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Review

Advancing Smart Lithium-Ion Batteries: A Review on Multi-Physical Sensing Technologies for Lithium-Ion Batteries

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Abstract: Traditional battery management systems (BMS) encounter significant challenges, including low precision in predicting battery states and complexities in managing batteries, primarily due to the scarcity of collected signals. The advancement towards a "smart battery", equipped with diverse sensor types, promises to mitigate these issues. This review highlights the latest developments in smart sensing technologies for batteries, encompassing electrical, thermal, mechanical, acoustic, and gas sensors. Specifically, we address how these different signals are perceived and how these varied signals could enhance our comprehension of battery aging, failure, and thermal runaway mechanisms, contributing to the creation of BMS that are safer and more reliable. Moreover, we analyze the limitations and challenges faced by different sensor applications and discuss the advantages and disadvantages of each sensing technology. Conclusively, we present a perspective on overcoming future hurdles in smart battery development, focusing on appropriate sensor design, optimized integration processes, efficient signal transmission, and advanced management systems.

Keywords: lithium-ion battery; smart battery; battery management system; battery-sensing technologies

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1. Introduction

The electrification of transportation and the application of renewable energy stand as pivotal technological pathways towards achieving the "carbon neutral" objective. Central to this pursuit is the battery, the cornerstone of electric transportation and energy storage systems, playing a crucial role in the industry's evolution [1]. Over two decades of technological advancement have positioned lithium-ion batteries (LiBs) as the predominant power technology for widespread application across consumer electronics, electric vehicles (EVs), and energy storage systems (ESSs). Despite their prevalence, current LiBs still face challenges in performance, longevity, and safety [2]. For instance, China experienced an average of seven EV fire incidents per day in the first half of 2022; and over 70 battery safety incidents related to ESSs have been reported globally over the past few years. Hence, improving battery lifespan and safety is paramount to the continued growth of EVs and ESSs.

The accurate assessment of battery health and the development of battery systems that boast reliable operation and maintenance are key to enhancing battery life and safety. A traditional battery management system (BMS) typically relies on external sensors (voltage, current, and temperature) to monitor battery status [3], which fail to capture the intricate changes in electrochemical, thermal, and mechanical characteristics within a battery cell. This limitation leads to inaccuracies in the data collected and the models/algorithms derived therefrom [4]. Consequently, traditional BMS falls short in precisely assessing the health, safety, and lifecycle evolution of batteries. Moreover, to boost energy density and reduce cost, the battery industry has a trend to increasing the capacity and size of a single battery cell (e.g., Tesla's 4680 cell, BYD's blade battery cell, etc.) [5], leading to more serious heterogeneity within a cell. This heterogeneity can exacerbate degradation and diminish its reliability, while current BMS with external sensors cannot capture internal cell information. Thus, the development of so-called "smart battery" technology, which incorporates multiple types of sensors for battery monitoring, has emerged as a promising research direction, and is highlighted in the EU's "Battery 2030+ Technology Roadmap" aiming to advance intelligent batteries and sensing technologies.

Figure 1 illustrates a schematic of the smart battery system, which fundamentally aims to enable real-time monitoring of the battery's internal and external status through multiple types of sensors. Signals are transmitted from the Printed Circuit Board (PCB) to the master Battery Management System (BMS) via wired or wireless connections, facilitating the execution of high-precision battery status estimation and safety warning algorithms either locally or in the cloud. Multiphysical sensing technology forms the bedrock of this innovative architecture. Against this backdrop, this review concentrates on various sensing technologies, seeking to evaluate their potential applications, current development status, and challenges within the lithium-ion battery domain.

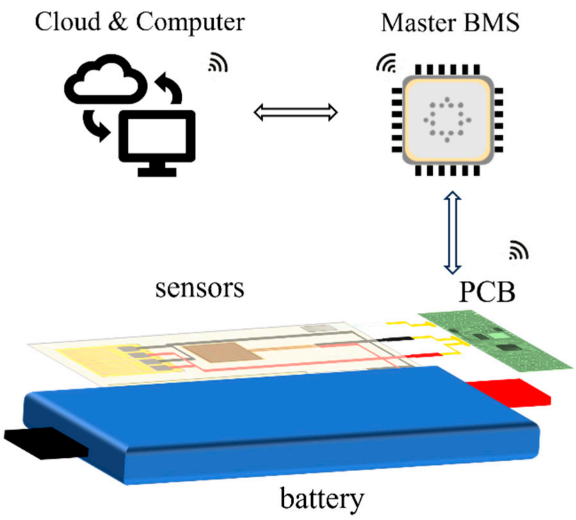


Figure 1. Schematic illustration of a smart battery equipped with multiple types of internal and external sensors.

2. Multi-Physical Sensing Technologies for Lithium-Ion Batteries

The essence of smart battery technology lies in leveraging multiple sensors to measure a spectrum of physical fields within the battery, encompassing electrical, thermal, mechanical, acoustic, and gas parameters.

2.1. Sensing of Electrical Signals

Electrical parameters, such as voltage and current, form the foundational data collected by a BMS. Typically, BMS monitors the voltage across parallel-connected individual cells at the module level and the current through series-connected modules at the pack level [6]. Although current and voltage signals underpin most battery state estimation algorithms within BMS [7], these signals often fall short in accurately depicting the battery's internal state. Consequently, the pursuit of novel techniques for measuring electrical signals in batteries, aimed at garnering a richer dataset, is a focal point of contemporary research. Noteworthy among these are internal potential measurements and electrochemical impedance measurements.

2.1.1. Electrochemical Impedance Spectroscopy

Electrochemical Impedance Spectroscopy (EIS) represents a prevalent non-destructive testing method for batteries. This technique involves the application of a series of small-amplitude alternating current (AC) potentials across a range of frequencies, allowing for the analysis of the cell's internal resistance as it varies with frequency [8]. The impedance signatures at different frequencies can be attributed to ohmic impedance, solid electrolyte interface (SEI) impedance, charge transfer impedance, and liquid phase diffusion impedance. These parameters collectively shed light on the heat and mass-transfer processes, as well as the electrochemical reactions occurring within the battery [9]. Thus, EIS offers a potent tool for state estimation and fault diagnosis over the battery's life cycle [10]. For instance, research by Cannarella et al. [11] indicated that the charge transfer impedance (Rct) of a battery escalates with increasing external pressure, more so at lower states of charge.

