

3D-structured Cathode Electrode for High Capacity Lithium-ion Battery

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ABSTRACT

A study was made of 3D structuring applied to electrode collectors for the purpose of heightening lithium-ion battery performance.

It was confirmed that loading, which is the electrolyte composite coating amount per unit area, could be increased to 150 mg/cm² on the cathode. The results from the calculation of energy density when that electrode was applied clearly showed that energy density could be increased 10% with respect to the foil-coated cathode.

The results from comparison of the foil-coated cathode and 3D-structured cathode with the cathode loading fixed at 90 mg/cm² confirmed that increasing the contact area of the active material and the collector can reduce the initial resistance by 17% with respect to the foil-coated cathode. It was also confirmed that, while the resistance increase during cycle testing was 149% for the foil-coated cathode, this amount was held to 29% for the 3D-structured cathode because of the suppression of structural change.

It was verified that application of the 3D-structured cathode in a lithium-ion battery could achieve a balance between enhancing energy density and addressing the issue of suppressing the increase in resistance and the decrease in durability.

1. Introduction

Reducing automobile CO₂ emissions is a crucial issue in moving toward realization of a low-carbon society. Enhancing fuel economy by electrification of automobiles and achieving full, widespread adoption of electric vehicles are key measures to address that issue^{(1),(2)}. For that purpose, increasing the energy density of lithium-ion batteries becomes a crucial issue^{(3),(4)}.

As shown in Fig. 1, the internal section of a lithium-ion battery consists of the cathode, anode, separator, and electrolyte. The electrodes (cathode and anode) consist of the active material, conductive agent, binder, and collector. The energy density (Wh/L) is calculated as the product of capacity (Ah) and voltage (V) divided by volume (L). The capacity of a battery is determined by the capacity per unit volume of active material in the electrodes and the filling amount of that material.

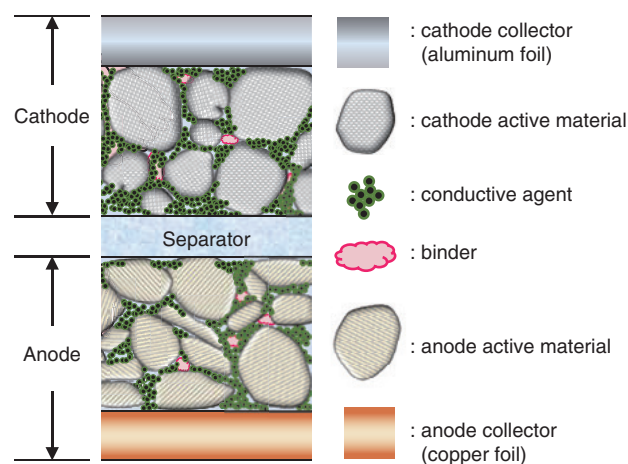


Fig. 1 Schematic section drawing of lithium-ion battery

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The electrodes for lithium-ion batteries in general are manufactured by the processes shown in Fig. 2. As shown in Fig. 2 (a), each of the materials is mixed with a solvent to adjust the composite slurry. Next, as shown in Fig. 2 (b), a coater is used to coat the surface of the metallic foil collector with the composite slurry. After that, it is dried and the solvent is caused to vaporize. Then, as shown in Fig. 2 (c), it is pressure-formed by roll pressing and the electrode is completed.

There are active initiatives to increase the energy density by giving the active material higher capacity or higher voltage. However, these involve such issues as decreases in durability and safety⁽⁵⁾⁻⁽¹⁰⁾.

On the other hand, increasing the coating amount per unit area (hereafter the loading) of electrodes without changing the active material causes a reduction in the number of electrode layers. As a result, the amount of separator and collector used can be reduced. That can raise the energy density of the battery by increasing the proportion of active material in the cell. It is necessary to coat the surface of the collector foil with a large amount of composite slurry in order to increase the loading, but as the amount of composite slurry is increased, an even surface becomes less readily retainable. There is, therefore, an upper limit on the loading⁽¹¹⁾⁻⁽¹³⁾. The increase in loading is further accompanied by an increase in the electrode coating thickness. This can lead to an increase in the internal resistance of the battery and deterioration of the structure, resulting in the issue of reduced durability⁽¹¹⁾⁻⁽¹³⁾. The approach of adopting a composite structure for electrodes in order to increase the loading has been studied in recent years⁽¹⁴⁾⁻⁽²⁴⁾. Applying porous nickel collectors in nickel-hydrogen batteries is another way of realizing enhanced loading⁽²⁵⁾⁻⁽²⁷⁾.

A 3D-structured collector made of aluminum has a thickness of 500 μm or more combined with a 90% or higher porosity. Consequently, filling those voids with active material can increase the loading and raise the energy density. The high conductivity of aluminum also reduces the resistance while the 3D frame structure can be expected to enhance the properties of durability, so that this can be considered a technology that addresses the issues associated with increased energy density.

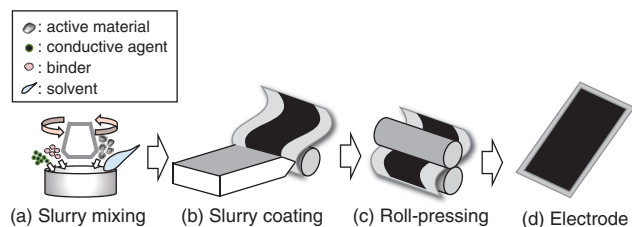


Fig. 2 Schematic view of lithium-ion battery electrode processes

2. Collector Design Guidelines

As indicated in the previous chapter, in order to raise the cell energy density in a lithium-ion battery under the conditions of a constant cell size and fixed active material, it is necessary to increase the amount of active material filling within the cell. The design guidelines for the electrodes in that case say to increase the electrode loading.

