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(54) Title: LI/METAL BATTERY WITH SHAPE CHANGE CONTROL

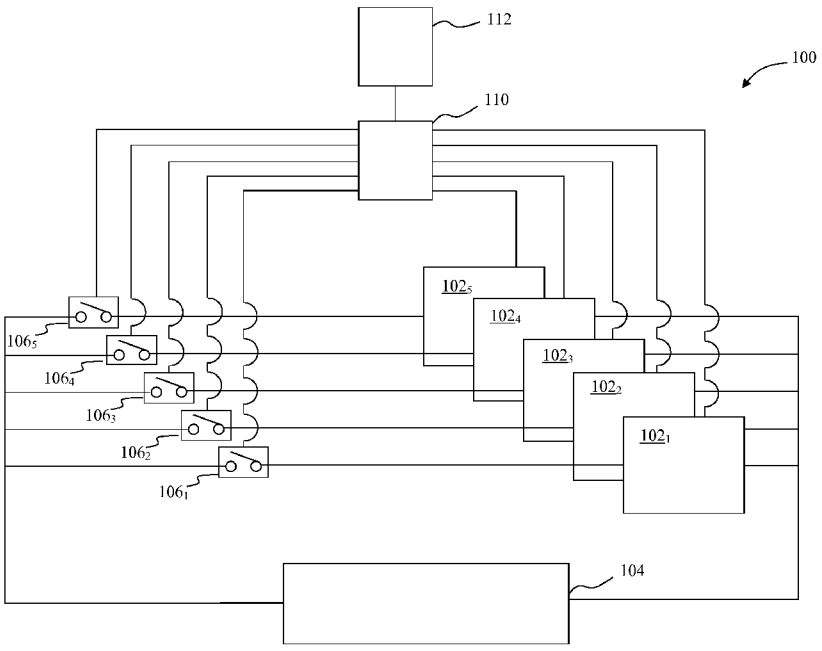


FIG. 4

(57) Abstract: An electrochemical battery system in one embodiment includes a first electrochemical cell including an anode with a form of lithium, a first plurality of pressure sensors positioned and configured to sense localized variations in pressure along the anode, a memory in which command instructions are stored, and a processor configured to execute the command instructions to (i) identify an indication of a variation in localized pressure along the anode, and (ii) selectively control the first electrochemical cell based upon the identified indication.

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Li/Metal Battery with Shape Change Control

Cross Reference

This application claims the benefit of U.S. Provisional Application No. 61/866,079 filed August 15, 2013, the entire contents of which is herein incorporated by reference.

Field of the Disclosure

[0001] The present disclosure relates to batteries and more particularly to lithium-metal batteries.

Background

[0002] Batteries are a useful source of stored energy that can be incorporated into a number of systems. Rechargeable lithium-ion ("Li-ion") batteries are attractive energy storage systems for portable electronics and electric and hybrid-electric vehicles because of their high specific energy compared to other electrochemical energy storage devices. In particular, batteries with a form of lithium metal incorporated into the negative electrode afford exceptionally high specific energy (measured in Wh/kg) and energy density (measured in Wh/L) compared to batteries with conventional carbonaceous negative electrodes.

[0003] When high-specific-capacity negative electrodes such as lithium are used in a battery, the maximum benefit of the capacity-increase over conventional systems is realized when a high-capacity positive electrode active material is also used. Conventional lithium-intercalating oxides (e.g., $LiCoO_2$, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, and $Li_{1.1}Ni_{0.3}Co_{0.3}Mn_{0.3}O_2$) are typically limited to a theoretical capacity of ~280 mAh/g (based on the mass of the lithiated oxide) and a practical capacity of 180 to 250 mAh/g. In comparison, the specific capacity of

lithium metal is about 3863 mAh/g. The highest theoretical capacity achievable for a lithium-ion positive electrode is 1168 mAh/g (based on the mass of the lithiated material), which is shared by Li_2S and Li_2O_2. Other high-capacity materials including BiF_3 (303 mAh/g, lithiated) and FeF_3 (712 mAh/g, lithiated) are identified in Amatucci, G.G. and N. Pereira, *Fluoride based electrode materials for advanced energy storage devices.* Journal of Fluorine Chemistry, 2007. 128(4): p. 243-262. All of the foregoing materials, however, react with lithium at a lower voltage compared to conventional oxide positive electrodes, hence limiting the theoretical specific energy. The theoretical specific energies of the foregoing materials, however, are very high (> 800 Wh/kg, compared to a maximum of ~500 Wh/kg for a cell with lithium negative and conventional oxide positive electrodes).

[0004] Thus the advantage of using a Li metal negative electrode (sometimes referred to as an anode) is the much higher energy density of the entire cell, as compared to cells with graphitic or other intercalation negative electrode. A disadvantage of using pure Li metal is that lithium is highly reactive. By way of example, FIG. 1 is a schematic of an electrochemical cell 10 including an anode 12 including a form of lithium, a cathode 14, and a separator 16 in a fully charged state. A tab 18 provides electrical connection to the anode 12 while a tab 20 provides electrical connection to the cathode 14. As the cell 10 discharges, the lithium in the anode 12 moves to the cathode 14 resulting in the configuration of FIG. 2 in a discharged state. In FIG. 2, the anode 12 has very little lithium remaining.

[0005] In the ideal case the plating and stripping of the Li metal would be completely uniform such that the thickness of the Li metal across the length of the cell would be uniform. In practice the current density in the cell is non-uniform. One reason for this is the tabs 18 and 20 that distribute the electronic current across the electrode surfaces create

electronic pathways of different lengths, thereby encouraging a non-uniform current distribution. Another reason is that temperature gradients create non-uniform local resistance to the flow of current, which will then distribute according to the lowest resistance pathway and in a non-uniform manner.

