

Recent Advances in Sensing Materials for Monitoring Thermal Runaway in Lithium-Ion Batteries

Qi Zhang ^{1,†}, Siming Wang ^{1,†}, Hongchen Li ^{2,†} and Yongfa Zhu ^{1,*}

¹ Department of Chemistry, Tsinghua University, Beijing 100084, China

² Institute of Chemicals & Advanced Materials, China National Offshore Oil Corporation, Beijing 102209, China

* Correspondence: zhuyf@tsinghua.edu.cn

† These authors contributed equally to this work.

How To Cite: Zhang, Q.; Wang, S.; Li, H.; et al. Recent Advances in Sensing Materials for Monitoring Thermal Runaway in Lithium-Ion Batteries. *Science for Energy and Environment* **2026**, *3*(2), 12. <https://doi.org/10.53941/see.2026.100012>

Received: 19 May 2026

Revised: 14 September

Accepted: 10 October 2026

Published: 27 October 2026

Abstract: Lithium-ion batteries (LIBs) play a critical role in modern energy technologies, powering portable electronics, electric vehicles, and renewable energy storage systems due to their high energy density, long cycle life, and lightweight properties. However, their high energy storage capacity presents intrinsic safety challenges posed by thermal runaway, a potentially catastrophic failure mode. Recent advances in safety monitoring leverage detectable thermal runaway precursors, including temperature fluctuations, pressure variations, and gas evolution. Although significant efforts have focused on developing smart materials for early-stage thermal runaway detection, limited reviews have systematically addressed these material innovations. This review seeks to fill this gap by providing a concise overview of the mechanisms underlying thermal runaway in LIBs and the corresponding smart monitoring strategies. It also examines recent progress in smart materials tailored for temperature, pressure, and gas sensing applications. The primary objective of this survey is to offer valuable insights and guidance for enhancing thermal runaway safety management in battery systems.

Keywords: lithium-ion batteries; thermal runaway; sensing materials; early warning; battery safety

1. Introduction

The global imperative to transition from fossil fuels to chemical batteries, driven by escalating energy security concerns and environmental crises like global warming, underscores a critical pathway toward sustainable development and a cleaner future [1–6]. Currently, lithium-ion and lead-acid batteries are the most widely adopted secondary batteries for everyday applications [7,8]. Researchers are also exploring other types, such as zinc-ion [9–11] and sodium-ion batteries [12–14], to address the global energy crisis. LIBs, in particular, are extensively used in applications like electric vehicles, laptops, and smartphones owing to their high specific capacity, energy density, extended cycle life, elevated voltage, and environmental sustainability [15–17]. According to data from the Web of Science website, the field of LIBs has undergone extensive research over the past two decades (Figure 1). Undoubtedly, the demand for battery energy storage is growing, along with increasing requirements for battery performance [18]. Higher energy density, a critical performance metric, often comes with increased safety risks due to the high reactivity of LIBs and flammable liquid electrolytes [19–21]. These factors can lead to thermal runaway, potentially causing fires or explosions that threaten personal and societal safety, thereby severely hindering LIBs development. Therefore, it is crucial to promptly monitor abnormal conditions in LIBs and alert users to take appropriate actions to prevent harm to human health and property damage.



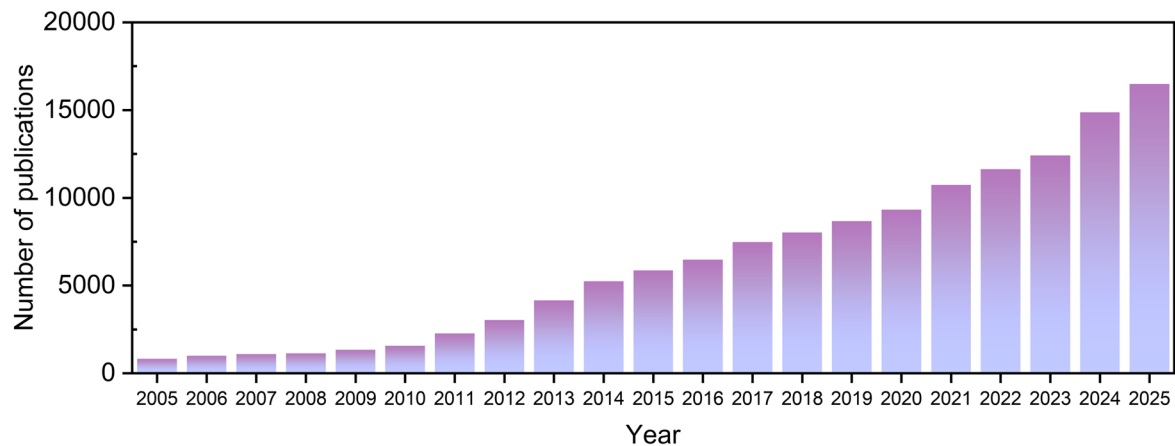


Figure 1. Annual distribution of lithium battery related literature in the Web of Science database (2005–2025).

Commercial LIBs must comply with safety assessment standards set by International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) before entering the market [22]. Despite these standards, the inherent complexity of real-world operating conditions makes it impossible to entirely eliminate the risk of thermal runaway [23]. While the mechanisms of thermal runaway are influenced by numerous factors, extensive research has been conducted to understand this phenomenon [24–27]. Thermal runaway in batteries is typically characterized by temperature rise, pressure increase, and gas generation [28,29]. Monitoring these characteristic signals, such as temperature changes or gas composition, offers the most effective approach for early thermal runaway detection. Previous studies have focused on traditional early detection technologies, including gas sensing [22,30–33] and temperature monitoring [34–36]. The performance of these technologies in detecting early-stage thermal runaway relies heavily on the material properties enabling sensing functions [37,38]. Hence, developing advanced thermal runaway sensing materials is critical to improving early detection capabilities and ensuring battery safety in practical applications.

Existing reviews on battery thermal runaway monitoring have predominantly focused on detection technologies [32,39–43], however, a comprehensive summary of sensor materials has rarely been provided. This review provides a comprehensive analysis of thermal runaway mechanisms, sensing principles based on associated physicochemical phenomena, and recent advancements in sensor materials. The remainder of this review is structured as follows: Section 2 introduces thermal runaway mechanisms and monitoring principles. Section 3 summarizes recent developments in sensor materials for practical applications. Section 4 explores future directions and recommendations for advancing early-stage thermal runaway monitoring technologies and sensor materials. Section 5 concludes the review. This review focuses on conventional lithium-ion batteries employing intercalation-type electrodes and predominantly liquid organic electrolytes. Lithium-metal, lithium-sulfur, and solid-state batteries are outside the primary scope unless explicitly discussed for comparison.

2. Mechanisms of Thermal Runaway and Monitoring

Thermal runaway refers to a phenomenon in chemical, battery, or energy storage systems where exceeding a critical temperature threshold hinders effective heat dissipation, resulting in an uncontrollable temperature escalation [44,45]. Furthermore, this acceleration in heat release initiates a chain reaction that amplifies internal chemical reactions, thereby producing more heat. Upon initiation, temperatures can rapidly rise to hundreds of degrees Celsius, causing battery decomposition, poisonous gas discharge, and potential combustion or explosion [46]. The thermal runaway process in LIBs is complex, involving multiple reaction stages [27,47]. Therefore, research on how to effective detection, prediction, and prevention of thermal runaway in LIBs has become crucial [48–50]. Till now, development of novel sensing materials has offered new approaches for real-time monitoring of lithium battery internal states, particularly in detecting temperature, pressure, and chemical composition changes, which is significant for the improvement of battery safety [51–53]. The following sections will discuss the mechanisms of thermal runaway in LIBs corresponding pivotal monitoring methodology based on thermal runaway induced physical and chemical changes in batteries.

2.1. Mechanisms of Thermal Runaway

Thermal runaway in lithium-ion batteries can be initiated by mechanical, electrical, thermal, or manufacturing-related factors [54]. Mechanical deformation caused by collision, compression, or penetration may damage the separator and induce direct contact between the electrodes, resulting in an internal short circuit and localized heat generation [55]. Electrical abuse includes overcharging, overdischarging, and external or internal short circuits. During overcharging, excessive delithiation destabilizes the cathode structure and promotes electrolyte oxidation, gas evolution, and heat release. Meanwhile, the inability of the graphite anode to accommodate incoming Li^+ at sufficiently high charging rates may result in lithium plating and subsequent dendrite growth [47,56]. In contrast, severe overdischarging raises the anode potential and can induce dissolution of the copper current collector. Copper ions may subsequently be reduced and deposited during recharging, increasing the risk of internal short circuits. Thermal abuse, insufficient heat dissipation, and manufacturing defects can further accelerate parasitic reactions and generate localized hot spots, thereby initiating thermal runaway [57–59].

Once initiated, thermal runaway generally proceeds through a series of mutually coupled reactions rather than a universal sequence defined by fixed temperature boundaries. In graphite-based lithium-ion batteries containing carbonate electrolytes, early self-heating is commonly associated with destabilization of the solid electrolyte interphase (SEI) and reactions between the lithiated anode and the electrolyte [60–62]. These processes expose additional active electrode surfaces, release heat and gaseous products, and increase the internal pressure. With further heating, electrolyte decomposition and separator shrinkage or melting intensify ion transport disruption and increase the probability of internal short circuits [63]. At higher temperatures, charged cathode materials may undergo structural degradation and release oxygen, although the onset temperature and amount of oxygen released depend strongly on the cathode chemistry and state of charge [64].

The oxygen released from the charged cathode can react rapidly with the organic electrolyte and other combustible components, producing additional heat and gaseous products [47,65]. Simultaneously, reactions between the lithiated anode and electrolyte become increasingly vigorous. These coupled exothermic processes establish a positive feedback loop in which heat generation exceeds heat dissipation, leading to rapid temperature and pressure increases. At the severe runaway stage, decomposition or combustion of the electrolyte, binder, separator, and electrode materials can result in cell venting, fire, or explosion [66]. Importantly, the onset temperatures and relative contributions of these reactions vary with electrode chemistry, state of charge, cell format, aging history, electrolyte composition, and triggering condition. Therefore, the temperature intervals reported for individual cells should be regarded as representative rather than universally applicable.

2.2. Mechanisms of Monitoring

2.2.1. Thermo-Responsive Monitoring

LIBs exhibit inherent heat generation during operation, storage, and cycling, stemming from multiple factors including electrochemical reactions, internal resistance, ambient conditions and their synergistic interactions [67]. The comprehensive understanding of these thermal mechanisms proves crucial for optimizing safety, durability and operational efficiency of batteries. The thermal dynamics in LIBs constitutes a multifaceted process involving three primary components: reversible reaction heat, irreversible polarization heat, and ohmic losses [68,69], while each mechanism may operate independently or synergistically, leading to various degrees of heat production. The electrochemical reaction heat refers to the heat generated during the charging and discharging process of LIBs, where lithium ions (Li^+) in the cathode and anode materials are continuously de-intercalated and intercalated due to chemical reactions [25,70]. This entropy-driven thermal component demonstrates polarity dependence, exhibiting endothermic characteristics during charging (negative heat generation) and exothermic behavior during discharging (positive heat generation). The quantitative relationship for reaction heat can be expressed as Equation (1) [71], where Q_{rev} represents the reversible heat-generation rate in W; I is the battery operating current in A (positive for discharging and negative for charging); T is the operating temperature of the LIBs in K; U_{OC} is open-circuit voltage of LIBs in V. Equation (1) defines the entropy-related heat term, while its contribution to the overall energy balance is interpreted according to the sign convention adopted in Equation (6). Note: unless otherwise specified, the heat-generation terms in Equations (1)–(6) are cell-level rates with units of W.

$$Q_{rev} = -IT \frac{dU_{OCV}}{dT} \quad (1)$$

The generation of polarization heat is attributed to Ohmic polarization, concentration polarization, and electrochemical polarization, all of which arise when current flows through the battery [72]. These polarizations lead to a voltage difference between the battery's terminal voltage and its open-circuit voltage, thereby generating heat. The voltage difference between the terminal voltage U_t and the open-circuit voltage U_{OCV} of LIBs generates polarization heat. In the modeling process, it is assumed that the battery contains an internal polarization resistance R_p , and the polarization heat is considered equivalent to the heat generated by this internal resistance. The calculation formula is given by Equation (2) [73], where Q_p is polarization heat rate; R_p , R_t , R_e are polarization resistance of LIBs, a portion of total battery resistance and electrical resistance, respectively.

$$Q_p = I^2 R_p = I^2 (R_t - R_e) \quad (2)$$

Ohmic heat refers to the heat generated as a result of resistance to current flow in components such as the cathodes and anodes, electrolyte, separator, and other parts exhibiting ohmic resistance [74,75], which is also referred as Joule heat [70]. This heat is an inherent consequence, as it is directly proportional to both the current magnitude and the internal resistance of the battery. It arises from exothermic reactions occurring during both charging and discharging processes classified as irreversible heat. The corresponding calculation is provided by Equation (3) [73], where Q_o is Ohmic heat rate; R_o is battery resistance.

$$Q_o = I^2 R_o \quad (3)$$

When calculating the total heat generation of a battery, researchers typically use the heat generation model proposed by Bernardi et al. [76]. in the 1980s, which laid the foundation for the modern thermal management theory of LIBs. The central concept of the Bernardi model is the assumption of uniform heat distribution within the battery. It further divides the total heat generation into two components: irreversible Joule heating and reversible reaction heat, as described in Equation (4). Here, Q_{irev} represents the irreversibly generated heat rate, which depends on the electrochemical reaction process of the battery and can be estimated through temperature and voltage variations of the battery. U_t represents the battery terminal voltage. Q_{total} is the total heat-generation rate.

$$Q_{total} = Q_{rev} + Q_{irev} \quad (4)$$

$$Q_{irev} = I(U_{OCV} - U_t) \quad (5)$$

The combination of Equations (1), (4) and (5) yield Equation (6):

$$Q_{total} = Q_{rev} + Q_{irev} = I(U_{OCV} - U_t) - IT \frac{dU_{OCV}}{dT} \quad (6)$$

Bernardi's model provides a relatively straightforward and accessible approach for estimating heat generation, offering a theoretical framework for advanced research in battery thermal management. However, the assumptions underlying the model raised by Bernardi are overly idealized. In practice, the heat generation in batteries is not uniformly distributed, and factors such as internal heat conduction and convection need to be further considered [77]. The model proposed by Newman et al. [78] subsequently considered the uneven temperature distribution within LIBs. In practical applications, the internal temperature of the battery is not completely uniform, especially under high-power charging and discharging conditions, where localized regions of the battery may generate more heat. Newman's model describes the distribution and conduction process of heat by solving the heat conduction equation. In this model, the temperature field of the battery is described by the following equation, where ρ is the battery density in kg m^{-3} ; C_p is specific heat capacity of the battery in $\text{J kg}^{-1} \text{K}^{-1}$; k is thermal conductivity in $\text{W m}^{-1} \text{K}^{-1}$, Q_{total} is interpreted as a local volumetric heat-generation rate with units of W m^{-3} .

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{total} \quad (7)$$

In the cells inside the battery, both current and potential exhibit spatial variation. Based on this observation, Rao and Newman developed a local heat generation model in their studies [79]. It is believed that the heat generated by electrochemical reactions is localized at the reaction interface and encompasses several components: irreversible resistive heat resulting from overpotentials, reversible heat associated

with entropy generation, and irreversible internal resistive heat [80]. The irreversible internal resistive heat can be further divided into electronic heat and ionic heat. Electronic heat refers to the Joule heating occurring within the solid phases, whereas ionic heat pertains to the Joule heating generated within the electrolyte phase. The rate of heat generation in the local heat generation model is represented by the following Equation (8):

$$C_p \frac{\partial T}{\partial t} - Q_{total} = -\sum_l \int a_{i,n,l} U_{H,l} dv - IV \quad (8)$$

where a denotes the specific electrochemically active interfacial area, $i_{n,l}$ is the corresponding local interfacial current density, and $U_{H,l}$ is the enthalpy potential associated with reaction l .

Taking thermal release into account, sensors for temperature monitoring used for battery thermal runaway are crucial safety devices, designed to detect the risk of overheating during battery operation, thereby preventing the occurrence of thermal runaway. The operational principles can be classified into three primary categories [81]. Firstly, the principle of thermistor-based temperature sensing relies on the relationship between material resistance and temperature variation. Within a detectable temperature range, changes in temperature are converted into electrical signals, enabling temperature monitoring. Secondly, the thermocouple principle is based on the Seebeck effect, which involves the electromagnetic effect generated in a circuit comprising two different metals. A temperature difference between two junctions induces a thermoelectric potential in the closed circuit. The temperature can be estimated by measuring this electrical potential. Thermocouples operate through a closed loop of two dissimilar conductors. A temperature gradient between the junctions induces charge carrier movement, creating a measurable electromotive force. Alternatively, semiconductor thermistors utilize the nonlinear resistance-temperature relationship of semiconductor materials for precise temperature detection.

2.2.2. Pressure-Responsive Monitoring

The mechanism of pressure generation in LIBs batteries is typically associated with internal reactions, temperature rise, electrolyte evaporation, and gas generation. Throughout the charge and discharge cycles, the battery components, including the electrodes (anode and cathode) and the separator, undergo a range of physical and chemical transformations. Under extreme conditions, such as over-charging, short-circuiting, or over-discharging, the internal temperature of the battery can rise significantly, leading to the decomposition of the electrolyte and the production of gases (H_2 and CO_2 etc.). The accumulation of these gases within the battery, if not released promptly, will result in increased internal pressure. Excessive pressure can cause the battery casing to rupture, potentially leading to flaming or explosion in severe cases [82]. In this section, we will conduct a comprehensive analysis of the various factors contributing to pressure generation in LIBs and explore underlying mechanisms.

