

^b Industrial Technology Center, Gifu Prefectural Government, 777 Maeno,

Mino, Gifu 501-3716

Abstract

Carbon coated silicon (Si/C) dispersed in a carbon paper (CP) was examined as the anode for solid polymer lithium-ion batteries. The CP was prepared by pyrolysis of poly(acrylonitrile) fiber and Manila hemp non-woven cloth at 2600 °C under an inert atmosphere. The Si/C composite was formed by pyrolysis of a slurry consisting of Si powder and a solution of polyvinylchloride in tetrahydrofuran as the carbon source. Si/C:CP with a weight ratio of 20:100 had a high initial capacity of 980 mAh g⁻¹ of Si/C and a high initial columbic efficiency of 77%, and also exhibited excellent capacity

retention with a reversible capacity of 710 mAh g⁻¹ of Si/C even after 250 cycles at a charge and discharge rate of 0.1 A g⁻¹. The carbon fiber framework in the carbon paper could adsorb the volume change of Si during the lithium insertion and stripping processes.

Keywords: PEO-based electrolyte, Si/C composite electrode, Carbon paper substrate, Lithium-ion batteries, Cycle performance

Corresponding author: [Tel:+81-59-231-9420](tel:+81-59-231-9420), Fax: +81-59-231-9478

E-mail: siqin@chem.mie-u.ac.jp

1. Introduction

In recent years, larger capacity and high energy density batteries have been required for applications such as hybrid electric vehicles (HEVs), electric vehicles (EVs) and load leveling devices. However, conventional lithium-ion batteries with high energy density include a higher risk of fire or explosion than those with aqueous electrolytes such as metal-hydride batteries, because the former includes a large amount of flammable electrolyte. Therefore, safer batteries that provide large capacity and high energy density are required. The use of lithium polymer electrolytes that employ a less flammable solid polymer electrolyte may be a reasonable solution to address these safety issues.

Since the introduction of polyethylene oxide (PEO)-based lithium polymer electrolytes to lithium batteries in the late 1970s [1], many researchers have attempted to identify solid polymer electrolyte formulations that would combine high ionic conductivity and good mechanical properties. At present, it is recognized that the PEO-based polymer electrolyte is the best candidate for lithium polymer batteries [2]. Previously developed solid polymer electrolyte lithium batteries have mainly used lithium metal as the anode and an oxide cathode [3]. Although lithium metal can provide high energy density, safety problems can arise due to dendrite formation on the

lithium metal electrode during the charging process [4] and a high reaction heat with the polymer electrolyte of 4500 J mAh^{-1} , which is compared with that of carbon and the polymer electrolyte of 1.2 J mAh^{-1} [5]. Therefore, an alternative anode for lithium polymer batteries should be developed. Initially, the carbon anode commonly used for lithium-ion batteries has been recognized to have poor compatibility with polymer electrolytes. Imanishi *et al.* [6] and Kobayashi *et al.* [7] have shown that spherical graphite exhibits a high reversible capacity as the anode for polymer electrolyte batteries, the capacity of which was comparable to that with a liquid electrolyte. However, the capacity of the carbon anode with the polymer electrolyte was dependent on the thickness of the electrode [6]. Recently, Imanishi and co-workers [8] reported a high capacity carbon anode that was $60 \text{ }\mu\text{m}$ thick for solid-polymer lithium-ion batteries. The electrode, which consists of mesocarbon microbeads (MCMB), $\text{PEO}_{19}\text{LiCF}_3(\text{SO}_2)_2\text{N}$ (LiTFSI), vapor growth carbon fiber (VGCF), and carbon nanofiber (CNF), has excellent cycling performance with a reversible capacity of *ca.* 310 mAh g^{-1} of MCMB and reversible capacity retention of 97% at the 50th cycle. However, the rate performance of the carbon anode with the polymer electrolyte was not sufficient for practical application.