[0006] The result of a non-uniform current density is a non-uniform thickness of Li metal, which is shown graphically in Fig 3. In FIG. 3, the Li metal is thicker at either end of the cell and thinner in the middle. The specific shape shown in FIG. 3 is meant to be indicative of the types of shape change that can occur, but other shapes are also recognized, including shapes in which one side is thicker than the other, and so on. The changing thickness of the Li metal may also lead to a changing thickness of other cell layers, including the separator and the cathode layers. In addition, while FIG. 3 shows all of the cell layers maintaining coherent interfaces, the layers may also partly separate as a result of shape changes, which in general is deleterious to cell performance.

[0007] Additionally, the lithium metal has a propensity to undergo morphology changes, which cause structures having a high surface area to form on and around the negative electrode when the cell is being charged. Exemplary high surface area structures include dendrites and mossy structures.

[0008] Dendrites are the most common failure mode for cells with Li metal anodes. The dendrites form with a needle-like structure and can grow through the separator during charging of the cell, resulting in an internal short. "Soft shorts" that burn out rapidly result in a temporary self-discharge of the cell, while "strong shorts" consisting of a higher, more stable contact area can lead to complete discharge of the cell, cell failure, and even thermal runaway. While dendrites typically grow through the separator during charge, shorts can

also develop during discharge depending on the external pressure placed on the cell and/or internal volume changes that occur in both the negative and positive electrodes.

[0009] Because Li metal is highly electronically conductive, the surface of the Li tends to roughen as the metal is plated and stripped. Peaks in the surface grow as dendrites during charge. During discharge, some smoothing of the dendrites occurs. Nonetheless, there is typically some roughness that remains at the end of discharge. Depending on the depth of discharge, the overall roughness can be amplified from one cycle to the next. Because the metal is essentially at the same electrochemical potential throughout, potential and, to a lesser extent, concentration gradients in the electrolyte phase drive the change in morphology.

[0010] What is needed, therefore, is a battery system that reduces the potential for dendrite formation and the undesired morphological changes in the anode of battery cells having metal anodes.

Summary

[0011] In accordance with one embodiment an electrochemical battery system includes a first electrochemical cell including an anode with a form of lithium, a first plurality of pressure sensors positioned and configured to sense localized variations in pressure along the anode, a memory in which command instructions are stored, and a processor configured to execute the command instructions to (i) identify an indication of a variation in localized pressure along the anode, and (ii) selectively control the first electrochemical cell based upon the identified indication.

[0012] In one or more of the embodiments, an electrochemical battery system further includes a second plurality of pressure sensors positioned and configured to sense localized variations in pressure along the cathode, wherein the processor is further configured to execute the command instructions to identify an indication of a variation in localized pressure along the cathode.

[0013] In one or more of the embodiments, the first plurality of pressure sensors is placed directly against the anode.

[0014] In one or more of the embodiments, the first electrochemical cell is one of a plurality of electrochemical cells, the system further including a housing enclosing the plurality of cells, wherein the first plurality of pressure sensors is positioned on an inner surface of the housing.

[0015] In one or more of the embodiments, the processor is further configured to execute the command instructions to identify a maximum pressure within the first electrochemical cell using input from the first plurality of pressure sensors, compare the identified maximum pressure to a first threshold, and stop operation of the first electrochemical cell when the identified maximum pressure exceeds the first threshold.

[0016] In one or more of the embodiments, the processor is further configured to execute the command instructions to compare the identified indication of a variation in localized pressure to a predetermined range, and selectively charge or discharge the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range.

[0017] In one or more of the embodiments, the processor is further configured to execute the command instructions to selectively discharge the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range.

[0018] In one or more of the embodiments, the processor is further configured to execute the command instructions to selectively completely discharge the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range.

[0019] In one or more of the embodiments, the processor is further configured to execute the command instructions to selectively discharge the first electrochemical cell to a second electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range.

[0020] In accordance with one embodiment, a method of operating an electrochemical battery system includes positioning a first plurality of sensors along an anode of an electrochemical cell with a form of lithium in the anode, sensing localized variations in pressure along the anode with the first plurality of sensors, identifying, by executing program instructions stored within a memory with a processor, an indication of a variation in localized pressure along the anode using inputs from the first plurality of sensors, and controlling the first electrochemical cell, by executing the program instructions with the processor, based upon the identified indication of a variation in localized pressure along the anode.

[0021] In accordance with one or more embodiments, the method of operating an electrochemical battery system includes positioning a second plurality of sensors along a cathode of the electrochemical cell, sensing localized variations in pressure along the cathode with the second plurality of sensors, identifying, by executing the program instructions with

the processor, an indication of a variation in localized pressure along the cathode using inputs from the second plurality of sensors, and controlling the first electrochemical cell, by executing the program instructions with the processor, based upon the identified indication of a variation in localized pressure along the cathode.

[0022] In accordance with one or more embodiments, positioning the first plurality of sensors includes positioning the first plurality of sensors directly against the anode.

[0023] In accordance with one or more embodiments, the method of operating an electrochemical battery system includes enclosing a plurality of electrochemical cells within a housing, the plurality of cells including the first electrochemical cell, wherein positioning the first plurality of sensors includes positioning the first plurality of sensors directly against an inner surface of the housing.

[0024] In accordance with one or more embodiments, the method of operating an electrochemical battery system includes identifying a maximum pressure within the first electrochemical cell using input from the first plurality of pressure sensors by executing the program instructions with the processor, comparing the identified maximum pressure to a first threshold by executing the program instructions with the processor, and stopping operation of the first electrochemical cell by executing the program instructions with the processor when the identified maximum pressure exceeds the first threshold.