With conventional foil-coated cathodes, it was considered possible to fabricate prototype cathodes with loading up to about 90 mg/cm^2 ⁽²³⁾⁻⁽²⁷⁾. On the other hand, a 3D-structured collector, as shown in Fig. 3, is a porous metallic structure, and the possibility of loading it to 150 mg/cm^2 or more per electrode area by filling those voids with electrolyte composite slurry has been confirmed⁽²⁸⁾.

With the cell size held constant and with the proportion of active material and active material in the electrodes fixed, the cell energy density was calculated for cases of different loading on electrodes using ordinary collector foil and on electrodes using a 3D-structured collector (3D-structured cathode), respectively. The calculation conditions are shown in Table 1 and the calculation results in Fig. 4. As indicated in Fig. 4, when comparisons were made with loading of 150 mg/cm^2 under the specified calculation conditions, the cell using the foil-coated cathode had an energy density of 599 Wh/L , while the cell using the 3D-structured cathode had an energy density of 641 Wh/L . An increase of 7% can be anticipated. Since the limit on loading for foil-coated cathodes that allow for prototype fabrication is 90 mg/cm^2 , the limit on energy density for foil-coated cathodes is 581 Wh/L . This means that the application of 3D-structured cathodes can be anticipated to yield a 10% increase in energy density. That cell configuration is shown in Table 2. It is apparent that reducing the number of electrode layers from 40 to 24 layers cuts down on the number of other components used, and the energy density increases as a result.

It can also be seen from Fig. 4 that with cathode loading of 90 mg/cm^2 or more, the energy density of the 3D-structured cathode exceeds that of the foil-coated cathode.

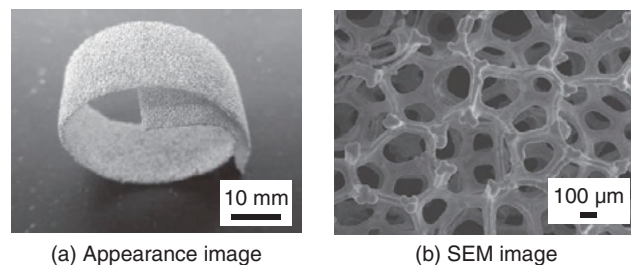


Fig. 3 Images of 3D-structured collector

Table 1 Calculation conditions of electrode

Cathode active material	$\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$
Cathode active material content	94 wt%
Cathode collector foil	Al 15 μm
Cathode 3D-structured collector porosity	97%
Anode active material	Graphite
Anode active material content	96.5 wt%
Anode 3D-structured collector porosity	97%
Element ratio	83 vol%
Anode collector foil	Cu 8 μm
Separator	15 μm
Negative/Positive ratio	1.05
Cell volume	360 mL

Table 2 List of cell components

	Cathode loading (mg/cm ²)	Cathode thickness (μm)	Number of electrodes (-)	Capacity (Ah)	Energy density (Wh/L)
Foil collector	90	250	40	57	581
3D-structured collector	150	469	24	61	641

Figure 5 shows the calculation results for the relationship between porosity and energy density in 3D-structured collectors with different porosities. The calculations were made in three patterns, with cathode loading of 90, 120, and 150 mg/cm². The porosity that exceeds the upper limit for energy density with the foil-coated cathode was 97% or higher at 90 mg/cm², 93% or

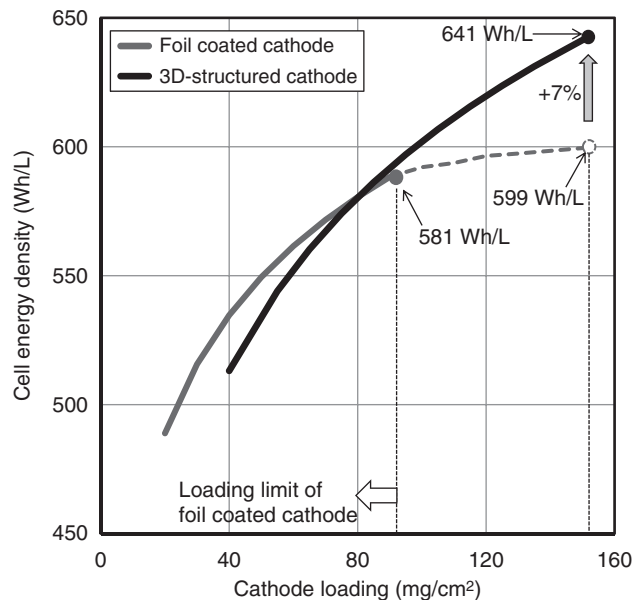


Fig. 4 Comparison between foil coated cathode and 3D-structured cathode

higher at 120 mg/cm², and 89% or higher at 150 mg/cm².

Based on the above results, the collector design guidelines call for increasing the porosity of the 3D structure collectors and increasing the active material filling amount in order to increase loading. Specifically, it was clearly shown that by fabricating electrodes with loading of 150 mg/cm² and with the collector porosity at 97%, the energy density of a cell using the foil-coated cathode would increase 10%.

