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Protection Devices in Commercial 18650 Lithium-Ion Batteries

BIN XU[1,2], LINGXI KONG[2], GUANGRUI WEN[1], AND MICHAEL G. PECHT[2], (Life Fellow, IEEE)

[1]School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[2]Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD 20742, USA

Corresponding author: Guangrui Wen (grwen@mail.xjtu.edu.cn)

ABSTRACT 18650 Lithium-ion batteries are wildly used as power sources for portable electronics because of the standardized format and economical manufacturing cost. However, commercial 18650 cells come in various designs due to the implementation of different protection devices. The current interrupt device and top vent are mandatory protection devices for all commercial 18650 Li-ion batteries. In contrast, the positive temperature coefficient thermistor, bottom vent, and protection circuit are optional protection devices that can be non-installed, installed separately, or combined in commercial 18650 batteries. Four representative commercial 18650 Li-ion batteries were disassembled and compared in terms of the similarities and differences of the protection devices. This paper overviews the working mechanism, advantages, and drawbacks of each protection device. Recommendations on battery selection and potential future trends are then provided.

INDEX TERMS 18650 Lithium-ion batteries, positive temperature coefficient, current interrupt device, top vent, bottom vent, protection circuit.

I. INTRODUCTION

18650 cylindrical battery was first released as a standard Lithium-ion (Li-ion) battery model in 1994 [1]. Since the late 1990s, 18650 Li-ion cells have been one of the most widely used secondary batteries [2]. The first four digits of the "18650" mean the physical dimensions: 18mm in diameter, 65mm in height, and 0 indicates the cylindrical format.

Today, 18650 Li-ion batteries are widely used in e-cigarettes [3], power banks [4], electric vehicles [5], and even deep space CubeSats [6]. The global 18650 Li-ion batteries market reached USD 6.03 billion in 2019 and is expanding at a compound annual growth rate of 1.7% to reach USD 6.69 billion by the end of 2024 [7]. The capacity of the 18650 battery has been increasing in the last decades and reached 3.4Ah in commercial cells [8]. The increasing market share and energy density puts more challenges on battery safety. Thermal runaway is the most catastrophic failure mode in Li-ion batteries, initiating uncontrollable temperature rise and potentially causing fire or explosion [9]. Though steel cases of 18650 Li-ion cells provide excellent mechanical stability, it causes catastrophic consequences once the battery catches fire and explode [10].

On February 13, 2016, a 20-year-old man from the UK suffered second and third-degree burns due to an e-cigarette battery that exploded in his pocket [3]. On April 21, 2019, a parked Tesla Model S spontaneously combusted in Shanghai, China, even though the car's battery was not being charged [11]. On June 19, 2019, a Nevada teen was vaping when his device exploded, shattering his jaw [12]. The 18650 battery was identified as the cause of all the above incidents, which led the battery industry and customers to pay more attention to the safety of 18650 cells.

Battery manufacturers not only install protection devices to prevent batteries from out-of-tolerance working conditions but also educate the public about the safety risk of battery misusage. On November 10, 2015, Sony released the safety warning of misusing Sony VTC 18650 batteries in e-cigarettes and vape pens [13]. Samsung also released a statement that their 18650 cells are not intended to use in vape or e-cigarettes [14]. On January 14, 2020, LG Chem posted a video showing burning 18650 cells to tell the public not to handle or touch bare cells [15].

Protection devices, including positive temperature coefficient (PTC), current interrupt device (CID), top vent,

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bottom vent, and protection circuit, are built-into commercial 18650 Li-ion cells for improving battery safety. However, the installation of protection devices varies in different 18650 cell models.

In this work, four different commercial 18650 cell designs were disassembled to show similarities and differences in their protection devices, and the working mechanism of each protection device was introduced. The rest of this paper is organized as follows. Section II describes four different commercial 18650 cell designs. Section III shows the mandatory protection devices. Optional protection devices are discussed in Section IV. The characteristics of protection devices in 18650 cells were discussed in Section V. Conclusions are drawn in Section VI.

II. DISASSEMBLY OF 18650 BATTERIES

In the 18650 Li-ion battery, the anode, separator, and cathode are rolled up and filled with a liquid electrolyte in the steel case to store electric energy. The standard 18650 Li-ion battery usually is cylindrical with both flat top and bottom for better arrangement in battery packs, as shown in Figure 1(a). Some types of 18650 cells were modified by welding a button top on the standard 18650 Li-ion battery for rigid connection in specific applications, for example, flashlights [16], as shown in Figures 1(b). Commercial 18650 cells with a protection circuit at the bottom are labeled as "protected" cells. Figure 1(c) displays the protected 18650 cells with a button top and protection circuit.

