

# A review of the classification and mechanism of action of battery-based sensors

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**Abstract.** Safety monitoring and lifespan management of lithium-ion batteries are crucial for new energy applications. However, traditional battery management systems (BMS) rely solely on electrical signals such as voltage, current, and surface temperature, making it difficult to detect internal hazards in a timely manner. They also suffer from limitations such as delayed response and a single observable quantity. In recent years, new sensing technologies have been introduced into the interior and surface of batteries to acquire various physical information, such as heat and force, enabling in-situ monitoring of the battery status. This article systematically discusses the main categories of battery sensors and their mechanisms of action. It compares the latest research progress and performance indicators of technology routes such as fiber Bragg grating (FBG), non-dispersive infrared (NDIR), and MXene-based flexible sensors. It also summarizes engineering challenges and coping strategies, including packaging integration, signal decoupling, early warning algorithms, and multimodal fusion. The application value of sensing technology in battery SoC/SoH estimation, safety warnings, and fast charging adaptation is discussed. Finally, the future development directions of battery sensing technology, including non-intrusive sensing, wireless transmission integration, and the fusion of physical models and machine learning, provide guidance for the next generation of intelligent battery monitoring and management.

**Keywords:** Sensor classification; multi-physics coupling; FBG; BMS; SoC.

## 1. Introduction

Lithium-ion batteries undergo a couple evolution of electrical, thermal, and mechanical multi-physics during operation. Traditional BMSs rely primarily on external measurements such as voltage, current, and surface temperature to estimate the battery's SoC and SoH [1]. These measurements often suffer from limitations such as response lag and single-signal signal processing when used for fault diagnosis. Therefore, real-time, in-situ sensing of individual cells has become a key complementary approach to improving battery safety and lifespan. In recent years, sensing technologies for internal battery thermal and mechanical stress/strain have emerged. These macroscopic quantities are tightly coupled with microscopic processes such as lattice volume changes caused by lithium insertion/deintercalation, Joule heating generated by polarization, and gas production from side reactions [1]. This allows for earlier and more direct reflection of the battery's internal safety and health status, significantly improving the accuracy of state estimation. Studies have shown that by integrating multiple sensor signals, such as temperature and strain, the SoC estimation error can be reduced to approximately 1%, significantly outperforming traditional single-electrical signal monitoring [1]. Based on this background, this article categorizes battery sensing technologies by sensing target (stress/strain, temperature, gas, acoustics, etc.), reviews the mechanisms and monitoring capabilities of various sensors, and compares and analyzes the performance indicators of different technology approaches, including fiber optic sensing, infrared detection, implantable/distributed sensing, and acoustic ultrasound. Furthermore, this article discusses demodulation methods for sensing signals, decoupling strategies for coupled multi-physics quantities such as temperature and strain, and challenges and corresponding countermeasures for engineering applications.

## **2. Sensor classification and action mechanism**

Physical quantities that can be monitored within a battery primarily include mechanical stress/strain, temperature, gas composition, and acoustic properties [2]. Different types of sensors use these physical quantities to detect changes in the battery's internal state. The sensor's operating mechanism is reflected in the coupling of the sensing quantity with the battery's internal physical and chemical processes. The following section categorizes battery sensors by sensing objects and explains their respective mechanisms of action and coupling with internal reactions.

### **2.1. Stress/Strain Sensors**

By monitoring the deformation or stress changes of the internal materials of the battery, the evolution of the structural stress of the battery during the charge and discharge process can be reflected [3]. The volume and interface changes caused by the insertion/extraction of lithium ions will accumulate stress in the electrode. These stress signals can reveal the battery aging mechanism (such as lithium dendrite growth and SEI film cracking) and provide early warning for safety hazards such as swelling [4]. A common solution is to embed sensors such as fiber Bragg gratings in the battery cell to measure strain through the drift of the grating reflection wavelength caused by strain, and it has almost no impact on battery performance [5].