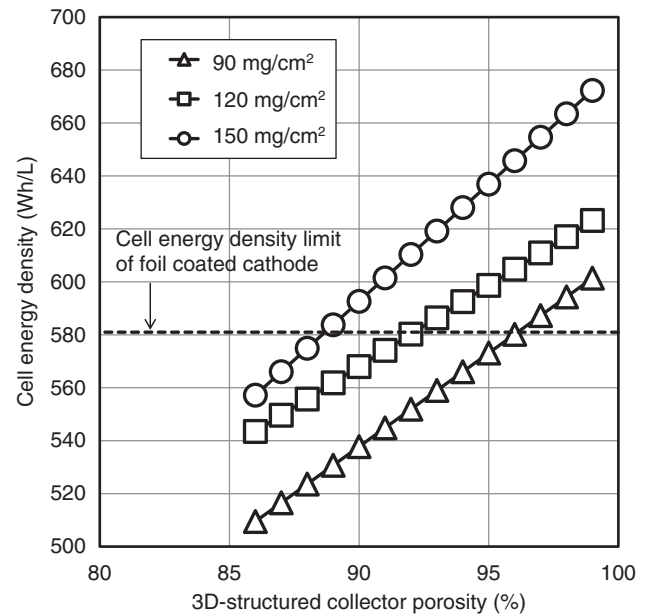


Fig. 5 Relationship between 3D-structured collector porosity and cell energy density

3. Testing Method

3.1. Cell Components

3.1.1. 3D-structured collector

For the cathode collector, Celmet manufactured from aluminum by Sumitomo Electric Industries, Ltd., was used^{(28), (29)}. Typical physical properties are listed in Table 3. As shown in Fig. 6, Celmet is made by applying a process to resin foam with continuous pores to make it electroconductive, after which aluminum is applied by a plating method and the resin foam is removed⁽³⁰⁾.

3.1.2. Cathode

The ternary layered oxide $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$ (NCM) is used as the active material, acetylene black (AB) is used as the conductive agent, and polyvinylidene difluoride (PVDF) is used as the binder. These were combined with a composition ratio of NCM/AB/PVDF=94/4/2 wt%. The 3D-structured collector was filled with composite slurry

Table 3 Physical property values of Celmet

	Aluminum-Celmet
Porosity (%)	97
Average pore size (μm)	550
Specific surface area (m^2/m^3)	5500
Thickness (μm)	1000
Area density (g/m^3)	100

and the range of application for loading was confirmed. Next, it was filled to have a loading of $90 \text{ mg}/\text{cm}^2$ and then pressed in a roller press at 120°C so that the electrode density would be $3.2 \text{ g}/\text{cm}^3$, and fabrication of the electrode was completed. The reference electrode, on the other hand, was manufactured to have an electrode density of $3.2 \text{ g}/\text{cm}^3$ by placing a coating on $15\text{-}\mu\text{m}$ aluminum foil for loading of $90 \text{ mg}/\text{cm}^2$ on both sides. The active material was also manufactured in three types with d50 average particle diameters of $5 \mu\text{m}$, $7 \mu\text{m}$, and $10 \mu\text{m}$ for the purpose of confirming the influence of the size of the active material on the lattice structure of the 3D-structured collector.

3.1.3. Anode

For the active material, natural graphite (Gr) was used; for the conductive agent, AB; for the binder, styrene butadiene rubber (SBR); and for the thickening agent, carboxymethylcellulose (CMC). These were combined in a composition ratio of Gr/AB/SBR/CMC=96.5/1/1.5/1 wt%. The above composite was used to coat $10\text{-}\mu\text{m}$ copper foil so that the loading on both sides would be $45 \text{ mg}/\text{cm}^2$. The anode was then pressed in a roller press at room temperature so that the electrode density would be $1.5 \text{ g}/\text{cm}^3$, and fabrication of the electrode was completed.

3.1.4. Separator

A microporous polyethylene film $15 \mu\text{m}$ thick was used.

3.1.5. Electrolyte

A mixture of ethylene carbonate (EC), dimethyl carbonate (DMC), and ethyl methyl carbonate (EMC) was used for the solvent at EC/DMC/EMC=30/40/30 wt%. The supporting salt lithium hexafluorophosphate (LiPF_6) was dissolved in a 1.2 mol concentration in the solvent to make the electrolyte.

Table 4 Test cell components

Cathode active material	$\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$
Cathode active material content	94 wt%
Cathode loading	$90 \text{ mg}/\text{cm}^2$
Cathode density	$3.2 \text{ g}/\text{cm}^3$
Anode active material	Graphite
Anode active material content	96.5 wt%
Anode loading	$45 \text{ mg}/\text{cm}^2$
Anode density	$1.5 \text{ g}/\text{cm}^3$
Electrolyte	1.2mol LiPF_6 EC/DMC/EMC = 30/40/30 wt%
Separator	$15 \mu\text{m}$
Negative/Positive ratio	1.2

3.1.6. Exterior body

A laminate film with a thickness of $150 \mu\text{m}$ was used.

3.2. Cell Manufacturing Method

The cathode was punched out to be $30 \text{ mm} \times 40 \text{ mm}$ in size, and the anode, $34 \text{ mm} \times 44 \text{ mm}$. The separator was punched out to be $40 \text{ mm} \times 50 \text{ mm}$ in size. The cell elements were fabricated by placing the anode, separator, cathode, separator, and anode in layers. The laminate film was punched out to be $88 \text{ mm} \times 220 \text{ mm}$ in size, then folded in half. The elements were placed inside it and 1 mL of electrolyte injected, then defoamed and sealed to fabricate the laminate cells. Three of each type of cell were prepared and the average values they yielded were used as the evaluation results. The cell configuration is shown in Table 4.