Nonetheless, conventional EIS testing necessitates bulky and intricate equipment, limiting its practical application. Recent efforts towards the development of rapid EIS testing methodologies represent a significant research trajectory. Lu et al. [12] introduced a swift EIS measurement technique utilizing Fast Fourier Transform (FFT) with a data acquisition card as an alternative to traditional electrochemical workstations. This approach reduces measurement time by two-thirds and occupies less space, although it remains rooted in static EIS detection. It takes approximately 580 s for a single measurement, rendering it unsuitable for real-time monitoring of cyclic processes. Crescentini et al. [13] engineered a compact EIS inspection system based on Vector Impedance Analyzer (VIA) architecture, capable of integrating into a coin cell to facilitate dynamic EIS analysis during cell cycling. While dynamic EIS exhibits regular variations with the State of Charge (SOC) and aging, the impedance spectrum significantly diverges from static EIS and is challenging to interpret due to detection time constraints. Consequently, advancing the rapid detection and dynamic analysis capabilities of EIS is essential for its application in practical battery assessments.

2.1.2. Sensing of Internal Electrode Potential

Fast charging is one of the core demands for EVs to eliminate range anxiety. Current LiBs, however, are susceptible to lithium plating at high charging rates, adversely impacting battery lifespan and potentially leading to safety hazards, such as fires and explosions [14]. Fundamentally, lithium plating is induced by anode polarization at high charging rates, causing the anode potential to fall below 0 V (versus Li/Li^+) [15]. Consequently, monitoring the internal potential at the anode side presents an effective strategy to prevent lithium plating while facilitating increased charging rates.

Liu et al. [16] introduced a novel fast-charging approach that hinges on real-time monitoring of the negative electrode potential and adjusting the charging current dynamically. The negative electrode potential is measured by a reference electrode inserted between the anode and cathode and shielded by a separator (Figure 2). This configuration enables the measurement of the negative electrode potential, allowing for the charging current to be modulated in real time to maintain the negative electrode potential slightly above 0 V. The authors demonstrated that this fast-charging technique could enhance the charging speed by 40% relative to the manufacturer's standard fast charging protocol, without inducing lithium plating at the negative electrode after 100 fast charging cycles, as verified by Scanning Electron Microscopy (SEM).

Similar studies, as in Refs. [17,18], explore analogous strategies. Nonetheless, the integration of reference electrodes in commercial batteries remains unachieved, primarily due to two reasons: Firstly, LiBs are expected to sustain >1000 cycles for EVs and >10,000 cycles for large-scale ESSs, yet existing reference electrodes cannot maintain stable operation within the harsh electrolyte environment over prolonged periods. Secondly, the positioning of the reference electrode significantly influences its measurement accuracy; ideally situated between the positive and negative electrodes, it might hinder lithium-ion transport, thereby degrading battery performance. Addressing the durability and accuracy of reference electrodes is thus crucial for their practical application in future battery applications.

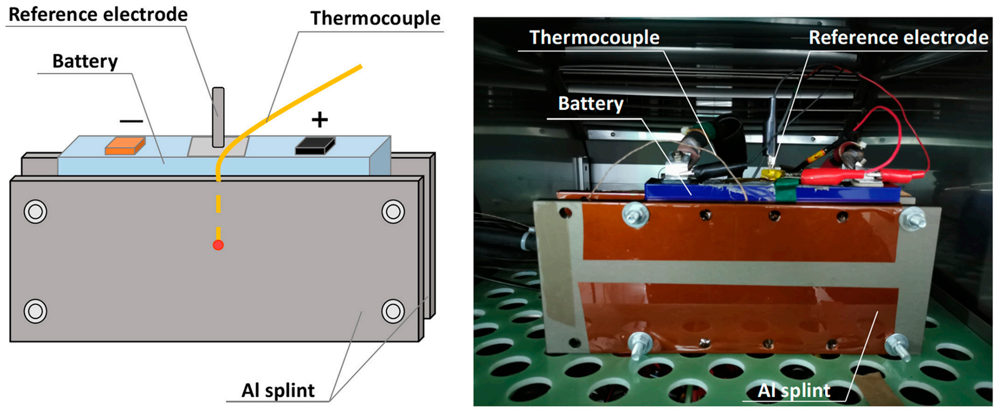


Figure 2. Sensing of internal electrode potential: high-capacity battery with built-in reference electrode and optimization of fast battery charging strategy based on reference electrode (reproduced with permission from Liu et al. International Journal of Energy Research; published by John Wiley and Sons, 2021) [16].

2.2. Sensing of Thermal Signals

Temperature has a significant impact on the internal mass-transfer rate and electrochemical kinetics of a battery [19], which in turn affects battery performance, life, and safety. Therefore, the battery thermal management system (BTMS) is a critical part of the battery system, whose core function is to control the battery operating temperature in a suitable range while ensuring the uniformity of the battery temperature. Currently, thermocouples are utilized in BTMS to sense the temperature at the surface or tabs of a battery. The external temperature is fed to a thermal model to estimate the heat generation rate and thereby the temperature distribution within the battery pack to optimize the BTMS design [20]. With the batteries becoming larger in size and capacity, the issue of temperature inhomogeneity has emerged. It has been found that uneven temperature affects the current distribution in the battery pack and leads to non-uniform aging [21]; however, research on studying temperature inhomogeneity and its coupled effects with electrochemistry and mechanics is still limited. Hence, sensing the internal temperature of a battery is of great importance for understanding the aging and failure mechanisms of a LiB cell and for optimizing the BTMS design.