### **2.2. Temperature Sensor**

The internal temperature of a battery cell is often higher than the external surface, especially under high-rate charge and discharge conditions or in high-temperature environments, where the internal temperature can be tens of degrees Celsius higher than the surface [6]. Therefore, sensors such as thermistors need to be directly implanted inside the battery cell to detect hot spots more promptly and warn of abnormal temperature rises. Fiber optic temperature sensing technology has the advantages of high sensitivity and immunity to electromagnetic interference, making it particularly suitable for high-voltage battery systems [7]. In recent years, there have also been studies integrating micro RTD thin film sensors on electrode current collectors to achieve high-precision in-situ measurement of the internal temperature of the battery cell [8].

### **2.3. Gas Sensors**

The chemical reaction state of the battery is monitored by detecting the gas generated inside the battery. Lithium batteries often release gas due to the decomposition of the SEI film or electrolyte during abnormal operating conditions or aging. This gas release phenomenon can serve as a precursor signal for battery abnormality and failure [9]. Commonly used non-dispersive infrared (NDIR) gas sensors quantitatively analyze gas concentrations by measuring the absorption of light in a specific infrared band by the gas [10]. For high-precision requirements, experimental methods such as gas chromatography-mass spectrometry can be used to deeply analyze the gas composition [11]. Given that the gas composition and timing of battery release under different fault conditions vary [12], gas sensor arrays are usually arranged near the battery pressure relief valve or exhaust port in engineering to capture key gas signals as early as possible [13].

### **2.4. Acoustic/Ultrasonic Sensors**

By sending ultrasonic waves into the battery and monitoring changes in its propagation characteristics, the internal state of the battery cell can be inferred non-invasively [14]. Due to the different mechanical moduli and densities of the materials in each layer of the battery, the propagation speed and attenuation of the sound waves will also change, making the flight time and amplitude of the ultrasonic signal highly sensitive to the battery state of charge and structural changes. Experiments have found that in the early stages of faults such as overcharging, abnormal ultrasonic signals often appear before temperature changes, which can provide significant early warning [15].

### **3. Research Status and Sensing Technology Pathways**

To achieve the measurement of these various physical quantities, researchers have developed a variety of novel sensing technology paths and conducted comparative studies on their performance indicators. Key technology paths include optical fiber-based sensing, gas detection based on infrared spectroscopy, flexible implantable/attached sensing based on new materials, and ultrasonic nondestructive testing using acoustic waves. Each path focuses on different sensing targets and has its own unique characteristics in terms of sensitivity, response rate, stability, and integration difficulty.

#### **3.1. Fiber-optic sensing technology**

Fiber-optic sensors, such as fiber gratings (FBGs) and Fabry-Perot interferometers (FPIs), are widely used in battery stress/strain and temperature monitoring due to their advantages in electromagnetic interference resistance, small size, and distributed measurement capabilities. By implanting fiber gratings (FBGs) or micro-interferometer probes within battery cells, strain and temperature information can be acquired at multiple locations, enabling distributed monitoring with high spatial resolution [16-18]. Researchers have designed an integrated multifunctional fiber optic sensor probe implanted in the center of an 18650-battery cell. During thermal runaway experiments, they continuously measured temperature (T) and pressure (P) over time, successfully capturing the dynamic internal temperature and pressure surges preceding thermal runaway [19]. Due to its passive nature and compact size, fiber optic sensing minimizes impact on the cell structure and safety, and demonstrates superior reliability compared to traditional electrical sensing in high-voltage and high-electromagnetic-noise environments.

#### **3.2. Infrared and optical gas sensing**

NDIR (Non-Dispersed Infrared) is one of the more mature approaches currently being researched for battery gas detection. Its advantages include high selectivity and accurate quantitative analysis, and it can sensitively detect changes in the concentrations of key gases such as CO<sub>2</sub> and CO, providing indicators of battery abnormalities. Experiments have shown that, in tests simulating cell overcharge, NDIR sensors can detect internal gas release signals approximately 580 seconds earlier than traditional temperature sensors, issuing warnings before the cell temperature reaches the BMS alarm threshold [20]. This demonstrates the significant advantages of optical gas sensing for providing early warning of faults such as thermal runaway. While infrared methods have limitations such as requiring a voluminous sampling chamber and optical path, and the sensor components are relatively bulky and power-hungry, optical methods are preferred in applications requiring electromagnetic interference resistance because they eliminate the need for electrical leads and the potential for introducing ignition sources [21]. Generally speaking, infrared/optical sensing is suitable for monitoring tasks requiring high selectivity and long lead times, but they are relatively costly and complex, often requiring integration with other sensing methods to form multimodal monitoring systems to maximize their advantages.

