A system and method to monitor lithium-ion battery for degradation estimation and fault detection

FIELD OF THE INVENTION

[0001] The present invention relates to a system and method to monitor lithium-ion battery for degradation estimation and fault detection using optical fibres.

BACKGROUND OF THE INVENTION

[0002] Optical fibres are thin, flexible, and transparent strands of glass or plastic that are used to transmit light signals over long distances. They are widely used in telecommunications and networking, as well as in medical equipment, scientific research, and other applications. The basic structure of an optical fibre consists of a core, a cladding, and a coating. The core is the innermost part of the fibre, through which the light travels. The cladding surrounds the core and helps to confine the light within it, while the coating protects the fibre from damage and external interference. Light is transmitted through the fibre by total internal reflection, which occurs when the light is reflected into the core at the boundary between the core and the cladding. This allows the light to travel through the fibre without leaking out or losing its intensity, even over very long distances.

[0003] Single mode fibres (SMFs) can be used to track the wavelength shift caused by strain or temperature changes. This technique is known as fibre Bragg grating (FBG) sensing. An FBG sensor consists of a short section of SMF in which the refractive index of the core is modulated along the length of the fibre, forming a periodic grating structure. When light is transmitted through the fibre, some of it is reflected back by the grating at specific wavelengths, depending on the spacing between the refractive index modulations. The reflected wavelengths correspond to the resonant Bragg wavelengths of the grating and are known as the Bragg wavelengths. When the fibre is subjected to strain or temperature changes, the grating spacing is altered, causing a shift in the reflected Bragg wavelengths. By measuring the change in wavelength, it is possible to determine the amount of strain or temperature change that has occurred.

[0004] Kneeing is commonly reported in batteries that carry faults introduced by the manufacturing process, cell chemistry, or operating conditions. Knee-point is defined as a transition point which spots a sharp decrease in the slope of the ageing curve. Kneeing occurs due to a sudden shift in the dominant degradation mechanism of Li-ion batteries under certain operating conditions. There are various potential factors triggering the knee-point formation, including manufacturing flaws, lithium plating, electrode saturation, resistance growth, electrolyte or additive depletion, mechanical deformation, etc. From a safety standpoint, regardless of the dominant degradation pathway that drives the cell to its knee-point, receiving an advance warning is crucial. This warning is less likely to be generated by the primary electrochemical parameters and is highly dependent on fault detection techniques. In general, model-based and data-driven fault detection methods rely on analysing electrical parameters such as voltage and current to define an anomaly threshold. Another approach is the signal-based method that employs detectable output signals such as terminal voltages, currents, and temperatures. However, the mentioned techniques rely on developing sophisticated models or complicated algorithm to expose the anomalous behaviour. Hence, developing supplementary or even alternative fault detection strategies would be crucial to reduce the risk-induced costs and to enhance battery safety.

[0005] For example, M. Nascimento et al. (2019) disclosed that strain and temperature are critical parameters to monitor in Li-ion batteries (LIBs) to improve their safety and long-term cycling stability. The said sensing platform consists of an SMF fibre being spliced to a multimode fibre (MMF) to create a Fabry-Perot (FP) cavity sensor. In the next step, an FBG is written right next to the FP sensor to form a hybrid sensor structure where both sensors would be responsive to temperature and strain variations, thereby enabling successful decoupling of these parameters. However, it did not present any results about the capability of the sensors to reveal the anomalous behaviour (whether thermal or mechanical) of the cell as an early warning of imminent abrupt capacity drop.

[0006] United States Patent No. 9209494 B2 disclosed a system that utilizes optical sensors arranged within or on portions of an electrochemical energy device (e.g., a rechargeable Li-ion battery, supercapacitor or fuel cell) to measure operating parameters (e.g., mechanical strain and/or temperature) of the electrochemical energy device during charge/discharge cycling. The measured parameter data is transmitted by way of light signals along optical fibers to a controller, which converts the light signals to electrical data signal using a light source/analyzer. A processor then extracts temperature and strain data features from the data signals and utilizes a model-based process to detect intercalation stage changes (i.e., characteristic crystalline structure changes caused by certain concentrations of guest species, such as Li-ions, within the electrode material of the electrochemical energy device) indicated by the data features. The detected intercalation stage changes are used to generate highly accurate operating state information (e.g., state-of-charge and state-of-health), and management/control signals for optimizing charge/discharge rates. However, this system did not present any results about the capability of the sensors to reveal the anomalous behavior (whether thermal or mechanical) of the cell as an early warning of imminent abrupt capacity drop.

[0007] In view of the above, there is a need for a system or a device to closely track the volume expansion and contraction of the cell during charge and discharge as a mechanical health indicator so that additional health indicators that support the primary strain amplitude results based on differential analysis of the electrochemical data and decoupled mechanical data are provided. The battery performance is monitored by these data to provide degradation estimation.