Silicon is an attractive anode material for lithium-ion batteries, due to a high

theoretical capacity ($4,200 \text{ mAh g}^{-1}$ as $\text{Li}_{4.4}\text{Si}$) and low lithium insertion potential versus Li/Li^+ [9-12]. However, its commercial use for the lithium-ion batteries has been hindered by the large volume change during Li-alloying and extraction, which inevitably introduces cracking or crumbling of the anode material and thus causes loss in capacity during cycling [13]. Many approaches have been proposed to overcome the large volume change and obtain excellent capacity retention and cycling performance for Si anodes, for example, using Si nanostructured materials [14,15], the preparation of Si-based composites [16-18], and modification of the current collector [19,20]. We previously examined a composite electrode of 50 nm Si powder and a pyrolytic carbon of polyvinyl chloride (PVC) with CNF using a copper foil substrate as an anode for solid-polymer lithium-ion batteries [21]. The electrode exhibited a high reversible capacity of more than $1,000 \text{ mAh g}^{-1}$ after 40 cycles. However, this electrode showed a large irreversible capacity at the first cycle. The coulombic efficiency at the first cycle was as low as 44%.

In this study, we have examine a new Si/C composite anode for solid polymer lithium-ion batteries that employs a carbon paper as a three-dimensional conductive substrate, and which was previously proposed by us as a possible anode configuration for lithium-ion batteries [22]. The three-dimensional structure can incorporate the active

material and polymer electrolyte into the current collecting network, due to improved adhesion between the carbon fiber of the paper and the Si/C composite deposited on the carbon paper matrix by the thermal decomposition of a Si-PVC mixture.

2. Experimental

The composite electrode with carbon paper substrate was prepared according to the following procedure. Si powder (average particle size of 0.5 μm , Kinsei Matec, Japan) and PVC (Sigma-Aldrich) were mixed in tetrahydrofuran (THF) at a weight ratio of 5:95 to form a slurry in which the carbon paper (CP) was steeped, and then heated at 900 $^{\circ}\text{C}$ for 2 h in 2% H_2 -Ar. The electrode contained only the composite active materials without a binder. The weight ratios of Si/C:CP were 20:100 (Si/C/CP-20) and 40:100 (Si/C/CP-40). Non-woven cloth made from a mixture of Manila hemp and poly(acrylonitrile) fibers (4:6 weight ratio) was carbonized in an inert atmosphere at 2600 $^{\circ}\text{C}$ to form the CP, the physical properties of which are summarized in Table 1. The composite electrode was cut into a 12 mm diameter disk, followed by drying at 120 $^{\circ}\text{C}$ under vacuum for 2 h. The specific capacity was based on the weight of Si/C in the electrode. The cathode prepared for the test cell consisted of a mixture of carbon-coated LiFePO_4 (Housen, Japan), CNF (10-20 nm diameter, 0.1-10 μm length,

Jemco, Japan), and polyvinylidene difluoride (PVdF). The weight ratio of $\text{LiFePO}_4/\text{CNF}/\text{PVdF}$ was 87:5:8. N-methyl pyrrolidone (NMP) was used as a solvent for preparation of the slurry. The electrode slurries were then coated on Al foil using a coating machine.

The PEO-based polymer electrolyte was prepared by dissolving PEO (Aldrich, average molecular weight: 6×10^5) and LiTFSI (Fluka) in acetonitrile (AN) with a molar ratio of $\text{Li}:\text{O}=1:18$. The polymer electrolyte solution was dripped onto a non-woven polyethylene and polyester composite sheet in a polytetrafluoroethylene (PTFE) dish under an argon atmosphere. After the evaporation of AN at room temperature, the formed film was dried at $110\text{ }^\circ\text{C}$ for 12 h in vacuum. The resulting film thickness was approximately $220\text{ }\mu\text{m}$.