Over-charging is the first issue to consider, which refers to the condition that a battery's voltage exceeds its design limitation, typically around 4.2 V for a single lithium-ion cell [83]. When LIBs operate under overcharging conditions, abnormal chemical reactions occur within the cell, leading to several consequences. Firstly, the decomposition of the electrolyte may take place. The electrolyte in LIBs typically consists of solvents (such as organic carbonates) and lithium salts (e.g., $LiPF_6$). Excessively high voltages during overcharging can cause the organic solvents in the electrolyte to decompose, and further generates gases such as CO_2 , CO, and HF, some of which are corrosive. The accumulation of these gases leads to a rapid increase in internal pressure. Secondly, over-charging may induce lithium metal to deposit on the anode, promoting the growth of lithium dendrites. These dendrites pose significant safety risks, as they can pierce the separator and cause short circuits, exacerbating gas generation and pressure buildup [84].

In addition to overcharging, severe overdischarging can compromise battery safety when the cell voltage falls below its lower cut-off limit [85]. During overdischarge, the anode potential increases substantially, which may cause copper current-collector dissolution and irreversible degradation of the electrode interfaces. If the cell is subsequently recharged, dissolved copper ions can be reduced and deposited on the electrode surfaces, potentially penetrating the separator and inducing an internal short circuit. The resulting localized heating accelerates electrolyte decomposition and gas evolution, thereby increasing the internal pressure and the risk of thermal runaway. Therefore, lithium plating and dendrite formation should primarily be associated with overcharging, high-rate charging, or low-temperature charging, rather than with the overdischarge process itself [84–87].

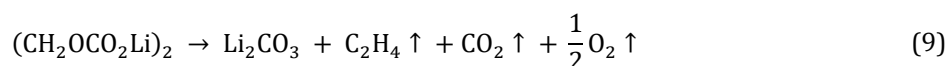
As discussed above, to prevent excessive pressure from leading to rupture or explosion, designs of battery typically incorporate safety mechanisms such as pressure relief valves and expansion membranes [88].

However, during operation, particularly under conditions of over-charging, over-discharging, high-temperature exposure, or physical damage, safety issues may still arise [58]. Therefore, proper usage and the avoidance of extreme conditions are crucial for ensuring battery safety.

Pressure sensors function by transducing mechanical pressure (e.g., from gaseous or liquid media) into measurable electrical signals through four principal transduction mechanisms: resistive, capacitive, piezoelectric, and fiber-optic [89]. In resistive sensors, pressure-induced deformation of the diaphragm alters the internal resistance of the sensor, generating an electrical signal proportional to the pressure. In capacitive sensors, pressure changes the distance between two electrodes, resulting in a change in capacitance, and producing the electrical signal [90]. Piezoelectric sensors produce an electrical charge when pressure is applied to piezoelectric materials, and this charge can be detected to measure the pressure [91]. Fiber-optic sensors measure pressure by altering the properties of the light signal within the fiber, such as refractive index or interference patterns [92]. In battery thermal runaway monitoring, piezoelectric or resistive pressure sensors are more commonly used because of their quick response time, making them suitable for detecting sudden pressure changes [93].

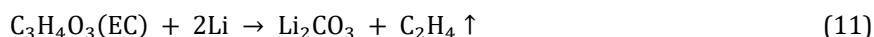
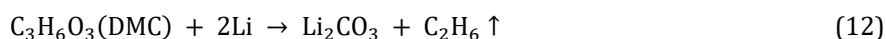
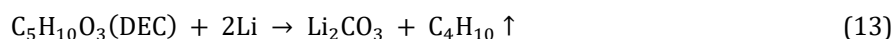
2.2.3. Gas-Responsive Monitoring

During thermal runaway, LIBs undergo complex multi-stage chemical reactions that generate various gaseous compounds, including flammable molecules that significantly elevate fire and explosion hazards due to heightened ignition risks [30]. The mechanism of gas generation during thermal runaway can be delineated into several key stages, including the internal temperature increase within the battery, the decomposition of the electrolyte, and the subsequent reactions between the positive and negative electrode materials, as similarly compared to thermal runaway process (Figure 2) [47,94,95]. At the onset of thermal runaway, the temperature rises to 90 °C, leading to the decomposition of the SEI, which in turn releases substantial amounts of heat and gas. Taking metastable materials such as $(\text{CH}_2\text{OCO}_2\text{Li})_2$ and ROCO_2Li as examples, the decomposition reaction is as follows:



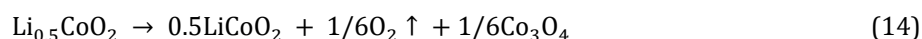
Equations (9) and (10) represent simplified overall decomposition pathways of representative metastable SEI components. The actual SEI contains multiple inorganic and organic species and may consequently produce additional gaseous and solid products [22,96].

The decomposition of SEI generates a significant amount of heat, causing the system temperature to continue rising. Upon the structural fracture of the anode, the intercalated lithium within becomes directly exposed to the electrolyte. This exposure triggers an exothermic reaction, resulting in the formation of combustible hydrocarbon compounds. Several possible chemical reactions that may occur are outlined as follows:

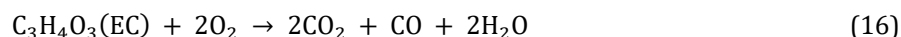


Equations (11)–(13) are balanced overall reactions used to illustrate the formation of lithium carbonate and gaseous hydrocarbons when lithiated species react with carbonate solvents. They do not imply that these are the only products or elementary reaction pathways [97,98].

Subsequently, electrochemical side reactions continue to occur, and the separator begins to melt. As the temperature increases rapidly to approximately 200 °C, the separator may shrink or melt, while reactions between the lithiated anode and the electrolyte become increasingly vigorous. At higher temperatures, charged cathode materials can undergo structural degradation accompanied by oxygen release. For example, delithiated Li_xCoO_2 , including $\text{Li}_{0.5}\text{CoO}_2$ as a charged cathode material [97] and the electrolyte LiPF_6 as an example [96], the chemical reaction equation is as follows:



The organic electrolyte solvent begins to undergo gradual oxidation, driven by the oxygen generated during the anode decomposition. This process releases a numerous amount of heat and gas, primarily composed of CO₂ and H₂O. Taking EC electrolyte solvent as an example [33].



PF₅, as a toxic compound, can promote the decomposition of electrolytes and react with water molecules released during the aforementioned stages, generating the toxic gas HF [99,100].



Finally, the binder polyvinylidene fluoride (PVDF) effectively stabilizes the overall structure of the electrode [101,102]. However, at elevated temperatures (around 260 °C), it may react with lithium metal deposited on the anode or cathode, leading to the generation of H₂ and hydrocarbons. Meanwhile, carbon-based materials are prone to undergo vigorous combustion, resulting in the huge releasing of CO and CO₂ [103]. They cannot be represented by a unique stoichiometric equation. Equation (18) is therefore presented only as a simplified schematic pathway.

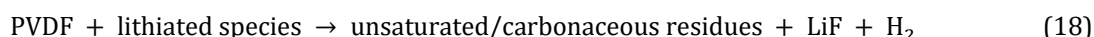
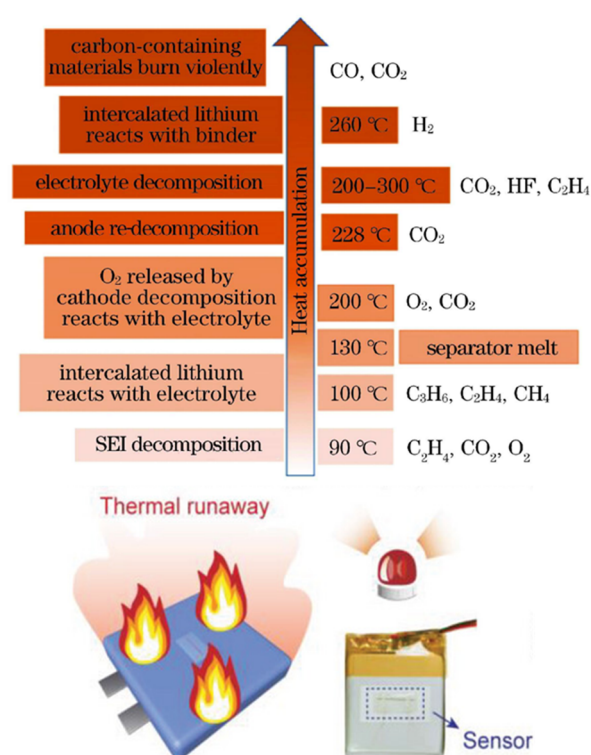


Figure 2. The mechanism of gas generation during thermal runaway. Upper panel: Reprinted with permission from Ref. [95]. Copyright © 2022, Chinese Laser Press. Lower panel: Ref. [104]. Copyright © 2024, John Wiley & Sons.

Gas evolution is a valuable indicator of battery failure, but neither the sequence nor the concentration of the released species is universal. The onset and relative abundance of H₂, CO, CO₂, CH₄, C₂H₄, other volatile hydrocarbons, O₂, and HF depend on cathode chemistry, anode composition, electrolyte formulation, state of charge, cell format, aging state, and abuse mode. CO₂ and light hydrocarbons can provide pre-runaway information in some cells, while H₂ and CO may also be detected before rapid temperature escalation under particular conditions. HF can arise from LiPF₆-related decomposition and hydrolysis reactions; however, its external concentration and apparent onset are strongly affected by moisture availability, secondary reactions, adsorption, and its high reactivity and corrosiveness. Oxygen release is similarly chemistry-dependent, and O₂ may be consumed by reactions with the electrolyte and lithiated anode before reaching an external sensor. Therefore, a gas should not be designated as intrinsically early or late solely from a nominal reaction temperature. The measured warning time further depends on vent-opening and leakage behavior, transport and dilution within the enclosure, sensor location, response time, detection limit,

selectivity, and environmental cross-sensitivities. Gas-sensing strategies should therefore be calibrated for the cell chemistry and deployment scenario, and pattern-based multi-gas detection, preferably combined with temperature, pressure, voltage, or impedance signals, is generally more robust than a universal single-gas threshold [30,96]. Currently, gas detection for LIBs thermal runaway is typically carried out using semiconductor sensors, electrochemical gas sensors, infrared optical gas sensors, and mass spectrometric sensors [30,96]. These sensors perform on different principles and exhibit varying advantages for detecting specific types of gases and operating conditions. Among them, semiconductor gas sensors, such as ZnO-based sensors [105], can detect characteristic gases by utilizing changes in surface conductivity resulting from the interaction between gases and the material surface, which exhibits high sensitivity and can efficiently detect gases [106]. However, it is susceptible to environmental factors such as temperature and humidity, necessitating frequent calibration [107]. In contrast, electrochemical gas sensors operate based on redox reactions of target gas molecules at the electrode, generating current or potential signals proportional to the gas concentration, thereby facilitating gas detection [108,109]. However, it may present a risk of sensor poisoning at elevated gas concentrations and typically exhibits a shorter operational lifespan. The latter two types of sensors track most gas molecules based on the absorption characteristics of specific infrared wavelengths associated with chemical bonds and the ionization mass-to-charge ratio principle, which are widely recognized for their broad detection range and high accuracy. However, a critical drawback of both types is their high detection cost, which limits their feasibility for widespread application in the safety monitoring of future energy storage devices [110].

2.2.4. Other *In-Situ* Diagnostic Approaches

During the charging process of LIBs, lithium ions diffuse toward the anode and undergo lithium deposition. The formation of lithium dendrites during deposition inevitably increases the risk of thermal runaway. Recent advancements in various *in-situ* characterization techniques, including *in-situ* electron microscopy, magnetic resonance, and neutron-based methods, have provided powerful tools for investigating dendritic growth mechanisms in LIBs [111].

In-Situ imaging technology integrates optical microscopy, X-ray tomography, transmission electron microscopy, or atomic force microscopy with specially designed electrochemical reaction cells, which enables experimental conditions to closely mimic actual battery operating states, permitting real-time observation of lithium dendrite nucleation and growth dynamics at the nanoscale [112,113]. *In-Situ* magnetic resonance techniques can be mainly categorized into *in-situ* nuclear magnetic resonance (NMR) and *in-situ* electron paramagnetic resonance (EPR). In particular, *in-situ* NMR can provide information on the molecular chemical environment and dynamic processes, offering advantages such as non-destructive quantification and high sensitivity [114]. *In-Situ* EPR exhibits higher sensitivity compared to NMR and enables the combined analysis of EPR spectroscopy and EPR imaging to study the morphology and spatial distribution of metallic lithium [115]. *In-Situ* neutron techniques leverage the interaction between neutron beams and atomic nuclei, offering isotope-specific and highly sensitive detection, particularly for lithium atoms, making them an effective method for characterizing lithium metal distribution [116]. However, the high cost of neutron sources prevents their large-scale implementation in laboratory settings, limiting their application in studying the growth mechanisms of lithium dendrites. These operando techniques provide valuable mechanistic and spatially resolved information on lithium deposition and internal degradation. However, their instrument complexity, cost, and cell-access requirements currently limit their direct integration into commercial battery-management systems; they are therefore best regarded as diagnostic platforms that guide the development and validation of deployable sensors.

3. The Research Development of Sensing Materials on Thermal Runaway in LIBs

3.1. Sensing Materials Based on Heat Generation

Thermoresponsive materials are a class of materials that can respond to external temperature changes and undergo reversible physical or chemical changes [117]. In recent years, with the growing demand for applications of thermoresponsive materials, significant progress has been made by researchers in areas such as synthesis, performance optimization, and applications [118]. The principle of material temperature sensing has been described in detail in Section 2.2.1, primarily involving the thermoresistive effect and the thermoelectric effect [119]. For real-time monitoring of the operating temperature in LIBs, sensors should possess characteristics such as miniaturization, flexibility, and high-temperature stability to facilitate their integration into the internal battery system [39,120,121]. To date, the most widely studied flexible

temperature sensors primarily include metals and their oxides [122–124], carbon-based materials [125,126], and conductive polymers [127,128]. Metal and metal oxide-based temperature sensors have been extensively studied due to their superiority, such as fast response time, high accuracy, and wide temperature measurement range [129]. Guo et al. [130] developed a multimodal flexible sensor utilizing a $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ functional oxide thin film, which was deposited on a mica substrate. The sensor demonstrates exceptional performance over a wide temperature range, from 20 K to 773 K, and exhibits outstanding mechanical flexibility, maintaining durability through up to 3600 bending cycles. Liu et al. [131] employed $\text{Pt}/\text{In}_2\text{O}_3$ as thermoelectric materials to fabricate a temperature sensor on a flexible polyimide substrate. The thermoelectric temperature sensor achieved a maximum output voltage of 34.33 mV and exhibited an exceptionally high sensitivity of $204.35 \mu\text{V}/^\circ\text{C}$. Additionally, the sensor demonstrated excellent repeatability, stability, and minimal temperature drift. NiO is regarded as an ideal thermosensitive semiconductor owing to its high temperature coefficient of resistance (TCR) and exceptional temperature sensing performance. Consequently, the development of highly sensitive NiO-based flexible material devices is critical for advancing flexible temperature sensors with both high deformation capability and enhanced sensing performance. Lu et al. [104] proposed a straightforward *in-situ* two-step synthesis method to fabricate flexible NiO/carbon nanotube fiber (CNTF) composites (Figure 3A). The resulting NiO/CNTF-based flexible temperature sensors demonstrated remarkable deformability and temperature sensing properties, exhibiting a wide operating range (-15 to 60°C), high sensitivity (with a maximum TCR of $-20.2\% \text{ } ^\circ\text{C}^{-1}$), and the ability to effectively detect early thermal runaway in LIBs (Figure 3B). Recent studies have focused on the potential of alloys to significantly improve temperature sensing performance. Li et al. [132] developed a flexible temperature sensor utilizing $\text{Mo}_{1-x}\text{W}_x\text{S}_2$ alloy films, fabricated through inkjet printing and thermal annealing techniques, which exhibited an exceptionally wide temperature detection range (20 K to 823 K) on a polyimide substrate, and extending up to 1073 K on flexible mica. It also demonstrated a rapid response time of approximately 30 ms, remarkable stability of 100 heating/cooling cycle, and excellent ability to accurately identify arbitrary shapes (Figure 3C).