Micro-thermocouples, Fiber Bragg Grating (FBG), film thermistors, and the Resistance Temperature Detector (RTD) are typical sensors for temperature sensing inside cells due to their small size, which are usually implanted in the middle layer of a prismatic or pouch cell or in the cavity of a cylindrical cell [22–26]. The working principle of a thermocouple is based on the thermoelectric effect of metal, and its terminal voltage can reflect the temperature. The working principle of FBG is based on the thermal expansion and contraction effect of the grating spacing. The FBG peak position can reflect the temperature but the grating spacing is also affected by stress. Therefore, FBG temperature measurement needs to decouple the temperature–stress effects. The temperature measurement principle of thermistors and RTDs is based on the resistance–temperature effect of the material, and its resistance reflects the temperature. Zhang et al. [27] arranged multiple micro-thermocouples in the axial center plane of an 18650 cell along the radial direction of the cell (Figure 3a), and then obtained the radial temperature distribution during the charging and discharging of the cell. The results showed that a higher rate and lower ambient temperature led to higher internal temperature of the cell and a larger temperature gradient. Increasing the convective heat transfer coefficient can reduce the battery temperature rise but the internal temperature gradient becomes larger, so treating the battery as an isothermal body under forced convection conditions will bring a large error. Huang et al. [22] placed FBGs into the central hole of an 18650 cell to measure the internal and surface temperatures simultaneously (Figure 3b). Joe et al. [23] placed film thermistors into the internal core of an 18650 cell and in the middle position of the thickness direction of a pouch cell (between the negative electrode and the separator), respectively (Figure 3c). Through cycling tests and post-mortem analysis, it was found that the implantation of thermistors could potentially result in capacity loss and increase the risk of lithium plating. Additionally, it could lead to uneven pressure and mechanical damage when assembling single cells to a module or pack. Removing a portion of electrode materials to leave space for internal thermistors could alleviate the uneven pressure caused by sensor implantation [24] but it would reduce the cell energy density and increase the complexity for real-world application. Wang et al. [28] designed an integrated functional electrode (IFE), which consists of two single-layer coating electrodes covering a fiber sensor integrated on a substrate (Figure 3d). The substrate ensures that the stacking stress between the electrodes does not squeeze the fiber sensor during cycling, allowing distributed measurement of the temperature inside the cell. Through comparative analysis of electrochemical parameters, disassembly characterization, and non-destructive in situ testing, it has been proven that the design of this IFE can achieve in situ measurement of internal temperature without affecting the electrochemical performance of the cell.

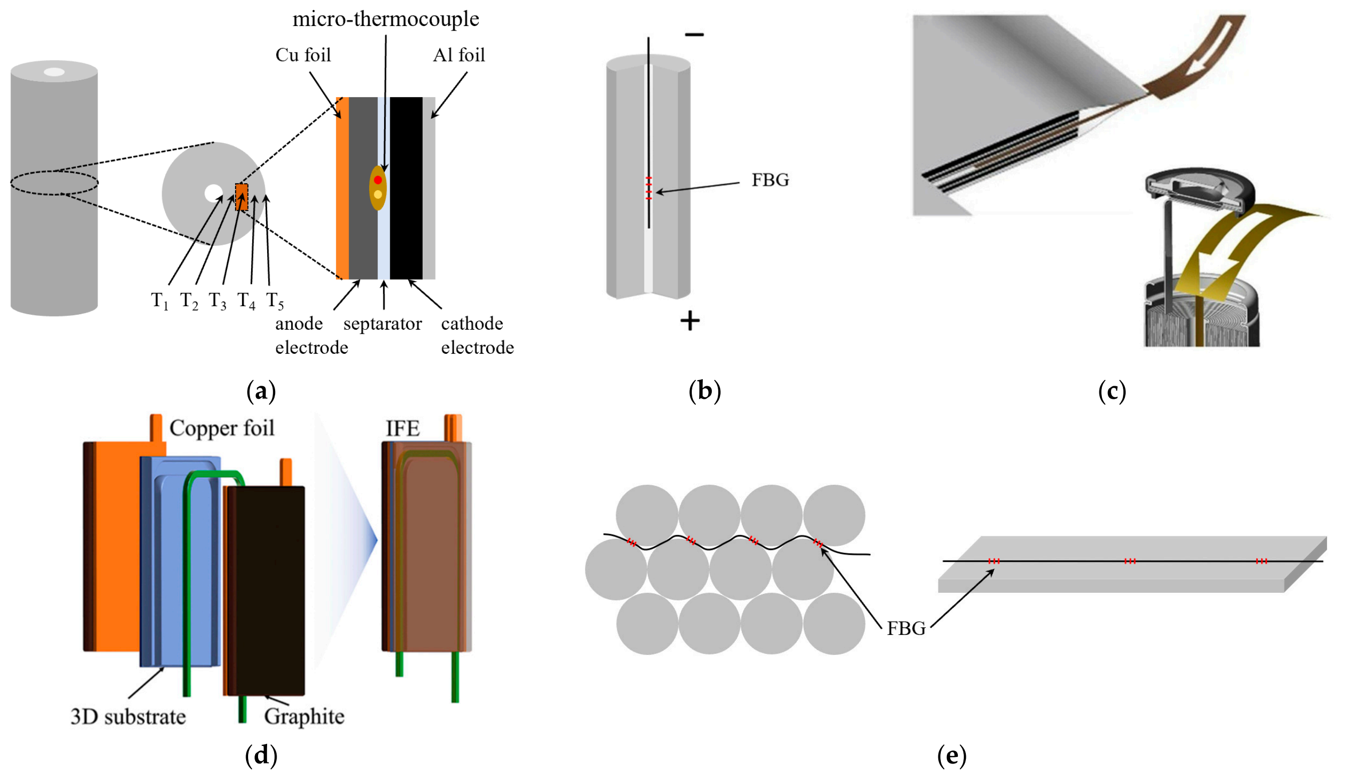


Figure 3. Sensing of cell temperature: (**a**) radial temperature measurement of 18650 cell using distributed micro-thermocouple; (**b**) measurement of internal and external temperatures of 18650 cells using FBG; (**c**) schematic of implanting thin-film thermistors into the internal cavities of an 18650 cell [23]; (**d**) implanting optical fibers in pouch cells (reproduced with permission from Wang et al. Energy Storage Materials; published by Elsevier, 2024) [28]; (**e**) application of distributed optical fibers in battery packs.