3.3. Cell Evaluation Method

3.3.1. Rated discharge test

This test was conducted to confirm cell capacity. As an aging treatment, the cells were placed in a thermostatic chamber at 25°C and charged at 0.1 C under constant current (CC), with the upper voltage limit at 4.2 V. After charging under constant current-constant voltage (CCCV) for a constant voltage (CV) time of one hour, the cells were rested for one hour, then discharged at CC at 0.2 C, with the lower voltage limit at 2.5 V. This constituted one cycle, and a total of five cycles were carried out. Cell capacity

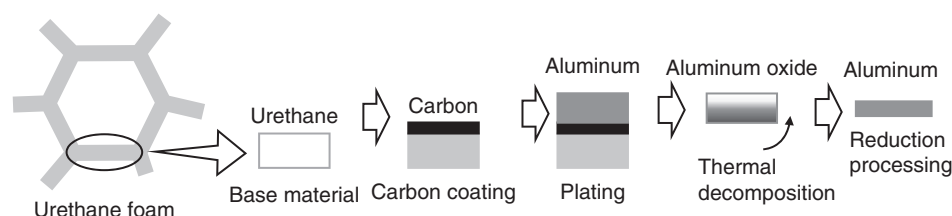


Fig. 6 Schematic processes of production method of Aluminum-Celmet

was defined as the capacity after CC charging at 0.3 C with the upper voltage limit at 4.2 V, charging for a CV time of one hour, then resting for one hour, after which the cell was discharged at CC at 0.3 C, with the lower voltage limit at 2.5 V. For the definition of the C-rate, the current value for full discharge in one hour is taken to be 1 C, where C is the cell capacity (Ah) divided by the full discharge time (h). In other words, for a cell with constant capacity, 0.5 C is the current value for full discharge in two hours, and 2 C is the current value for full discharge in 0.5 hour.

3.3.2. 10-second direct current resistance (10-sec DCR)

This test was conducted to evaluate the internal resistance of the cell. The state of charge (SOC) of the cell was adjusted to 50%. Next, the cell was discharged for 10 seconds at each set current value and the voltage was measured at 0.1 second, 1 second, and 10 seconds of discharge time. The set current values were 0.3 C, 0.5 C, 0.75 C, 1.0 C, 1.5 C, 2.0 C, and 2.5 C. The voltage at each time with respect to each current value was plotted, with the horizontal axis as the current value and the vertical axis as the voltage. The slope of that curve was taken as the resistance, and the resistance at 10 seconds was taken as the overall resistance. Resistance was viewed as having these primary components: the resistance at 0.1 seconds (0.1-sec DCR), which was taken to be electronic resistance; the resistance from 0.1 to 1 second, ((1-0.1)-sec DCR), which was taken to be reaction resistance; and the resistance from 1 to 10 seconds ((10-1)-sec DCR), which was taken to be ionic diffusion resistance⁽³⁰⁾.

3.3.3. C rate discharge characteristics

This test was conducted to evaluate cell capacity at each discharge current value. With the upper voltage limit at 4.2 V and the lower voltage limit at 2.5 V, capacity was measured at the respective discharge current values of 0.3 C, 0.5 C, 0.75 C, 1.0 C, 1.5 C, 2.0 C, and 2.5 C.

3.3.4. Cycle test

This test was conducted to evaluate cell durability. Measurements were made with the cells placed in a thermostatic chamber at 45°C, the upper voltage limit set at 4.2 V and the lower voltage limit at 2.5 V, and subjected to CC discharge at 0.5 C and CCCV charging at 0.5 C for CV time of one hour and rest time of one hour. Every 200 cycles, the thermostatic chamber was set to 25°C and discharge capacity at 0.3 C was confirmed. At the completion of 600 cycles, the 10-sec DCR was measured.

3.4. Analysis of Electrodes

3.4.1. Analysis of particle size distribution

The particle size distribution was measured using the LS13320 manufactured by Beckman Coulter, Inc. for the purpose of quantifying the particle diameter of active material particles.

3.4.2. Scanning electron microscope (SEM)

Cross sections were prepared using a cross-section polisher and observed using an ULTRA 55 SEM from Carl Zeiss AG to confirm the state of active material contact with the collector in the electrode.

3.4.3. Micropore distribution measurement

Measurements for the purpose of quantifying changes in micropore distribution in the electrodes before and after cycle tests were carried out by the mercury penetration method using the PoreMaster 60-GT, a fully automatic micropore distribution measurement device manufactured by Quantachrome Instruments.

4. Results and Discussion

4.1. Confirmation of Cathode Loading

Figure 7 shows the results for confirmation of the range of loading when the 3D-structured collector is filled with composite slurry using active material with $d_{50}=7\ \mu\text{m}$. It is apparent from Fig. 7 that the coating thickness and loading are in a linear relationship and that the filling is stable when the slurry is within the range of 40 to 165 mg/cm^2 . The possibility of manufacturing electrodes with loading of 150 mg/cm^2 is, therefore, confirmed. This shows that it is possible to achieve the energy density shown in Fig. 4.

In the testing that followed, the respective foil-coated cathodes that are possible to manufacture at the upper limit of 90 mg/cm^2 were fabricated and evaluated for the purpose of comparing the foil-coated cathode and 3D-structured cathode. The results of that comparison are shown.