Laminate-type sandwich cells of $\text{Li}/\text{PEO}_{18}\text{LiTFSI}/\text{Si}/\text{C}/\text{CP}$ were used to examine the performance of the $\text{Si}/\text{C}/\text{CP}$ electrodes. The thickness of the lithium sheet was approximately $20\text{ }\mu\text{m}$. The two sheets of $\text{Si}/\text{C}/\text{CP}$ electrode and PEO electrolyte were preheated at $80\text{ }^\circ\text{C}$ for 3 h to ensure a good contact between the two components and to induce penetration of the PEO electrolyte into the $\text{Si}/\text{C}/\text{CP}$ electrode. These cells were assembled in an Ar-filled glove box. The cells were galvanostatically charged and discharged at $60\text{ }^\circ\text{C}$ with a cut-off voltage range of 0.02-1.5 V using a battery cycler

(Nagano BTS 2004H). For the liquid electrolyte system, coin-cells (type 2025) were assembled in an Ar-filled glove box using 1 M LiClO₄ in a mixed solution of (1:1 v/v) ethylene carbonate (EC) and diethylene carbonate (DEC) as the electrolyte. The charge/discharge rate was 0.1 A g⁻¹ of Si/C, except for the rate performance measurements, where a charge/discharge rate of 0.1 mA cm⁻² was used. The morphology of the electrode was examined using scanning electron microscopy (SEM; Hitachi SEM S-4800) and energy-dispersive X-ray spectroscopy (EDX; Horiba). Impedance measurements were performed using an impedance/gain-phase analyzer (Solartron SI1260) and an electrochemical interface (Solartron SI1287).

3. Results and discussion

Figure 1 shows SEM images of the CP (Fig. 1 (a)) and Si/C/CP-20 (Fig. 1(b)) surfaces, and the EDX distribution maps for Si (Fig. 1(c)) and S (Fig. 1(d)) in Si/C/CP-20. The magnified SEM image of Si/C/CP shows that Si particles are deposited on the carbon fiber matrix (*ca.* 7 μm in diameter) of the CP, and the pyrolytic carbon of PVC on Si may act as a binder to connect Si and the carbon fibers. The distribution of Si is homogenous over the CP matrix. The S distribution map suggests that the polymer electrolyte penetrated the entire CP matrix by heat treatment at 80 °C.

Although Si has a high lithium insertion capacity, Li insertion into Si is accompanied by a large change in volume (maximum 320%), which causes strong mechanical stress to the Si crystallites, and thus a loss of electrical contact [23]. The mechanical stress results in rapid loss of the reversible capacity with prolonged cycling. In particular, a large irreversible capacity over 50% was observed during the first few cycles. We have previously examined a composite electrode of 50 nm Si powder and a pyrolytic carbon of PVC with CNF (Si/C/CNF) as an anode for solid-polymer lithium-ion batteries [21]. This Si/C/CNF composite electrode exhibited good cycling performance, but suffered from a low initial coulombic efficiency, which was as low as 44%. In contrast, the present Si/C/CP composite electrode had a high initial coulombic efficiency. Figure 2 (a) shows initial charge-discharge curves for the Li/PEO₁₈LiTFSI/Si/C/CP-20 cell at 60 °C. The initial discharge capacity of the Si/C/CP electrode was 1,280 mAh g⁻¹, while the charge capacity was 980 mAh g⁻¹. The irreversible capacity for the initial cycle was 23%. The irreversible capacity rate for the first cycle is comparable to that of a carbon electrode composed of spherical MCMBs with the polymer electrolyte (ca. 20-30%) [8]. The irreversible capacity of the Si/C/CP-20 electrode was significantly lower than that observed for the Si/C/CNF electrode (ca. 56%) with the polymer electrolyte [21] and also lower than that for Si/C/CNF (ca. 38%) with a liquid electrolyte [24], where silicon