#### **3.3. Flexible Embedded/Attached Sensing**

Battery sensors can be categorized as either attached or implantable, depending on how they are integrated with the battery. Attached sensors are relatively simple to implement and non-invasive to the battery cell itself. Externally attached sensors, on the other hand, typically require fixtures or adhesives for fixation, which can alter the battery's thermodynamic boundary conditions to some extent, causing measurements to deviate from the actual battery state and necessitate correction based on calibration models. Implantable solutions can directly obtain internal battery information, but face engineering challenges such as material compatibility, packaging reliability, and lead routing and insulation isolation. Recent research suggests that these challenges can be partially overcome through advanced material and structural design [22]. For example, a flexible pressure sensor based on two-dimensional MXene material employs a hybrid piezoresistive and piezocatalytic sensing mechanism: mechanical pressure compresses and contracts the porous conductive network, increasing conduction

and simultaneously extruding ions to alter dielectric properties, thereby amplifying signals in both the resistance and capacitance channels. This achieves an ultra-low detection limit of 4 Pa and a wide pressure range of 0–1 MPa, with stable performance for over  $2 \times 10^4$  cycles. This ultrathin, flexible pressure sensing membrane, applied to the outer surface of a soft-pack battery cell, accurately tracks changes in the battery's SoC and provides real-time warning of abnormal expansion caused by mild overcharge ( $>100\%$  SoC), successfully avoiding the occurrence of significant high temperatures. This flexible patch sensor adheres tightly to the cell surface and exhibits a certain degree of stretchability, providing a low-invasive, manufacturable solution for in-service mechanical stress monitoring and safety warnings [23]. In general, externally applied sensors are easy to install but require calibration and compensation to obtain accurate results. Implantable sensors offer richer information but face challenges in material compatibility and packaging. In practical applications, the two methods are often combined to achieve coordinated monitoring of the battery's internal and surface conditions.

### **3.4. Acoustic Ultrasonic Sensing Technology**

Using acoustics for battery testing has been an emerging trend in recent years. Ultrasonic testing offers the advantages of being non-destructive and penetrating, allowing internal information to be obtained without opening the battery. Furthermore, acoustic signals can be correlated with various internal battery changes, providing a new dimension for condition monitoring [24]. Numerous studies have explored the use of ultrasonic sensing for battery SoC/SoH estimation and fault warning. For example, ultrasonic ToF and amplitude features are incorporated into the extended Kalman filter algorithm for joint estimation of battery SoC and SoH. Results show that integrating acoustic signals significantly improves the convergence speed and accuracy of estimation compared to using voltage and current observations alone. Another example is combining ultrasonic signals with optimization algorithms and relevance vector machines to predict SoC and SoH, achieving a relative error of less than 1.5% for SoC and an absolute error of approximately 0.8% for SoH, demonstrating the strong correlation between internal battery acoustic characteristics and charge and state of health [25]. These results demonstrate the feasibility of using new acoustic sensing data for battery state estimation, and have the advantages of non-invasive, in-service real-time monitoring. Overall, as an emerging approach to battery monitoring, acoustic/ultrasonic sensing shows great potential in accelerating state estimation convergence, improving fault warning advances, and improving the interpretability of diagnostic results.

## **4. Engineering Challenges and Strategies**

Although battery sensing technology demonstrates tremendous application potential, numerous challenges remain to be overcome in the transition from experimental research to practical engineering. Key challenges include packaging and integration of sensors and batteries, coupling and decoupling of different physical quantity signals, signal processing algorithms for fault warning, multi-sensor data fusion and management, and system-level communication and cost-efficiency. Researchers have proposed corresponding strategies and optimization solutions to address these challenges.