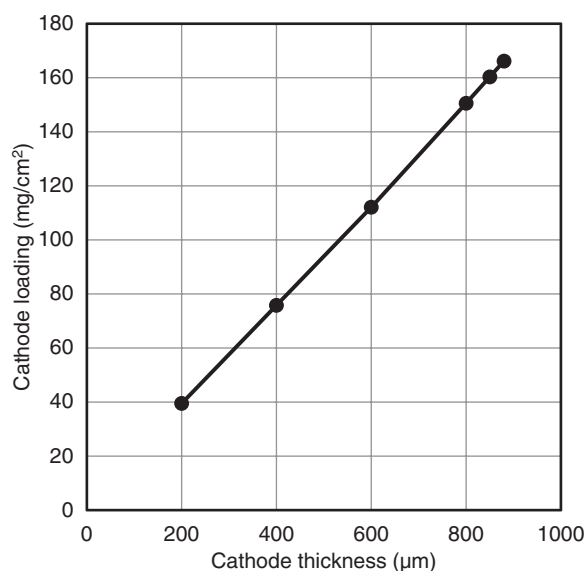


Fig. 7 3D-structured cathode loading

4.2. Particle Diameter and Electrode Characteristics

Figure 8 shows the discharge curves from the rated discharge tests. This confirms that the open circuit voltage (OCV) and discharge capacity for the reference electrode and the 3D-structured cathode are the same and that the active material is functioning fully in both electrodes.

Figure 9 shows the 10-sec DCR results. This confirms that the overall resistance of the 3D-structured cathode is suppressed relative to the reference electrode by 17% and 22% at the diameters (a) d50=5 μm and (b) d50=7 μm ,

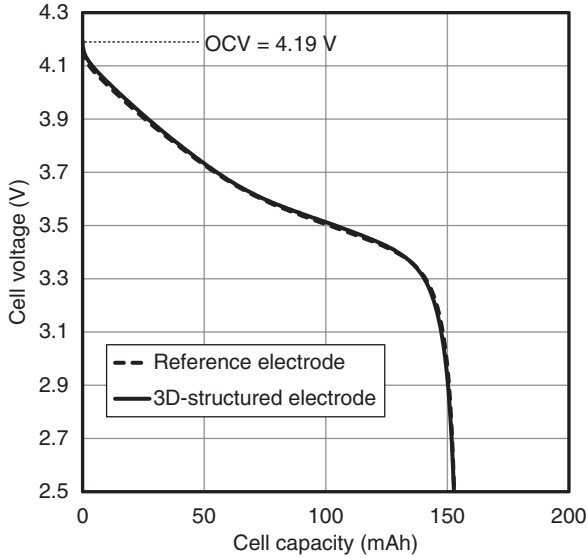


Fig. 8 Discharge curves at 0.3 C

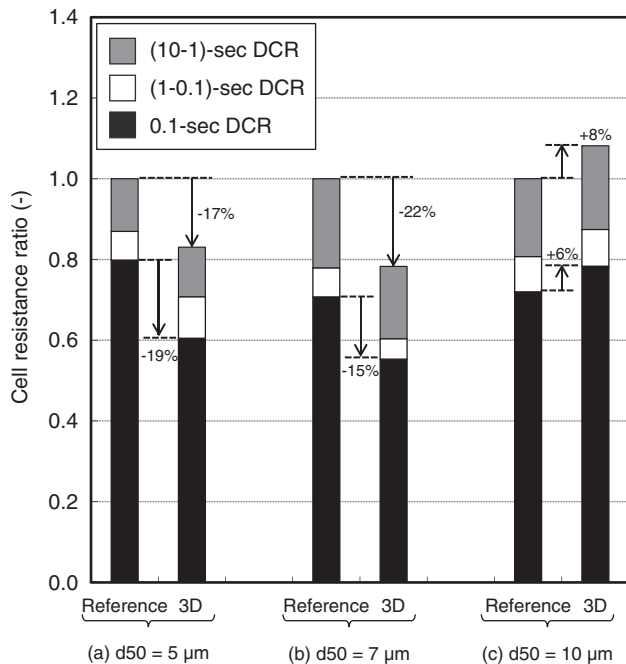


Fig. 9 Results of 10-sec DCR

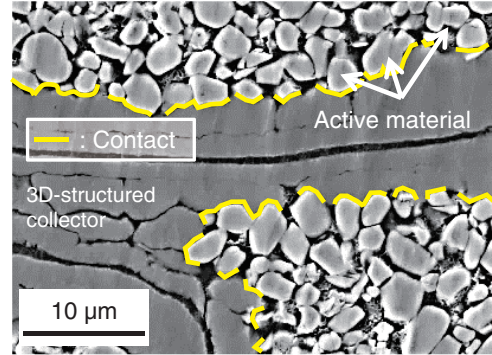
Table 5 List of particle sizes

	D ₁₀ (μm)	D ₅₀ (μm)	D ₉₀ (μm)
(a) d50 = 5 μm	2.5	5.0	7.5
(b) d50 = 7 μm	2.7	7.0	8.1
(c) d50 = 10 μm	6.1	10.1	16.9

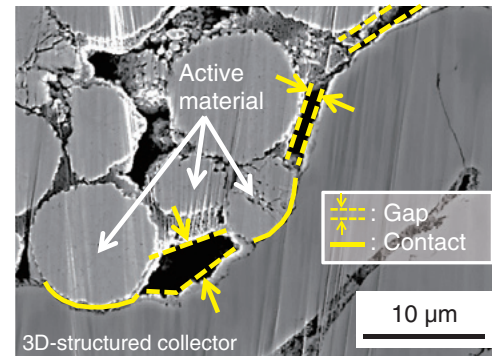
respectively. The portion of that contributed by the 0.1-sec DCR was 19% and 15%, respectively. This clearly established that application of the 3D-structured collector suppresses the electronic resistance. At the diameter (c) d50=10 μm , on the other hand, the total resistance value was found to have increased by 8% and the 0.1-sec DCR by 6%.