Nevertheless, metallic materials generally display lower temperature sensitivity compared to carbon nanomaterials and conductive polymers, and the flexibility of metallic materials is comparatively limited. In recent years, there has been rapid advancement in the development of temperature sensors based on carbon nanomaterials and conductive polymers [104,125–136]. For instance, Wang et al. [137] developed graphene fibers through a straightforward microfluidic spinning technique, utilizing vitamin C as a reducing agent. The resulting fibers demonstrated high electrical conductivity (2448 S/m), exceptional flexibility, and a lightweight nature. Building on its unique physical properties, flexible temperature sensor incorporating both graphene fibers and platinum were fabricated, which displayed a sensitivity of $29.9 \mu\text{V}/^\circ\text{C}$. Under a temperature gradient of 120°C , the sensor's thermoelectric voltage output reached 3.45 mV, indicating outstanding temperature-sensing capabilities. These results highlight the sensor's promising potential for applications in the monitoring of LIBs. To obtain better temperature sensing characteristics, the type of carbon materials and the design of sensor devices were considered. Buga and Viana [138] utilized two types of commercial carbon inks (carbon nanoparticles and CNTs) along with three distinct design approaches to fabricate a range of temperature sensors. They assessed the morphological and electronic structural properties of the sensors and optimized their sensing performance using statistical factor analysis (Figure 3D). The results demonstrated that the temperature sensor based on carbon nanoparticles, combined with Design 1, achieved a resistance of 7.8 k Ω at room temperature, a TCR of $1.13\% \text{ } ^\circ\text{C}^{-1}$, and a correlation coefficient (R) of 0.99. Liu et al. [139] developed a linearly tunable conductive hydrogel through the *in-situ* polymerization of polyaniline (PANI) onto a CNFs/MEO₂MA/PEGMA hydrogel substrate (PANI@CMP hydrogel). The composite hydrogel exhibited temperature-dependent electrical conductivity, with PANI incorporation significantly enhancing its stiffness and elasticity. The compression modulus increased by 42%, enabling effective temperature detection within the range of 20 – 60°C (Figure 3E). Zhang and Cui [140] reported the development of a PEDOT:PSS-based temperature sensor that integrates flexible plastic substrates and cotton fabrics. The sensor indicated exceptional performance, with broad detection range, rapid response time, and remarkable stability under both operational and bending conditions. An exceptionally wide measurable temperature range is not, by itself, a sufficient criterion for battery early warning. More relevant parameters include accuracy and sensitivity near the onset of abnormal self-heating, short thermal time constants under realistic mounting conditions, and minimal signal drift during repeated cycling. Cryogenic, ultrahigh-temperature, or flame-mapping demonstrations are therefore treated as evidence of material robustness rather than direct proof of battery-warning performance.

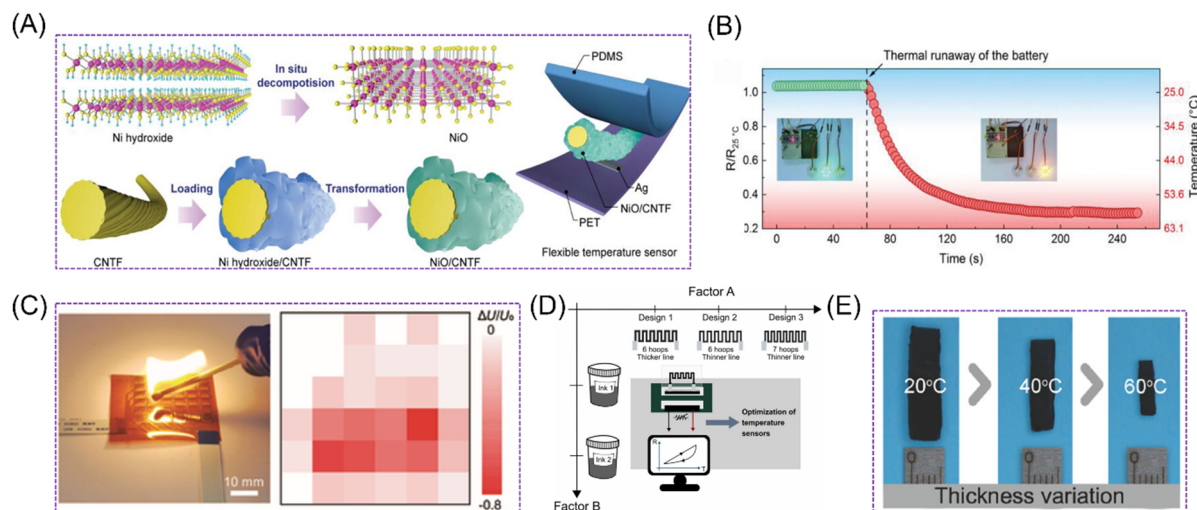


Figure 3. The preparation and performance of temperature sensing materials. (A) The synthesis route and morphology of the NiO/CNTF-based temperature sensor. Reprinted with permission from Ref. [104]. Copyright © 2024, John Wiley & Sons. (B) Temperature sensing of thermal runaway in LIBs. Reprinted with permission from Ref. [104]. Copyright © 2024, John Wiley & Sons. (C) The photograph of the sensor array in proximity to a biomass flame (left) and corresponding voltage mapping that spatially correlates with the flame morphology (right). Reproduced from Ref. [132] under the CC BY 4.0 license. (D) The influence of design and ink on the temperature sensor. Reprinted with permission from Ref. [138] under the CC BY 4.0 license. (E) Thermally-induced dimensional changes of PANI@CMP hydrogel from 20 to 60 °C. Reprinted with permission from Ref. [139]. Copyright © 2018, John Wiley & Sons.

Although flexible temperature sensors have shown great potential in the field of thermal runaway monitoring for LIBs, several challenges still remain, including the need to further enhance the high-temperature resistance of the sensors, effectively integrate flexible sensors with the battery management system (BMS) of LIBs, and address issues related to cost control. With the continued advancement of flexible electronics, materials science, and intelligent algorithms, flexible temperature sensors are expected to play an increasingly important role in thermal runaway monitoring for LIBs in the future, enhancing battery safety and ensuring the reliability of sustainable energy systems.

3.2. Sensing Materials Based on Pressure Generation

A detailed discussion based on the principle of pressure sensing has been presented in Section 2.2.2. Due to the high sensitivity and rapid response characteristics of piezoelectric and piezoresistive sensors, they can be applied to thermal runaway warning systems in LIBs [141,142]. Thus, the following section will mainly focus on a review of the research progress in piezoelectric and piezoresistive pressure sensors. The materials presently used in piezoelectric-based pressure sensors primarily include two-dimensional (2D) materials [143–145], metal compounds [146–148], polymers [149,150], or inorganic-organic composite materials [151,152].

2D materials such as graphene and MXenes have been extensively studied for pressure sensing due to their excellent electronic structures, good conductivity, and high mechanical strength [153,154]. For example, Wang et al. [155] fabricated a piezoelectric film pressure sensor composed of electrospun polyvinylidene fluoride-trifluoroethylene (PVDF-TrFE)/MXene nanofiber mats. Their study demonstrated that the sensing performance of the piezoelectric film was strongly dependent on the MXene content. Specifically, the composite films containing 2.0 wt.% MXene exhibited an instantaneous output power density of approximately 3.64 mW/m² under a 20 N applied pressure at a frequency of 1 Hz. Significantly improved pressure sensing capabilities was attributed to the incorporation of MXene facilitated interactions with PVDF-TrFE molecular chains via dipole-dipole interactions, while also enhancing the conductivity of composite films. The introduction of MXene also boosted the dispersion of piezoelectric materials within the matrix, further verifying their practical applications. The research team led by Liu [156] integrated MXene into the BaTiO₃/PVDF-TrFE system and successfully manufactured BaTiO₃/MXene/PVDF-TrFE composite films via electrospinning, and the fabricated pressure sensor based on composite films exhibited a wide detection range (0.2–400 kPa) and a rapid response time (56 ms).

Additionally, the tensile strength of the composite films containing only 0.15 wt.% MXene (20.8 MPa) was 77.8% higher than that of the MXene-free film (11.7 MPa), while the piezoelectric response remained stable after over 5000 compression cycles. The enhanced pressure-sensing performance can be attributed to MXene's ability to significantly improve the dispersion of BaTiO₃ within the PVDF-TrFE matrix and the corresponding optimized polarization efficiency (Figure 4A). The doping of carbon-based structures like graphene and CNTs can also enhance the dielectric response of the system by improving its electrical conductivity. Ahmed et al. [157] successfully developed a high-performance pressure sensor by incorporating reduced graphene oxide (rGO) and multi-walled carbon nanotubes (MWCNTs) into PVDF-TrFE nanofibers, with the subsequently loading of composites onto the surface of PEDOT. The resulting hybrids displayed a lower resistivity of the electrode with a surface resistivity of 2.5–8.5 MΩ/sq, and the fabricated pressure sensor demonstrated an enhanced sensitivity of 19.09 kPa⁻¹, with a wide effective sensing range from 1.0–25 kPa, and exceptional stability over 10,000 cycles (Figure 4B).

Metal compounds such as ZnO [158,159], AlN [160], GaN [161], LiNbO₃ [162,163], and BiScO₃-PbTiO₃ [164] are widely utilized in pressure sensing applications due to their excellent high-temperature resistance and high sensitivity. Moreover, the optimization of geometric morphology of piezoelectric materials can regulate their piezoelectric performance. To illustrate, Adhikary's group [152] synthesized polydimethylsiloxane (PDMS)-ZnO piezoelectric nanocomposites by incorporating two distinct forms of piezoelectric ZnO fillers: nanoparticles (NP) and nanoflowers (NF), into a flexible PDMS polymer matrix. The latter experiments revealed that the morphology of ZnO could influence the piezoelectric properties of the resulting composites, for NF-based piezoelectric composites generated a voltage of 4.2 V, while the NP-based composite yields a voltage of only 1.86 V under same applied pressure of 36 kPa. The enhanced piezoelectric response of NF-based composites was attributed to their superior geometric connectivity, which facilitated more efficient charge transfer (Figure 4C). Li et al. [159] fabricated a piezoelectric pressure sensor using vanadium-doped zinc oxide (V-ZnO) thin films, by introducing metallic vanadium (Figure 4D). The findings demonstrated that the voltage-pressure relationship of the undoped ZnO sensor remained linear and stable over a temperature range from room temperature to 450 °C, while V-ZnO based sensor presented undesirable many-to-one response and degradation temperature of only 150 °C, indicating that doping is not always positive for sensing. However, certain limitations were also noted, including high signal noise and relatively low sensitivity (1.68 mV/kPa).

Lithium niobate (LiNbO₃) single crystals, distinguished by their high piezoelectric coefficient and elevated Curie temperature, are ideally suited for the fabrication of piezoelectric pressure sensors. Xu et al. [162] adopted chemical mechanical polishing (CMP) method to fabricate pressure sensors based on LiNbO₃ crystal with varying thicknesses, which indicated that the sensitivity of the 300 μm sample (0.218 mV/kPa) was roughly 1.23 times greater than that of the 500 μm sample (0.160 mV/kPa), unveiling a thickness-controlled charge output ability (Figure 4E). To improve sensing performance, the integration of both inorganic and organic piezoelectric materials has emerged as a promising research pathway. For example, Kim et al. [165] developed ceramic-epoxy nanocomposites by combining Pb(Zr_{1/2}Ti_{1/2})O₃-(Pb(Zn_{1/3}Nb_{2/3})O₃-Pb(Ni_{1/3}Nb_{2/3})O₃) and epoxy resin in weight ratios of 81 wt.% and 19 wt.%, respectively, which were applied as high-sensitivity piezoelectric pressure sensors. Furthermore, they surveyed the effect of MWCNTs as conductive fillers on the conductivity, dielectric properties, and piezoelectric performance of the ceramic-epoxy nanocomposite films. The research revealed that the flexible ceramic-epoxy nanocomposite film containing 0.07 wt.% MWCNTs exhibited the highest piezoelectric coefficient, with values of 68 pC/N (*d*₃₃) and 434 mV·m/N (*g*₃₃), which were 2.5 times and 2.2 times greater, respectively, than those of the MWCNT-free nanocomposite films. Further analysis suggested that the incorporation of a small amount of MWCNTs significantly strengthened the dielectric and piezoelectric properties of the nanocomposite films, likely due to the MWCNTs acting as conductive bridges between the piezoelectric ceramic particles.

Pressure sensors based on the piezoresistive principle are promising for early warning applications in LIBs due to their advantages of simple fabrication processes, low cost, and ease of miniaturization. Researchers have demonstrated that carbon-based materials (such as 3D graphene, CNTs, etc.) [166–170], metal nanowires and their particles [171,172], as well as polymers [173] or hybrid composite materials [174–176] exhibited excellent piezoresistive properties. Nevertheless, the primary challenge in developing high-performance flexible piezoresistive pressure sensors lies in simultaneously achieving high sensitivity and a broad monitoring range. Optimizing the morphology of sensing materials is critical to enhancing sensor performance. Wang's research team [177] has explored a flexible piezoresistive sensor based on a micro-dome array of PDMS/CNTs thin films and a thermoplastic polyurethane (TPU)/Ti₃C₂T_x MXene multilayer interlocking "sandwich" structure nanofiber film. The multilayer interlocking structure not only

significantly increased the contact area inside of interlayers and sensitivity but also greatly improved mechanical and electrical stability. The results demonstrated that the PDMS/CNT-TPU/MXene pressure sensor exhibited a high sensitivity of 82.17 kPa^{-1} , a wide pressure detection range of 0–25 kPa, an extremely short response and recovery time of 100 ms, and over 2000 cycles of stability (Figure 4F). Polypyrrole (PPy), a conductive polymer, is also a prospective candidate for application in piezoresistive pressure sensors. However, the brittleness of PPy films complicates the fabrication of subsequent sensors. Pan et al. [178] successfully deposited PPy uniformly onto nanofibers composed of polydopamine (PDA) and electrospun PVDF, resulting in a significant enhancement of the sensor's mechanical strength. This modification notably improved its sensitivity (139.9 kPa^{-1}), response (22 ms), stability (over 10,000 cycles), and lowered its detection limit (0.9 Pa) (Figure 4G).

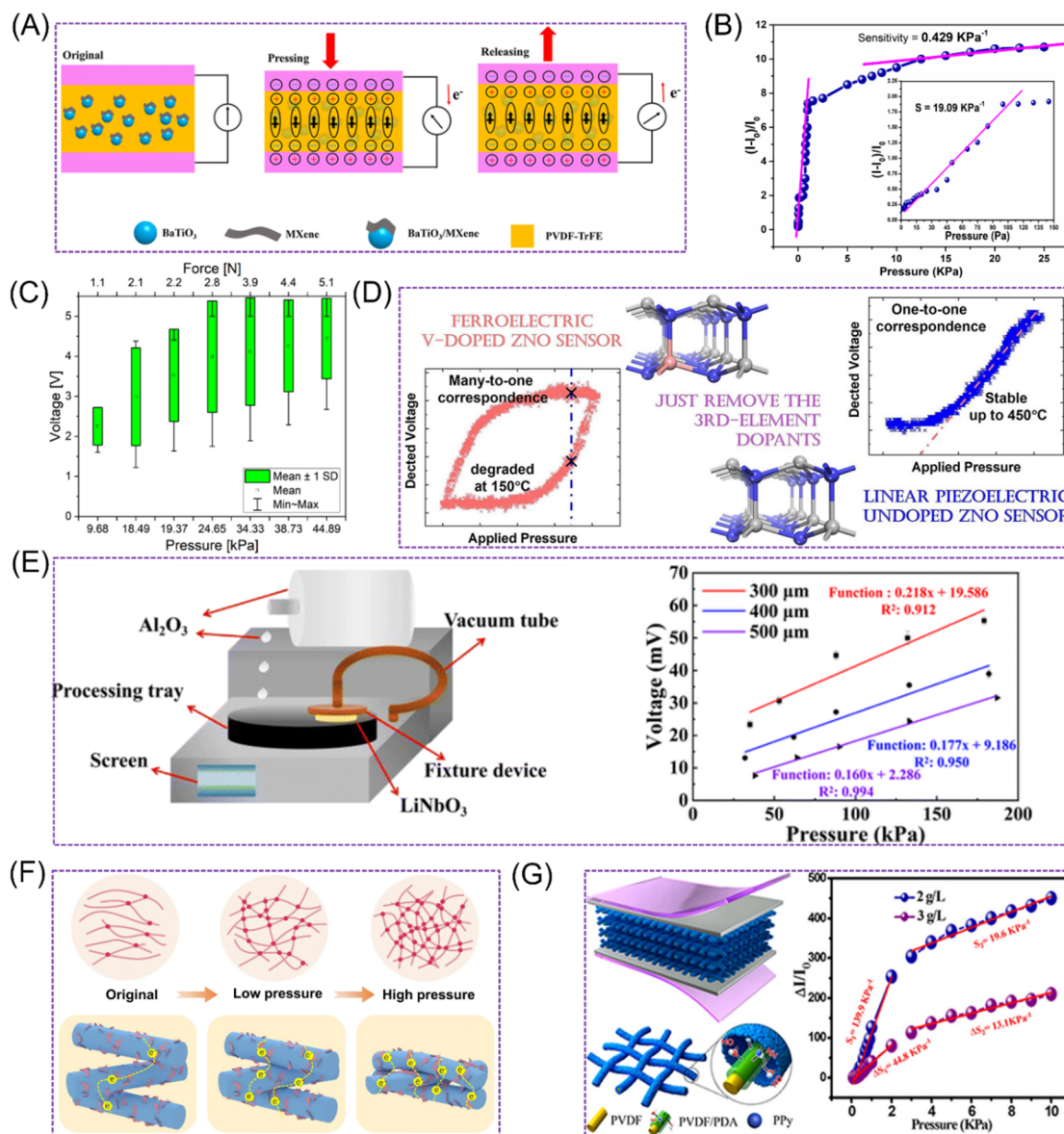


Figure 4. The preparation, sensing performance and mechanisms on pressure sensing materials. (A) The sensing mechanism of the $\text{BaTiO}_3/\text{MXene}/\text{PVDF-TrFE}$ -based pressure sensor. Reprinted with permission from Ref. [156]. Copyright © 2023, Royal Society of Chemistry. (B) The sensitivity response of the fibrous mat sensor. Reproduced from Ref. [157] under the CC BY 4.0 license. (C) Piezoelectric response of the PDMS piezocomposites sensors. Reproduced from Ref. [158] under the CC BY 4.0 license. (D) The voltage vs pressure curves of undoped ZnO and V-doped ZnO sensors. Reproduced from Ref. [159] under the CC BY 4.0 license. (E) Schematic diagrams of the CMP machine, and linear fit error bar curve for comparison of different thicknesses. Reproduced from Ref. [162] under the CC BY 4.0 license. (F) Structural evolution of the TPU/MXene fiber film under compression. Reprinted with permission from Ref. [177]. Copyright © 2024, Royal Society of Chemistry. (G) The production method and sensing performance of the PPP-based elastomer featuring 3D topological network. Reprinted with permission from Ref. [178]. Copyright © 2020, American Chemical Society.