### **4.1. Packaging Reliability and Lifetime Matching**

When sensors are implanted or attached to batteries, chemical compatibility of the materials with the electrolyte and electrodes must be ensured, and calibration stability must be maintained throughout the battery's lifecycle. To this end, sensors undergo rigorous compatibility testing and accelerated aging tests before mass deployment to ensure a lifespan no less than that of the battery itself. The packaging process is also crucial: for example, fiber optic sensors require special coatings and protective layers to prevent corrosion or fracture within the battery; for patch-type strain/pressure sensors, bonding stress must be controlled to prevent delamination during cycling [26, 27]. Standardization and reliability improvements in sensor packaging are fundamental to the engineering application of sensing technology.

## **4.2. Multi-physical parameter coupling and signal decoupling**

Inside a battery, thermal and mechanical phenomena are tightly coupled, which complicates sensor readings. For example, temperature fluctuations lead to expansion or contraction of materials, which can skew strain or pressure sensor measurements [28]. Likewise, a release of mechanical stress might produce heat, entangling the temperature and stress signals. Long-term sensor drift adds another challenge: NDIR gas sensors can suffer baseline shifts as their light source ages or optics foul, and MOS gas sensors gradually lose sensitivity due to humidity and contaminants [29, 30]. All these factors make it difficult to interpret any single sensor's data in isolation. Decoupling the overlapping effects of temperature, stress, gas, etc., to obtain accurate measurements remains a complex task in multi-physics battery environments.

## **4.3. Early Warning Signal Extraction and Intelligent Diagnostic Algorithms**

The flood of real-time data from embedded battery sensors is only useful if we can derive meaningful warnings and diagnostics from it. Identifying the subtle signs of impending failure or safety events in this data is challenging. Simple threshold-based alarms (e.g., temperature or pressure limits) may catch gross anomalies but could miss complex precursors. More sophisticated pattern recognition and machine learning approaches have been proposed to recognize multivariate signal patterns that correspond to specific faults (like lithium plating, separator damage, etc.) [31]. However, implementing these intelligent diagnostic algorithms in practice is non-trivial. They must run in real time on battery management systems (BMS) hardware with limited computational power and memory. Ensuring timely, reliable early warnings without overloading the BMS requires efficient data processing architectures [32]. In summary, extracting early-warning features and making robust diagnoses from sensor data is a significant challenge that demands careful algorithm design and validation.

## **4.4. Multi-sensor fusion and system integration**

As the number and types of sensors increase, effective system-level fusion and integration face huge challenges. First, in terms of communication transmission, traditional wired sensors need to lead wires from the closed battery cell or battery pack, which may increase safety risks and wiring complexity. Especially in electric vehicle battery packs, a large number of sensor cables not only increases system complexity but also introduces electromagnetic noise interference. Second, at the battery system integration level, the potential impact of sensor deployment on thermal management and mechanical structure must be evaluated. For example, embedding optical fibers or placing pressure sensing membranes in battery modules may change the cooling airflow distribution of the module or generate additional stress concentration. Therefore, these impacts must be evaluated through modeling and testing during the design phase, and the bias introduced by the sensors must be corrected in the BMS algorithm [33]. In addition, multi-sensor data fusion and management require new strategies: the BMS must simultaneously process data from multiple sensor channels, such as temperature, stress, gas, and acoustic data, and extract the most valuable information for safety control. This can be achieved by designing a hierarchical information fusion architecture and priority strategy to minimize the system's computational and communication burden while ensuring safety [34]. These are practical problems that must be gradually solved as sensor technology moves from the laboratory to engineering applications.

## **5. Conclusion**

Battery sensing technologies are reshaping the safety and intelligence of lithium-ion batteries. Stress/strain, temperature, gas, and acoustic sensors complement traditional monitoring by providing internal information that improves SoC/SoH estimation and fault prediction. Despite their potential, engineering challenges remain, including packaging reliability, multiphysics signal coupling, data processing, and multi-sensor integration. Looking ahead, key directions include non-invasive or "sensorless" monitoring to reduce system impact, wireless integration to simplify communication,

and combining physical models with machine learning for interpretable, accurate diagnostics. Multisensor collaborative strategies will further enhance lifecycle management, making future batteries safer, smarter, and more efficient.

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