[0025] In accordance with one or more embodiments, the method of operating an electrochemical battery system includes comparing the identified indication of a variation in localized pressure to a predetermined range by executing the program instructions with the processor, and selectively charging or discharging the first electrochemical cell when the

identified indication of a variation in localized pressure is outside of the predetermined range by executing the program instructions with the processor.

[0026] In accordance with one or more embodiments, the method of operating an electrochemical battery system includes selectively discharging the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range by executing the program instructions with the processor.

[0027] In accordance with one or more embodiments, selectively discharging includes selectively completely discharging the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range by executing the program instructions with the processor.

[0028] In accordance with one or more embodiments, the method of operating an electrochemical battery system includes selectively discharging the first electrochemical cell to a second electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range by executing the program instructions with the processor.

Brief Description of the Drawings

[0029] FIG. 1 depicts a simplified schematic showing the layers that may be contained within a cell containing Li metal in a charged condition;

[0030] FIG. 2 depicts the cell of FIG. 1 in a discharged condition showing the volume change (especially of the Li metal) that takes place during the charge and discharge process;

[0031] FIG. 3 depicts a schematic showing the result of a non-uniform current density resulting in a non-uniform Li metal thickness, and thereby a non-uniform cell thickness;

[0032] FIG. 4 depicts a simplified schematic of a battery system including several electrochemical cell packs which can be independently controlled for charging or discharging operations;

[0033] FIG. 5 depicts a simplified schematic of the cell packs of FIG. 4 showing the independently controlled connection switches for each of the electrochemical cells within the electrochemical cell packs;

[0034] FIG. 6 depicts a schematic an electrochemical cell of FIG. 5 including pressure sensors along the length of the cathode and the anode. In some embodiments an enclosure (not shown) is used. In other embodiments, the pressure sensors are very thin (e.g., <5 microns) and integrated directly into a stack of cells;

[0035] FIG. 7 depicts a schematic of a cell stack showing pressure sensors within a stiff enclosure that contains numerous cells. The pressure sensors can also be located on the surface of an enclosure that has some flexibility and contains numerous cells; and

[0036] FIG. 8 depicts a simplified schematic of a control strategy that uses pressure sensor input to control charging and discharging of a cell to reduce uneven lithium deposition in an anode.

Description

[0037] For the purpose of promoting an understanding of the principles of the disclosure, reference will now be made to the embodiments illustrated in the drawings and described in the following written description. It is understood that no limitation to the scope of the disclosure is thereby intended. It is further understood that the present disclosure includes any alterations and modifications to the illustrated embodiments and includes further

applications of the principles of the disclosure as would normally occur to one of ordinary skill in the art to which this disclosure pertains.

[0038] FIG. 4 depicts a battery system 100 including several lithium metal battery cell packs 102_x. In the embodiment of FIG. 4, five battery cell packs 102_{1-5} are depicted. In alternative embodiments, more or fewer battery cell packs of different or the same chemistry may be provided. Each of the lithium metal battery cell packs 102_x is selectively connected to a load or voltage source 104 through a respective switch 106_x. Each of the switches 106_x are controlled by a processor 110 which is operably connected to a memory 112. Various command instructions, discussed in further detail below, are programmed into the memory 112. The processor 110 is operable to execute the command instructions programmed into the memory 112.

[0039] The lithium metal battery cell packs 102_x in this embodiment are identical and are described in further detail with reference to FIG. 5 and the lithium metal battery cell pack 102_5. The lithium metal battery cell pack 102_5 includes five lithium metal battery cells 114_{1-5}. A two-way connection switch 116_{1-5} is associated with each of the battery cells 114_{1-5}. The connection switches 116_{1-5}, which are independently controlled by the processor 110 (control lines are omitted for clarity), can alternatively connect the respective battery cells 114_{1-5} to an internal battery cell circuit 118 or bypass the respective battery cell 114_{1-5}. In FIG. 2, the connection switches $116_{1,\ 2,\ 4,\ \text{and}\ 5}$ are positioned to connect the respective battery cells $114_{1,\ 2,\ 4,\ \text{and}\ 5}$ to the battery cell circuit 118 while the connection switch 116_3 is positioned to a bypass position whereby the respective battery cell 114_3 is effectively electrically isolated from the battery cell circuit 118.

[0040] The lithium metal battery cells 114_{1-5} in this embodiment are identical and are described in further detail with reference to the lithium metal battery cell 114_1 shown in FIG. 6. The lithium metal cell 114_1 includes . The electrochemical cell 114_1 includes an anode 120, a cathode 122 with an aluminum current collector 124, and a separator 126. The anode 120 includes lithium metal or a lithium alloy metal, or other desired metal, and is in electrical communication with a tab 128 through a current collector 130.

[0041] The cathode 122 in various embodiments includes a sulfur or sulfur-containing material (e.g., PAN-S composite), an air electrode, or any other active material or blend of materials that react with and/or insert Li cations and/or electrolyte anions. In some embodiments, the cathode 122 includes Li-conducting liquid, gel, polymer, or other solid electrolyte. Materials in the cathode 122 may further include lithium conducting garnets such as NCM-garnet, $LiNi_{0.5}Mn_{1.5}O_4$-garnet mixtures, lithium conducting sulfides or phosphates, Li_3N, Li_3P, LIPON. Other materials in the cathode 122 may include electronically conductive additives such as carbon black, and a binder material. The cathode materials are selected to allow sufficient electrolyte-cathode interfacial area for a desired design. The cathode is in electrical communication with a tab 132 through the current collector 124. In some embodiments, one or both of the current collectors 124/130 are omitted.