Table 5 shows the particle diameters for the particles of each active material at D₁₀ (the particle diameter at which the volume cumulative frequency will be 10%), D₅₀ (the particle diameter at which the volume cumulative frequency will be 50%), and D₉₀ (the particle diameter at which the volume cumulative frequency will be 90%). It was confirmed from Table 5 that the D₉₀ range for (a) and (b) is 8.1 μm or less. On the other hand, it was confirmed that the D₉₀ range for (c) was approximately 16.1 μm or less. This showed that there is a greater difference in particle sizes in (c) than there is in (a) and (b).

Figure 10 shows the results for an SEM observation



(a) d50 = 5 μm



(c) d50 = 10 μm

Fig. 10 Cross-section SEM images of 3D-structured cathode

of cross-sections of 3D-structured cathodes with diameters (a) $d_{50}=5\ \mu\text{m}$ and (c) $d_{50}=10\ \mu\text{m}$. It can be confirmed from the SEM images that at diameter (a) $d_{50}=5\ \mu\text{m}$, the active material has penetrated into the lattice structure of the 3D-structured collector. As indicated by the solid line in the figure, the active material can be confirmed to be uniformly in contact with the collector aluminum. Figure 10 confirmed, however, that a portion of the active material that is close to the collector aluminum had gaps where it was not in direct contact with the collector at diameter (c) $d_{50}=10\ \mu\text{m}$, as shown by the broken line in the figure. This is thought to happen because active material particles of $10\ \mu\text{m}$ or greater diameter can no longer readily penetrate in a uniform manner all the way inside the lattice structure to the region where the aluminum frame is curved when the 3D-structured collector is being filled with electrolyte composite. Electrons are supplied directly to the active material that is in contact with the aluminum, but the supply of electrons at locations that are not in contact will occur through the mediation of other active materials or auxiliary agents, so the resistance will increase. In other words, the fact that the active material has different particle diameters alters the status of contact between the active material and the collector, and the change in the state of electron transfer from the collector is thought to change the 0.1-sec DCR resistance value.

These results showed clearly that resistance is suppressed in the active material applied to the 3D-structured collector covered in this paper when the particle diameter at d_{50} is $7\ \mu\text{m}$ or less.

4.3. Electrode Characteristics

4.3.1. Rate discharge characteristics

Figure 11 shows capacity retention based on evaluation of the C-rate discharge characteristics at $d_{50}=5\ \mu\text{m}$. The effect of enhanced capacity retention from use of the 3D-structured collector could be confirmed in the region of 1 C and above. At 2.5 C, the retention increase was 3%.

The discharge curves for the reference electrode and the 3D-structured cathode are shown at 0.3 C and 2.5 C in Fig. 8 and Fig. 12, respectively. The discharge curves coincide at 0.3 C, confirming that there was no difference between the two types of electrode. The voltage drop at 0.1 second after discharge begins was also the same 20 mV or less for both electrodes. By contrast, a distinct difference was confirmed at 2.5 C. The voltage drop at 0.1 second after discharge begins was 301 mV in the reference electrode and 181 mV in the 3D-structured cathode electrode, for a confirmed difference of 120 mV. This voltage drop is IR loss, and it shows a tendency similar to the suppression of electronic resistance in Fig. 9. This difference is thought to occur because the 3D-structured collector has a specific surface area of $5500\ \text{m}^2/\text{m}^3$, and the increase in surface area by a factor of five or more relative to the reference electrode

means there is an increased area of contact between the collector and the active material, which results in heightened conductivity at the interface. It is also conceivable that the distribution of the aluminum frame throughout the entire electrode heightens conductivity in the electrode thickness direction. On the other hand, both discharge curves display similar profiles from 0.1 second on, which indicates that the electrodes have the same ion diffusion. The suppression of IR loss means there is a lag in reaching the discharge cut-off voltage, and this is known to contribute to the capacity increase in the higher rate region. It is clear from the above that with the 3D-structured cathode, the heightened conductivity produces suppression of the voltage drop immediately following discharge and increases capacity retention in the higher rate region.