SUMMARY OF THE INVENTION

[0008] It is an objective of the present invention to provide a system or a device to closely track the volume expansion and contraction of the cell during charge and discharge as a mechanical health indicator, as well as to provide additional health indicators that support the primary strain amplitude results based on differential analysis of the electrochemical data and decoupled mechanical data.

[0009] It is also an objective of the present invention to provide a system or a device that provides an early warning for battery faults and at the same time for battery degradation estimation.

[0010] Accordingly, these objectives can be achieved by following the teachings of the present invention, which relates to a system and method to detect faulty lithium-ion battery and battery degradation, the system comprising of: a first sensor coupled to a second sensor parallel to each other on a surface of the lithium-ion battery configured to measure variations in temperature and volumetric changes in the lithium-ion battery; and a test module.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The features of the invention will be more readily understood and appreciated from the following detailed description when read in conjunction with the accompanying drawings of the preferred embodiment of the present invention, in which:

[0012] **Figure 1** illustrates an overview of the lithium-ion battery monitoring and fault detection system;

[0013] **Figure 2** illustrates the decoupled strain (change in strain) in conjunction with voltage;

[0014] **Figure 3** illustrates the battery reaching a knee-point with sudden capacity drop after around 90 cycles;

[0015] **Figure 4** illustrates the incremental capacity analysis (ICA) in conjunction with the corresponding incremental strain analysis (ISA) for 90 cycles;

[0016] **Figure 5** illustrates the rise and fall of the strain derivative peak value during charge;

[0017] **Figure 6** illustrates the rise and fall of the strain derivative peak value during discharge; and,

[0018] **Figure 7** illustrates the general trend of the decoupled strain and temperature evolution during charge and discharge.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0019] For the purposes of promoting and understanding the principles of the invention, reference will now be made to the embodiments illustrated in the drawings and described in the following written specification. It is understood that the present invention includes any alterations and modifications to the illustrated embodiments and includes further applications of the principles of the invention as would normally occur to one skilled in the art to which the invention pertains.

[0020] The present invention teaches a battery monitoring and fault detection system **10** for a lithium-ion battery, the system comprising: a first sensor **12** coupled to a second sensor **14** parallel to each other on a surface of the lithium-ion battery configured to measure variations in temperature and volumetric changes in the lithium-ion battery; and a test module and the structure of the present invention is further illustrated in **Figure 1**.

[0021] The present invention can be used to monitor battery and to detect fault in battery including but not limited to button cells, pouch cells, cylindrical cells, coin cells etc. by mounting the fibre optic sensors in different orientations.

[0022] In another embodiment, the sensors are fibre Bragg grating sensors and the first sensor **12** is a silica-based optical fibre and the second sensor **14** is a polymer-based optical fibre.

[0023] In another embodiment, the first **12** and second **14** sensors are affixed on the surface of lithium-ion battery up to 1-2 mm apart.

[0024] In one of the embodiments of the present invention, the test module is a cycling test under long-term cycling conditions and the first **12** and second **14** sensors collect the mechanical data and thermal data in the measurement. For example, the decoupled strain (change in strain) in conjunction with voltage demonstrated in **Figure 2** reveals that the sensors can closely track the volume expansion and contraction of the cell during charge and discharge, respectively. This intimate correlation defines the amplitude of strain signal fluctuation as the primary mechanical health indicator during charge and discharge. For a non-faulty battery undergoing normal degradation over extended cycling conditions, strain amplitude is expected to be correlated with the cell capacity. Consequently, any significant discrepancy between the evolution of the capacity and strain amplitude could hypothetically be an indication of anomalous behaviour.

[0025] In another embodiment, the mechanical data are data of variations in strain amplitudes while undergoing the cycling test. As shown by **Figure 3**, the battery reaches a knee-point showing sudden capacity drop after around 90 cycles. Before the kneeing occurs, both charge and discharge capacities exhibit a stable behaviour with a small fading slope. In other words, the primary electrochemical data do not provide any early warnings before the knee-point appears. However, tracking the strain amplitude evolution for both charge and discharge reveals that an unexpected rise in strain amplitudes occurs after around 24 cycles, hitting a peak at cycle 40 before dropping back to lower values. This remarkable shift in the strain signal trajectory occurs around 60 cycles before the sudden kneeing happens, making it a strong advance warning of the imminent cell failure.

[0026] In another embodiment of the present invention, the system further comprises an analysis module, which is deployed to analyse the data collected by the test module and a display module for displaying the condition of the lithium-ion battery.