[0042] A number of pressure sensors 134 are located along the length of the anode 120 while another plurality of pressure sensors 136 are located along the length of the cathode 122. As depicted in FIG. 6, current collectors 124 and 130 are positioned between the anode 120 and cathode 122 and the respective pressure sensors 134/136. In embodiments without one or more of the current collectors 124/130, the pressure sensors are placed directly against

the anode/cathode. This configuration of pressure sensors is particularly useful for two-sided or bipolar designs. In this scheme the pressure sensors can be located on every layer, or alternate over some specified number of cell layers, so long as the pressure sensors are integrated directly among the cell layers. Extra separator or other cell layers may be inserted with cutout regions in which the pressure sensors are located so that the pressure sensors do not disturb the good contact among all of the layers.

[0043] The purpose of the pressure sensors 134 and 136 is to provide an indication as to the local thickness of the lithium metal in the anode 120. As the thickness in a particular area of the anode 120 increases, the corresponding pressure sensor will register an increase in pressure. Consequently, regions where the pressure is highest have the thickest Li metal, while regions with the lowest pressure have the thinner Li metal. The variation in pressure thus indicates uneven buildup of Li metal.

[0044] Rather than each individual cell including sets of pressure sensors, in some embodiments multiple cells are monitored with a set of pressure sensors. For example, FIG. 7 depicts a cell stack 150 which includes a number of cells 152 within a housing 154. A number of pressure sensors 156 are located on an inner surface of the housing 154. The cells 152 may be substantially the same as the cell 114_1. The housing 154 is relatively stiff and may be may be a metal or composite case. Alternatively, the housing could be flexible to provide some resistance to swelling of the cells 152. In the embodiment of FIG. 7, the pressure sensors 156 are not provided within the cell layers 152. Nonetheless, they are positioned to provide data regarding the localized pressure conditions within the cells 152.

[0045] In a further embodiment (not shown) the pressure sensors are located on an outer surface of a flexible housing and configured to detect shape changes of the housing. A flexible enclosure may be a pouch.

[0046] Regardless of the particular positioning of the pressure sensors, once information on the local pressure is obtained over the surface of a cell or collection of cells, an algorithm is used to act on that information. The algorithm in one embodiment is stored in the memory 112 and the processor 110 is configured to receive pressure data from the pressure sensors and to execute command instructions including the algorithm. Thresholds for various control actions are also stored in the memory.

[0047] FIG. 8 depicts a process 170 for controlling the system 100 using a stored algorithm. At block 172, the processor receives pressure data from the pressure sensors 134 and 136. At block 174, the obtained pressures are compared to stored values. If the pressures are within an acceptable range, battery operations continue at block 176. In some embodiments, the upper limit of the range is a high pressure limit. In other embodiments, the range is an allowed variation or difference between the obtained pressures, and a separate absolute value is provided as an upper pressure limit.

[0048] If the pressures are not within the desired range at block 174, the processor determines if an emergency pressure threshold has been exceeded at block 178. If the emergency pressure is exceeded, operation of the cell 114_x is terminated at block 180.

[0049] If the pressure has exceeded the desired pressure range at block 174 but has not yet exceeded the emergency pressure sensor at block 178, then the controller operates the cell 114_x to restore the pressure to the desired range at block 182.

[0050] Different control strategies may be used in different embodiments to effect a return to a desired pressure range. In one embodiment, the cell 114_x is controlled to fully strip the lithium from the anode 120 (full discharge). For example the cell 114_x is fully discharged in one embodiment by selectively discharging the cell 114_x to another cell in the battery system 100 or to preferentially supply an external load.

[0051] Depending upon operational constraints which may also be incorporated into the control algorithm, the processor may instead of complete discharge only discharge to a deep level. This may be used to ameliorate the uneven lithium deposition.

[0052] In some embodiments, the processor may control the cell 114_x to provide current pulses to establish a non-uniform current density in the cell 114_x for preferential removal of Li metal from specific areas of the cell 114_x, thereby improving the uniformity of the Li metal.

[0053] The above described steps may be taken while the battery is plugged into an electrical outlet by the user, as the restoration of a uniform thickness of Li metal may involve several discharge and charge steps. However, operation schemes can also be envisioned while a vehicle is in operation. For example, during regenerative braking (charging), the current may be modulated to improve the uniformity of the current density and thereby the uniformity of the Li metal thickness to keep it within a specified range.

[0054] The above described embodiments reduce or reverse deleterious Li metal shape change. By incorporating pressure sensors that monitor Li metal shape change, the disclosed embodiments identify when the shape of the Li metal is outside the desired range as detected by the pressure, and modifies the operating strategy to restore a uniform shape. The shape is returned to a uniform shape in a different ways for different embodiments. In some

embodiments, a complete stripping cycle of Li metal (when a current collector is used in addition to the Li metal, such as copper) is effected while in other embodiments, a series of current pulses that result in a non-uniform current density is used to restore a uniform Li metal shape. Some embodiments use combinations of the strategies described above.

[0055] The disclosed embodiments thus enable the use of Li metal, which offers a higher energy content than batteries that do not include Li metal, by providing a strategy that addresses the problem of shape change that occurs with Li metal during cycling associated with non-uniform current densities.

[0056] While the disclosure has been illustrated and described in detail in the drawings and foregoing description, the same should be considered as illustrative and not restrictive in character. It is understood that only the preferred embodiments have been presented and that all changes, modifications and further applications that come within the spirit of the disclosure are desired to be protected.