Piezoresistive or piezoelectric devices attached to the cell exterior generally measure deformation or contact force rather than internal pressure directly. Converting these signals into an estimate of internal pressure requires cell-specific mechanical calibration. The calibration must account for cell format, casing stiffness, fixture preload, irreversible electrode swelling, and pressure-relief behavior; otherwise, externally applied-pressure tests may overstate the relevance of the sensor to thermal-runaway warning.

3.3. Sensing Materials Based on Gas Generation

The mechanism of gas composition detected by gas sensors has been fully elaborated in Section 2.2.3. Different types of sensors are capable of detecting different characteristic gases, and the characteristics of generated gases during LIBs thermal runaway are predominantly influenced by the battery material composition and the state of charge (SOC). Therefore, understanding the gas generation characteristics of different battery systems is crucial. The table below presents the types and quantities of gas emissions during thermal runaway in lithium batteries as studied in recent years.

As shown in the Table 1, the major gas products released during the thermal runaway process of LIBs are CO₂, CO, H₂, and flammable hydrocarbons, whose respective proportions are influenced by the chemical composition of battery materials. As indicated by this, Wang et al. [179] conducted both qualitative and quantitative analyses of the thermal induced solid hazards associated with gases emitted during the thermal runaway of batteries featuring different cathode materials. Their investigation comprehensively examined the combustion and explosion characteristics of these gases. The results revealed the following order of severity for thermal runaway hazards: Li(Ni_{0.8}Co_{0.1}Mn_{0.1})O₂ > Li(Ni_{0.6}Co_{0.2}Mn_{0.2})O₂ > Li(Ni_{0.5}Co_{0.2}Mn_{0.3})O₂ > Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O₂ > LiFePO₄. Notably, the gases released from LiFePO₄ batteries contained the highest concentrations of H₂ and C₂H₄ (up to 51%), while the gases from Li(Ni_xCo_yMn_{1-x-y})O₂ batteries exhibited CO and CO₂ concentrations reaching as high as 60%. Furthermore, the SOC of the batteries was found to significantly influence the gas production behavior during thermal runaway. The Golubkov's research group [180] carried out a detailed investigation into the thermal runaway characteristics of two kinds of commercially available 18650 batteries, based on Li_xFePO₄ and Li_x(Ni_{0.80}Co_{0.15}Al_{0.05})O₂, by pre-treating the batteries across a SOC range from 0% to 143%. They concluded that higher SOC levels increased the oxygen release from the cathode and the intercalated lithium content in the anode. Simultaneously, as gas production increased sharply with rising SOC, the concentrations of H₂ and CO also showed a proportional increase. Ma et al. [181] also obtained the same conclusion on the impact of SOC on the overall gas generation characteristics of thermal runaway in ternary 18650 LIBs in their study.

Table 1. The gas generation behavior of thermal runaway in different lithium battery.

Battery Material	Capacity (Ah)	SOC (%)	Overall Gas Generation	Gas Yield per Unit Volume (L Ah ⁻¹)	The Types and Quantities of Gas Produced	Reference
Cathode: LiNi _{1/3} Co _{1/3} Mn _{1/3} O ₂ Anode: graphite	37		168.9 L	4.565	CO ₂ (42.91%), CO (14.82%), H ₂ (20.81%), CH ₄ (5.88%), C ₂ H ₄ (8.11%), C ₂ H ₆ (1.57%)	
Cathode: LiNi _{0.5} Co _{0.2} Mn _{0.3} O ₂ Anode: graphite	2.1		144.1 L	2.882	CO ₂ (37.96%), CO (21.27%), H ₂ (20.24%), CH ₄ (7.51%), C ₂ H ₄ (7.08%), C ₂ H ₆ (1.58%)	
Cathode: LiNi _{0.5} Co _{0.2} Mn _{0.3} O ₂ Anode: graphite	50	100	129.1 L	2.582	CO ₂ (41.09%), CO (20.07%), H ₂ (15.48%), CH ₄ (10.56%), C ₂ H ₄ (6.47%), C ₂ H ₆ (2.45%)	[179]
Cathode: LiNi _{0.5} Co _{0.2} Mn _{0.3} O ₂ Anode: graphite	53		103.1 L	1.945	CO ₂ (34.37%), CO (25.65%), H ₂ (16.07%), CH ₄ (17.39%), C ₂ H ₄ (1.17%), C ₂ H ₆ (3.98%)	
Cathode: LiFePO ₄ Anode: graphite	23		15.6 L	0.678	CO ₂ (25.24%), CO (7.39%), H ₂ (1.28%), CH ₄ (6.41%), C ₂ H ₄ (15.2%), C ₂ H ₆ (2.36%)	
Cathode: Li _{0.925} (Ni _{0.80} Co _{0.15} Al _{0.05})O ₂ Anode: graphite	4.42	100	314 mmol	-	CO ₂ (17.5%), CO (44%), H ₂ (26.1%), CH ₄ (8.9%), C ₂ H ₄ (2.7%), C ₂ H ₆ (0.9%)	[180]
Cathode: LiNiMnCoO ₂ /LiMn ₂ O ₄ Anode: graphite	41	100	121.5 L	2.963	CO ₂ (38.33%), CO (16.59%), H ₂ (22.93%), CH ₄ (3.46%), C ₂ H ₄ (5.88%), C ₂ H ₆ (0.99%)	[182]

Table 1. Cont.

Battery Material	Capacity (Ah)	SOC (%)	Overall Gas Generation	Gas Yield per Unit Volume (L Ah ⁻¹)	The Types and Quantities of Gas Produced	Reference
Cathode: LiNi _x Mn _y Co _z O ₂ Anode: graphite	20–81	100	-	1.3–2.5	CO ₂ (36.56%), CO (28.38%), H ₂ (22.27%), CH ₄ (5.26%), C ₂ H ₄ (5.61%), C ₂ H ₆ (0.99%)	[183]
Cathode: Li _x FePO ₄ Anode: carbon family	2.5	135	1643 mL	0.657	CO ₂ (47%), CO (4.9%), H ₂ (30.9%), C ₂ H ₄ (10%), C ₂ H ₅ F (4.6%)	[184]
Cathode: LiNi _{0.8} Co _{0.15} Al _{0.05} O ₂ Anode: -	3.2	100	3078.80 mL	0.962	CO ₂ (20.40%), CO (58.41%), H ₂ (15.94%), CH ₄ (2.50%), C ₂ H ₄ (2.44%), C ₂ H ₆ (0.09%), C ₂ H ₂ (0.22%)	[185]
	3.5	100	5260.90 mL	1.503	CO ₂ (9.76%), CO (37.22%), H ₂ (43.15%), CH ₄ (6.97%), C ₂ H ₄ (2.69%), C ₂ H ₆ (0.06%), C ₂ H ₂ (0.16%)	
Cathode: LiFePO ₄ Anode: graphite	3.8		3790 mL	0.997	CO ₂ (25.39%), CO (4.5%), H ₂ (24.24%), CH ₄ (5.9%), C ₂ H ₄ (3.26%), C ₂ H ₆ (1.29%), C ₂ H ₂ (0.08%)	
Cathode: lithium titanate Anode: graphite	1.3	100	8980 mL	6.908	CO ₂ (37.6%), CO (5.3%), H ₂ (8.41%), CH ₄ (1.23%), C ₂ H ₄ (1.38%), C ₂ H ₆ (0.4%), C ₂ H ₂ (0.0008%)	[186]
Cathode: lithium nickel manganese cobalt Anode: graphite	3.2		11,720 mL	3.663	CO ₂ (13.22%), CO (30.30%), H ₂ (12.39%), CH ₄ (10.50%), C ₂ H ₄ (0.1%), C ₂ H ₆ (0.16%), C ₂ H ₂ (0.0026%)	

To achieve the goal of early gas sensing and monitoring for thermal runaway in LIBs, detecting gases such as CO₂, CH₄, and C₂H₄ can provide useful warning information in certain battery systems. Generally, traditional gas-sensitive materials can be categorized into four types: metal oxide semiconductors (MOS), conductive polymers, carbon-based materials, and 2D materials [187]. Among them, MOS materials are widely used in commercial sensors due to the privileges of convenient fabrication processes, low cost, and excellent stability. However, the high energy consumption and excessive heat generation of these sensors degrade their sensing performance, limiting their applicability in wearable applications such as smartphone or smartwatch safety monitoring systems in human life [188]. Conductive polymer sensors, on the other hand, can operate without external energy input, but they have a critical drawback, for whose sensing performance is extremely susceptible to environmental humidity, deteriorating as humidity increases [189]. Carbon-based materials, known for their high chemical and mechanical stability, as well as excellent electronic properties, are regarded as promising candidates for next-generation gas sensor materials. Nevertheless, their long response/recovery time, high fabrication costs, and limited applications environments still remain significant challenges [190]. 2D materials refer to materials in which electrons are confined to free motion within two dimensions at a non-nanoscale range (1–100 nm). Notable examples include graphene and transition metal dichalcogenides (TMDs), etc., which display potential advantages in gas sensing applications, such as high sensitivity, fast response, and excellent stability [191].

CO₂ is primarily generated during the SEI decomposition stage in the early thermal runaway process. Therefore, MOS has become a research hotspot for early-staged released CO₂ gas sensing materials due to its excellent conductivity, stability, and tunability. The working principle is typically based on the reaction between CO₂ and the surface of metal oxides, which alters the modification of resistance or conductivity of the sensing material [192]. Tanvir et al. [193] reported comprehensive measurements of the work function (using a Kelvin probe) for CuO nanoparticles (CuO-NPs) as a novel CO₂ gas-sensitive material. Under stepwise conditions with CO₂ concentrations ranging from 400 to 4000 ppm, the reversible interaction between CO₂ and the thick CuO-NPs layer induced a work function shift of approximately 42 mV in dry air and ~97 mV under humid conditions (r.h. = 20%) (Figure 5A). Fourier-transform infrared spectroscopy (FT-IR) analysis further demonstrated that the reversible formation of hydroxycarbonates, specifically malachite and aurichalcite, were account for the observed gas sensing effect (Figure 5B). In addition to the p-type semiconductor CuO, several other metal oxides, including ZnO and Co₂O₃, are also of significant interest [194]. For instance, Yu et al. [195] has synthesized polycrystalline NiO nanowires via hydrothermal calcination, which could be used for CO₂ monitoring; however, the response time is relatively long. Kim et al. [196] employed spinel-structured Co₃O₄ as the sensing material to produce a MOS-based CO₂ gas sensor and displayed superior sensing performance. The research team confirmed the formation of metal carbonate species, resulting from the reaction between Co₃O₄ and CO₂, supported by X-ray photoelectron

spectroscopy (XPS) analysis. The majority charge carriers are holes in p-type semiconductors, which hampered the achievement for higher gas response compared to n-type semiconductors, including MOS such as common SnO_2 , ZnO , In_2O_3 , and WO_3 [194]. Bolli et al. [197] reported a room-temperature CO_2 gas sensor based on n-type SnO_2 thin films deposited onto an alumina printed circuit board via electron beam evaporation. The fabricated sensor displayed a sensing response of 7% to 20% exposed to CO_2 concentrations ranging from 1000 to 2000 ppm, and increasing up to 40% at 5000 ppm. Combined with Raman and XPS analysis, it is indicated that the sensing layer was consisted of a 1 μm thick SnO thin film with a non-stoichiometric SnO_2 overlayer, which was co-deposited during the film formation. Therefore, the electron potential disparity between these layers generated a natural SnO - SnO_2 interface, thereby creating a p-n junction that significantly enhanced the sensitivity (Figure 5C). Moreover, Abdulsattar et al. [198] performed a theoretical first-principles calculations on the interactions between pyramid-shaped SnO_2 clusters and both inert and environmental gases. Their findings suggested that, on the basis of Gibbs free energy of the reactions, oxygen deficiency was observed within the clusters, with $\text{Sn}_{10}\text{O}_{16}$ being identified as the most stable configuration. The observed difference in SnO_2 sensitivity between these two gas categories stems principally from variations in their interaction strengths.

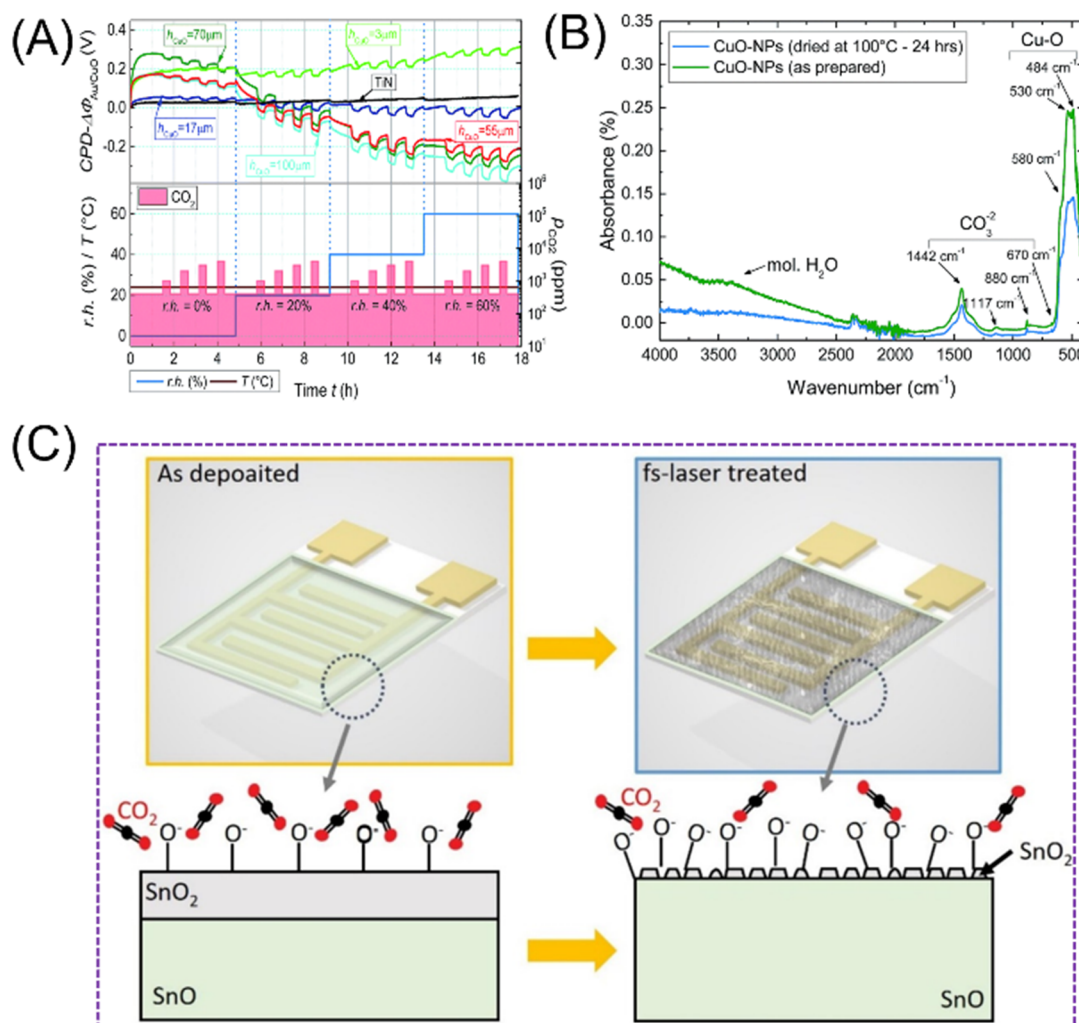


Figure 5. Performance characterization, and sensing enhancement mechanisms of CO_2 gas sensing materials. (A) Variation in the work function of a CuO nanoparticle layer upon exposure to CO_2 concentrations ranging from 400 to 4000 ppm with different r.h. Reproduced from Ref. [193] under the CC BY 4.0 license. (B) FT-IR spectrum of the as-deposited CuO-NPs film in comparison to CuO-NPs dried. Reproduced from Ref. [193] under the CC BY 4.0 license. (C) The gas sensing mechanism without and with the fs-laser treatment. Reproduced from Ref. [197] under the CC BY 4.0 license.