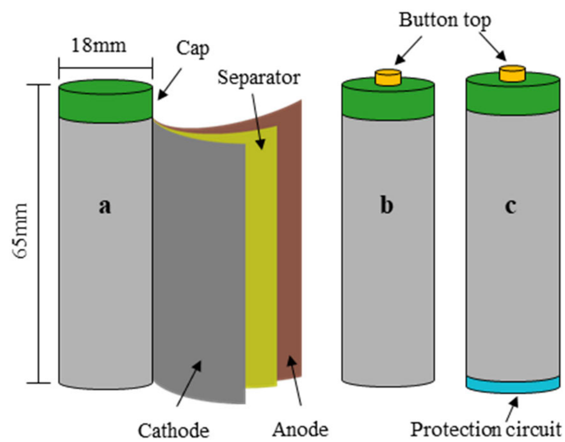

FIGURE 1. Commercial 18650 Li-ion battery designs.

Four representative commercial 18650 cells were purchased to investigate the similarities and differences of their protection devices. As shown in Figure 2, the cell models are Sony VTC5, Samsung 26F, Sony VTC5D, and protected Samsung 30Q from left to right. Sony VTC5 is a battery with only two protection devices: CID and top vent. Samsung 26F, Sony VTC5D, and protected Samsung 30Q are featured with an additional PTC, bottom vent, and protection circuit, respectively. The specifications of purchased four 18650 cells are listed in Table 1.

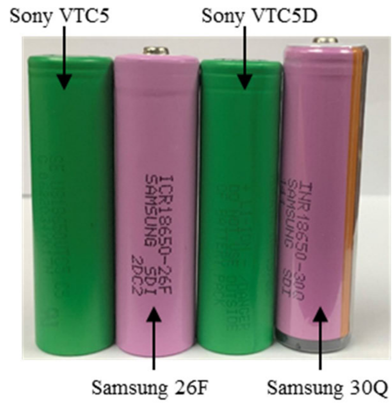

FIGURE 2. Four different types of commercial 18650 Li-ion batteries.

TABLE 1. Specifications of purchased 18650 cells.

Model	Capacity	Voltage range
Sony VTC5	2.6Ah	2.5V – 4.2V
Samsung 26F	2.6Ah	2.75V – 4.2V
Sony VTC5D	2.8Ah	2.5V – 4.2V
Samsung 30Q	3.0Ah	2.5V – 4.2V

From the appearance, Sony VTC5 and Sony VTC5D are standard 18650 cells with a flat top, while Samsung 26F and protected Samsung 30Q show an increase in physical length due to the button top and/or protection circuit. To illustrate the difference of protection devices, four types of batteries were discharged to their cut-off voltage and disassembled in a glove box at room temperature.

The protection device-related components of the four 18650 cells are displayed in Figure 3. The metal outer jacket, first plastic insert, positive terminal, vent holes, top disk, second plastic insert, bottom disk, and metallic foil are components of the CID and top vent. Hence, CID and top vent are mandatory protection devices in commercial 18650 cells. Other three safety devices, including PTC, bottom vent, and protection circuit, can only be found in one of the batteries. Sony VTC5 battery functions well without those three protection devices. Hence, PTC, bottom vent, and protection circuit are classified as optional protection devices in 18650 cells. Button top is not related to battery safety, thus not in the scope of this paper.

III. MANDATORY PROTECTION DEVICES

The CID and top vent are mandatory protection devices in commercial 18650 cells and installed in the battery cap. Figure 4 shows the cap structure of a commercial 18650 Li-ion battery to understand how CID and top vent works together. During regular operation, the current flows from the current collector attached to the cathode through the positive tab to the metallic foil, bottom disk, top disk, PTC, terminal contact, and button top, respectively, then out to provide electric energy. The current pathway will be cut off if the CID