Claims

Claim 1. An electrochemical battery system, comprising:

a first electrochemical cell including an anode with a form of lithium;

a first plurality of pressure sensors positioned and configured to sense localized variations in pressure along the anode;

a memory in which command instructions are stored; and

a processor configured to execute the command instructions to (i) identify an indication of a variation in localized pressure along the anode, and (ii) selectively control the first electrochemical cell based upon the identified indication.

Claim 2. The system of claim 1, further comprising:

a second plurality of pressure sensors positioned and configured to sense localized variations in pressure along the cathode, wherein the processor is further configured to execute the command instructions to identify an indication of a variation in localized pressure along the cathode.

Claim 3. The system of claim 1, wherein the first plurality of pressure sensors is placed directly against the anode.

Claim 4. The system of claim 1, wherein the first electrochemical cell is one of a plurality of electrochemical cells, the system further including:

a housing enclosing the plurality of cells, wherein the first plurality of pressure sensors is positioned on an inner surface of the housing.

Claim 5. The system of claim 1, wherein the processor is further configured to execute the command instructions to:

identify a maximum pressure within the first electrochemical cell using input from the first plurality of pressure sensors;

compare the identified maximum pressure to a first threshold; and

stop operation of the first electrochemical cell when the identified maximum pressure exceeds the first threshold.

Claim 6. The system of claim 5, wherein the processor is further configured to execute the command instructions to:

compare the identified indication of a variation in localized pressure to a predetermined range; and

selectively charge or discharge the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range.

Claim 7. The system of claim 6, wherein the processor is further configured to execute the command instructions to:

selectively discharge the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range.

Claim 8. The system of claim 7, wherein the processor is further configured to execute the command instructions to:

selectively completely discharge the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range.

Claim 9. The system of claim 7, wherein the processor is further configured to execute the command instructions to:

selectively discharge the first electrochemical cell to a second electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range.

Claim 10. A method of operating an electrochemical battery system, comprising:

positioning a first plurality of sensors along an anode of an electrochemical cell with a form of lithium in the anode;

sensing localized variations in pressure along the anode with the first plurality of sensors;

identifying, by executing program instructions stored within a memory with a processor, an indication of a variation in localized pressure along the anode using inputs from the first plurality of sensors; and

controlling the first electrochemical cell, by executing the program instructions with the processor, based upon the identified indication of a variation in localized pressure along the anode.

Claim 11. The method of claim 10, further comprising:

positioning a second plurality of sensors along a cathode of the electrochemical cell;

sensing localized variations in pressure along the cathode with the second plurality of sensors;

identifying, by executing the program instructions with the processor, an indication of a variation in localized pressure along the cathode using inputs from the second plurality of sensors; and

controlling the first electrochemical cell, by executing the program instructions with the processor, based upon the identified indication of a variation in localized pressure along the cathode.

Claim 12. The method of claim 10, wherein positioning the first plurality of sensors comprises:

positioning the first plurality of sensors directly against the anode.

Claim 13. The method of claim 10, further comprising:

enclosing a plurality of electrochemical cells within a housing, the plurality of cells including the first electrochemical cell, wherein positioning the first plurality of sensors comprises:

positioning the first plurality of sensors directly against an inner surface of the housing.

Claim 14. The method of claim 10, further comprising:

identifying a maximum pressure within the first electrochemical cell using input from the first plurality of pressure sensors by executing the program instructions with the processor;

comparing the identified maximum pressure to a first threshold by executing the program instructions with the processor; and

stopping operation of the first electrochemical cell by executing the program instructions with the processor when the identified maximum pressure exceeds the first threshold.

Claim 15. The method of claim 14, further comprising:

comparing the identified indication of a variation in localized pressure to a predetermined range by executing the program instructions with the processor; and

selectively charging or discharging the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range by executing the program instructions with the processor.

Claim 16. The method of claim 14, further comprising:

selectively discharging the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range by executing the program instructions with the processor.

Claim 17. The method of claim 16, wherein selectively discharging comprises:

selectively completely discharging the first electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range by executing the program instructions with the processor.

Claim 18. The method of claim 14, further comprising:

selectively discharging the first electrochemical cell to a second electrochemical cell when the identified indication of a variation in localized pressure is outside of the predetermined range by executing the program instructions with the processor.

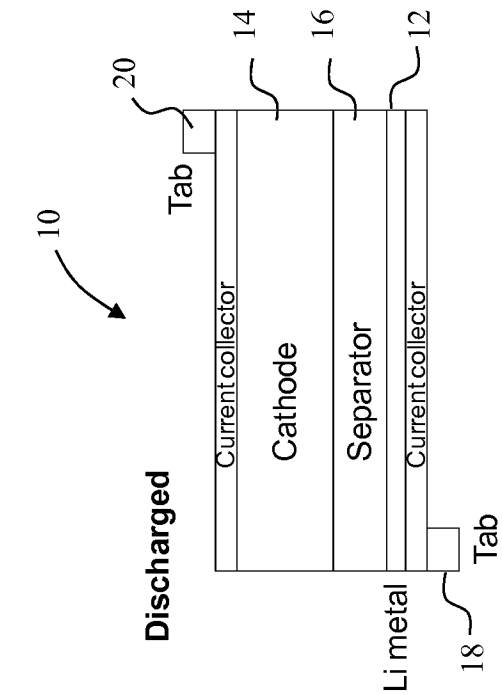


FIG. 2
(PRIOR ART)