powder with 50 nm particles were used. Furthermore, the 60-70 μm thick Si/C/CNF electrode with the polymer electrolyte exhibited a smaller initial discharge capacity of ca. 500 mAh g^{-1} [21]. Figure 2(b) shows the cycling performance and coulombic efficiency of the Si/C/CP-20 electrode. The electrode had a high initial reversible capacity of 980 mAh g^{-1} , and the reversible capacity of 710 mAh g^{-1} was retained even after 250 cycles at a charge and discharge rate of 0.1 A g^{-1} (0.1 mA cm^{-2}). The reversible capacity loss rate of 0.11% per cycle is higher than that for the carbon electrode with polymer electrolyte (0.06%) [8], but lower than that of Si nanowires with a liquid electrolyte (0.83%) [25]. The coulombic efficiency at 250 cycles was still 100%. The capacity increase during the first ten cycles could be explained by a decrease in the electrode resistance due to the good contact maintained between Si/C and CP during the lithium insertion and stripping processes.

A problem of the carbon anode with the polymer electrolyte is the poor rate performance [6]. The capacity of 320 mAh g^{-1} at a 1/10C rate for the MCMB carbon electrode decreased to 100 mAh g^{-1} at a 1/2C rate (ca. 0.25 mA cm^{-2}). Figure 3 shows the cyclic performance of the Si/C/CP electrode at 60 $^{\circ}\text{C}$ up to 10 cycles at various rates. A reversible capacity of 500 mAh g^{-1} and good cyclic performance were obtained at 0.4 A g^{-1} and the charge and discharge coulombic efficiency was 100%. The rate of 0.4 A g^{-1}

corresponds to 0.8C and 0.4 mA cm^{-2} . At a high current density of 1.0 A g^{-1} (3.7C), the discharge capacity of 300 mAh g^{-1} was obtained, but the lithium stripping capacity (discharge) was higher than the lithium deposition capacity (charge); however, the reason for this difference has yet to be clarified.

To further understand the characteristics of the Si/C/CP-20 electrode, the change in the impedance profiles of the Si/C/CP-20 electrode with cycling was examined. Figure 4 shows impedance profiles measured as a function of cycling and the change in capacity with cycling, where the cells were cycled at 60°C and at a rate of 0.1 A g^{-1} . The impedance profiles of the Li/PEO₁₈LiTFSI/Si/C/CP-20 cell at a cell voltage of 0.8 V after 6 cycles show a semicircle in the high frequency range and a diminished semicircle in the low frequency range. The high frequency semicircle could be attributed to the formation of a solid electrolyte interface (SEI) at the interface of Li and the electrolyte, and the low frequency semicircle to the interface resistance between Si/C/CP-20 and the polymer electrolyte (including charge transfer resistance) [26]. The intercept of the semicircle at the high frequency range on the real axis at a high frequency represents the bulk resistances of the electrolyte and electrode. The Si/C/CP-20 electrode with the PEO-based electrolyte shows a decrease of interface resistance between Si/C/CP-20 and the polymer electrolyte with cycling. The increase

of the reversible capacity up to 10 cycles could be explained by a decrease in the interface resistance. It is not clear why the interface resistance decreases with cycling, but this may be due to an increase of active sites for charge transfer by the morphological change caused by lithium insertion and stripping, which results in a decrease of the charge transfer resistance.

The Si/C/CP-20 composite electrode with the polymer electrolyte has excellent cycling performance at a high rate, but the capacity per total weight of electrode is not so high, because the loading ratio of Si/C to CP is only 20 wt% to CP. The capacity of the composite electrode per gram of total weight is approximately 193 mAh g^{-1} after 30 cycles, which is higher than the 149 mAh g^{-1} obtained for the $60 \text{ }\mu\text{m}$ thick carbon electrode [8]. The high Si/C loaded composite anode of Si/C/CP-40 (Si/C:CP = 40:100 weight ratio) was examined. Figure 5 shows the cycling performance at a charge and discharge rate of 0.1 A g^{-1} and the change in the impedance profile with cycling for the Li/PEO₁₈LiTFSI/Si/C/CP-40 cell at a cell voltage of 0.8 V. The specific capacity increases slightly with cycling, but the capacity after 30 cycles is almost half that of the Si/C/CP-20 electrode. The impedance profiles of the Si/C/CP-40 electrode are similar to those of Si/C/CP-20. The lower specific capacity of the high Si/C loaded electrode could be explained by a disproportional increase in the number of charge transfer active