[0027] To further explore the capability of the sensors in responding and sending an early warning before the abrupt kneeing, differential analyses of the electrochemical data as well as the decoupled mechanical data are carried out. **Figure 4** shows the incremental capacity analysis (ICA) in conjunction with the corresponding incremental strain analysis (ISA) for 90 cycles, where each peak represents a specific phase transition stage during the electrochemical cycling of the cell. As clearly depicted by **Figures 5** and **6**, while the peak value of the capacity derivative exhibits a stable behaviour before the knee point, the trajectory of the peak value of the strain derivative during charge undergoes a remarkable rise and fall after around 24 cycles, indicating anomalous performance of the cell (**Figure 5**). The same trend is observed for the peak value of the strain derivative upon discharge (**Figure 6**), implying that the anomalous behaviour is revealed by the differential analysis of the mechanical data captured using the FBG sensing platform. In other words, the differential analysis can provide additional health indicators that support the primary strain amplitude results in terms of revealing the abnormal behaviour of a given cell.

[0028] The present invention also teaches a method to monitor the condition and to detect fault in lithium-ion battery, the method comprises: affixing a first sensor **12** and a second sensor **14** on a lithium-ion battery surface; calibrating the first sensor **12** and the second sensor **14**; running a long-term cycling test to collect wavelength shift data; analysing the data collected to decouple strain and temperature values; and determining the condition and fault of the lithium-ion battery.

[0029] In another embodiment, the method further comprises initially fabricating the first sensor **12** and the second sensor **14** and inscribing grating on each sensor's core by UV beam using a mask with a suitable pitch.

[0030] In a preferred embodiment, the strain calibration of the first sensor **12** and the second sensor **14** is conducted prior to affixing such sensors on the lithium-ion battery surface.

[0031] In another embodiment of the present invention, the method further comprises thermal calibrating the first sensor **12** and the second sensor **14** after affixing such sensors on the lithium-ion battery surface.

[0032] In one of the embodiments, the running of the cycling test collects the mechanical data of variations in strain amplitudes and the differentials of such mechanical data.

[0033] In another embodiment, the running of the cycling test further collects the differences in thermal data.

[0034] In addition to the above, the method comprises decoupling of mechanical data and thermal data before analysing the data collected and displaying the analysed data in the form of a curve plot.

[0035] In another embodiment, the step of determining the condition and fault of a lithium-ion battery further comprises observing the strain amplitude, and such observation includes the data in the fluctuation of strain amplitude during charge and discharge and the data in the correlation of strain amplitude with capacity of the battery. Specifically, for a faulty lithium-ion battery, strain amplitude captured by both sensors fluctuates with discrepancy to capacity during charge and discharge indicating anomalous behaviour wherein for a non-faulty lithium-ion battery, the strain amplitude is expected to be correlated with capacity of the battery.

[0036] The present invention explained above is not limited to the aforementioned embodiment and drawings, and it will be obvious to those having an ordinary skill in the art of the present invention that various replacements, deformations, and changes may be made without departing from the scope of the invention.

CLAIMS

WHAT IS CLAIMED:

1. A battery monitoring and fault detection system (10) for a lithium-ion battery, the system comprising:
   a first sensor (12) coupled to a second sensor (14) parallel to each other on a surface of the lithium-ion battery configured to measure variations in temperature and volumetric changes in the lithium-ion battery; and
   a test module.

2. The system as claimed in claim 1 wherein the first sensor (12) is a silica-based optical fibre and the second sensor (14) is a polymer-based optical fibre.

3. The system as claimed in claim 1 or 2 wherein the first (12) and second (14) sensors are affixed on the surface of lithium-ion battery up to 1-2 mm apart.

4. The system as claimed in claim 3 wherein the test module is a cycling test under long-term cycling conditions and the first (12) and second (14) sensors collect the mechanical data and thermal data in the measurement.

5. The system as claimed in claim 4 wherein the mechanical data are data of variations in strain amplitudes while undergoing the cycling test.

6. The system as claimed in claim 1 or 5, further comprises an analysis module, which is deployed to analyse the data collected by the test module and a display module for displaying the condition of the lithium-ion battery.

7. A method to monitor the condition and to detect fault in lithium-ion battery, the method comprises:
   affixing a first sensor (12) and a second sensor (14) on a lithium-ion battery surface;
   calibrating the first sensor (12) and second sensor (14);
   running a long-term cycling test to collect wavelength shift data;
   analysing the data collected to decouple strain and temperature values; and
   determining the condition and fault of the lithium-ion battery.

8. The method as claimed in claim 7 wherein the method further comprising initially fabricating the first sensor (12) and a second sensor (14) and inscribing grating on each sensor's core by UV beam using a mask with a suitable pitch.

9. The method as claimed in claim 7 wherein the strain calibration of the first sensor (12) and the second sensor (14) is conducted prior to affixing such sensors on the lithium-ion battery surface.

10. The method as claimed in claim 9 further comprises thermal calibration of the first sensor (12) and the second sensor (14) after affixing such sensors on the lithium-ion battery surface.

11. The method as claimed in claim 10, wherein the running of the cycling test collects the mechanical data of variations in strain amplitudes and the differentials of such mechanical data.