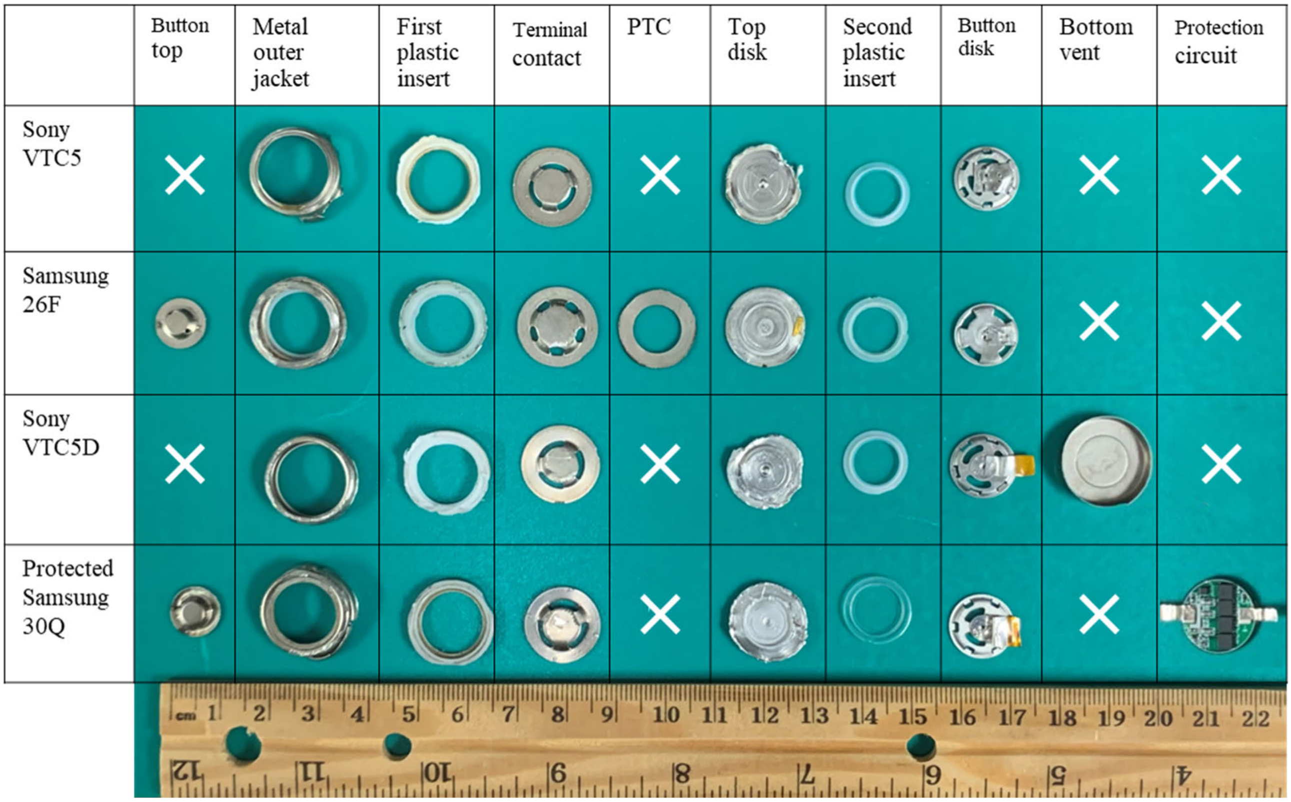

FIGURE 3. Safety devices disassembled from 18650 Li-ion batteries.

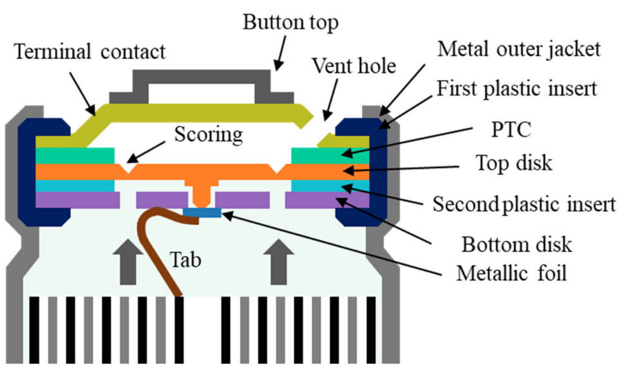

FIGURE 4. The cap structure of commercial 18650 Li-ion battery.

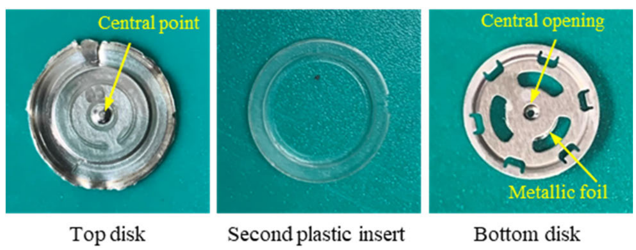

FIGURE 5. Components of CID in protected Samsung 30Q battery.

or top vent is activated. The working mechanisms of CID and the top vent will be explained next.

A. CURRENT INTERRUPT DEVICE

In commercial 18650 cells, the CID consists of the top disk, second plastic insert, bottom disk, and metallic foil. The top disk is a conductive flexible member that can move upwards under excessive pressures. The center point of the top disk is welded to the metallic foil through the central opening of the bottom disk, and the metallic foil is, in turn, affixed to the bottom disk. The second plastic insert electrically insulate the rest areas between the top disk and the bottom disk. Thus, the welding point is the only electrical connection between the top and bottom disk, which is a "weak point" in the current pathway. Figure 5 shows the CID parts of the protected Samsung 30Q battery.