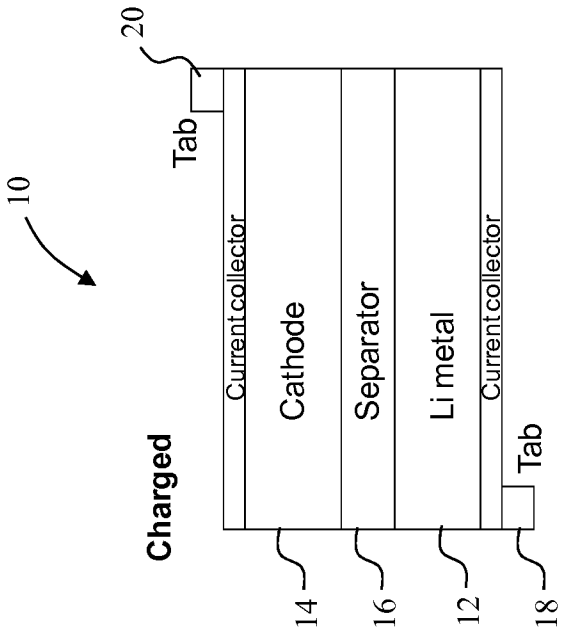


FIG. 1
(PRIOR ART)

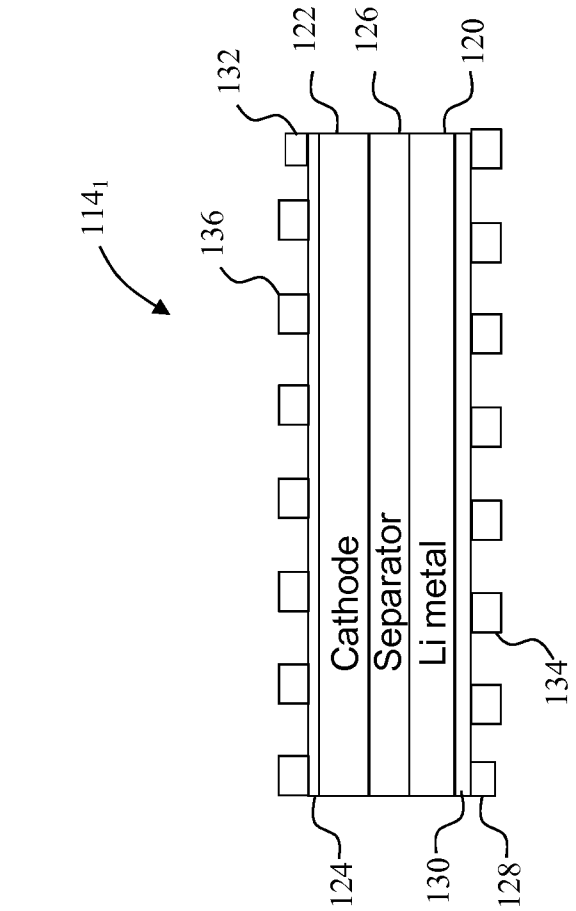


FIG. 6

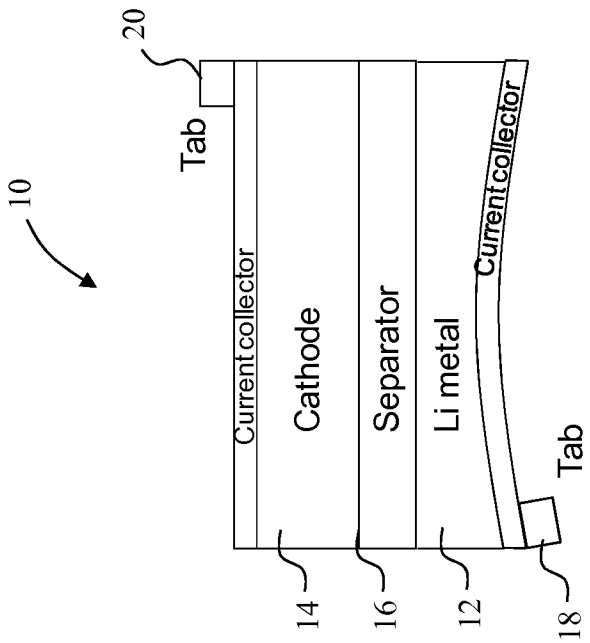


FIG. 3
(PRIOR ART)