12. The method as claimed in claim 11 wherein the running of the cycling test further collects the differences in thermal data.

13. The method as claimed in claim 12 further comprises decoupling of mechanical data and thermal data before analysing the data collected and displaying the analysed data in a form of a curve plot.

14. The method as claimed in claim 11 or 13 wherein the step of determining the condition and fault of a lithium-ion battery further comprises observing the strain amplitude, and such observation includes the data in the fluctuation of strain amplitude during charge and discharge and the data in the correlation of strain amplitude with capacity of the battery.

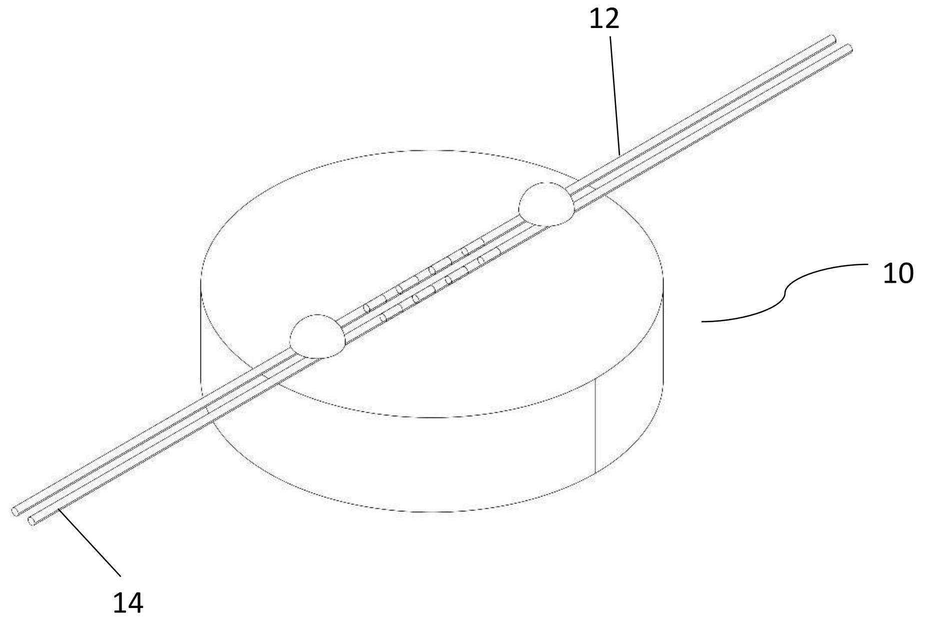

Figure 1

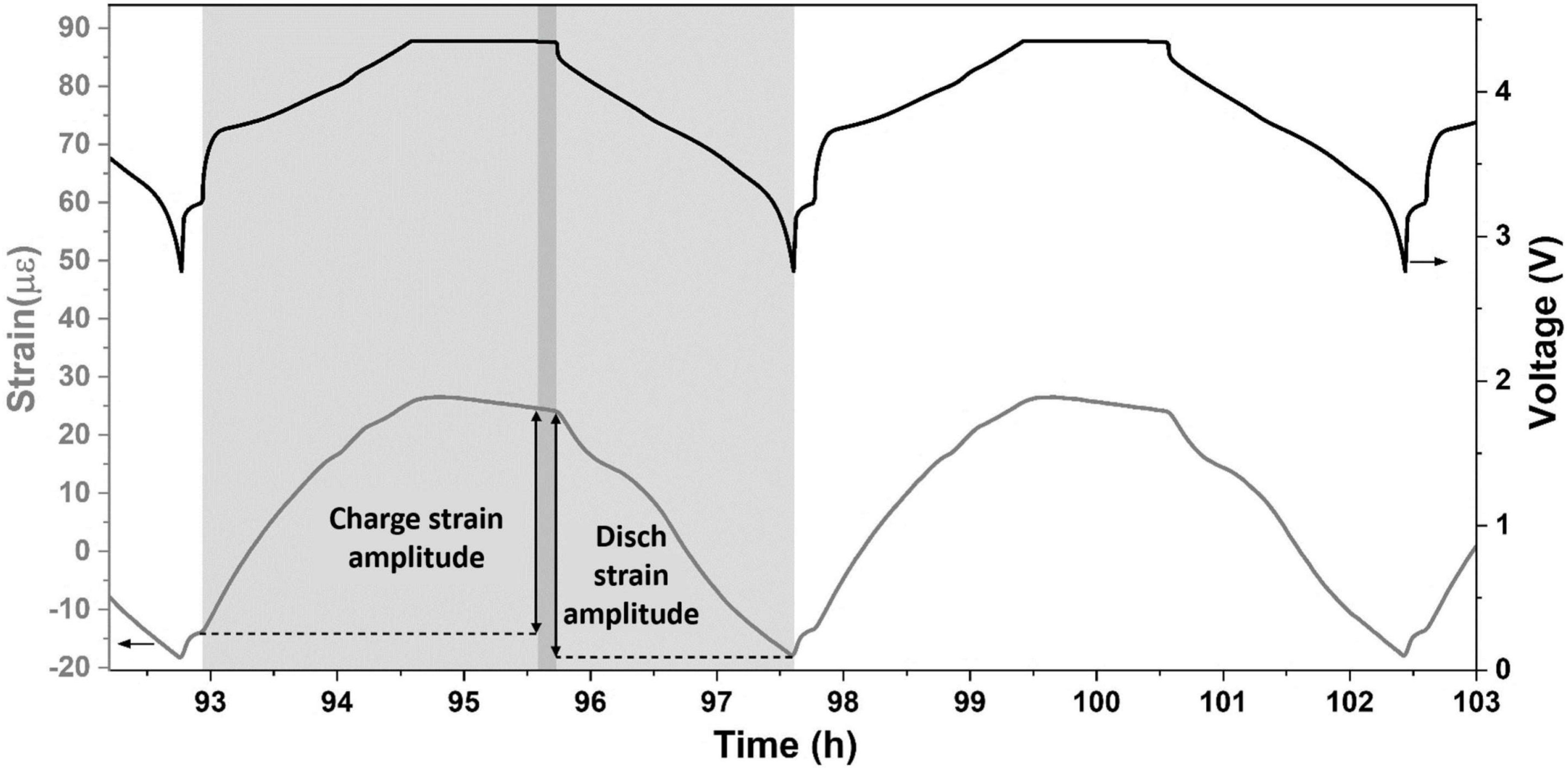
Strain(με)
90
80
70
60
50
40
30
20
10
0
-10
-20
Voltage (V)
4
3
2
1
0
93
94
95
96
97
98
99
100
101
102
103
Time (h)
Charge strain amplitude
Disch strain amplitude