The tab, metallic foil, bottom disk, and top disk are electrically connected during regular operation. When the battery is operating in abnormal modes, such as overcharging [17], a large amount of gas will be generated from both electrodes. The internal pressure will increase because the cavity is well-sealed. Once the internal pressure rises to a pre-defined level (e.g., 1.0$\sim$1.2 MPa [18]), the top disk will be forced to move upwards to break the "weak point", which is the welding connection between the central point and the metallic foil. Then, the electrical pathway from the current collector to the external load will be cut-off, and the electrochemical reaction

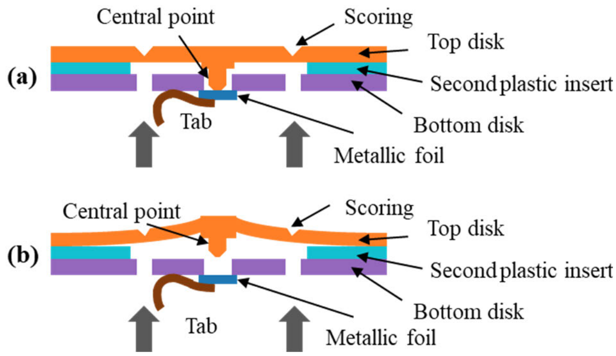

FIGURE 6. CID structure before and after being triggered.

inside the battery will be halted. Figure 6 shows the CID structure before and after being triggered.

The CID in commercial 18650 cells is an irreversible protection device, which means the battery will be useless as an energy source once the CID is triggered. Since the current path is determined by the welding connection between the top disk and the metallic foil, the CID does not always provide the expected protection when needed if the connection is either too strong or too weak. It has been reported that the CID in some commercial 18650 cells fails to activate under overcharge conditions in high-voltage modules [19]. If the 18650 battery undergoes thermal runaway, the CID may fail to stop the increasing internal pressure. Therefore, it is mandatory to build a top vent in commercial 18650 cells to prevent the battery case from rupturing or explosion.

B. TOP VENT

''venting'' is defined by International Electrotechnical Commission 62133 standard as ''release of excessive internal pressure from a cell or a battery in a manner intended by design to preclude rupture or explosion'' [20]. In commercial 18650 cells, both the top vent and the CID are pressure-responsive protection devices. Like the CID, the top vent involves a ''weak point'' for safely releasing internal pressure, which is the ''C'' shape scorings on the top disk. Figure 7 shows the components of the top vent in the protected Samsung 30Q battery. The peripheral holes on the bottom disk, ''C'' shape scorings on the top disk, and ''vent holes'' on the terminal contact constitute the gas venting pathway of the top vent.

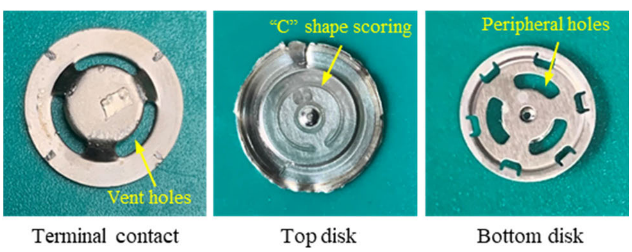

FIGURE 7. Components of the top vent in the protected Samsung 30Q battery.

The top vent-related components work as conductors in the battery circuit during normal conditions. When the internal short circuit occurs, the cathode and anode continue to react and generate gases though the CID is activated. The internal pressure will increase to a higher level (e.g., 2.2∼2.3 MPa [18], 2.58 MPa [21]) till break the ''C'' shape scorings on the top disk. Then the gas will be venting through peripheral holes, ''C'' shape opening, and vent holes to outside. Figure 8 shows the releasing pathway during venting. The battery cap or sidewall can be protected from an uncontrolled rupture since the internal pressure is released in a controlled pathway.

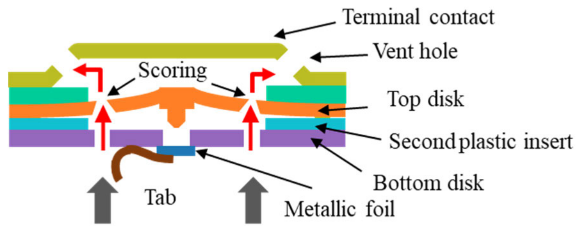

FIGURE 8. Gas releasing pathway during venting.

Not only gas but also the electrolyte and electrode material can be vented out through the releasing pathway [22]. The releasing pathway could be clogged if the battery undergoes thermal runaway and the vent opening area is insufficient. The peripheral holes of the bottom disk and vent holes of the terminal contact are designed to avoid clogging during venting. If the only top vent is clogged or cannot vent efficiently, the battery case may be ruptured or exploded. Battery manufacturers have introduced new cylindrical cell designs with a bottom vent for better venting.

IV. OPTIONAL PROTECTION DEVICES

Apart from the CID and top vent, optional protection devices, including the PTC, bottom vent, and protection circuit, also can be found in some commercial 18650 cells. This section introduces the characteristic of optinal protection devices in purchased 18650 cells.