The integration of built-in sensors for monitoring internal temperature variations and distributions proves crucial for optimizing battery thermal management. Nevertheless, aligning sensor compatibility with diverse battery manufacturing processes presents notable challenges, particularly concerning battery formats. In cylindrical cells, embedding sensors within internal cavities effectively minimizes sensor contact with electrode materials and electrolytes, thus safeguarding the cell's integrity. Conversely, prismatic and pouch cells face significant hurdles in sensor implantation, chiefly the need to shield sensors from electrolyte corrosion while preserving electrode material integrity and overall battery performance. Yang et al. [29] conducted a comprehensive analysis of the cost associated with implementing thermocouples, thermistors, RTDs, and FBGs within battery systems. Their findings reveal that while the former three sensors incur relatively low costs, the FBG system is notably more expensive, primarily due to the high price of the demodulator. This discrepancy underscores the necessity for advancing multiplexing technology, particularly for its application in large-scale ESSs, as a means to mitigate the high costs associated with FBG systems. Lu et al. [5] propose leveraging multiplexing technology in battery packs, encompassing both prismatic and cylindrical formats, to facilitate efficient distributed measurement of every cell without compromising the structural integrity of the original module (Figure 3e). This approach represents a promising avenue for enhancing thermal management through the strategic application of sensor technology.

2.3. Sensing of Mechanical Signals

The performance of a battery is closely linked to its mechanical state. When a battery is charged or discharged, lithium ions move in and out of the electrode materials, causing these materials to expand or contract. This process, known as intercalation/de-intercalation, results in changes in the volume of the material particles and generates stress and strain, commonly referred to as intercalation-induced stress–strain [30]. Over time, this stress can lead to cracks in the electrode particles and the development of fractures [31]. Such damage not only results in the loss of active material, reducing the battery's efficiency but also creates new surfaces that can react with the electrolyte. This reaction further consumes active lithium, contributing to the battery's capacity degradation [32]. Understanding how the mechanical properties of batteries evolve over time is crucial for unraveling the reasons behind their performance decline.

It is crucial to acknowledge that as micromechanical characteristics within a battery evolve, so too do its macroscopic properties, such as modulus of elasticity and volume. Therefore, the monitoring of mechanical signals at the cell level serves as a vital indicator of the cell's internal status, with many common methodologies focusing on alterations in cell shape. For instance, in the case of prismatic and pouch cells, the use of a Linear Variable Differential Transformer (LVDT) [33–35] enables the measurement of internal cell pressure within the module (Figure 4a), whereas film strain resistance sensors [36] are adept at mapping pressure distribution across the cell (Figure 4b). Additionally, variations in cell thickness can be precisely gauged using inductive coil eddy current sensors (Figure 4c) [4]. Conversely, cylindrical cells, by virtue of their lack of planar constraints, permit the indirect calculation of cell pressure through the measurement of circumferential strain under the radial confines of the battery casing. Zhu et al. [37] developed a miniature film strain sensor, which, by displacing some electrode material, was successfully integrated between the layers of an 18650 cell to measure the circumferential strain of the electrode (Figure 4d). Despite its effectiveness, this method is not without its challenges, particularly those related to processing and potential damage as delineated in Section 2.2. Expanding on this, Nascimento et al. [38] employed two distinct types of FBG sensors affixed along the x and y axes of a pouch cell's surface to measure strain, while concurrently utilizing non-strain-sensitive FBG sensors to monitor temperature variations. This setup enables the decoupling of battery strain from thermal effects, necessitating careful consideration of the temperature differential between FBGs to ensure the precision of strain measurements.

According to the principle of force balance, the benefits of measuring battery pressure internally are not obvious, and it is more meaningful to study the relationship between pressure and battery performance through external pressure measurement. To understand how pressure impacts the performance of battery cells, Cannarella et al. [33] utilized an LVDT to track the pressure changes in pouch cells subjected to preload forces during charging and discharging cycles. Their findings revealed a direct correlation between the maximum pressure experienced by the cells and the applied preload force. This relationship is attributed to the cells' nonlinear elastomechanical properties. Furthermore, they observed that cell pressure progressively increased with each cycle, and this increase was more rapid under higher preload forces, leading to reduced cycle life. Interestingly, when compared to cells without any preload, a moderate application of preload force was found to actually prolong cell life. Disassembly experiments provided additional insights, indicating that higher mechanical stress resulted in increased electrochemical impedance, a phenomenon demonstrating the interplay between mechanical and electrochemical factors. The experiments also identified layer delamination as a key factor behind the capacity decline observed in cells not subjected to preload, highlighting the critical role of mechanical stress in cell longevity. As mentioned earlier, when external pressure is measured according to the principle of force balance, pressure sensors can be arranged at the module level to achieve pressure measurement of multiple cells, thus reducing the number of sensors to reduce costs.