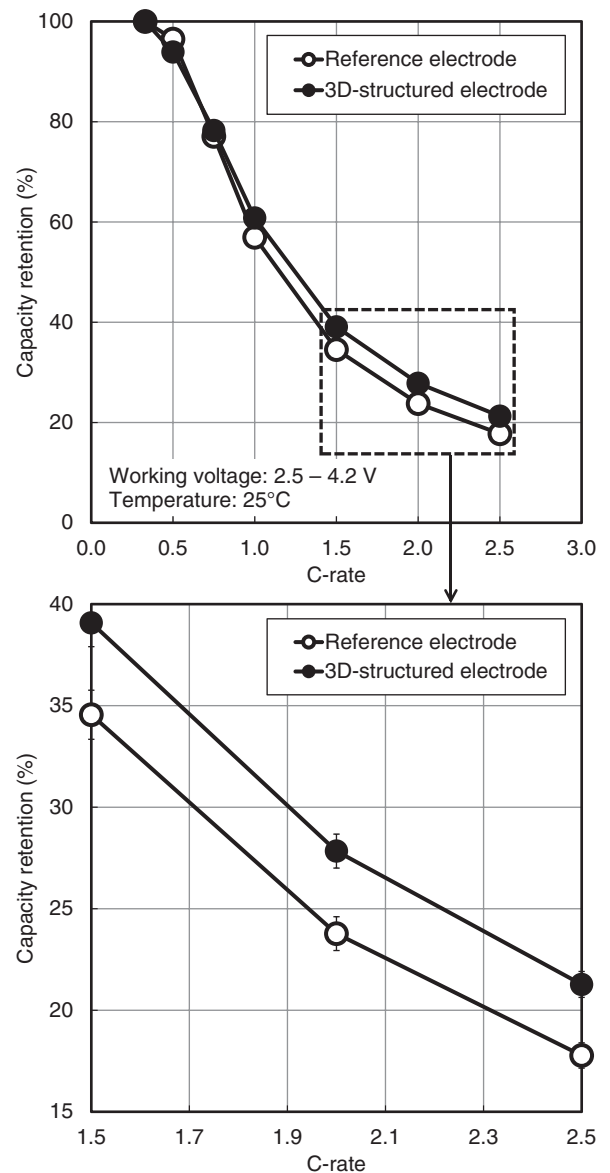


Fig. 11 Capacity retentions at different C-rate

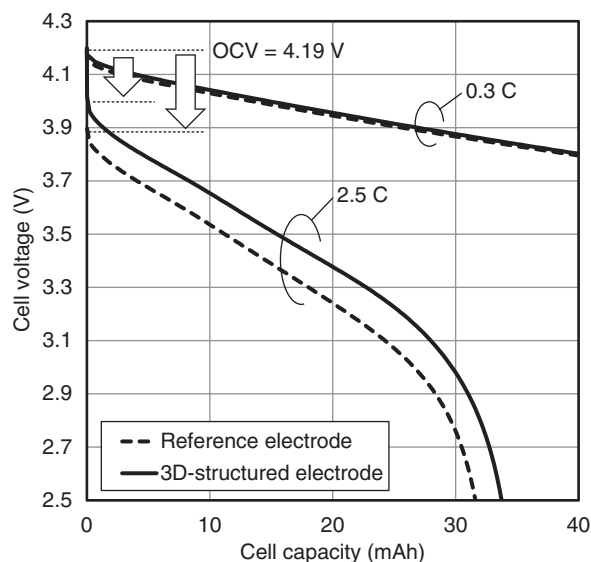


Fig. 12 Discharge curves at 2.5 C

4.3.2. Cycle test

Figure 13 shows the rate of change in capacity from the cycle test at 45°C.

In contrast to the reference electrode, which has 77.4% capacity retention at 600 cycles, the 3D-structured cathode has 87.9% capacity retention. This confirms that capacity retention is heightened in the 3D-structured cathode. This is thought to occur because the aluminum frame that forms the 3D structure maintains its structure during cycle testing, and maintaining the binding of the various constituent materials throughout the electrode keeps the active material from detaching.

Figure 14 shows that the overall resistance of the reference electrode and 3D-structured cathode increased by 149% and 29%, respectively, before and after the cycle test. Their respective 0.1-sec DCR increased by 141% and 14%. Based on the above results, the suppression of increases in electronic resistance in the 3D-structured cathode causes suppression of increases in all components of resistance. In the reference foil-coated cathode, on the other hand, active material detached from the collector and active material in the composite slipped off due to the influence of the formation of a thicker layer, and this is thought to interrupt the electron conductive path to the active material so that the increase in resistance is accelerated.

There was also an increase in the (10-1)-sec DCR before and after the cycle test that was 74% in the reference electrode and 18% in the 3D-structured cathode. The (10-1)-sec DCR is ionic diffusion resistance, so when an electrolyte is used in common, it is considered to be a component of resistance that depends on the electrode structure⁽³⁰⁾. In the present tests, the (10-1)-sec DCR accounts for 20% or less in

the 10-sec DCR as a whole. However, suppression of the increase in resistance was confirmed to occur during the cycle tests with 3D-structured cathodes. Figure 15 shows micropore distribution in the electrode before and after the cycle test. Where the average micropore diameter in the reference electrode shrank by 65 μm before and after the cycle test, the shrinkage was limited