A. POSITIVE TEMPERATURE COEFFICIENT

Based on the standard Institute of Electrical and Electronics Engineers 1725-2011, PTC is defined as ''A component that has the characteristic of a sudden large increase in resistance when the device reaches a specified temperature and/or current''. In commercial 18650 cells, a PTC is an annular-shape disk with a three-layer structure: one conductive polymer layer sandwiched in two metal layers. Figure 9 shows the PTC in the Samsung 26F battery and the cross-sectional view taken along line A-A. The brighter layers of both sides are metal layers that play roles in conductivity and supporting the conductive polymer. The middle layer is the conductive polymer layer that increases resistance at elevated temperatures. Each layer was measured at two different locations. The average

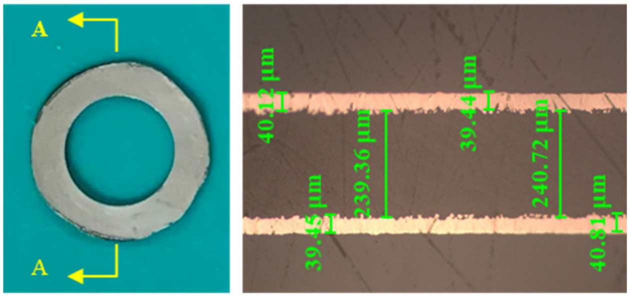

FIGURE 9. The PTC in the Samsung 26F battery.

thickness of the metal layer and the polymer layer is about 40 μm and 240 μm, respectively.

In the PTC, the conductive polymer layer is the polythene polymer mixed with conductive particles [23], which has a small resistance around 20 mΩ at room temperature. When the PTC temperature increases to a specific level around 100 °C, the polymer expansion increases the distance between the embedded conductive particles. It then causes a non-linear and sharp increase in resistance of the PTC. The current on the battery will be significantly reduced to a relatively low and safe level. The PTC thermistor is effective for a single 18650 cell due to the quick reaction to overcurrent conditions.

An experimental test was conducted to validate the characteristics of the PTC in the Samsung 26F battery. The PTC was applied to the electric circuit in Figure 10. The DC power controls the circuit current, and the PTC resistance can be calculated using the measured voltage and current. When the circuit current increases, the PTC temperature rises due to ohmic heating, causing the PTC resistance to increase. Two K-type thermocouples were used to collect the surface temperature of the PTC.

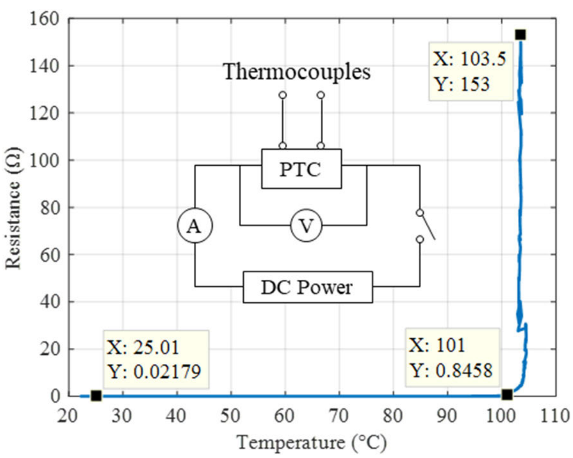

FIGURE 10. The experimental test for the PTC in the Samsung 26F battery.

Figure 10 shows the changes of the PTC resistance with temperature. The PTC resistance is 21 mΩ at 25 °C and slightly increases to 84 mΩ at 101 °C, whereas, sharply increases to 153 Ω at 103.5 °C. Thus, the PTC can protect the 18650 battery from over-current as designed. However, when used in series or parallel configurations, the PTC may fail to protect cells as it does for single cells. The PTC in 18650 battery was reported to be ignited under external short circuits in a high-voltage string [19].

In this study, the PTC was taken out from the battery to investigate the resistance response to the temperature, which may slightly differ from the results when the PTC was embedded in the battery. Besides, both the PTC shape and the particle size distribution in the conductive polymer affect the performance of the PTC [24].

Unlike the CID and the top vent in 18650 cells, the PTC is a reversible protection device to inhibits high current surges. It returns to a conductive state once the temperature drops to room temperature. However, the PTC is not applicable for high-current specialized 18650 batteries. For example, Samsung INR18650-25R doesn't equip the PTC because the continuous discharge current is designed as high as 20 A [8]. Manufacturing complexity and cost also inhibit the application of the PTC; thus, not all commercial 18650 cells feature the PTC thermistor.

B. BOTTOM VENT

The energy stored in the Li-ion battery will be suddenly released within milliseconds during thermal runaway, resulting in the rapid increase of the internal pressure [25]. If the vent opening area is insufficient or the releasing pathway is clogged by battery material, the metal case rupture or explosion occurs [10]. To prevent sidewall rupture in the battery packaging, some battery manufactures provide a second vent design for efficient venting. Sony VTC5D is a typical commercial 18650 battery with a second vent on the bottom. The design of the bottom vent varies in different types of 18650 cells. In Figure 11, the Sony VTC5D battery bottom has a smooth outside and a "C" shape scoring inside. In the LG M36-BV battery, the "C" shape scoring is located at the outside of the bottom with a smaller diameter [21].