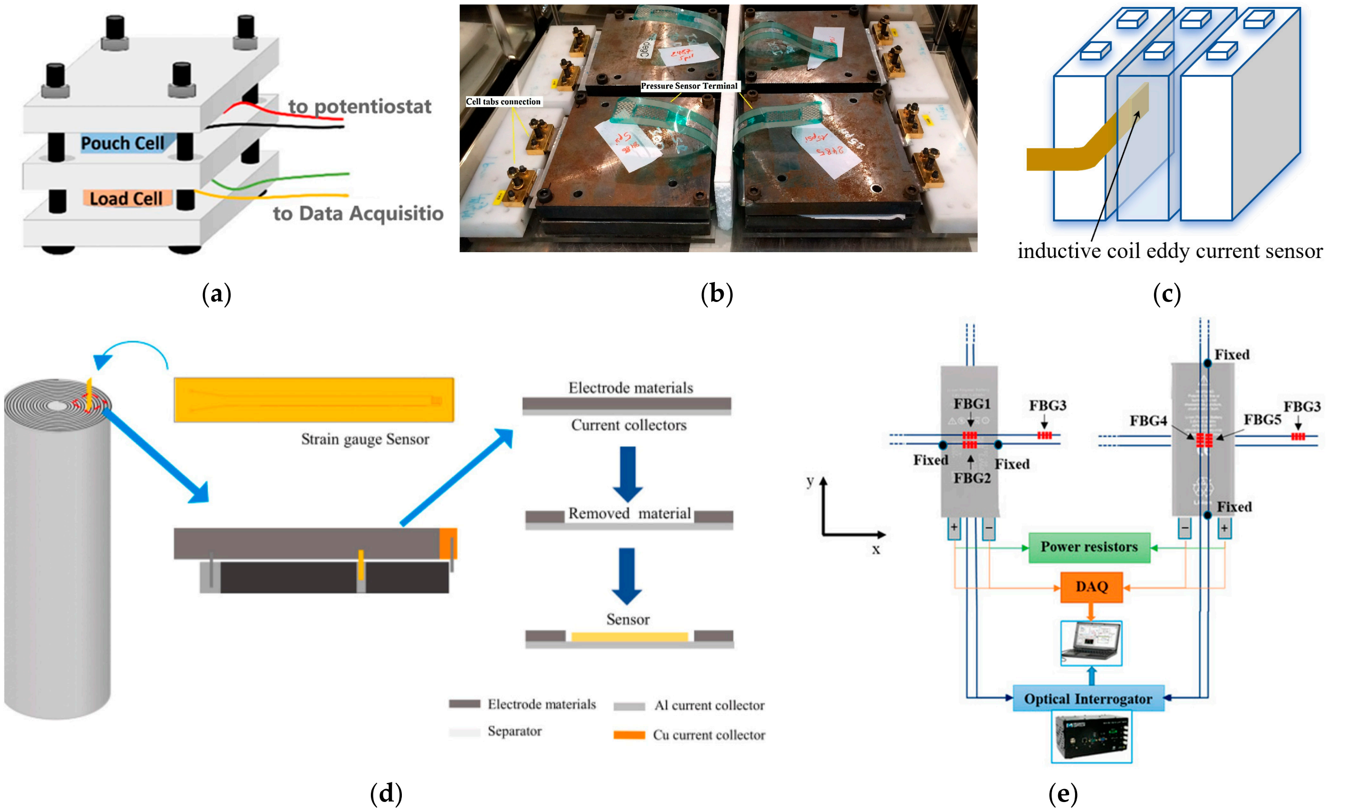


Figure 4. Sensing of mechanical signals: (**a**) mechanics-sensing device based on LVDT [35]; (**b**) pressure distribution measured by a thin film strain resistance sensor (reproduced with permission from Barai et al. Journal of Energy Storage; published by Elsevier, 2017) [36]; (**c**) inductive coil eddy current sensor to measure cell thickness variation; (**d**) miniature thin-film strain sensor implanted with 18650 cell(reproduced with permission from Zhu et al. Journal of Power Sources; published by Elsevier, 2021) [37]; (**e**) adhering two different types of FBG sensors on the x and y directions of the battery surface [38].

On the modeling side, Oh et al. [39] developed a phenomenological mechanical model specifically for prismatic cells contained within a module. In this model, the module is considered a fixed boundary, whereas both the module and the internal gaskets are modeled as linear springs. To represent the dynamic relationship between cell pressure and thickness, a nonlinear spring model was formulated. This approach allows for the estimation of constrained cell pressure through the measurement of cell thickness changes. However, the model does not offer a detailed mechanistic insight into the causes of cell thickness variations and depends heavily on empirical data, which limits its applicability across different contexts.

To encapsulate, current research has yet to fully elucidate the physicochemical processes inside batteries—such as aging and failure—and how these processes influence the mechanical signal patterns observed. This gap represents a significant hurdle for the practical use of mechanical signals in battery technology. Addressing this, there is a pressing need for comprehensive mechanical studies at multiple levels of battery structure, including the materials, electrodes, and the battery unit as a whole. The aim is to decipher the core interdependencies between battery modulus, stress–strain behaviors, state of charge, and overall health. Ultimately, the ambition is to develop a cohesive model that integrates aspects of battery electrochemistry, mechanics, and sensor data. Advancing in this direction is crucial for the future of battery research and technology.