A widely employed strategy to improve the sensitivity and selectivity of gas sensing materials is the fabrication of heterojunctions. This approach is based on the fundamental principles of interactions between different semiconductors, including p-n, p-p, and n-n junctions [199], such as ZnO/CuO [200,201],

PEI/PEG/Ti₃C₂T_x [202], PSI/CuO/Cu₂O [203], NiO/ZnO [204], and others. The Bhowmick's group [201] synthesized a CuO/ZnO bilayer film with a top porous copper oxide layer. The CuO/ZnO film sensor manifested a notable response of 47% to 2500 ppm CO₂ at 375 °C, with its adsorption behavior adhering to the extended Freundlich adsorption model. The CO₂ sensing performance of the CuO/ZnO bilayer film sensor was primarily attributed to the formation of a p-n heterojunction. The corresponding sensing process involved oxygen adsorption, the creation of a space charge layer at the surface and interfaces, and alterations in electron concentration at the junctions, with all of which attributed to the modulation of band bending. Taheripour et al. [205] proposed a star-shaped heterostructure consisting of Ag₂O/BaTiO₃/ZnO to investigate the impact of component ratios on the gas sensing performance of resistive-type sensors. The results indicated that an optimal component ratio facilitates efficient CO₂ detection at a reduced operating temperature of 180 °C, while achieving favorable response and recovery times of 50/9 s. The enhanced sensing performance of Ag₂O/BaTiO₃/ZnO is attributed to several key factors, including the high specific surface area resulting from the star-shaped morphology, the favorable band alignment at the p-n interface, and the catalytic effect of Ag₂O. In addition to constructing heterojunctions, another key strategy to effectively boost the performance of sensors focuses on metallic doping, such as Sb/SnO₂ [206], Ga/ZnO [207], Cu/MoSe₂ [208], In/SnO₂ and Ti/SnO₂ [209]. Panday et al. [206] employed a sol-gel spin-coating technique to deposit Sb-doped SnO₂ films onto glass substrates, subsequently evaluating sensing performance as CO₂ gas sensor, which exhibited a CO₂ gas response of up to 78.57%, with a response factor of 1.78, together with rapid response and recovery times of 2.6 s and 5.8 s, respectively. Liu et al. [210] rationally designed and synthesized La₂O₂CO₃ and La₂O₂CO₃: Eu³⁺ one-dimensional (1D) nanostructures, including nanofibers (NFs), hollow nanofibers (HNFs), and nanobelts (NBs), via electrospinning technique. The CO₂ sensor based on La₂O₂CO₃:Eu³⁺ 1D hollow nanofibers demonstrated excellent selectivity, high response, short response/recovery time, and good reproducibility. The improved gas-sensing properties were attributed to the doping of Eu³⁺ ions and the high surface area of the HNFs.

Besides MOS, the incorporation of conductive polymers, carbon-based materials, 2D materials, and their derivatives, has also been proved to significantly enhance CO₂ gas sensing capabilities. Yagüe et al. [211] conducted an investigation into the fabrication of conductive PPy films using plasma-enhanced chemical vapor deposition (PECVD) technology, and explored their applications in CO₂ sensing. Furthermore, Gupta et al. [212] reported a chemically synthesized rGO film with extensive edged functional groups, which were responsive for facilitated rapid CO₂ gas sensing response at room temperature. Modulating the properties of sensing materials (such as surface properties and electronic structures) can lead to improved high-sensitivity gas sensing. The Kumar's group [213] investigated the influence of surface electronic properties of graphene and MXene on the performance of CO₂ sensors. Experimental results revealed that CO₂ sensors incorporating MXene layers exhibited shorter response and recovery times (12/17 s) compared to their functionalized graphene counterparts (32/43 s). Additionally, the MXene-based sensors demonstrated a 25% response, which was 6% higher than that of the singly compounded functionalized graphene sensors. However, the functionalized graphene sensors showed slightly superior stability. This difference in performance is attributed to the enhanced hydrophilicity and approximately 1.2 times higher conductivity of the MXene surface compared to functionalized graphene. Therefore, there are still efforts have to been made to precisely selected sensing materials and design unique meta-structure to achieve better performance. Karthik et al. [214] synthesized both bulk and exfoliated *g*-C₃N₄ films from powder precursors using the drop-casting method and evaluated their CO₂ sensing performance. The exfoliated samples prepared at the highest achievable temperature, demonstrated superior response ability, including enhanced sensitivity, rapid response/recovery kinetics, and excellent selectivity and stability. As the thermal oxidation temperature increased, the *g*-C₃N₄ surface demonstrated both enhanced specific surface area and elevated free electron density. These modifications promoted oxygen adsorption and consequently improved CO₂ detection performance. The highly exfoliated form of *g*-C₃N₄ displayed considerable potential as a promising material for future CO₂ sensing applications.

Hydrocarbons are mainly generated during the intercalated lithium reaction with the electrolyte and the SEI decomposition stages (Figure 2). Compared to the amount of CO₂ produced during the thermal runaway process in LIBs, hydrocarbons are produced approximately only 1/30 of the quantity. Therefore, this imposes requirements of superior performance on the monitoring of hydrocarbons, especially with lower sensing limitations using gas-sensitive materials. The detection of hydrocarbons is similar to aforementioned methods for CO₂, such as intrinsic MOS-type resistors, construction of heterostructures, and doping etc. (Figure 6). Shehzad et al. [215] reported a method for synthesizing SnO₂ nanowires on a silicon

substrate through a gold-catalyzed carbothermal reduction process, demonstrating excellent CH₄ gas sensing performance, with a response value of 1.20 and response/recovery times of 70/70 s (Figure 6A).

Theoretical and experimental studies both indicate that doping can significantly enhance the gas sensing performance of hydrocarbons. For instance, Joy et al. [216] utilized both density functional theory (DFT) and molecular dynamics (MD) simulations to examine the adsorption and diffusion behaviors of CH₄ molecule in Au doped VO₂. Through the analysis of adsorption energy, charge transfer, density of states (DOS) and radial distribution functions (RDFs), which synergically demonstrated that Au-VO₂ unveiled strong sensing properties for CH₄ molecules. Specifically, RDF displayed V-O bond distance increase from 1.78 Å to 1.9 Å for CH₄, revealing CH₄ lead to relatively higher impact on molecular structure of Au-VO₂. Likewise, Dong et al. [217] also explored the gas-sensing properties of Mo-doped WSe₂ for CH₄ using theoretical simulations, which unveiled that the structure is most stable when Mo atom is placed above the upper Se atoms, with an adsorption energy of -1.194 eV for CH₄ at this configuration. These results demonstrate robust sensing performance while providing fundamental theoretical guidance for designing CH₄-sensitive functional materials. In addition, Qian et al. [218] used DFT first-principle calculations to study the adsorption of C₂H₄ molecules on both intrinsic and Au-doped MoS₂ monolayers, and thoroughly analyzed the adsorption mechanism of MoS₂-based monolayers by considering descriptors such as adsorption energy, bond distance, band gap structure, charge transfer amount, and DOS. The findings exhibited that, in comparison to the intrinsic MoS₂ monolayer, the C₂H₄ molecule manifested a higher adsorption energy on the Au-doped MoS₂ monolayer (Figure 6B, left up panel), along with a more stable adsorption configuration, which displayed a shorter Au-C bond distance (Figure 6B, right up panel). Moreover, the increased charge transfer of 0.309|e⁻|, together with stronger orbital hybridization of Au-5d, C-2p, and H-1s orbitals further confirmed the C₂H₄ gas sensing mechanism (Figure 6B). Additionally, Wang et al. [219] investigated the CH₄ gas sensing properties of Pd/In₂O₃ composites synthesized via a simple thermal solution method. Compared to pure In₂O₃, the 6.0% Pd/In₂O₃ microspheres exhibited obviously enhanced gas sensing performance toward CH₄, with the response to 500 ppm CH₄ at 50 °C reached 15.317. The enhanced gas sensing performance can primarily be attributed to the chemical catalytic and spillover effects of the palladium nanoparticles, as well as the Schottky barrier formed between Pd and In₂O₃. Li et al. [220] developed self-assembled Ag-Ru-doped ZnO nanorod arrays using a one-step hydrothermal method. The optimized AgRu_{0.0025}-ZnO nanorod array demonstrated exceptional CH₄ sensing performance, with a detection limit as low as 2.24 ppm under both thermal-free and optical-free conditions, meeting the requirements for thermal runaway detection in LIBs. Theoretical calculations suggested that the introduction of oxygen vacancies and local ionic defects into the ZnO lattice induced by heteroatoms doping, which promoted charge density accumulation at the Ru sites, resulting in the formation of a strong local electric field that significantly enhanced the gas-sensing performance (Figure 6C). Leangtanom et al. [221] synthesized CeO_x-SnO₂ nanocomposites with different Ce:Sn ratios using a double-reagent coprecipitation method. The addition of CeO_x to SnO₂ significantly enhanced the C₂H₄ response. The CeO_x-SnO₂ nanocomposite (Ce:Sn = 33:67) exhibited a response of 5.18 to 10 ppm C₂H₄ at 350 °C, with a response time of 12 s. Furthermore, the detection limitation for ethylene was as low as 0.3 ppm.

During the initial stage of thermal runaway in LIBs, the temperature typically ranges around 100 °C, whereas most MOS-based gas sensors exhibit optimal sensitivity at elevated temperatures (approximately 200 °C). Therefore, it is a critical need to develop gas-sensitive materials that can detect hydrocarbon compounds with high sensitivity at lower operating temperatures. To emphasize, Shaalan et al. [222] synthesized a novel one-dimensional nanostructure of CuO-doped In₂O₃ through the co-evaporation of Cu and in metal particles. The resulting sensor, based on as-synthesized CuO-doped In₂O₃, displayed exceptional sensing performance at relatively lower temperature 50 °C, with response and recovery time of 61.0 s and 25 s, respectively (Figure 6D), which indicated practical applications in early-staged safety monitoring. In recent years, carbon materials have attracted progressive attention for their prospective applications in room-temperature sensing of methane and other hydrocarbon compounds, due to their high specific surface area, good conductivity, and favorable electronic properties. Afrin et al. [223] demonstrated the usage of thiol-functionalized CNT-based pressure-reduced paper as a room-temperature sensor for CH₄ detection. The thiolated CNT pressure-reduced paper exhibited high sensitivity (2.08%) to 400 ppm CH₄. The sensing mechanism is attributed to the interaction between CH₄ and functionalized nanotubes, which withdraws electrons from the CNTs. This increases hole carriers in the semiconducting CNTs, causing the Fermi level to shift downward or closer to the valence band. Conductive polymers are also considered as candidates for detecting hydrocarbon compounds. To note, Aldalbahi et al. [224] synthesized both functionalized and non-functionalized MWCNTs hybridized with PANI and polymers

(PANI/polymer/MWCNTs and PANI/polymer/MWCNTs-COOH) polymer-based conductive nanomaterials. The sensing performance demonstrated that both types of conductive nanocomposites displayed excellent sensing ability for CH₄ at room temperature, with response and recovery times around 5 s. Compared to the PANI/polymer/MWCNTs-COOH-based sensor, device fabricated with the MWCNTs without oxygen-containing functional groups exhibited faster/shorter response times (<1 s) and higher sensitivity (3.1%), which is assigned to the non-conductive -COOH groups in PANI/polymer/MWCNTs-COOH leading to lower sensitivity of the sensor.

The research on methane (CH₄) and ethylene (C₂H₄) sensing materials is rapidly progressing in aim for higher sensitivity, selectivity, and stability. Despite significant progress in methane and ethylene detection technologies, practical applications-particularly in early warning systems for LIBs thermal runaway have been made, the demands for sensors with exceptionally high sensitivity and selectivity are still critical. While semiconductor- and nanomaterial-based sensors have achieved significant breakthroughs in sensitivity and response time, cross-sensitivity to interfering gases persists as a critical challenge. Despite persistent technical challenges, the application prospects for LIBs safety monitoring remain highly promising, driven by the continuous emergence of novel materials and advanced technologies.

Table 2 summarizes the performance of representative temperature, pressure, and gas sensors discussed in this review, including measurement ranges or detection limits, test temperatures, sensitivities or responses, response and recovery times, and stability assessments. Units are presented consistently where applicable, while the original definitions of sensitivity and response are retained because the sensing principles differ across modalities. The comparison should therefore be interpreted together with the reported test conditions rather than as a direct ranking of sensor performance. In particular, the operating temperature of a gas sensor should be distinguished from the battery temperature, and performance measured under laboratory conditions does not by itself establish the warning capability in a battery system.

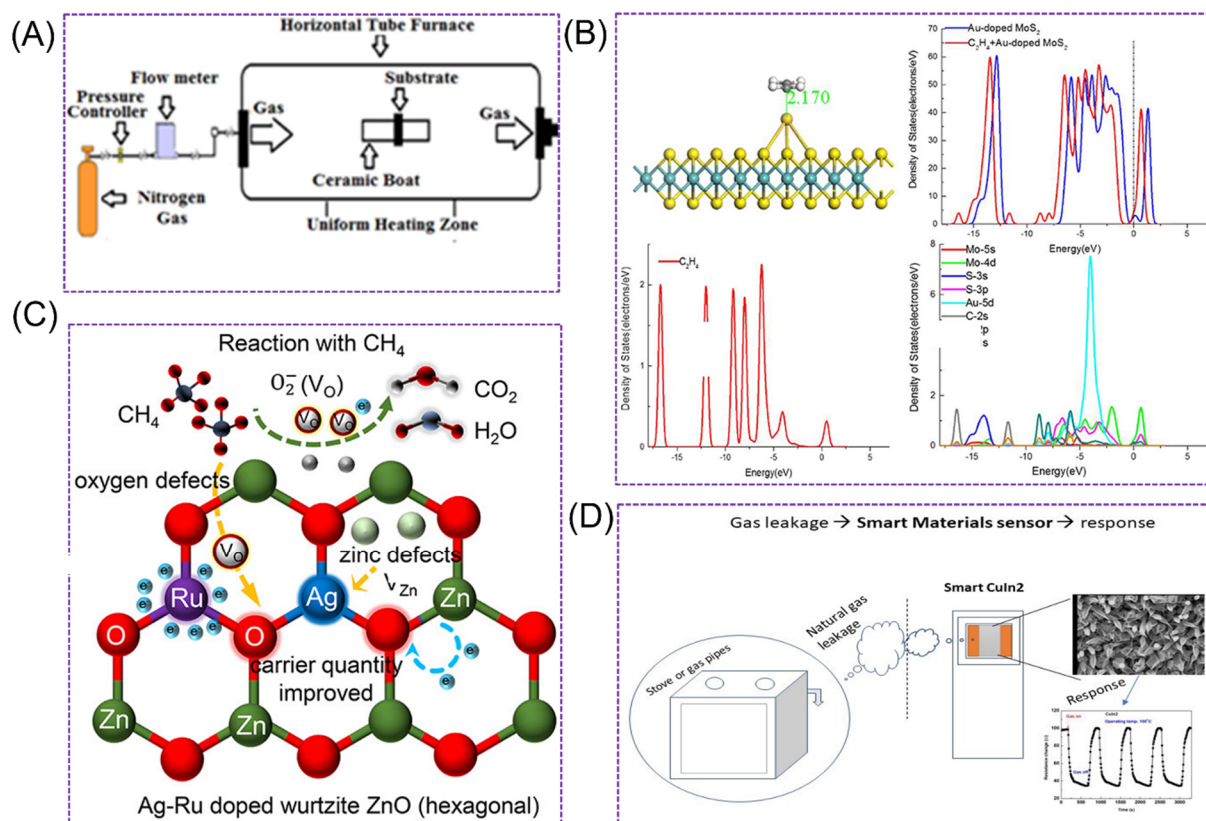


Figure 6. Theoretical and experimental studies on hydrocarbons gas sensing materials. **(A)** The diagram of the experimental layout. Reproduced from Ref. [215] under the CC BY 4.0 license. **(B)** The stable structures, DOS and partial density of states (PDOS) of C₂H₄ on the MoS₂ monolayer and the DOS of C₂H₄ molecular. Reproduced from Ref. [218] under the CC BY 4.0 license. **(C)** Schematic representation of the methane detection mechanism by defective ZnO. Reprinted with permission from Ref. [220]. Copyright © 2024, American Chemical Society. **(D)** The preparation and performance of sensors based on CuO-doped In₂O₃. Reproduced from Ref. [222] under the CC BY 4.0 license.

Table 2. Comparison of representative temperature, pressure, and gas sensors discussed in this review.

Sensing Modality	Active Material	Measurement Range, Detection Limit, or Test Concentration	Operating Temperature	Reported Sensitivity or Response	Response/ Recovery Time	Reference
Temperature	NiO/CNTF	−15 to 60 °C	−15 to 60 °C	TCR: −20.2% °C ^{−1}	-	[104]
	Pt/In ₂ O ₃	-	-	204.35 μV °C ^{−1}	-	[131]
Pressure	BaTiO ₃ /MXene/PVDF-TrFE	0.2–400 kPa	-	-	56 ms/-	[156]
	PPy/PDA/PVDF	Detection limit: 0.9 Pa	-	139.9 kPa ^{−1}	22 ms/-	[178]
Gas: CO ₂	CuO nanoparticles	400–4000 ppm	Room temperature	42 mV at 0% RH; 97 mV at 20% RH	-	[193]
	Ag ₂ O/BaTiO ₃ /ZnO	-	180 °C	-	50 s/9 s	[205]
Gas: CH ₄	Pd/In ₂ O ₃	Test concentration: 500 ppm; detection limit: 1.78 ppm	50 °C	Response: 15.317	-	[219]
	CeO _x -SnO ₂	0.3–10 ppm	350 °C	Response: 5.18	12 s/-	[221]

4. Summary and Prospect

4.1. Summary

To encapsulate, this review summarizes the mechanisms of thermal runaway in LIBs and elaborates on the fundamental principles of early-stage thermal runaway monitoring. Subsequently, based on the consequence and features of LIBs after thermal runaway, such as severe heat release (90–100 °C) and accompanied temperature/internal pressure increase and thermal/gas emission, the research progress on temperature sensors, pressure sensors, and gas sensors for LIBs safety monitoring is discussed in detail. To achieve early thermal runaway detection, corresponding countermeasures must be developed based on the physicochemical changes occurring in the early stages of thermal runaway in lithium batteries, for example, hydrocarbon compounds and CO₂ gases, rather than CO and H₂ that are produced at higher temperatures, should be selectively detected with high sensitivity. Therefore, we summarized the state-of-the-art corresponding high-performance sensors to monitor the battery's operational status.