Figure 2

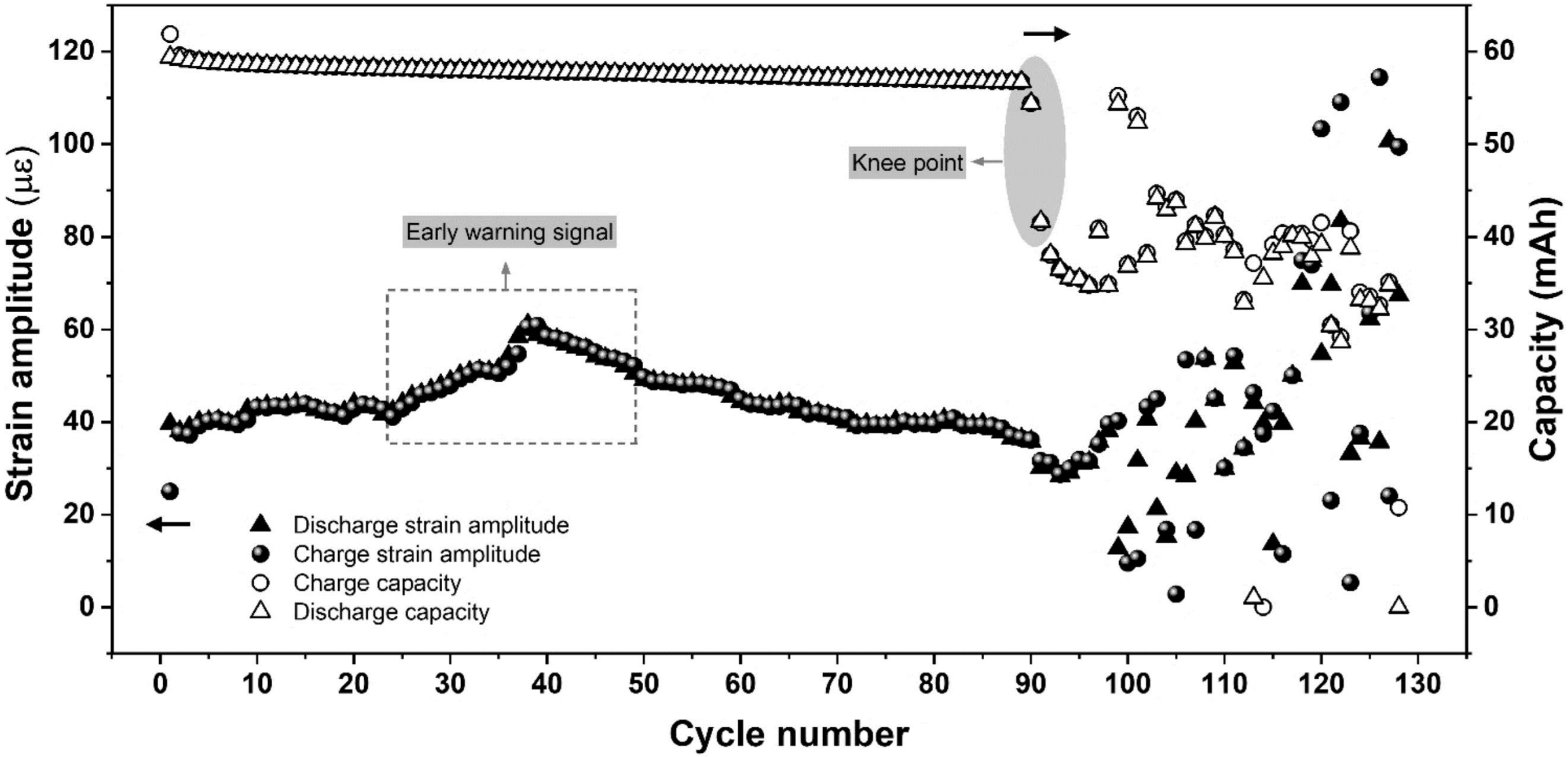
Strain amplitude (με)
Capacity (mAh)
Cycle number
Early warning signal
Knee point
Discharge strain amplitude
Charge strain amplitude
Charge capacity
Discharge capacity
0
20
40
60
80
100
120
0
10
20
30
40
50
60
0
10
20
30
40
50
60
70
80
90
100
110
120
130