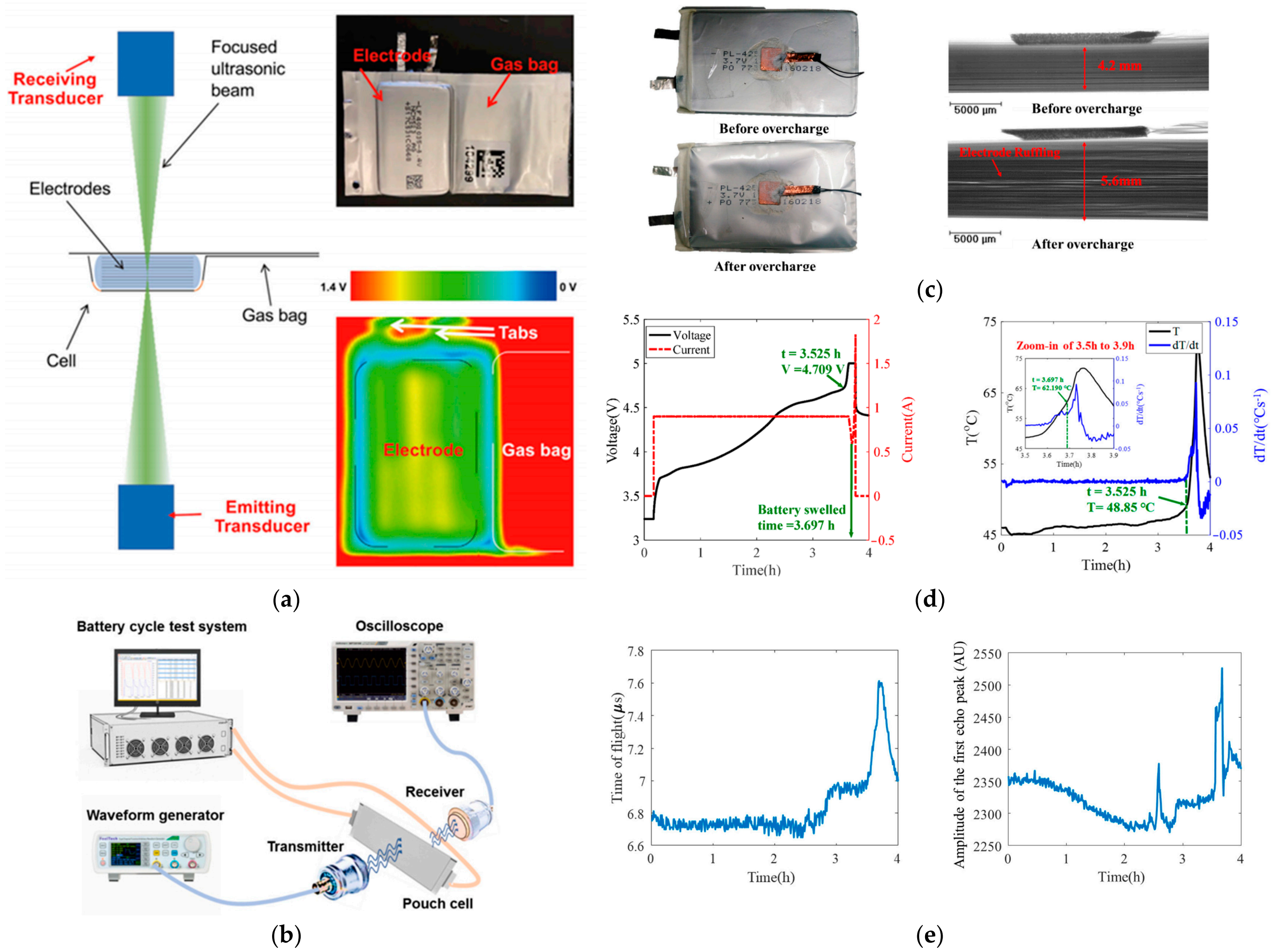
2.4. Sensing of Acoustics Signals

Acoustic sensing encompasses non-destructive testing methods, such as stress wave testing—often referred to as acoustic emission testing—and ultrasonic testing. Of these, ultrasonic testing is notably prevalent. This method relies on ultrasonic waves, which, upon encountering interfaces of media with varying acoustic resistances within a test piece, are either reflected or transmitted. Analyzing the Time of Flight (TOF) and the first echo's peak intensity reveals the test piece's internal condition [40].

In battery technology, ultrasonic testing proves invaluable for identifying internal damage [41], gas accumulation, and electrolyte infiltration [42], among other issues. A notable advancement was made by Deng et al. [42], who introduced an ultrasonic transmission imaging technique tailored for assessing electrolyte wetting conditions in prismatic and pouch cells (Figure 5a). This method not only facilitates the detection of battery defects and failure modes but also aids in determining the optimal electrolyte filling volume and wetting duration, thereby refining the battery manufacturing process. Meng et al. [43] further expanded the utility of ultrasonic guided-wave testing by devising a method to quantify the State of Charge (SOC) of batteries through frequency domain ultrasonic damping analysis (Figure 5b). Their approach leverages time-harmonic continuous waves across a broad frequency spectrum to examine pouch cells at various SOC levels, using a multilayer model to describe the ultrasonic waves' propagation within the cells. This study significantly broadens the applicability of ultrasonic-based methods for estimating battery SOC and State of Health (SOH). Wu et al. [44] investigated the behavior of Li-ion pouch cells under overcharge conditions (Figure 5c–e), offering insights into how ultrasonic signals, along with voltage, current, and temperature data, can signal electric abuse risks. They observed that gas production during overcharge alters the internal electrode interface and increases the cell's macroscopic thickness (Figure 5c). A rapid increase in both TOF and the amplitude of the first echo peak was noted (Figure 5e), underscoring the efficacy of ultrasonic waves in monitoring electric abuse risks. Despite the advantages of non-destructive internal detection, the application scenario of an acoustic sensor is more inclined to the detection of battery products, and its application in equipment needs to be further verified.

2.5. Sensing of Gas Signals

Throughout the lifecycle of LiBs, gases are generated during several key processes. Initially, during battery formation, the electrolyte is consumed to form the Solid Electrolyte Interface (SEI), a process accompanied by gas generation [45,46]. As the battery ages, further gas production can occur due to SEI growth, phase transformation of cathode materials, and electrolyte decomposition [47]. Under extreme conditions such as thermal runaway, a significant amount of gases will be generated; hence, sensing of gas signals plays a pivotal role in understanding battery aging mechanisms, improving battery materials, and ensuring battery safety.



(a) (b) (c) (d) (e)

Figure 5. Sensing of acoustic signals: (**a**) imaging of the electrolyte infiltration process using ultrasonic detection (reproduced with permission from Deng et al. Joule; published by Elsevier, 2020) [42]; (**b**) schematic of an ultrasonic battery detection system(reproduced with permission from Meng et al. Journal of Power Sources; published by Elsevier, 2022) [43]; (**c**–**e**) ultrasonic scanning of a pouch cell under overcharge test [44]: (**c**) cell imaging, (**d**) evolution of voltage, current, and temperature, (**e**) evolution of ultrasonic TOF and amplitude of first echo peak.

2.5.1. Sensing of Gas Types

Identifying the characteristic gases produced within a cell poses significant challenges, particularly due to the difficulty in collecting gas samples. Schmiege et al. [48] developed an innovative in situ gas collection device equipped with a gas sampling port specifically for LiBs. This device facilitated the study of gas composition and concentration changes in NMC811 pouch cells under various charge and discharge cycles and electrolyte formulations (Figure 6a). The findings linked the peaks of electrolyte reduction (as observed in dQ/dV curves) directly with gas generation during the initial charge/discharge cycle, demonstrating how slight variations in the electrolyte system can influence gas production. Although this method enables in situ gas collection, it falls short of providing real-time detection capabilities. Understanding the mechanisms of gas production during aging, failure, and thermal runaway processes, together with finding the relationship between gas signals and the evolution of electrical, temperature, and mechanical signals, are essential for the effective deployment of gas-sensing technologies. However, achieving simultaneous in situ and real-time gas monitoring remains a challenge. Lyu et al. [49] attempted to overcome this by using a modified soft pack battery and an NDIR gas sensor within a sealed container, though this approach compromises the battery's integrity and faces practical limitations regarding sensor size for implantation, thus hindering scalability.