While various types of sensors categorized by the response to different physicochemical changes can achieve monitoring objectives, the materials and systems used in these sensors are similar. For example, carbon-based materials can serve both as temperature sensors and gas-sensitive materials, although the sensing principles are different. In the case of gas sensors, whose performance can be effectively enhanced through strategies such as doping, heterojunctions constructing, and modulating the electronic structure of materials. On the other hand, as for temperature sensors, combining metals and carbon-based materials to leverage their individual sensing advantages can synergistically improve thermal sensing performance. While enhancing the conductivity of sensing materials, such as by adding conductive polymers, can improve the response performance of pressure sensors. However, the current sensing techniques and industry are still in the developmental stage. Many novel sensing materials, such as those based on nanotechnology, high-sensitivity temperature sensors, and gas sensors, are gradually being applied in the field of LIBs safety monitoring. With the continuous advancement of these technologies, the application of sensor materials in LIBs safety monitoring will become more precise, real-time, and reliable, and may potentially lead to more efficient and cost-effective solutions in the future. Further progress requires coordinated advances in sensing materials, BMS integration, packaging, and validated multi-signal fusion, with particular attention to false alarms and the medium-dependent interpretation of acidity signals.

4.2. Prospect

The growing demands for batteries have necessitated the insurance of their safety to prevent potential harm to human lives and damages to property. In the future, sensors will likely be widely integrated into battery systems to guide proper function. Despite extensive research into various sensor types for monitoring thermal runaway in LIBs, several problems remain unresolved.

- **High accuracy:** The existing pressure sensors, temperature sensors, gas sensors and other similar devices still engage with a range of issues, including insufficient detection accuracy, susceptibility to external interference, inadequate stability, and a need for improved heat resistance. Thus, further research and development of both sensing materials and structures of novel-designed sensors are required.
- **Engineering compatibility:** Practical deployment requires compatibility with BMSs, including signal conditioning, communication interfaces, electrical isolation, and acceptable power consumption.

Sensor packaging should withstand electrolyte vapors, vibration, and thermal cycling without compromising thermal contact, gas access, or cell venting. Protective layers and sensor placement may introduce response delays and should therefore be evaluated within the actual battery configuration. Calibration must account for long-term drift and distinguish failure signatures from normal charging-induced heating, electrode swelling, and environmental interference. Validation under both normal operation and abuse conditions is needed to quantify false alarms and missed detections, alongside sensitivity and response time.

- Integrated monitoring and signal fusion: Combining temperature, pressure or strain, gas, and electrical measurements may improve early warning by capturing complementary failure signatures. Fusion should consider signal magnitude, rates of change, and temporal correlations against baselines appropriate to the operating state. Differences in thermal response and gas-transport time must be accounted for, rather than requiring all signals to exceed thresholds simultaneously. Lightweight, interpretable algorithms are preferable for implementation within BMS hardware constraints. Their benefits should be assessed against single-signal methods across different cell chemistries, states of charge, aging conditions, and abuse modes. Warning lead time, false-alarm frequency, missed-detection rate, and processing latency should be reported to establish practical effectiveness.
- Novel sensing technology: Acidity-sensitive devices warrant exploration, but their applicability depends on the sensing medium. Aqueous-buffer calibration cannot be directly extrapolated to nonaqueous battery electrolytes, where proton activity and sensor response require medium-specific interpretation and calibration. For external aqueous or hydrated sensing layers, the measured response reflects the absorption and reaction of released species rather than the intrinsic acidity of the electrolyte. Gas transport, humidity, buffering, and interference from CO₂ or other acidifying species can affect response timing and specificity. Such devices should therefore be regarded as indirect, supplementary indicators of acidic products. Their warning capability requires battery-relevant validation of selectivity, response latency, and stability.
- Resettable and durable warning devices: Resettable sensing materials may support repeated monitoring after non-destructive abnormal excursions or after an early warning has enabled timely intervention. Once full thermal runaway has occurred, however, the cell should be regarded as irreversibly damaged and unsafe for reuse. Accordingly, future work should separately evaluate sensor resetability under reversible precursor conditions and sensor survivability under severe abuse, without conflating either property with recovery of the battery. Early-warning sensors should be considered alongside strategies for improving battery safety.
- Complementary safety strategies: Early-warning monitoring should be complemented by protective electrode and electrolyte designs. Recent studies on poly(3-alkylthiophene)-based temperature-responsive electrodes demonstrate that molecular and side-chain engineering can enhance positive temperature coefficient effects, enabling increased electrical resistance during overheating and providing a route to limiting current flow [225,226]. Electrolyte design offers another approach to reducing fire hazards. Recent progress in non-flammable electrolytes for sodium-ion batteries provides useful perspectives on electrolyte-level safety strategies, although their applicability to lithium-based systems requires separate validation [227]. Combining sensing technologies with these protective designs warrants further investigation, with particular attention to electrochemical compatibility, protective response thresholds, and long-term stability under realistic operating conditions.
- Sensor integration and safety: A battery-integrated sensor must remain chemically and electrically benign throughout the service life of the cell. Encapsulation and feedthrough design should prevent electrolyte leakage, parasitic reactions, and unintended current paths, while the sensor should add minimal thermal mass and mechanical constraint. Long-term drift under cycling and storage must also be quantified. For heated chemiresistive sensors, heater power, local surface temperature, and ignition risk should be considered explicitly when selecting the installation location.

Author Contributions

Q.Z.: Conceptualization, methodology, data curation, writing—original draft preparation, visualization; S.W.: Conceptualization, methodology, data curation, writing—original draft preparation, visualization; H.L.: Conceptualization, methodology, data curation, writing—original draft preparation, visualization; Y.Z.: Conceptualization, methodology, supervision, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This work was partly supported by National Key Research and Development Project of China (2020YFA0710304), National Natural Science Foundation (22136002, U24A20540).

Data Availability Statement

The data are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest. Given the role as Editor-in-Chief, Yongfa Zhu had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. Allen, M.R.; Frame, D.J.; Friedlingstein, P.; et al. Geological Net Zero and the need for disaggregated accounting for carbon sinks. *Nature* **2025**, *638*, 343–350. <https://doi.org/10.1038/s41586-024-08326-8>.
2. Foster, V.; Trotter, P.A.; Werner, S.; et al. Development transitions for fossil fuel-producing low and lower-middle income countries in a carbon-constrained world. *Nat. Energy* **2024**, *9*, 242–250. <https://doi.org/10.1038/s41560-023-01440-3>.
3. Fuso Nerini, F.; Tomei, J.; To, L.S.; et al. Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nat. Energy* **2018**, *3*, 10–15. <https://doi.org/10.1038/s41560-017-0036-5>.
4. Wang, F.; Harindintwali, J.D.; Yuan, Z.; et al. Technologies and perspectives for achieving carbon neutrality. *Innovation* **2021**, *2*, 100180. <https://doi.org/10.1016/j.xinn.2021.100180>.
5. Meckling, J.; Galeazzi, C.; Shears, E.; et al. Energy innovation funding and institutions in major economies. *Nat. Energy* **2022**, *7*, 876–885. <https://doi.org/10.1038/s41560-022-01117-3>.
6. Yao, Z.; Lum, Y.; Johnston, A.; et al. Machine learning for a sustainable energy future. *Nat. Rev. Mater.* **2023**, *8*, 202–215. <https://doi.org/10.1038/s41578-022-00490-5>.
7. Lu, Y.; Chen, J. Prospects of organic electrode materials for practical lithium batteries. *Nat. Rev. Chem.* **2020**, *4*, 127–142. <https://doi.org/10.1038/s41570-020-0160-9>.
8. Goodenough, J.B. How we made the Li-ion rechargeable battery. *Nat. Electron.* **2018**, *1*, 204. <https://doi.org/10.1038/s41928-018-0048-6>.
9. Wang, F.; Borodin, O.; Gao, T.; et al. Highly reversible zinc metal anode for aqueous batteries. *Nat. Mater.* **2018**, *17*, 543–549. <https://doi.org/10.1038/s41563-018-0063-z>.
10. Dai, Y.; Lu, R.; Zhang, C.; et al. Zn²⁺-mediated catalysis for fast-charging aqueous Zn-ion batteries. *Nat. Catal.* **2024**, *7*, 776–784. <https://doi.org/10.1038/s41929-024-01169-6>.
11. Wei, J.; Zhang, P.; Sun, J.; et al. Advanced electrolytes for high-performance aqueous zinc-ion batteries. *Chem. Soc. Rev.* **2024**, *53*, 10335–10369. <https://doi.org/10.1039/d4cs00584h>.
12. Jin, T.; Ji, X.; Wang, P.F.; et al. High-Energy Aqueous Sodium-Ion Batteries. *Angew. Chem. Int. Ed.* **2021**, *60*, 11943–11948. <https://doi.org/10.1002/anie.202017167>.
13. Rudola, A.; Sayers, R.; Wright, C.J.; et al. Opportunities for moderate-range electric vehicles using sustainable sodium-ion batteries. *Nat. Energy* **2023**, *8*, 215–218. <https://doi.org/10.1038/s41560-023-01215-w>.
14. Wan, Y.; Huang, B.; Liu, W.; et al. Fast-Charging Anode Materials for Sodium-Ion Batteries. *Adv. Mater.* **2024**, *36*, 2404574. <https://doi.org/10.1002/adma.202404574>.
15. Xiao, J.; Li, Q.; Bi, Y.; et al. Understanding and applying coulombic efficiency in lithium metal batteries. *Nat. Energy* **2020**, *5*, 561–568. <https://doi.org/10.1038/s41560-020-0648-z>.
16. Gao, X.; Zhou, Y.N.; Han, D.; et al. Thermodynamic Understanding of Li-Dendrite Formation. *Joule* **2020**, *4*, 1864–1879. <https://doi.org/10.1016/j.joule.2020.06.016>.
17. Niu, C.; Liu, D.; Lochala, J.A.; et al. Balancing interfacial reactions to achieve long cycle life in high-energy lithium metal batteries. *Nat. Energy* **2021**, *6*, 723–732. <https://doi.org/10.1038/s41560-021-00852-3>.
18. IEA. *Global EV Outlook 2024*; International Energy Agency: Paris, France, 2024.
19. Cheng, X.B.; Zhang, R.; Zhao, C.Z.; et al. Toward Safe Lithium Metal Anode in Rechargeable Batteries: A Review. *Chem. Rev.* **2017**, *117*, 10403–10473. <https://doi.org/10.1021/acs.chemrev.7b00115>.

20. Zhang, W.; Liu, Y.; Guo, Z. Approaching high-performance potassium-ion batteries via advanced design strategies and engineering. *Sci. Adv.* **2019**, *5*, eaav7412. <https://doi.org/10.1126/sciadv.aav7412>.
21. Tian, Y.; Zeng, G.; Rutt, A.; et al. Promises and Challenges of Next-Generation “Beyond Li-ion” Batteries for Electric Vehicles and Grid Decarbonization. *Chem. Rev.* **2021**, *121*, 1623–1669. <https://doi.org/10.1021/acs.chemrev.0c00767>.
22. Liao, Z.; Zhang, S.; Li, K.; et al. A survey of methods for monitoring and detecting thermal runaway of lithium-ion batteries. *J. Power Sources* **2019**, *436*, 226879. <https://doi.org/10.1016/j.jpowsour.2019.226879>.
23. Wang, Q.; Ping, P.; Zhao, X.; et al. Thermal runaway caused fire and explosion of lithium ion battery. *J. Power Sources* **2012**, *208*, 210–224. <https://doi.org/10.1016/j.jpowsour.2012.02.038>.
24. Hou, J.; Lu, L.; Wang, L.; et al. Thermal runaway of Lithium-ion batteries employing LiN(SO₂F)₂-based concentrated electrolytes. *Nat. Commun.* **2020**, *11*, 5100. <https://doi.org/10.1038/s41467-020-18868-w>.
25. Galushkin, N.E.; Yazvinskaya, N.N.; Galushkin, D.N. Mechanism of Thermal Runaway in Lithium-Ion Cells. *J. Electrochem. Soc.* **2018**, *165*, A1303–A1308. <https://doi.org/10.1149/2.0611807jes>.
26. Liu, X.; Ren, D.; Hsu, H.; et al. Thermal Runaway of Lithium-Ion Batteries without Internal Short Circuit. *Joule* **2018**, *2*, 2047–2064. <https://doi.org/10.1016/j.joule.2018.06.015>.
27. Feng, X.; Ren, D.; He, X.; et al. Mitigating Thermal Runaway of Lithium-Ion Batteries. *Joule* **2020**, *4*, 743–770. <https://doi.org/10.1016/j.joule.2020.02.010>.
28. Liu, C.; Dai, H.; Wang, D.; et al. Review—Understanding Thermal Runaway in Lithium-Ion Batteries: Trigger, Mechanism, and Early Warning Strategies. *J. Electrochem. Soc.* **2024**, *171*, 120527. <https://doi.org/10.1149/1945-7111/ad9b9d>.
29. Duh, Y.S.; Sun, Y.; Lin, X.; et al. Characterization on thermal runaway of commercial 18650 lithium-ion batteries used in electric vehicles: A review. *J. Energy Storage* **2021**, *41*, 102888. <https://doi.org/10.1016/j.est.2021.102888>.
30. Pan, J.; Chu, J.; Zhang, L.; et al. Bi₂O₃ Nanosheets for Early Warning Thermal Runaway of Lithium Battery. *Adv. Funct. Mater.* **2024**, *34*, 2407408. <https://doi.org/10.1002/adfm.202407408>.
31. Shao, X.; Zhang, D.; Tang, M.; et al. Amorphous Ag catalytic layer-SnO₂ sensitive layer-graphite carbon nitride electron supply layer synergy-enhanced hydrogen gas sensor. *Chem. Eng. J.* **2024**, *495*, 153676. <https://doi.org/10.1016/j.cej.2024.153676>.
32. Parekh, M.H.; Li, B.; Palanisamy, M.; et al. In Situ Thermal Runaway Detection in Lithium-Ion Batteries with an Integrated Internal Sensor. *ACS Appl. Energy Mater.* **2020**, *3*, 7997–8008. <https://doi.org/10.1021/acsaem.0c01392>.
33. Santos-Carballal, D.; Lupan, O.; Magariu, N.; et al. Al₂O₃/ZnO composite-based sensors for battery safety applications: An experimental and theoretical investigation. *Nano Energy* **2023**, *109*, 108301. <https://doi.org/10.1016/j.nanoen.2023.108301>.
34. Wang, J.; Feng, X.; Yu, Y.; et al. Rapid temperature-responsive thermal regulator for safety management of battery modules. *Nat. Energy* **2024**, *9*, 939–946. <https://doi.org/10.1038/s41560-024-01535-5>.
35. Bang, J.; Chun, B.; Kim, M.; et al. Rapid thermal runaway detection of lithium-ion battery via swelling-based state-of-charge monitoring using piezoresistive sponge sensor. *eTransportation* **2025**, *24*, 100404. <https://doi.org/10.1016/j.etrans.2025.100404>.
36. Daniels, R.K.; Kumar, V.; Chouhan, S.S.; et al. Thermal runaway fault prediction in air-cooled lithium-ion battery modules using machine learning through temperature sensors placement optimization. *Appl. Energy* **2024**, *355*, 122352. <https://doi.org/10.1016/j.apenergy.2023.122352>.
37. Isaac, N.A.; Pikaar, I.; Biskos, G. Metal oxide semiconducting nanomaterials for air quality gas sensors: Operating principles, performance, and synthesis techniques. *Microchim. Acta* **2022**, *189*, 196. <https://doi.org/10.1007/s00604-022-05254-0>.
38. Tan, C.; Dong, Z.; Li, Y.; et al. A high performance wearable strain sensor with advanced thermal management for motion monitoring. *Nat. Commun.* **2020**, *11*, 3530. <https://doi.org/10.1038/s41467-020-17301-6>.
39. Mei, W.; Liu, Z.; Wang, C.; et al. Operando monitoring of thermal runaway in commercial lithium-ion cells via advanced lab-on-fiber technologies. *Nat. Commun.* **2023**, *14*, 5251. <https://doi.org/10.1038/s41467-023-40995-3>.
40. Yin, S.; Liu, J.; Cong, B. Review of Thermal Runaway Monitoring, Warning and Protection Technologies for Lithium-Ion Batteries. *Processes* **2023**, *11*, 2345. <https://doi.org/10.3390/pr11082345>.
41. Wang, K.; Ouyang, D.; Qian, X.; et al. Early Warning Method and Fire Extinguishing Technology of Lithium-Ion Battery Thermal Runaway: A Review. *Energies* **2023**, *16*, 2960. <https://doi.org/10.3390/en16072960>.
42. Kong, D.; Lv, H.; Ping, P.; et al. A review of early warning methods of thermal runaway of lithium ion batteries. *J. Energy Storage* **2023**, *64*, 107073. <https://doi.org/10.1016/j.est.2023.107073>.
43. Li, Y.; Jiang, L.; Zhang, N.; et al. Early warning method for thermal runaway of lithium-ion batteries under thermal abuse condition based on online electrochemical impedance monitoring. *J. Energy Chem.* **2024**, *92*, 74–86. <https://doi.org/10.1016/j.jechem.2023.12.049>.