sites in Si/C/CP-40 with the amount of Si/C. SEM images of the surface and cross-section of the Si/C/CP electrode before and after cycling were examined. Figure 6 shows SEM images of (a) the Si/C/CP-20 surface after 250 cycles, and a cross-sections of the same (b) before, and (c) after 250 cycles at 0.1 A g^{-1} and 60°C . The thickness of the cross-section after 250 cycles is almost the same as that before cycling, which suggest that the carbon fiber matrix absorbs the volume change of Si with cycling. In contrast, the Si/C/CP-40 electrode was significantly expanded with cycling. Figure 6 shows SEM images of (d) the Si/C/CP-40 surface after 60 cycles, and a cross-section of the same (e) before and (f) after 60 cycles at 0.1 A g^{-1} and 60°C . The electrode thickness of $150 \text{ }\mu\text{m}$ before cycling was expanded to $248 \text{ }\mu\text{m}$ after 60 cycles. Thus, the CP matrix with a high content of Si/C may not absorb the volume change of all the Si/C particles with cycling. Therefore, the specific capacity of the Si/C/CP electrode cannot be improved by further addition of Si/C into the CP matrix. The specific capacity of the total weight including CP for Si/C/CP-20 is only 193 mAh g^{-1} after 30 cycles. The previously reported specific capacities of various anodes for polymer electrolyte cells are summarized in Table 2. The Si/C/CP electrode has the highest gravimetric specific capacity of these anodes. The Si/C/CP electrode has another advantage of low resistance, so that the amount of current collector could be lowered for battery fabrication.

The Si/C/CP-20 electrode with less expensive semi-micron sized silicon powder particles exhibits excellent cyclic performance as an anode for lithium polymer electrolyte cells. An all-solid-state cell using the Si/C/CP-20 electrode and the less expensive and safe cathode of LiFePO_4 was constructed and the cell performance was examined at 60 °C. Figure 7 shows charge and discharge profiles for the Si/C/CP/PEO₁₈LiTFSI/LiFePO₄ cell at 0.1 A g⁻¹ and 60 °C. The reversible capacity of LiFePO₄ was *ca.* 150 mAh g⁻¹, which is comparable to that observed for the Li/1M LiClO₄-EC-DEC/LiFePO₄ cell. Thus, it was confirmed that this cell exhibits excellent cycling performance.

4. Conclusion

A new composite electrode composed of carbon coated Si (Si/C) and carbon paper was examined as an anode for solid-polymer Li-ion batteries. The electrode with a PEO-based polymer electrolyte had a high initial coulombic efficiency of 77% and a steady reversible capacity of 710 mAhg⁻¹ after 250 cycles at 60 °C with a charge and discharge rate of 0.1 A g⁻¹. The capacity of this electrode with the polymer electrolyte is higher than that of the carbon electrode with the polymer electrolyte, and the rate performance of the composite electrode is better than that of the carbon electrode. The

improved performance of the electrode with the polymer electrolyte could be due to a synergistic effect of the conductive network within the carbon paper and the Si/C composite active materials. The other advantage of this type of composite silicon anode is that less expensive submicron silicon could be used. All-solid-state batteries of Si/C/CP/polymer electrolyte/LiFePO₄ have potential for application in for large scale electric power storage systems, due to their safety and less expensive material cost.

Acknowledgement

This research was sponsored by the Japan Science and Technology Agency (JST) under the Adaptable and Seamless Technology Transfer Program (A-STEP).