Currently, external gas sensors offer a more feasible solution, although the gas signal it detects is somewhat delayed because the gas can only be detected after the battery has ruptured. Cai et al. [50] conducted an investigation into the gas composition resulting from thermal runaway under various conditions. Note that a mix of gases, including CO_2, CO, H_2, CH_4, and volatile organic compounds (VOCs), would be produced during thermal runaway. Cai's study assessed the efficacy and cost-effectiveness of different gas-sensing techniques, ultimately selecting a Non-Dispersive Infrared (NDIR) CO_2 sensor for thermal runaway gas monitoring. When integrated with pressure, temperature, and humidity sensors, this setup allowed for a comprehensive analysis of the electrical, thermal, mechanical, and gas-related signals during the thermal runaway of overcharged LiBs (Figure 6b). Notably, the battery pressure signal was identified as the earliest and most sensitive indicator of battery failure. The CO_2 signal followed, showing a sharp change 11 s after the initial pressure signal alteration. This suggests that, while useful, external gas leak sensors may not detect battery failure as promptly as mechanical-sensing methods due to the delayed release of gases relative to their initial production. If the gas is used as a thermal runaway alarm signal, the detection requirements can be met by placing a small number of gas sensors in the closed battery pack. The usual way is to design the gas sensor module on the PCB of the BMS.

2.5.2. Sensing of Gas Pressure

Monitoring the internal gas pressure within LiBs offers a practical and informative alternative to the complex task of identifying and measuring the concentration of individual gases. A noteworthy advancement was made by Mei et al. [51], who embedded optical fiber sensors with a dual-function probe—an FBG for precise temperature readings and a Fabry–Perot interferometer (FPI) that exhibits a highly linear pressure response to various gases—into commercial 18650 cells (Figure 6c). Such a combination provides a method to predict the battery's condition through the observation of temperature and pressure changes over time, particularly before the activation of the battery's safety valve. As shown in Figure 6d, the relationship between temperature increase, due to heat from the heater and the subsequent evaporation of the electrolyte, highlights the dynamics within the battery that lead to changes in internal gas pressure. As the temperature rises, it accelerates the vaporization of the electrolyte and triggers the irreversible decomposition of SEI, causing a significant increase in gas generation and, consequently, in internal pressure. To address the potential risks associated with these processes, a safety warning range has been established. This range, delineated by the onset of electrolyte evaporation and the end of normal SEI decomposition, marks a period during which the battery can safely operate without the occurrence of irreversible reactions. However, the implementation of this sensing technology does not come without challenges. One of the most significant is the difficulty in differentiating the sources of pressure increase—whether they stem from the accumulation of gas or the expansion of the battery's active materials. This distinction is critical for accurate interpretation of sensor data and the development of reliable multi-physical sensing strategies. By addressing these challenges, the monitoring of gas pressure inside LiBs stands as a promising avenue for enhancing battery safety and performance, offering a simpler yet equally valuable alternative to gas concentration analysis.

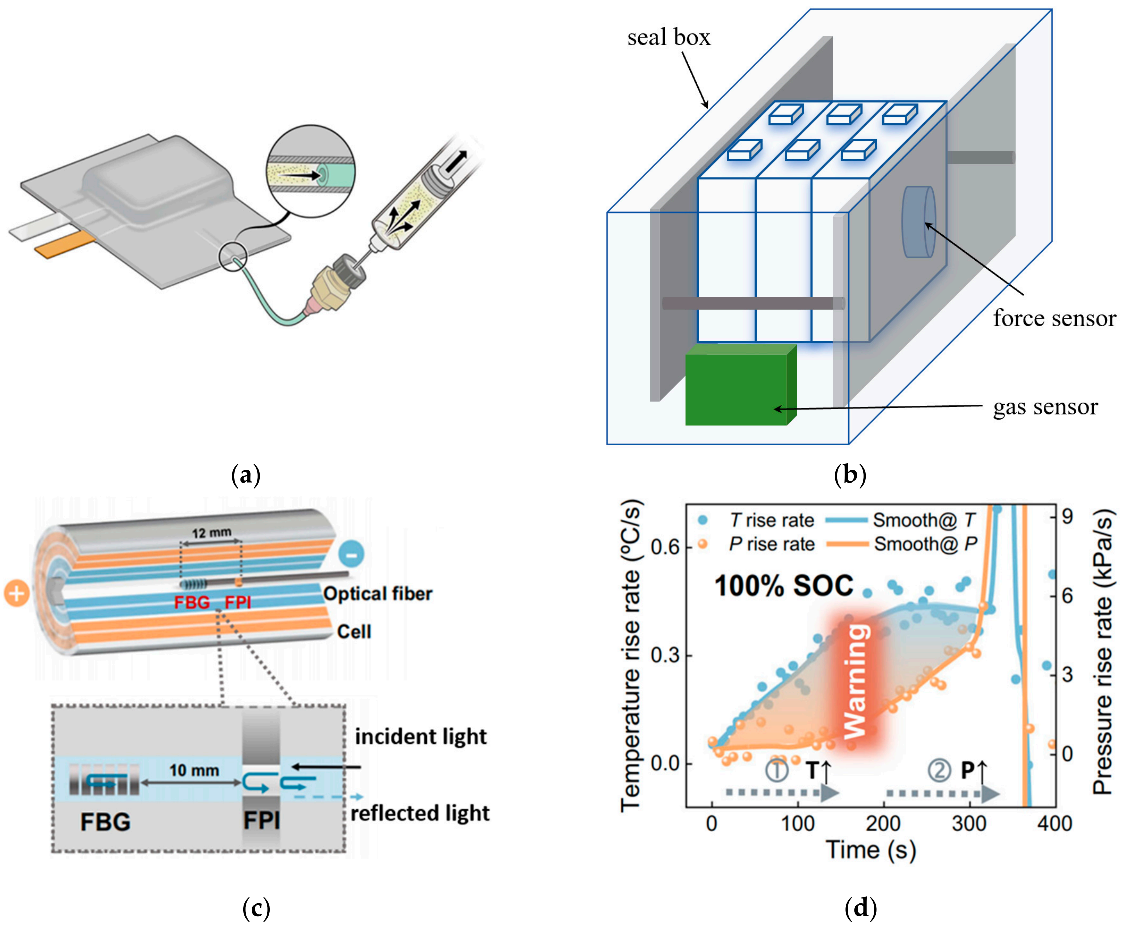
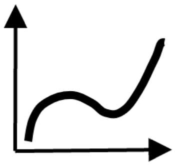
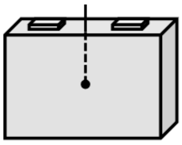
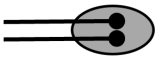
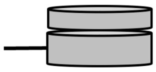
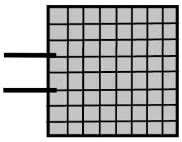
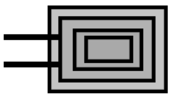
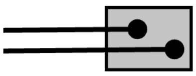
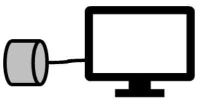
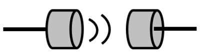
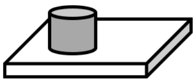