44. Börger, A.; Mertens, J.; Wenzl, H. Thermal runaway and thermal runaway propagation in batteries: What do we talk about? *J. Energy Storage* **2019**, *24*, 100649. <https://doi.org/10.1016/j.est.2019.01.012>.
45. Zheng, J.; Kim, M.S.; Tu, Z.; et al. Regulating electrodeposition morphology of lithium: Towards commercially relevant secondary Li metal batteries. *Chem. Soc. Rev.* **2020**, *49*, 2701–2750. <https://doi.org/10.1039/c9cs00883g>.
46. Wang, Y.W.; Shu, C.M. Energy generation mechanisms for a Li-ion cell in case of thermal explosion: A review. *J. Energy Storage* **2022**, *55*, 105501. <https://doi.org/10.1016/j.est.2022.105501>.
47. Feng, X.; Ouyang, M.; Liu, X.; et al. Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. *Energy Storage Mater.* **2018**, *10*, 246–267. <https://doi.org/10.1016/j.ensm.2017.05.013>.
48. Tran, M.K.; Mevawalla, A.; Aziz, A.; et al. A Review of Lithium-Ion Battery Thermal Runaway Modeling and Diagnosis Approaches. *Processes* **2022**, *10*, 1192. <https://doi.org/10.3390/pr10061192>.
49. Das Goswami, B.R.; Abdissobbouhi, Y.; Du, H.; et al. Advancing battery safety: Integrating multiphysics and machine learning for thermal runaway prediction in lithium-ion battery module. *J. Power Sources* **2024**, *614*, 235015. <https://doi.org/10.1016/j.jpowsour.2024.235015>.
50. Le, P.A.; Vuong, D.T.; Natsuki, J.; et al. Overview of the Thermal Runaway in Lithium-Ion Batteries with Application in Electric Vehicles: Working Principles, Early Warning, and Future Outlooks. *Energy Fuels* **2023**, *37*, 17052–17074. <https://doi.org/10.1021/acs.energyfuels.3c02548>.
51. Peng, J.; Zhao, X.; Ma, J.; et al. Enhancing lithium-ion battery monitoring: A critical review of diverse sensing approaches. *eTransportation* **2024**, *22*, 100360. <https://doi.org/10.1016/j.etrans.2024.100360>.
52. Yu, K.; Chen, W.; Deng, D.; et al. Advancements in Battery Monitoring: Harnessing Fiber Grating Sensors for Enhanced Performance and Reliability. *Sensors* **2024**, *24*, 2057. <https://doi.org/10.3390/s24072057>.
53. Wei, Z.; Zhao, J.; He, H.; et al. Future smart battery and management: Advanced sensing from external to embedded multi-dimensional measurement. *J. Power Sources* **2021**, *489*, 229462. <https://doi.org/10.1016/j.jpowsour.2021.229462>.
54. Kaliaperumal, M.; Dharanendrakumar, M.S.; Prasanna, S.; et al. Cause and Mitigation of Lithium-Ion Battery Failure—A Review. *Materials* **2021**, *14*, 5676. <https://doi.org/10.3390/ma14195676>.
55. Naguib, M.; Allu, S.; Simunovic, S.; et al. Limiting Internal Short-Circuit Damage by Electrode Partition for Impact-Tolerant Li-Ion Batteries. *Joule* **2018**, *2*, 155–167. <https://doi.org/10.1016/j.joule.2017.11.003>.
56. Ren, D.; Feng, X.; Lu, L.; et al. Overcharge behaviors and failure mechanism of lithium-ion batteries under different test conditions. *Appl. Energy* **2019**, *250*, 323–332. <https://doi.org/10.1016/j.apenergy.2019.05.015>.
57. Nie, B.; Dong, Y.; Chang, L. The evolution of thermal runaway parameters of lithium-ion batteries under different abuse conditions: A review. *J. Energy Storage* **2024**, *96*, 112624. <https://doi.org/10.1016/j.est.2024.112624>.
58. Zhao, J.; Feng, X.; Tran, M.K.; et al. Battery safety: Fault diagnosis from laboratory to real world. *J. Power Sources* **2024**, *598*, 234111. <https://doi.org/10.1016/j.jpowsour.2024.234111>.
59. Lai, T.; Zhao, H.; Song, Y.; et al. Mechanism and Control Strategies of Lithium-Ion Battery Safety: A Review. *Small Methods* **2025**, *9*, 2400029. <https://doi.org/10.1002/smt.202400029>.
60. Ma, X.; Lu, Y.; Ou, Y.; et al. Strategies for flame-retardant polymer electrolytes for safe lithium-based batteries. *Nano Res.* **2024**, *17*, 8754–8771. <https://doi.org/10.1007/s12274-024-6902-4>.
61. Xu, K. Electrolytes and Interphases in Li-Ion Batteries and Beyond. *Chem. Rev.* **2014**, *114*, 11503–11618. <https://doi.org/10.1021/cr500003w>.
62. Gao, X.; Chak, C.; Hao, Q.; et al. Thermal Safety of Lithium-Ion Batteries: Mechanism, Modeling, and Characterizations. *Annu. Rev. Heat Transf.* **2023**, *26*, 69–129. <https://doi.org/10.1615/annualrevheattransfer.2023048695>.
63. Rong, D.; Zhang, G.; Sun, Q.; et al. Experimental study on gas production characteristics of electrolyte of lithium-ion battery under pyrolysis conditions. *J. Energy Storage* **2023**, *74*, 109367. <https://doi.org/10.1016/j.est.2023.109367>.
64. Sannagowdar, A.D.; Nataraj, S.K. Environmental Impact, Safety Aspects, and Recycling Technologies of Lithium-Ion Batteries. In *Nanostructured Materials for Energy Storage*; Wiley: Weinheim, Germany, 2024; pp. 763–792. <https://doi.org/10.1002/9783527838851.ch21>.
65. Yang, Y.; Wang, R.; Shen, Z.; et al. Towards a safer lithium-ion batteries: A critical review on cause, characteristics, warning and disposal strategy for thermal runaway. *Adv. Appl. Energy* **2023**, *11*, 100146. <https://doi.org/10.1016/j.adapen.2023.100146>.
66. Chen, S.; Gao, Z.; Sun, T. Safety challenges and safety measures of Li-ion batteries. *Energy Sci. Eng.* **2021**, *9*, 1647–1672. <https://doi.org/10.1002/ese3.895>.
67. Ma, S.; Jiang, M.; Tao, P.; et al. Temperature effect and thermal impact in lithium-ion batteries: A review. *Prog. Nat. Sci. Mater. Int.* **2018**, *28*, 653–666. <https://doi.org/10.1016/j.pnsc.2018.11.002>.
68. Kantharaj, R.; Marconnet, A.M. Heat Generation and Thermal Transport in Lithium-Ion Batteries: A Scale-Bridging Perspective. *Nanoscale Microscale Thermophys. Eng.* **2019**, *23*, 128–156. <https://doi.org/10.1080/15567265.2019.1572679>.

69. Choudhari, V.G.; Dhoble, D.A.S.; Sathe, T.M. A review on effect of heat generation and various thermal management systems for lithium ion battery used for electric vehicle. *J. Energy Storage* **2020**, *32*, 101729. <https://doi.org/10.1016/j.est.2020.101729>.
70. Ren, D.; Feng, X.; Lu, L.; et al. An electrochemical-thermal coupled overcharge-to-thermal-runaway model for lithium ion battery. *J. Power Sources* **2017**, *364*, 328–340. <https://doi.org/10.1016/j.jpowsour.2017.08.035>.
71. Liu, G.; Ouyang, M.; Lu, L.; et al. Analysis of the heat generation of lithium-ion battery during charging and discharging considering different influencing factors. *J. Therm. Anal. Calorim.* **2014**, *116*, 1001–1010. <https://doi.org/10.1007/s10973-013-3599-9>.
72. Song, L.; Zheng, Y.; Xiao, Z.; et al. Review on Thermal Runaway of Lithium-Ion Batteries for Electric Vehicles. *J. Electron. Mater.* **2022**, *51*, 30–46. <https://doi.org/10.1007/s11664-021-09281-0>.
73. Sato, N. Thermal behavior analysis of lithium-ion batteries for electric and hybrid vehicles. *J. Power Sources* **2001**, *99*, 70–77. [https://doi.org/10.1016/s0378-7753\(01\)00478-5](https://doi.org/10.1016/s0378-7753(01)00478-5).
74. An, Z.; Shah, K.; Jia, L.; et al. Modeling and analysis of thermal runaway in Li-ion cell. *Appl. Therm. Eng.* **2019**, *160*, 113960. <https://doi.org/10.1016/j.applthermaleng.2019.113960>.
75. Lei, D.; Wang, Y.; Shi, J.; et al. Investigation on heat generation in fast charging of lithium-ion batteries: Effect of charging rate and battery component thickness. *Numer. Heat Transf. Part A Appl.* **2026**, *87*, 2372698. <https://doi.org/10.1080/10407782.2024.2372698>.
76. Bernardi, D.; Pawlikowski, E.; Newman, J. A General Energy Balance for Battery Systems. *J. Electrochem. Soc.* **1985**, *132*, 5–12. <https://doi.org/10.1149/1.2113792>.
77. Bahiraei, F.; Ghalkhani, M.; Fartaj, A.; et al. A pseudo 3D electrochemical-thermal modeling and analysis of a lithium-ion battery for electric vehicle thermal management applications. *Appl. Therm. Eng.* **2017**, *125*, 904–918. <https://doi.org/10.1016/j.applthermaleng.2017.07.060>.
78. Newman, J.; Tiedemann, W. Temperature Rise in a Battery Module with Constant Heat Generation. *J. Electrochem. Soc.* **1995**, *142*, 1054–1057. <https://doi.org/10.1149/1.2044130>.
79. Rao, L.; Newman, J. Heat-Generation Rate and General Energy Balance for Insertion Battery Systems. *J. Electrochem. Soc.* **1997**, *144*, 2697–2704. <https://doi.org/10.1149/1.1837884>.
80. Gu, W.B.; Wang, C.Y. Thermal-Electrochemical Modeling of Battery Systems. *J. Electrochem. Soc.* **2000**, *147*, 2910–2922. <https://doi.org/10.1149/1.1393625>.
81. Frank, R. Jacob Fraden: Handbook of modern sensors: Physics, designs, and applications. *Anal. Bioanal. Chem.* **2005**, *382*, 8–9. <https://doi.org/10.1007/s00216-004-3037-8>.
82. Li, K.; Chen, L.; Gao, X.; et al. Influence of ambient temperature on multidimensional signal dynamics and safety performance in lithium-ion batteries during overcharging process. *Process Saf. Environ. Prot.* **2024**, *189*, 288–301. <https://doi.org/10.1016/j.psep.2024.06.070>.
83. Chen, Y. Recent advances of overcharge investigation of lithium-ion batteries. *Ionics* **2022**, *28*, 495–514. <https://doi.org/10.1007/s11581-021-04331-3>.
84. Du, H.; Wang, Y.; Kang, Y.; et al. Side Reactions/Changes in Lithium-Ion Batteries: Mechanisms and Strategies for Creating Safer and Better Batteries. *Adv. Mater.* **2024**, *36*, 2401482. <https://doi.org/10.1002/adma.202401482>.
85. Ouyang, D.; Liu, J.; Chen, M.; et al. Investigation into the Fire Hazards of Lithium-Ion Batteries under Overcharging. *Appl. Sci.* **2017**, *7*, 1314. <https://doi.org/10.3390/app7121314>.
86. Ouyang, D.; Chen, M.; Liu, J.; et al. Investigation of a commercial lithium-ion battery under overcharge/over-discharge failure conditions. *RSC Adv.* **2018**, *8*, 33414–33424. <https://doi.org/10.1039/c8ra05564e>.
87. Zhang, G.; Wei, X.; Tang, X.; et al. Internal short circuit mechanisms, experimental approaches and detection methods of lithium-ion batteries for electric vehicles: A review. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110790. <https://doi.org/10.1016/j.rser.2021.110790>.
88. Song, Y.; Hou, J.; Lyu, N.; et al. Electric-controlled pressure relief valve for enhanced safety in liquid-cooled lithium-ion battery packs. *J. Energy Chem.* **2024**, *90*, 98–109. <https://doi.org/10.1016/j.jechem.2023.11.007>.
89. Chittibabu, S.K.; Chintagumpala, K.; Chandrasekhar, A. Porous dielectric materials based wearable capacitance pressure sensors for vital signs monitoring: A review. *Mater. Sci. Semicond. Process.* **2022**, *151*, 106976. <https://doi.org/10.1016/j.mssp.2022.106976>.
90. Vo, T.S.; Kim, K. Recent Trends of Functional Composites and Structures for Electromechanical Sensors: A Review. *Adv. Intell. Syst.* **2024**, *6*, 2300730. <https://doi.org/10.1002/aisy.202300730>.
91. Wang, G.; Li, Y.; Cui, H.; et al. Acceleration self-compensation mechanism and experimental research on shock wave piezoelectric pressure sensor. *Mech. Syst. Signal Process.* **2021**, *150*, 107303. <https://doi.org/10.1016/j.ymssp.2020.107303>.
92. Elsherif, M.; Salih, A.E.; Muñoz, M.G.; et al. Optical Fiber Sensors: Working Principle, Applications, and Limitations. *Adv. Photonics Res.* **2022**, *3*, 2100371. <https://doi.org/10.1002/adpr.202100371>.

93. Williams, D.; Copley, R.; Bugryniec, P.; et al. A review of ultrasonic monitoring: Assessing current approaches to Li-ion battery monitoring and their relevance to thermal runaway. *J. Power Sources* **2024**, *590*, 233777. <https://doi.org/10.1016/j.jpowsour.2023.233777>.
94. He, C.X.; Yue, Q.L.; Chen, Q.; et al. Modeling thermal runaway of lithium-ion batteries with a venting process. *Appl. Energy* **2022**, *327*, 120110. <https://doi.org/10.1016/j.apenergy.2022.120110>.
95. Chen, D.; Hao, C.; Liu, T.; et al. Raman Spectrum Analysis Method of Thermal Runaway Gas from Lithium-Ion Batteries. *Chin. J. Lasers* **2022**, *49*, 2311001. <https://doi.org/10.3788/cjl202249.2311001>.
96. Wang, Z.; Zhu, L.; Liu, J.; et al. Gas Sensing Technology for the Detection and Early Warning of Battery Thermal Runaway: A Review. *Energy Fuels* **2022**, *36*, 6038–6057. <https://doi.org/10.1021/acs.energyfuels.2c01121>.
97. Bilyaz, S.; Marr, K.C.; Ezekoye, O.A. Modeling of Thermal Runaway Propagation in a Pouch Cell Stack. *Fire Technol.* **2020**, *56*, 2441–2466. <https://doi.org/10.1007/s10694-020-00970-6>.
98. Liu, Y.; Chang, C.; Li, S.; et al. Efficiency of dodecafluoro-2-methylpentan-3-one microemulsion to inhibit thermal runaway in lithium-ion batteries. *J. Therm. Anal. Calorim.* **2023**, *148*, 12891–12905. <https://doi.org/10.1007/s10973-023-12554-x>.
99. Liu, M.; Vatamanu, J.; Chen, X.; et al. Hydrolysis of LiPF₆-Containing Electrolyte at High Voltage. *ACS Energy Lett.* **2021**, *6*, 2096–2102. <https://doi.org/10.1021/acsenenergylett.1c00707>.
100. Metzger, M.; Egawa, M.; Solchenbach, S.; et al. Gas Evolution from Thermal and Electrochemical Side Reactions with Contaminants in Lithium-Ion Batteries. *ECS Meet. Abstr.* **2017**, *MA2017-02*, 272. <https://doi.org/10.1149/ma2017-02/4/272>.
101. Zou, F.; Manthiram, A. A Review of the Design of Advanced Binders for High-Performance Batteries. *Adv. Energy Mater.* **2020**, *10*, 2002508. <https://doi.org/10.1002/aenm.202002508>.
102. Li, J.T.; Wu, Z.Y.; Lu, Y.Q.; et al. Water Soluble Binder, an Electrochemical Performance Booster for Electrode Materials with High Energy Density. *Adv. Energy Mater.* **2017**, *7*, 1701185. <https://doi.org/10.1002/aenm.201701185>.
103. Yasin, G.; Arif, M.; Mehtab, T.; et al. Understanding and suppression strategies toward stable Li metal anode for safe lithium batteries. *Energy Storage Mater.* **2020**, *25*, 644–678. <https://doi.org/10.1016/j.ensm.2019.09.020>.
104. Lu, Y.; Zhang, H.; Zhao, Y.; et al. Robust Fiber-Shaped Flexible Temperature Sensors for Safety Monitoring with Ultrahigh Sensitivity. *Adv. Mater.* **2024**, *36*, 2310613. <https://doi.org/10.1002/adma.202310613>.
105. Krishna, K.G.; Umadevi, G.; Parne, S.; et al. Zinc oxide based gas sensors and their derivatives: A critical review. *J. Mater. Chem. C* **2023**, *11*, 3906–3925. <https://doi.org/10.1039/d2tc04690c>.
106. Liu, X.; Cheng, S.; Liu, H.; et al. A Survey on Gas Sensing Technology. *Sensors* **2012**, *12*, 9635–9665. <https://doi.org/10.3390/s120709635>.
107. Alam, M.W.; Sharma, A.; Sharma, A.; et al. VOC Detection with Zinc Oxide Gas Sensors: A Review of Fabrication, Performance, and Emerging Applications. *Electroanalysis* **2025**, *37*, e202400246. <https://doi.org/10.1002/elan.202400246>.
108. Gorbova, E.; Tzorbatzoglou, F.; Molochas, C.; et al. Fundamentals and Principles of Solid-State Electrochemical Sensors for High Temperature Gas Detection. *Catalysts* **2021**, *12*, 1. <https://doi.org/10.3390/catal12010001>.
109. Kim, I.D.; Rothschild, A.; Tuller, H.L. Advances and new directions in gas-sensing devices. *Acta Mater.* **2013**, *61*, 974–1000. <https://doi.org/10.1016/j.actamat.2012.10.041>.
110. Barik, P.; Pradhan, M. Selectivity in trace gas sensing: Recent developments, challenges, and future perspectives. *Analyst* **2022**, *147*, 1024–1054. <https://doi.org/10.1039/d1an02070f>.
111. Yang, S.; Min, X.; Fan, H.; et al. In Situ characterization of lithium-metal anodes. *J. Mater. Chem. A* **2022**, *10*, 17917–17947. <https://doi.org/10.1039/d2ta04309b>.
112. Merryweather, A.J.; Schnedermann, C.; Jacquet, Q.; et al. Operando optical tracking of single-particle ion dynamics in batteries. *Nature* **2021**, *594*, 522–528. <https://doi.org/10.1038/s41586-021-03584-2>.
113. Yang, H.; Tang, P.; Piao, N.; et al. In-situ imaging techniques for advanced battery development. *Mater. Today* **2022**, *57*, 279–294. <https://doi.org/10.1016/j.mattod.2022.05.021>.
114. Pecher, O.; Carretero-González, J.; Griffith, K.J.; et al. Materials' Methods: NMR in Battery Research. *Chem. Mater.* **2017**, *29*, 213–242. <https://doi.org/10.1021/acs.chemmater.6b03183>.
115. Dutoit, C.E.; Tang, M.; Gourier, D.; et al. Monitoring metallic sub-micrometric lithium structures in Li-ion batteries by in situ electron paramagnetic resonance correlated spectroscopy and imaging. *Nat. Commun.* **2021**, *12*, 1410. <https://doi.org/10.1038/s41467-021-21598-2>.
116. Liu, D.; Shadike, Z.; Lin, R.; et al. Review of Recent Development of In Situ/Operando Characterization Techniques for Lithium Battery Research. *Adv. Mater.* **2019**, *31*, 1806620. <https://doi.org/10.1002/adma.201806620>.
117. Kim, Y.J.; Matsunaga, Y.T. Thermo-responsive polymers and their application as smart biomaterials. *J. Mater. Chem. B* **2017**, *5*, 4307–4321. <https://doi.org/10.1039/c7tb00157f>.