References

- [1] M. Armand, J.M. Chabagno, M.J. Duclot, in: P. Vashishita, J.N. Mundy, G.K. Shenoy (Eds.), Fast Ion Transport in Solids, Elsevier, New York, 1979.
- [2] J.-M. Tarascon, A. M. Armand, Nature 414 (2001) 359.
- [3] M. Gauthier, D. Fauteux, G. Vassort, A. Bélanger, M. Duval, P. Ricoux, J.M. Chabagno, D. Muller, P. Rigaud, M.B. Armand, D. Deroo, J. Electrochem. Soc. 132 (1985) 1333.

- [4] C. Brissot, M. Rosso, J.N. Chazalviel, S. Lascaud, J. Power Sources 81/82 (1999) 925.
- [5] D. Saito, Y. Ito, K. Hanai, T. Kobayashi, N. Imanishi, A. Hirano, Y. Takeda, O. Yamamoto, J. Power Sources 195 (2010) 6172.
- [6] N. Imanishi, Y. Ono, K. Hanai, R. Uchiyama, Y. Liu, A. Hirano, Y. Takeda, O. Yamamoto, J. Power Sources 178 (2008) 744.
- [7] Y. Kobayashi, S. Seki, Y. Mita, Y. Ohno, H. Miyashiro, P. Charest, A. Guerfi, K. Zaghib, J. Power Sources 185 (2008) 542.
- [8] M. Kawakubo, Y. Takeda, O. Yamamoto, N. Imanishi, J. Power Sources 225 (2013) 187.
- [9] M.N. Obrovac, L. Christensen, Electrochem. Solid-State Lett. 7 (2004) A93.
- [10] R.A. Sharma, R.N. Seefurth, J. Electrochem. Soc. 123 (1976) 1763.
- [11] B.A. Boukamp, O.C. Lesh, R.A. Huggins, J. Electrochem. Soc. 128 (1981) 725.
- [12] W.J. Weylanz, M. Wohlfahrt-Mehnes, R.A. Hugins, J. Power Sources 81-82 (1999) 237.
- [13] W.J. Zhang, J. Power Sources 196 (2011) 13.
- [14] H. Wu, Y. Cui, Nano Today, 7 (2012) 414.
- [15] R. Jeannine, S. Szczech, Energy Environ. Sci. 4 (2011) 56.

- [16] Y. Li, B.K. Guo, L.W. Ji, Z. Lin, G.J. Xu, Y.Z. Liang, S. Zhang, O. Toprakci, Y. Hu, M. Alcoutlabi, X.W. Zhang, Carbon 51 (2013) 185.
- [17] Y. Hwa, W.S. Kim, S.H. Hong, H.J. Sohn, Electrochim. Acta 71 (2012) 201.
- [18] X.Y. Zhou, J.J. Tang, J. Yang, J. Xie, L.L. Ma, Electrochim. Acta 87 (2013) 663.
- [19] Y.L. Kim, Y. K. Sun, S.M. Lee, Electrochim. Acta 53 (2008) 4500.
- [20] Q. Sa, Y. Wang, J. Power Sources 208 (2012) 46.
- [21] Q. Si, K. Hanai, T. Ichikawa, A. Hirano, N. Imanishi, O. Yamamoto, Y. Takeda, J. Power Sources 196 (2011) 6982.
- [22] Q. Si, M. Matsui, T. Horiba, O. Yamamoto, Y. Takeda, N. Seki, N. Imanishi, J. Power Sources 241 (2013) 744.
- [23] S. Bourderau, T. Brouse, D.M. Schleich, J. Power Sources 81-82 (1999) 233.
- [24] Q. Si, K. Hanai, T. Ichikawa, A. Hirano, N. Imanishi, Y. Takeda, O. Yamamoto, J. Power Sources 195 (2010) 1720.
- [25] N.S. Choi, Y. Yao, Y. Cui, J. Cho, J. Mater. Chem. 21 (2011) 9825.
- [26] Y. Ito, M. Kawakubo, M. Ueno, H. Ohkuma, Q. Si, T. Kobayashi, K. Hanai, N. Imanishi, A. Hirano, M.B. Phillipps, Y. Takeda, O. Yamamoto, J. Power Sources 214 (2012) 84.
- [27] J. Yang, Y. Takeda, C. Capiglia, X.D. Liu, N. Imanishi, O. Yamamoto, J. Power

Sources 119-121 (2003) 56.