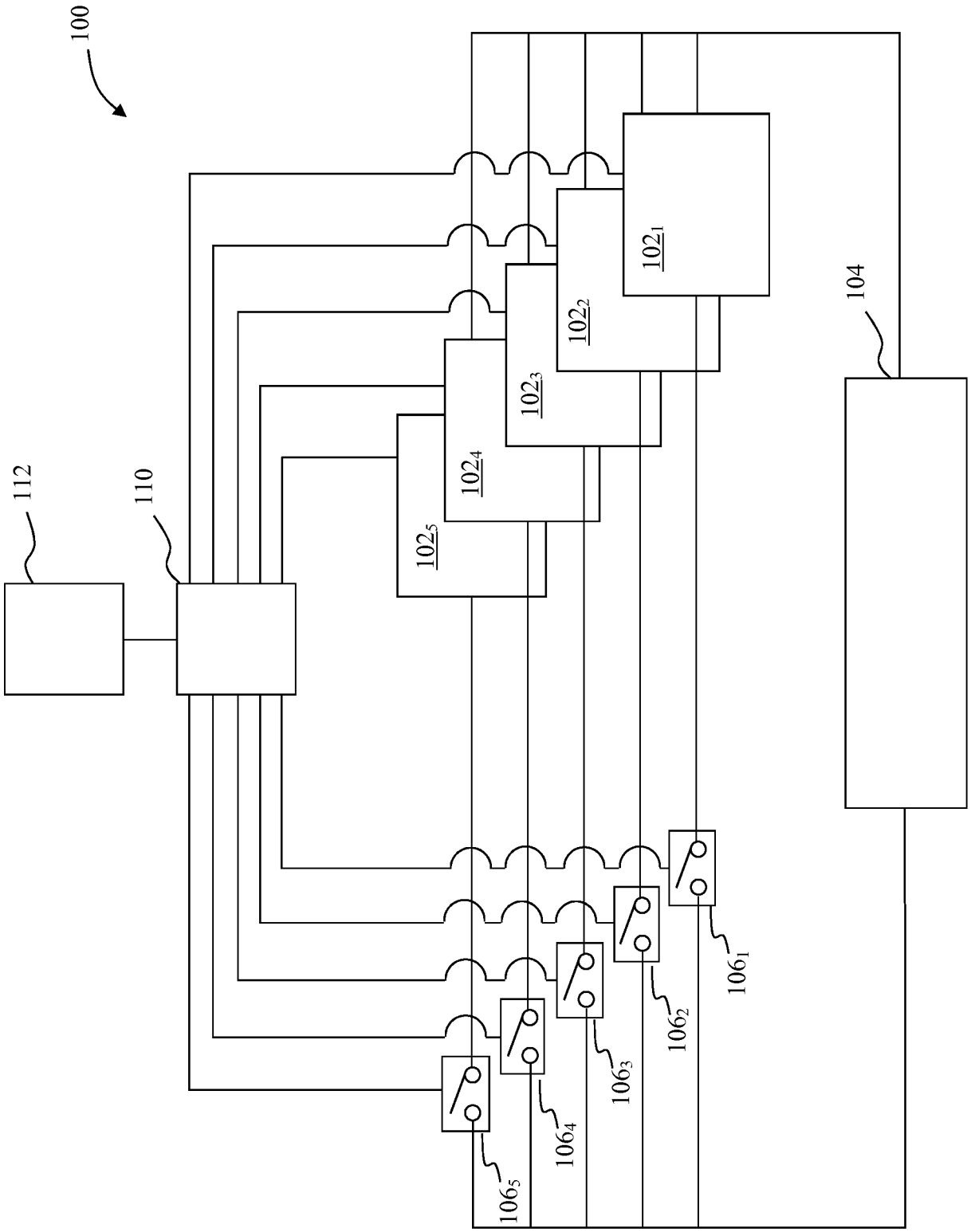

100
112
110
102_1
102_2
102_3
102_4
102_5
104
106_1
106_2
106_3
106_4
106_5

FIG. 4

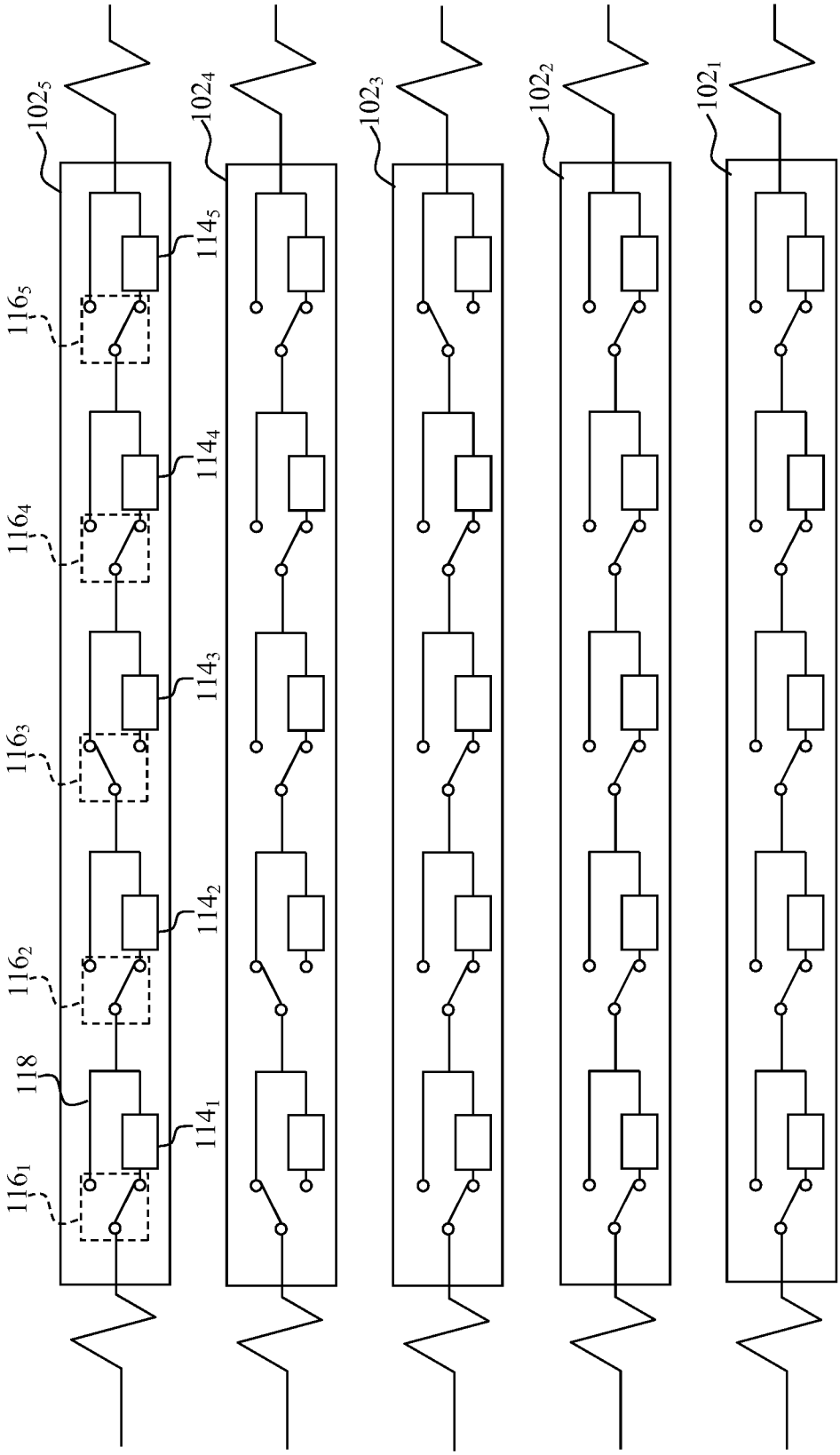

102_5
102_4
102_3
102_2
102_1
114_5
114_4
114_3
114_2
114_1
116_5
116_4
116_3
116_2
116_1
118