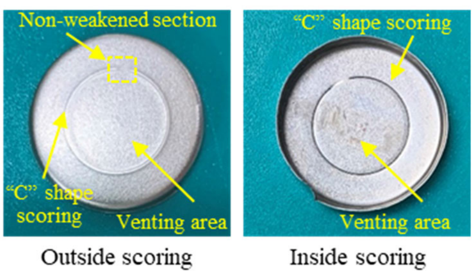

FIGURE 11. Bottom vent in the Sony VTC5D battery.

Figure 12 shows the cross-sectional view of the "C" shape scoring on the bottom of Sony VTC5D. The average thickness of the bottom is about 314 μm while the thickness of scoring is reduced to 74.8 μm. Moreover, the 38° triangle scoring concentrates the stress to a point and creates a "weak point" for better venting.

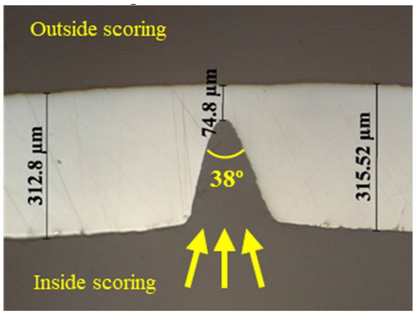

FIGURE 12. Cross-sectional of the "C" shape scoring of the bottom vent in the Sony VTC5D battery.

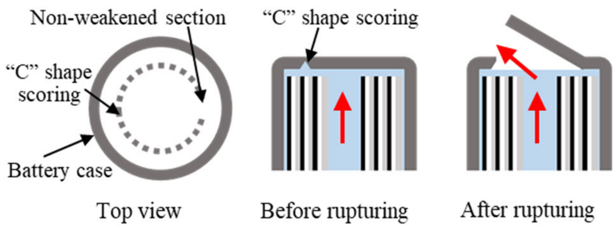

FIGURE 13. Before and after rupturing of the bottom vent.

Figure 13 shows the bottom vent before and after rupturing and the pressure releasing pathway. When the gas cannot be efficiently transported to the top vent, the internal pressure will increase to a specific level (2.47 MPa [21]) and break the "weak point". The "C" shape section will open outwards, allowing the release of gas and material of the cell. The venting area takes about 62% of the whole bottom, which is sufficient to vent out gas or battery material. The non-weakened section except for "C" shape scoring can prevent the disk from flying out when it ruptures.

The bottom vent has gradually been implemented in more and more commercial 18650 cell models, such as Sony VTC5D, Sony VC7, and LG M36-BV. The bottom vent shows a slightly lower activation pressure than the top vent in commercial 18650 cells. However, it can reduce the risk of sidewall rupture and significantly decrease the impact to adjacent cells in a battery package by releasing generated gas through an alternative escape route [21].

C. PROTECTION CIRCUIT

Nowadays, a battery management system (BMS) is commonly used at the battery pack level to extend lifespan and improve safety by controlling the operation of the battery. However, the single cell-level failures could propagate to adjacent cells and result in pack-level catastrophic incidents [26]. The smart cells embedded with sensors, controllers, actuators, and communicators could be the solution for the challenges of current BMS [27]. Moreover, cell-level active protection methods, such as internal short circuit diagnostic [28], [29], thermal runaway detection [30], have also been widely studied.

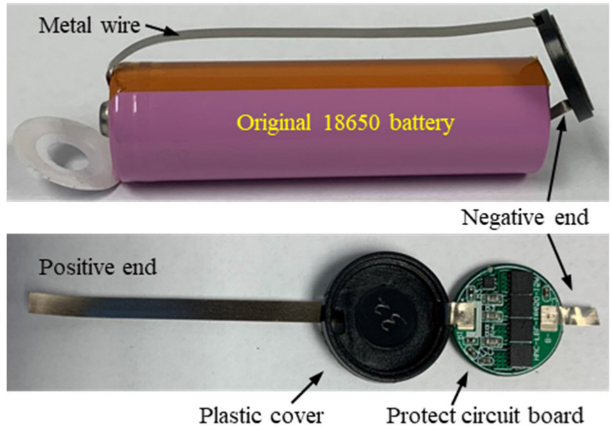

FIGURE 14. Protection circuit in the protected Samsung 30Q battery.

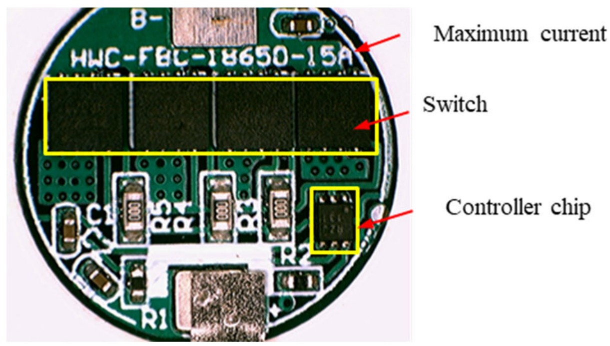

FIGURE 15. Enlarged view of the protection circuit board.