Figure captions

Fig. 1. SEM images of (a) the surface of CP, and (b) the surface of the Si/C/CP electrode.

EDX distribution maps of (c) Si, and (d) S in the Si/C/CP electrode.

Fig. 2. (a) Initial charge and discharge curves and (b) cyclic performance for the Si/C/CP electrode with PEO₁₈LiTFSI at 0.1 A g⁻¹ and 60 °C at cut-off voltages from 0.02 to 1.5 V.

●: lithium insertion into Si/C/CP, ○: lithium stripping from Si/C/CP

Fig. 3. Rate performance for the Si/C/CP electrode with PEO₁₈LiTFSI at 60 °C at cut-off voltages from 0.02 to 1.5 V.

●: lithium insertion into Si/C/CP, ○: lithium stripping from Si/C/CP

Fig. 4. (a) Impedance profiles for the Li/PEO₁₈LiTFSI/Si/C/CP cell after cycling and (b) cycling performance of the cell at 0.1 A g⁻¹ and 60 °C with cut-off voltages from 0.02 to 1.5 V.

●: lithium insertion into Si/C/CP, ○: lithium stripping from Si/C/CP

Fig. 5. (a) Cyclic performance and (b) impedance profiles for the Si/C/CP-40 electrode at 0.1 A g⁻¹ and 60 °C with cut-off voltages from 0.02 to 1.5 V.

●: lithium insertion into Si/C/CP, ○: lithium stripping from Si/C/CP

Fig. 6. (a) Surface SEM images of the Si/C/CP-20 electrode after 250 cycles and cross-sectional SEM image of the same (b) before and (c) after 250 cycles at 0.1 A g^{-1} and 60°C . (d) Surface SEM image of the Si/C/CP-40 electrode after 60 cycles and cross-sectional of the same (e) before and (f) after 60 cycles at 0.1 A g^{-1} and 60°C with cut-off voltages from 0.02 to 1.5 V

Fig. 7. Charge and discharge performance of the Si/C/CP/PEO₁₈LiTFSI/LiFePO₄ cell at 0.1 A g^{-1} and 60°C and the charge capacity change of LiFePO₄ by cycling with cut-off voltages from 1.5 to 3.8 V.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Table 1 Physical properties of the carbon paper

Fiber (wt. %)	Carbonization temperature (°C)	Thickness (μm)	Density (g cm ³)	Graphitization (%)	Electrical conductivity (S cm ⁻¹)
Manila hemp/PAN=4/6	2,600	150	0.301	28.5	303

Table 2 Gravimetric capacities based on the total weight of various anodes for polymer electrolytes

	Electrode weight (mg cm ⁻²)	Electrode thickness (μm)	Capacity (mAh g ⁻¹)		Electrode conductivity (S cm ⁻¹)	Reference
			Initial	After 30 cycles		
Si/C/CP	1.0	150	163	193	3.0	
SnSb/Li _{2.6} Co _{0.4} N/PEO ¹ /PE ² /Ni		45~55	360	192 ³		27
MCMB ⁴ /CNF ⁵ /VGCF ⁶ /PEO	2.4	60	149	149	0.62	8

¹ polyethylene oxide with Li(CF₃SO₂)₂N, ² polyethylene, ³ after 10 cycles

⁴ mesocarbon microbeads, ⁵ carbon nano-fiber, ⁶ vapor grown carbon fiber