FIG. 5

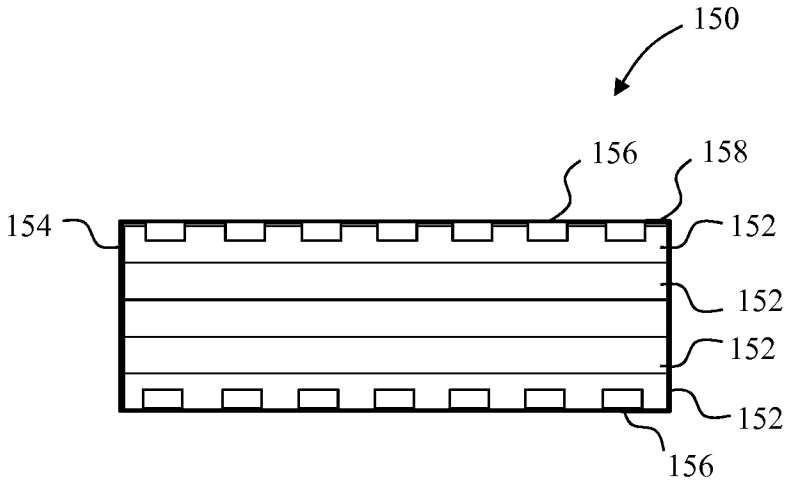

150
156
158
154
152
152
152
152
156

FIG. 7

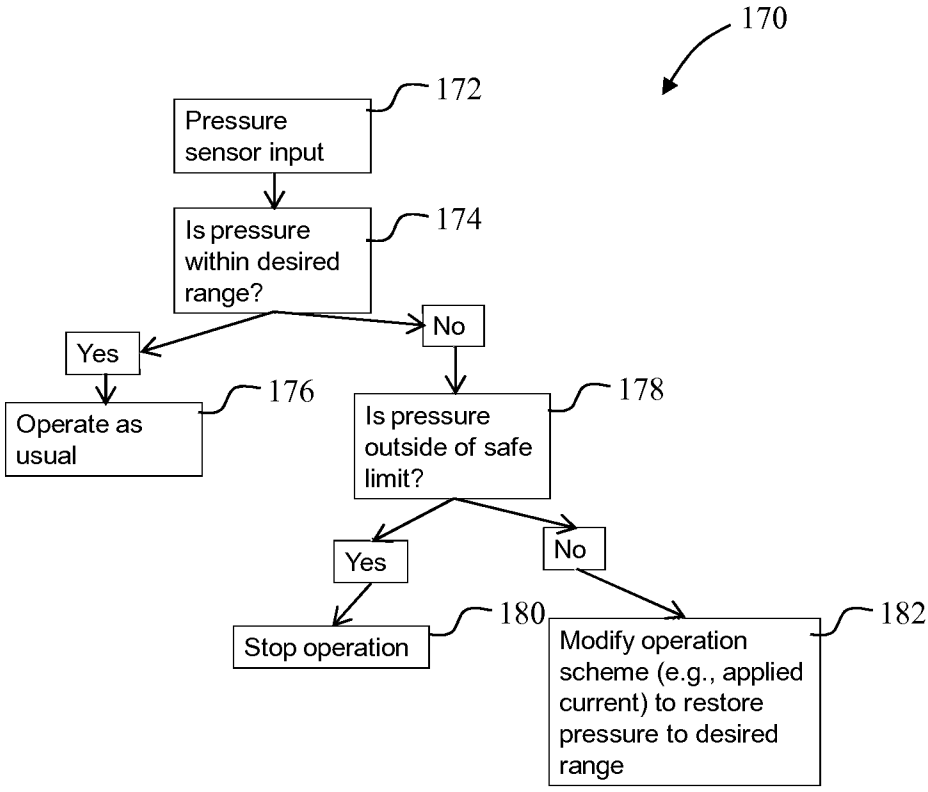

170
172
Pressure sensor input
174
Is pressure within desired range?
No
Yes
176
Operate as usual
178
Is pressure outside of safe limit?
Yes
No
180
Stop operation
182
Modify operation scheme (e.g., applied current) to restore pressure to desired range

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/051085

A. CLASSIFICATION OF SUBJECT MATTER

H01M 10/48(2006.01)i, H01M 10/052(2010.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01M 10/48; H01M 10/052

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords:lithium metal, pressure sensor, anode, localized pressure, processor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 05628973 A (NISHIMURA; KATSUNORI et al.) 13 May 1997 See the abstract, whole claims and fig. 1-4	1-18
A	US 2012-0270077 A1 (KOETTING WILLIAM) 25 October 2012 See the abstract, whole claims and fig. 1-8	1-18
A	US 2012-0270126 A1 (MATSUMOTO YUJI et al.) 25 October 2012 See the abstract, whole claims and fig. 1,5	1-18
A	US 2012-0280692 A1 (PARK KYU-HA) 08 November 2012 See the whole document	1-18

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 November 2014 (28.11.2014)	**28 November 2014 (28.11.2014)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2014/051085

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