TABLE 2. Pin configuration of the controller chip.

Symbol	Description
VDD	Input pin for positive power
VSS	Input pin for negative power
VINI	Overcurrent detection pin
DO	Connection pin for discharge control FET1 gate
CO	Connection pin for charge control FET2 gate
VM	Input pin for external negative voltage

Cells with a protection circuit can be considered simplified smart cells that only have a controller and switches. This is because the protection circuit can provide full-time active protection against overcharging, over-discharging, overcurrent, and short-circuits, thus significantly improving the overall safety.

The protected Samsung 30Q battery featured a protection circuit at the bottom of the battery. Figure 14 shows the disassembled protected Samsung 30Q battery. The protection circuit board is electrically connected with the positive and negative of the original Samsung 30Q battery through metal wires and fixed at the bottom of the battery by a plastic cover. Figure 15 shows the enlarged view of the protection circuit board.

According to the manufacturer's specifications sheet, the protection circuit in the protected Samsung 30Q battery is

TABLE 3. Summary of protection devices in 18650 cells.

Protection devices	Activation conditions	Advantages	Disadvantages	Safety improvement
CID	Internal pressure over 1.0 ~ 1.2 MPa	Effective for the single cell	Irreversible protection device; difficult to control the connection strength;	Middle
Top vent	Internal pressure over 2.2 ~ 2.3 MPa, or 2.58 MPa	Protect battery case from rupturing	May fail to protect the cells in series or/and parallel configures	High
PTC	PTC temperature over 100 °C	Compact size; lightweight; resettable.	Increases cell resistance and energy loss.	Low
Bottom vent	Internal pressure over 2.47 MPa	Prevent sidewall rupture;	Increases the risk of electrolyte leakage.	Middle
Protection circuit	Overcharge, over-discharge, overcurrent, and short circuit	Active full-time protection; works for both the single cell-level or pack-level	Increases cost and manufacturing complexity.	High

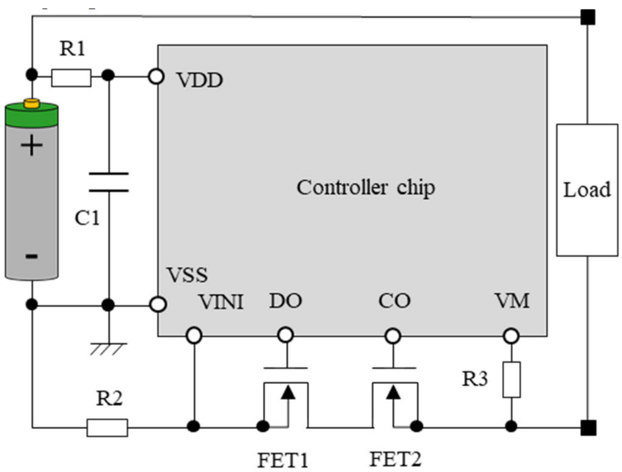

FIGURE 16. Pin configuration of the controller chip.

manufactured by ABLIC Inc.. Figure 16 shows the block diagram of the S-82A1A series battery protection circuit manufactured by ABLIC Inc. for the single-cell [31]. There are six pins configured at the controller chip, and the field-effect transistor (FET) works as a switch. The pin configuration of the controller chip was displayed in Table 2. A high-accuracy voltage detection circuit was embedded in the controller chip.

The controller chip controls charging by monitoring the voltage between the VDD pin and VSS pin, and controls discharging by monitoring the voltage between the VINI pin and VSS pin. The controller chip turns on both the switch FET1 and FET2 when the battery works at normal operating conditions. If the battery voltage is lower than the over-discharge detection voltage or the VINI pin voltage lower than the discharge overcurrent detection voltage, the controller chip will turn off the switch FET2. Similarly, if the overcharge detection voltage or charge overcurrent voltage is being surpassed, the switch FET2 will be turned off.

Because of the protection circuit, the battery cut-off voltage range expands from 2.5V – 4.2V for the original Samsung 30Q battery to 2.3V – 4.35V for the protected Samsung 30Q battery. The protection cut-off current is capable of up to 15A. However, the weight and height of the protected Samsung 30Q battery increase by 2.9g and 3.8mm, respectively. The increases in the overall resistances and manufacturing cost are also inevitable. Thus, the protected 18650 cells are usually manufactured for specialized applications, e.g., high-power flashlights, headlamps, and bike lights, instead of large-scale power sources.

V. DISCUSSION

The characteristics of protection devices in 18650 cells were summarized in Table 3, including activation conditions, advantages, disadvantages, and safety improvement.

As seen in Table 3, any of the protection devices can improve battery safety. The absence of some protection devices may cause severe consequences, such as the top vent, while other protection devices are less important, such as the bottom vent. Besides, the overall safety could be significantly improved after integrating with some protection devices, such as the protection circuit, while other protection devices contribute less to battery safety, such as the PTC. These features are taken into account to rank their contributions to battery safety, and the results can be found in Table 3.