Figure 6. Sensing of gas signals: (**a**) in situ gas collection of a LiB pouch cell using a sampling port combined with gas chromatography [48]; (**b**) experimental setup to measure electrical, thermal, mechanical, and gas signals of a LiB prismatic cell under over-charge conditions; (**c**) the cascade structure of an FBG–FPI sensor(reproduced with permission from Mei et al. Nature Communication; published by Springer Nature, 2023) [51]; (**d**) the rate of temperature and pressure rise during thermal runaway sensed by the FBG–FPI sensor [51].

3. Conclusions and Future Perspectives

In summary, the integration of electrical, thermal, mechanical, acoustic, and gas signals plays a crucial role in monitoring the evolution of a battery's internal state. This integration is instrumental in elucidating the mechanisms behind battery degradation, failure, thermal runaway, and other critical processes; furthermore, it aids in the development of highly reliable battery management technologies. The advancement of smart battery technology, equipped with multi-physical sensing capabilities, promises to address the current limitations of battery state estimation accuracy and life-cycle management, which are primarily due to the insufficient sensing signals in existing BMS. Nonetheless, as a nascent technology, the development of smart batteries is closely related to sensor technology, and the cost and characteristics of sensors determine whether they are suitable for application in smart batteries. We have sorted out the costs, advantages, and disadvantages of the above sensors in Table 1, and we can see that appropriate sensor design will be one of the important challenges facing smart batteries. In addition, it still encounters grand challenges in optimized integration processes, efficient signal transmission, and the development of advanced management systems. These challenges include the following.

Table 1. Comparison of different types of sensors for Li-ion batteries.

Type of Signal	Type of Sensor	Diagram	Base Cost (System +One Sensor)	Location	Advantages	Disadvantages
Electrical	Compact dynamic EIS		USD 2000	Internal	Compact	Impedance spectrum diverging
	Internal potential		Implementation-dependent	Internal	Accurate detection of potential	Short lifespan
Thermal	RTD		USD 200	Internal	Accurate detection of temperature	Increase in internal impedance and impedes ionic transport
	FBG		USD 10,000	Internal/external	Accurate detection of temperature; multiplexing	Temperature and strain coupling; sealing problem
	Thermistor		USD 400	Internal/external	Accurate detection of temperature	Increase in internal impedance and impedes ionic transport
Mechanical	LVDT		USD 4000	External	Accurate detection of pressure	Oversize
	Film strain resistance sensor		USD 10,000~40,000	External	Distributed monitoring	Expensive
Mechanical	Inductive coil eddy current sensor		Implementation dependent	External	Accurate detection of volume	Gap required
	Miniature film strain sensor		USD 4000	Internal/external	Accurate detection of strain	Increase in internal impedance and impedes ionic transport
	FBG		USD 10,000	Internal/external	Accurate detection of strain/multiplexing	Temperature and strain coupling; sealing problem
Acoustic	Ultrasonic transmission imaging		Implementation dependent	External	Non-destructive testing of electrolyte content	Oversize
	Ultrasonic-guided wave		USD 400	External	Non-destructive testing of electrode structure	Limited detection range
Gas	NDIR		USD 300	External	Accurate detection of gas types	Postponement of information
	FPI		USD 10,000	Internal	Accurate detection of gas pressure	Sealing problem

The costs presented are approximated from vendor-provided pricing information on off-the-shelf products. Base costs are dominated by the interrogation cost, especially for fiber optic sensors and film strain resistance sensors.

Appropriate Sensor Design: Sensors, the core components of smart batteries, must fulfill several criteria: (1) Miniaturization: sensor integration should minimally impact the battery's energy density. (2) Corrosion resistance: sensors must remain stable in harsh electrolyte environments over extended periods. (3) Non-destructive implantation (built-in sensors): sensor implantation should not affect the battery's performance, lifespan, or safety. (4) Low power consumption (built-in sensors): sensor power requirements should be significantly below the battery's self-discharge rate. (5) Cost-effectiveness: keeping costs low is essential for widespread adoption, especially for applications such as large-scale energy storage power systems.

Optimized Integration Processes: Integrating sensors poses significant challenges to the battery's manufacturing process and reliability. Designing and optimizing sensor layouts within cells, minimizing the impact on production lines, and developing cost-effective manufacturing processes for smart batteries are key future challenges.

Efficient Signal Transmission: Sensing signals must be transmitted to the external BMS via wired or wireless means. While wired communication challenges cell processing and sealing, wireless communication enhances system integration but requires overcoming obstacles in miniaturization, non-destructiveness, corrosion resistance, power consumption, and cost. Additionally, achieving reliable wireless signal transmission through the battery's metal casing is a significant hurdle.

Advanced Management Systems: The ultimate objective of smart battery development is to ensure reliability and safety throughout the battery's lifespan. This goal hinges on uncovering the relationships between various sensing signals and the mechanisms of battery degradation, failure, and thermal runaway. Establishing a correlation between sensing signals and battery health and safety states, and developing high-precision SOC/SOH estimation algorithms and refined management systems, represent important directions for future research.

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