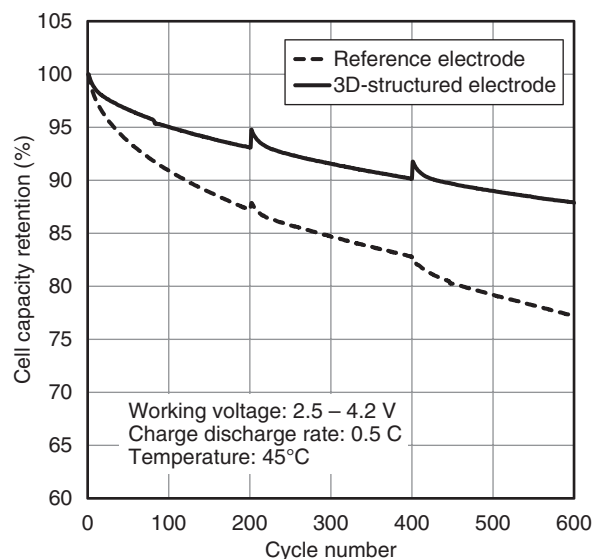


Fig. 13 Cell performances of capacity retention

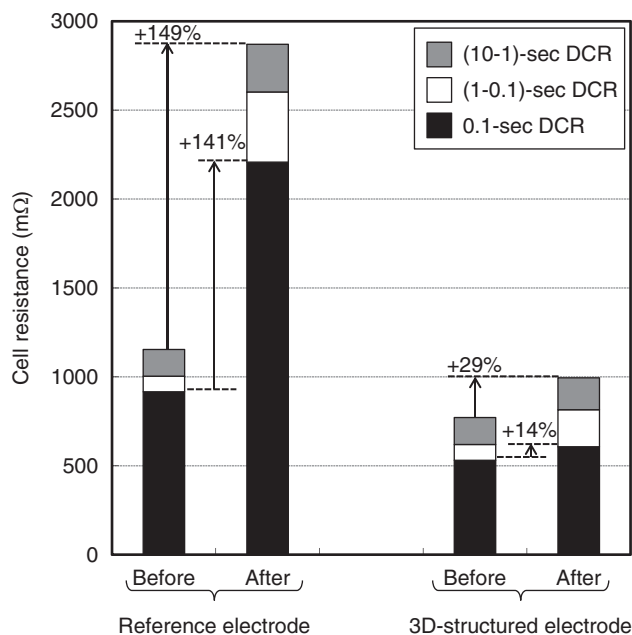


Fig. 14 Performance of cell resistance retention

to 15 μm in the 3D-structured cathode. A reduction in porosity also resulted, as calculated from Fig. 15, amounting to 15% in the reference electrode and 12% in the 3D-structured cathode. Based on these results, the suppression of structural changes in the micropores, voids, and gaps in the 3D-structured cathode that is due to its aluminum frame enables the retention of ion conductive paths before and after the cycle test, and this is thought to suppress the increase in resistance.

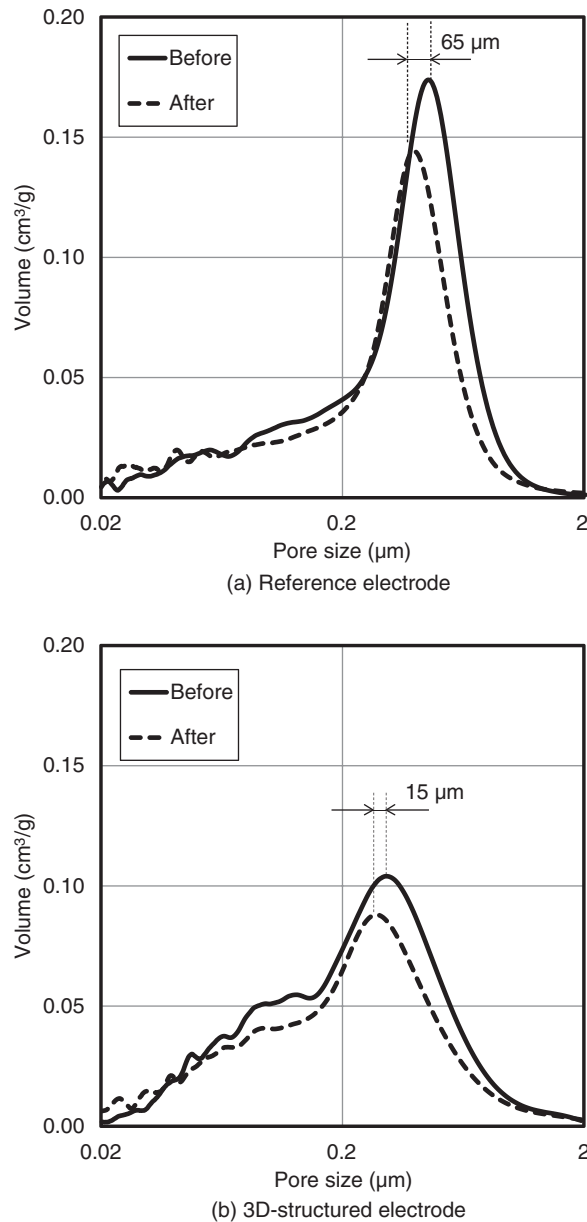


Fig. 15 Electrode pore distribution before and after cycle test

5. Conclusion

Cell evaluation was conducted for the purpose of confirming that the application of a 3D-structured collector made from aluminum as the cathode collector in a lithium-ion battery would increase the energy density while at the same time having the effect of suppressing the associated increase of internal resistance in the cell and the decrease in durability, which are issues. The following results were obtained as a result.

As regards energy density, it was confirmed that it is possible to manufacture electrodes with a loading of 150 mg/cm². Calculations yielded the result that reducing the number of electrode layers would have the effect of increasing energy density 10%.

As regards the internal resistance of the cell, a reduction in resistance relative to conventional foil-coated cathodes was confirmed. When the particle diameter of the active material is d50=7 μm or less, the overall resistance is reduced by 17% relative to the foil-coated cathode and the 0.1-sec DCR is reduced by 24%, confirming that the reduction in electronic resistance makes a large contribution. It is thought that the enhanced contact between the active material and the collector is a major factor in this.

As regards durability, heightened capacity retention and suppression of the increase in resistance were confirmed during cycle testing. It was confirmed that after 600 cycles, capacity retention in the foil-coated cathode was reduced by 22.6%, while in the 3D-structured cathode, the decrease was held down to 12.1%. As to the increase in resistance, it was confirmed that the foil-coated cathode showed a 149% increase in the total resistance value, while the figure in the 3D-structured cathode was held to 29%. It is thought that the way the aluminum frame maintains its structure, thus maintaining the binding of the various constituent materials throughout the electrode and keeping the active material from detaching, is a major factor in this.

It was clearly shown by these results that application of the 3D-structured cathode in a lithium-ion battery makes it possible to achieve a balance between enhancement of energy density and suppression of the increase in resistance and decrease in durability, which are issues.

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