In the same battery, the top vent has a higher activation pressure than the CID and thus provides a solution when the CID failed to stop the increasing internal pressure. In different cylindrical cells, the activation pressures of the top vent vary due to chemistry and battery structure.

The bottom vent provides a backup venting pathway when the top vent is insufficient to release the internal pressure. Hence, the activation pressure of the bottom vent may higher or lower than the top vent, depends on the battery design and the clogging during thermal runway. The contribution of the PTC to battery safety is smaller than other protection devices; however, its self-activating thermal protection mechanism can be used for PTC electrodes.

Compared to conventional 18650 cells, installing a protection circuit increases the manufacturing cost and decreases the overall energy density. However, it provides full-time active protection and improves battery safety.

VI. CONCLUSION

Four representative commercial 18650 cells were disassembled to investigate the different protection devices, including mandatory ones (current interrupt device and top vent) and optional ones (positive temperature coefficient, bottom vent, and protection circuit). For each protection device, the generic working mechanism, pros, cons, and contributions to the overall battery safety have been summarized.

In commercial 18650 cells, installing the current interrupt device and top vent can meet the basic safety requirements at the single-cell level. The positive temperature coefficient, bottom vent, and protection circuit can improve battery safety and work as supplementary to deal with potential hazards. All these protection devices are not involved with internal electrochemical reactions, increasing battery resistance and decreasing energy density inevitably. Compared to unprotected batteries, protected 18650 Li-ion batteries are recommended because they are safer to operate and less like to cause property damage.

Although the implementation of these protection devices has probably reduced the occurrence of thermal runaway at the cell level, they are not as effective in battery packs as they did in the single cell. Moreover, the battery industry is moving towards higher energy density and larger scales. One of the challenges is to prevent the propagation of thermal run away from the single cell to the pack level. The smart battery embedded with a cell-level battery management system could be the solution to escalate the safety at the pack level.

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BIN XU received the M.S. degree in mechanical engineering from Xi'an Jiaotong University, Xi'an, China, in 2017, where he is currently pursuing the Ph.D. degree with the School of Mechanical Engineering. From 2019 to 2021, he was a Visiting Student with the Center for Advanced Life Cycle Engineering, University of Maryland, College Park, MD, USA. His research interests include failure analysis, testing, and safety of lithium-ion batteries.

LINGXI KONG received the B.E. degree in material molding and control engineering from Sichuan University, Sichuan, China, in 2013, and the M.Eng. degree in materials science and engineering from the University of Maryland, College Park, MD, USA, in 2015, where he is currently pursuing the Ph.D. degree in mechanical engineering with the Center for Advanced Life Cycle Engineering. His research interests include lithium-ion battery testing and failure analysis.

GUANGRUI WEN received the B.S., M.S., and Ph.D. degrees in mechanical engineering from Xi'an Jiaotong University, Xi'an, China, in 1998, 2002, and 2006, respectively.

From 2008 to 2010, he was a Postdoctoral Fellow with Xi'an Shaangu Power Company Ltd., Xi'an. He has authored or coauthored two books and more than 80 articles and held more than 20 items of patents. His current research interests include mechanical system fault diagnosis and prognosis, mechanical equipment life cycle health monitoring, and intelligent maintenance.

Dr. Wen was a recipient of the New Century Excellent Talents of Ministry of Education MOE, in 2013, the Tenth Youth Scientific Prize of Shaanxi Government, in 2015, the Youth Science and Technology Achievement Award of Chinese Mechanical Engineering Society, in 2013, and the Youth Science and Technology Achievement Award of Chinese Society for Vibration Engineering, in 2014. He is a member of the Chinese Mechanical Engineering Society (CIME) and the Chinese Society for Vibration Engineering (CSVE).

MICHAEL G. PECHT (Life Fellow, IEEE) received the B.S. degree in physics, the M.S. degree in electrical engineering, and the M.S. and Ph.D. degrees in engineering mechanics from the University of Wisconsin–Madison.

He is currently the Founder and the Director of the Center for Advanced Life Cycle Engineering, University of Maryland, College Park, MD, USA, which is funded by more than 150 of the world's leading electronics companies at more than US6M/year. He is also the Chair Professor of mechanical engineering and a Professor of applied mathematics, statistics, and scientific computation with the University of Maryland. He has written more than 230 books, 500 technical articles, and has ten patents. He has also served for three U.S. National Academy of Science studies, two U.S. Congressional investigations in automotive safety, and as an Expert to the U.S. Food and Drug Administration.

Dr. Pecht is a Professional Engineer and a fellow of the American Society of Mechanical Engineers and the Society of Automotive Engineers. He was the Editor-in-Chief of IEEE ACCESS and served as the Chief Editor for the IEEE TRANSACTIONS ON RELIABILITY for nine years and *Microelectronics Reliability* for 16 years.