Figure 3

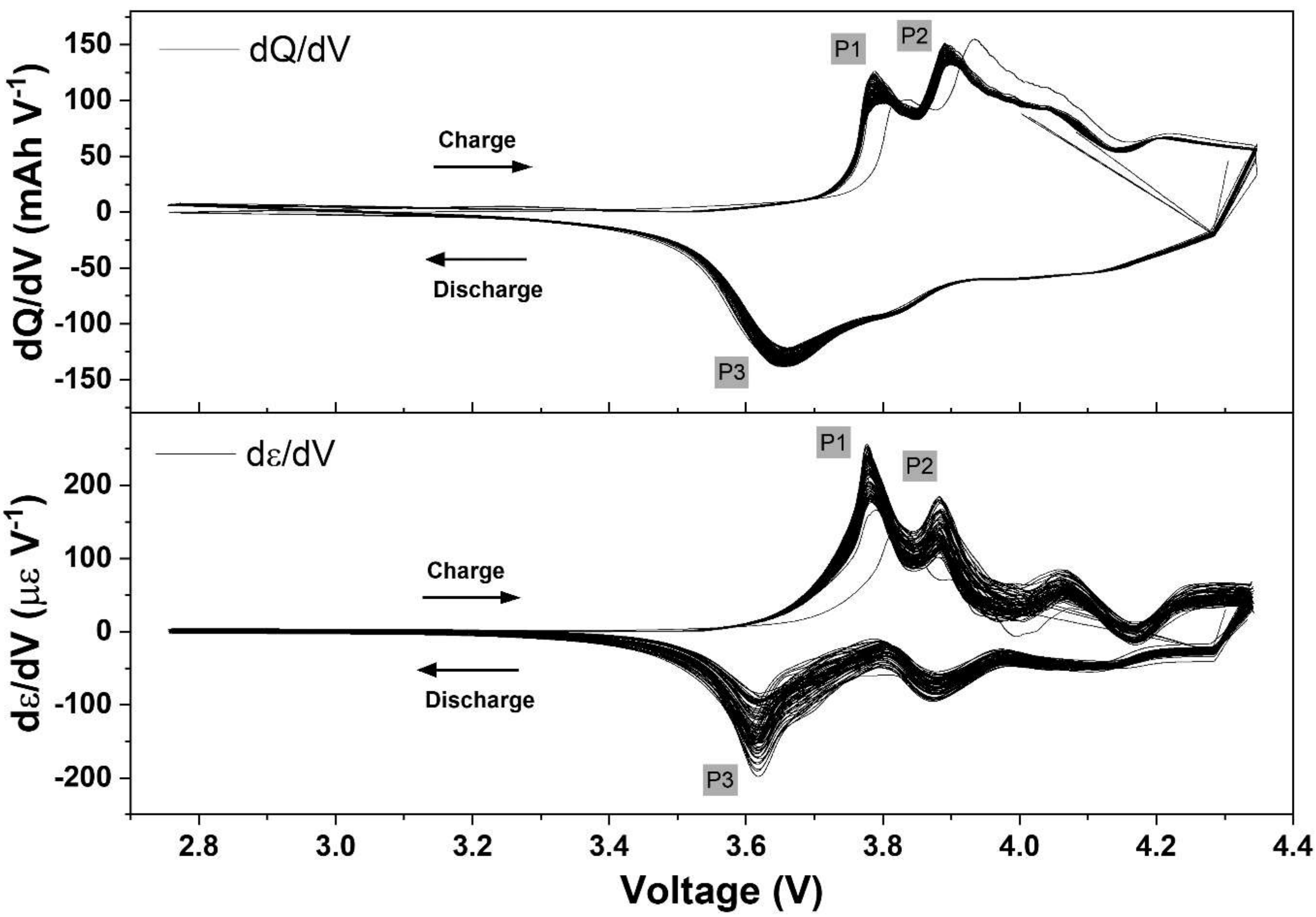

Figure 4

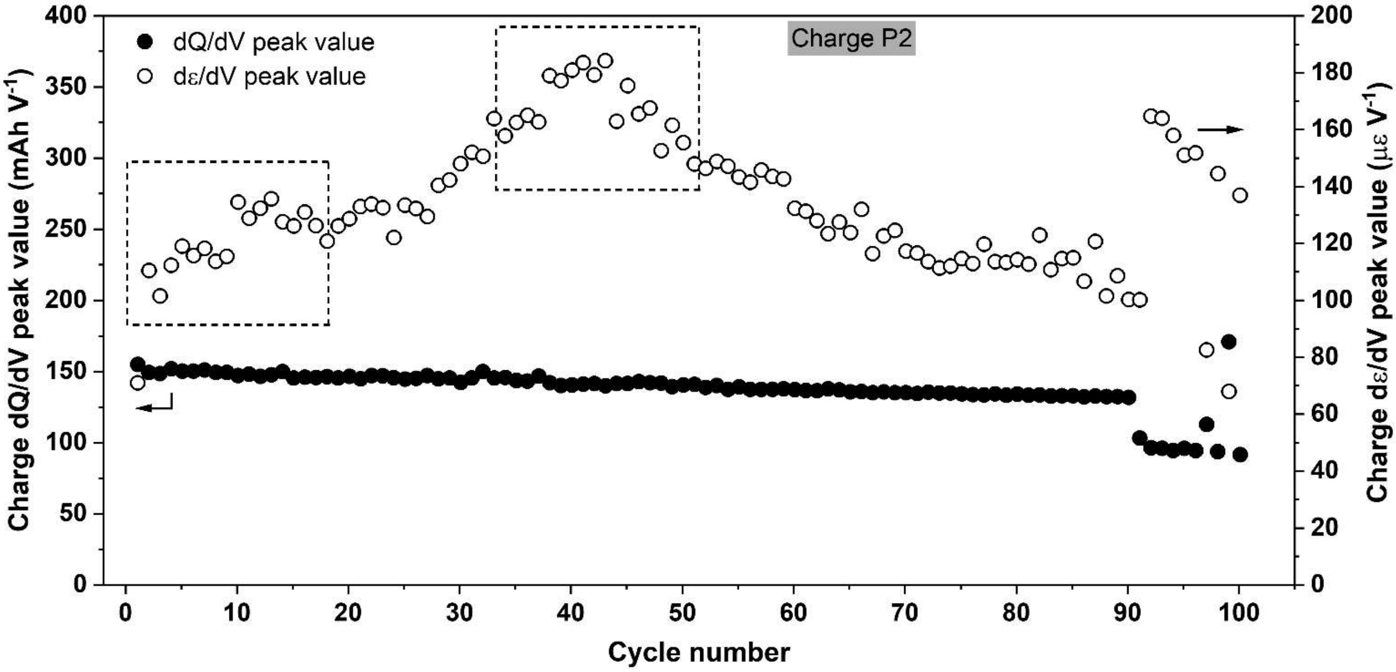

Figure 5

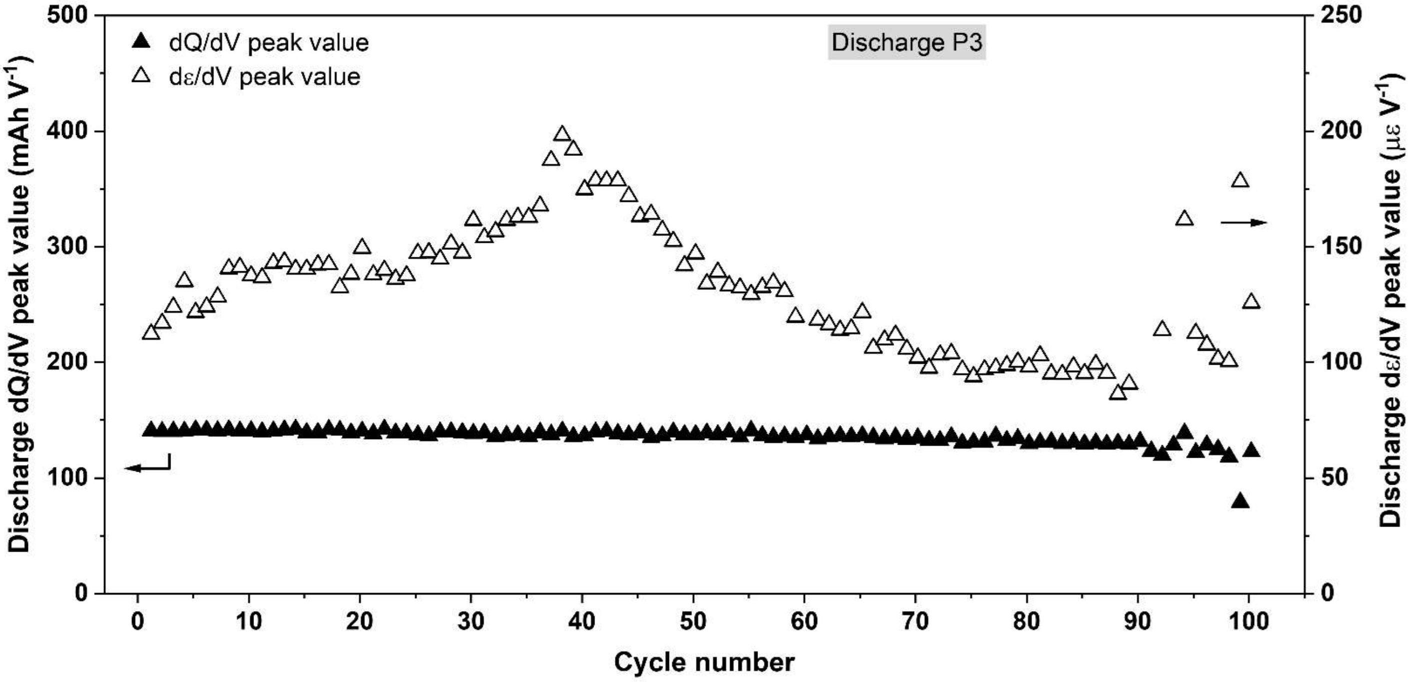

Figure 6

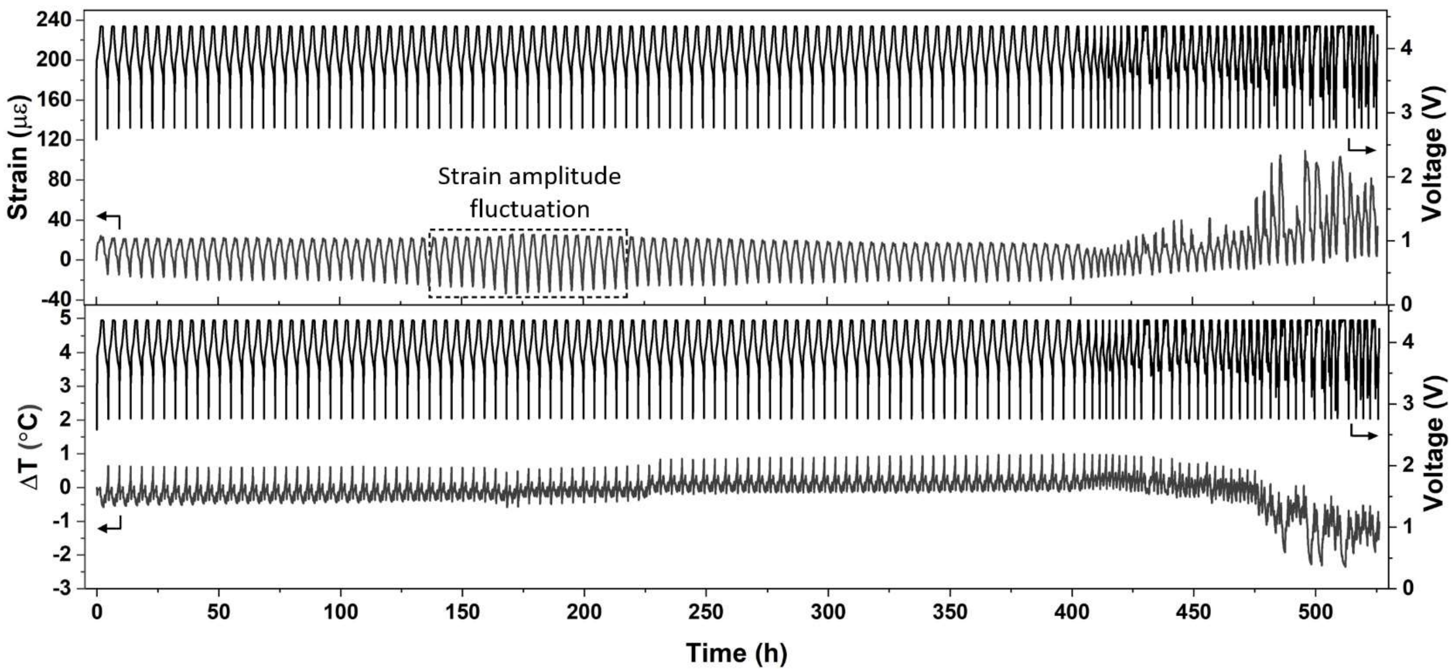

Figure 7