118. Sponchioni, M.; Capasso Palmiero, U.; Moscatelli, D. Thermo-responsive polymers: Applications of smart materials in drug delivery and tissue engineering. *Mater. Sci. Eng. C Mater. Biol. Appl.* **2019**, *102*, 589–605. <https://doi.org/10.1016/j.msec.2019.04.069>.
119. Liu, Y.; Zhang, M.; Ji, A.; et al. Measuring methods for thermoelectric properties of one-dimensional nanostructural materials. *RSC Adv.* **2016**, *6*, 48933–48961. <https://doi.org/10.1039/c5ra23634g>.
120. Wu, B.; Ouro-Koura, H.; Lu, S.H.; et al. Functional materials for powering and implementing next-generation miniature sensors. *Mater. Today* **2023**, *69*, 333–354. <https://doi.org/10.1016/j.mattod.2023.09.001>.
121. Lin, X.; Salari, M.; Arava, L.M.R.; et al. High temperature electrical energy storage: Advances, challenges, and frontiers. *Chem. Soc. Rev.* **2016**, *45*, 5848–5887. <https://doi.org/10.1039/c6cs00012f>.
122. He, Y.; Jiao, M. A Mini-Review on Metal Oxide Semiconductor Gas Sensors for Carbon Monoxide Detection at Room Temperature. *Chemosensors* **2024**, *12*, 55. <https://doi.org/10.3390/chemosensors12040055>.
123. Ou, L.X.; Liu, M.Y.; Zhu, L.Y.; et al. Recent Progress on Flexible Room-Temperature Gas Sensors Based on Metal Oxide Semiconductor. *Nano-Micro Lett.* **2022**, *14*, 206. <https://doi.org/10.1007/s40820-022-00956-9>.
124. Xie, S.; Theuwissen, A. All-MOS self-referenced temperature sensor. *Electron. Lett.* **2019**, *55*, 1045–1047. <https://doi.org/10.1049/el.2019.1784>.
125. Cai, J.; Du, M.; Li, Z. Flexible Temperature Sensors Constructed with Fiber Materials. *Adv. Mater. Technol.* **2022**, *7*, 2101182. <https://doi.org/10.1002/admt.202101182>.
126. Lim, S.; Suk, J.W. Flexible temperature sensors based on two-dimensional materials for wearable devices. *J. Phys. D Appl. Phys.* **2023**, *56*, 063001. <https://doi.org/10.1088/1361-6463/acaf38>.
127. Dan, L.; Elias, A.L. Flexible and Stretchable Temperature Sensors Fabricated Using Solution-Processable Conductive Polymer Composites. *Adv. Healthc. Mater.* **2020**, *9*, 2000380. <https://doi.org/10.1002/adhm.202000380>.
128. Huang, Y.; Peng, C.; Li, Y.; et al. Elastomeric polymers for conductive layers of flexible sensors: Materials, fabrication, performance, and applications. *Aggregate* **2023**, *4*, e319. <https://doi.org/10.1002/agt2.319>.
129. Nunes, D.; Pimentel, A.; Gonçalves, A.; et al. Metal oxide nanostructures for sensor applications. *Semicond. Sci. Technol.* **2019**, *34*, 043001. <https://doi.org/10.1088/1361-6641/ab011e>.
130. Guo, M.; Yang, C.; Gao, D.; et al. A flexible and high temperature tolerant strain sensor of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3/\text{Mica}$. *J. Mater. Sci. Technol.* **2020**, *44*, 42–47. <https://doi.org/10.1016/j.jmst.2019.10.019>.
131. Liu, Z.; Tian, B.; Fan, X.; et al. A temperature sensor based on flexible substrate with ultra-high sensitivity for low temperature measurement. *Sens. Actuators A Phys.* **2020**, *315*, 112341. <https://doi.org/10.1016/j.sna.2020.112341>.
132. Li, W.; Kong, L.; Xu, M.; et al. Microsecond-Scale Transient Thermal Sensing Enabled by Flexible $\text{Mo}_{1-x}\text{W}_x\text{S}_2$ Alloys. *Research* **2024**, *7*, 0452. <https://doi.org/10.34133/research.0452>.
133. Krishna, R.S.S.M.R.; Mal, A.K.; Mahapatra, R. All MOS noise-shaped time-mode temperature sensor. *Integration* **2019**, *65*, 74–80. <https://doi.org/10.1016/j.vlsi.2018.11.004>.
134. Wen, N.; Zhang, L.; Jiang, D.; et al. Emerging flexible sensors based on nanomaterials: Recent status and applications. *J. Mater. Chem. A* **2020**, *8*, 25499–25527. <https://doi.org/10.1039/d0ta09556g>.
135. Lin, J.C.; Liatsis, P.; Alexandridis, P. Flexible and Stretchable Electrically Conductive Polymer Materials for Physical Sensing Applications. *Polym. Rev.* **2023**, *63*, 67–126. <https://doi.org/10.1080/15583724.2022.2059673>.
136. Megha, R.; Ali, F.A.; Ravikiran, Y.T.; et al. Conducting polymer nanocomposite based temperature sensors: A review. *Inorg. Chem. Commun.* **2018**, *98*, 11–28. <https://doi.org/10.1016/j.inoche.2018.09.040>.
137. Wang, C.; Zhang, Y.; Han, F.; et al. Flexible Thermoelectric Type Temperature Sensors Based on Graphene Fibers. *Micromachines* **2023**, *14*, 1853. <https://doi.org/10.3390/mi14101853>.
138. Buga, C.S.; Viana, J.C. Development and characterization of flexible carbon temperature sensors: A study on different inks and sensor designs. *Sens. Actuators A Phys.* **2024**, *378*, 115823. <https://doi.org/10.1016/j.sna.2024.115823>.
139. Liu, L.; Luo, S.; Qing, Y.; et al. A Temperature-Controlled, Conductive PANI@CNFs/MEO₂MA/PEGMA Hydrogel for Flexible Temperature Sensors. *Macromol. Rapid Commun.* **2018**, *39*, 1700836. <https://doi.org/10.1002/marc.201700836>.
140. Zhang, Y.; Cui, Y. Development of Flexible and Wearable Temperature Sensors Based on PEDOT:PSS. *IEEE Trans. Electron Devices* **2019**, *66*, 3129–3133. <https://doi.org/10.1109/ted.2019.2914301>.
141. Dotoli, M.; Rocca, R.; Giuliano, M.; et al. A Review of Mechanical and Chemical Sensors for Automotive Li-Ion Battery Systems. *Sensors* **2022**, *22*, 1763. <https://doi.org/10.3390/s22051763>.
142. Li, H.; Guo, Q.; Yu, W.; et al. Piezoresistive-piezocapacitive hybrid pressure sensor based on synergetic MXene porous conducting and ion trapping effects for operando battery state-of-charge monitoring. *Chem. Eng. J.* **2024**, *497*, 154929. <https://doi.org/10.1016/j.cej.2024.154929>.
143. Ismail, S.N.A.; Nayan, N.A.; Mohammad Haniff, M.A.S.; et al. Wearable Two-Dimensional Nanomaterial-Based Flexible Sensors for Blood Pressure Monitoring: A Review. *Nanomaterials* **2023**, *13*, 852. <https://doi.org/10.3390/nano13050852>.

144. Guo, Y.; Li, Y.; Sun, J.; et al. Status, Applications, and Challenges of Flexible Pressure Sensors Based on 2-D Materials: A Review. *IEEE Sens. J.* **2024**, *24*, 9251–9277. <https://doi.org/10.1109/jsen.2024.3359279>.
145. Wu, Y.; Ma, Y.; Zheng, H.; et al. Piezoelectric materials for flexible and wearable electronics: A review. *Mater. Des.* **2021**, *211*, 110164. <https://doi.org/10.1016/j.matdes.2021.110164>.
146. Shirley, J.A.; Florence, S.E.; Sreeja, B.S.; et al. Zinc oxide nanostructure-based textile pressure sensor for wearable applications. *J. Mater. Sci. Mater. Electron.* **2020**, *31*, 16519–16530. <https://doi.org/10.1007/s10854-020-04206-9>.
147. Sun, J.; Zhang, X.; Lang, Y.; et al. Piezo-phototronic effect improved performance of n-ZnO nano-arrays/p-Cu₂O film based pressure sensor synthesized on flexible Cu foil. *Nano Energy* **2017**, *32*, 96–104. <https://doi.org/10.1016/j.nanoen.2016.12.028>.
148. Yoon, Y.; Truong, P.L.; Lee, D.; et al. Metal-Oxide Nanomaterials Synthesis and Applications in Flexible and Wearable Sensors. *ACS Nanosci. Au* **2022**, *2*, 64–92. <https://doi.org/10.1021/acsnanoscienceau.1c00029>.
149. Ramadan, K.S.; Sameoto, D.; Evoy, S. A review of piezoelectric polymers as functional materials for electromechanical transducers. *Smart Mater. Struct.* **2014**, *23*, 033001. <https://doi.org/10.1088/0964-1726/23/3/033001>.
150. Guo, W.T.; Tang, X.G.; Tang, Z.; et al. Recent Advances in Polymer Composites for Flexible Pressure Sensors. *Polymers* **2023**, *15*, 2176. <https://doi.org/10.3390/polym15092176>.
151. Iranmanesh, E.; Liang, Z.; Li, W.; et al. Organic-inorganic hybrid piezotronic bipolar junction transistor for pressure sensing. *Microsyst. Nanoeng.* **2024**, *10*, 80. <https://doi.org/10.1038/s41378-024-00699-0>.
152. Adhikary, P.; Mandal, D. Piezoelectric Materials Based on Polymers and Their Composites. In *Handbook of Energy Materials*; Gupta, R., Ed.; Springer Nature Singapore: Singapore, 2022; pp. 1–37. https://doi.org/10.1007/978-981-16-4480-1_74-1.
153. Qin, R.; Shan, G.; Hu, M.; et al. Two-dimensional transition metal carbides and/or nitrides (MXenes) and their applications in sensors. *Mater. Today Phys.* **2021**, *21*, 100527. <https://doi.org/10.1016/j.mtphys.2021.100527>.
154. Qin, R.; Nong, J.; Wang, K.; et al. Recent Advances in Flexible Pressure Sensors Based on MXene Materials. *Adv. Mater.* **2024**, *36*, 2312761. <https://doi.org/10.1002/adma.202312761>.
155. Wang, S.; Shao, H.Q.; Liu, Y.; et al. Boosting piezoelectric response of PVDF-TrFE via MXene for self-powered linear pressure sensor. *Compos. Sci. Technol.* **2021**, *202*, 108600. <https://doi.org/10.1016/j.compscitech.2020.108600>.
156. Liu, X.; Tong, J.; Wang, J.; et al. BaTiO₃/MXene/PVDF-TrFE Composite Films via an Electrospinning Method for Flexible Piezoelectric Pressure Sensors. *J. Mater. Chem. C* **2023**, *11*, 4614–4622. <https://doi.org/10.1039/d2tc05291a>.
157. Ahmed, A.; Khoso, N.A.; Arain, M.F.; et al. Development of Highly Flexible Piezoelectric PVDF-TRFE/Reduced Graphene Oxide Doped Electrospun Nano-Fibers for Self-Powered Pressure Sensor. *Polymers* **2024**, *16*, 1781. <https://doi.org/10.3390/polym16131781>.
158. Jeronimo, K.; Koutsos, V.; Cheung, R.; et al. PDMS-ZnO Piezoelectric Nanocomposites for Pressure Sensors. *Sensors* **2021**, *21*, 5873. <https://doi.org/10.3390/s21175873>.
159. Li, Y.; Lin, H.; Lin, J.; et al. Thermally stable piezoelectric sensors for quantitative pressure sensing based on linear piezoelectric zinc oxide thin films. *Mater. Des.* **2023**, *235*, 112466. <https://doi.org/10.1016/j.matdes.2023.112466>. Correction in: *Mater. Des.* **2024**, *237*, 112498. <https://doi.org/10.1016/j.matdes.2023.112498>.
160. Yenuganti, S.; Gandhi, U.; Umapathy, M. Piezoelectric microresonant pressure sensor using aluminum nitride. *J. Micro/Nanolithogr. MEMS MOEMS* **2017**, *16*, 025001. <https://doi.org/10.1117/1.jmm.16.2.025001>.
161. Waseem, A.; Johar, M.A.; Hassan, M.A.; et al. Flexible self-powered piezoelectric pressure sensor based on GaN/p-GaN coaxial nanowires. *J. Alloys Compd.* **2021**, *872*, 159661. <https://doi.org/10.1016/j.jallcom.2021.159661>.
162. Xu, W.; Geng, W.; Zhang, H.; et al. Enhancing the electric charge output in LiNbO₃-based piezoelectric pressure sensors. *RSC Adv.* **2024**, *14*, 8313–8321. <https://doi.org/10.1039/d3ra07712h>.
163. Xu, W.; Wang, Z.; Li, J.; et al. High-sensitivity piezoelectric pressure/stress sensors based on LiNbO₃ for minuscule pressure/stress detection. *Ceram. Int.* **2024**, *50*, 23500–23508. <https://doi.org/10.1016/j.ceramint.2024.04.072>.
164. Xin, Y.; Tong, J.; Hou, T.; et al. BiScO₃-PbTiO₃ nanofibers piezoelectric sensor for high-temperature pressure and vibration measurements. *Measurement* **2023**, *212*, 112694. <https://doi.org/10.1016/j.measurement.2023.112694>.
165. Kim, H.J.; Kim, Y.J. High performance flexible piezoelectric pressure sensor based on CNTs-doped 0–3 ceramic-epoxy nanocomposites. *Mater. Des.* **2018**, *151*, 133–140. <https://doi.org/10.1016/j.matdes.2018.04.048>.
166. Zhu, S.E.; Krishna Ghatkesar, M.; Zhang, C.; et al. Graphene based piezoresistive pressure sensor. *Appl. Phys. Lett.* **2013**, *102*, 161904. <https://doi.org/10.1063/1.4802799>.
167. Yang, C.; Liu, W.; Liu, N.; et al. Graphene Aerogel Broken to Fragments for a Piezoresistive Pressure Sensor with a Higher Sensitivity. *ACS Appl. Mater. Interfaces* **2019**, *11*, 33165–33172. <https://doi.org/10.1021/acsaami.9b12055>.
168. Lv, Y.; Zhang, M.; Zhao, B.; et al. Flexible Laser-Reduced Graphene with Gradient-Wrinkled Microstructures for Piezoresistive Pressure Sensors. *ACS Appl. Nano Mater.* **2024**, *7*, 18986–18994. <https://doi.org/10.1021/acsaanm.4c02725>.
169. Park, S.J.; Kim, J.; Chu, M.; et al. Flexible Piezoresistive Pressure Sensor Using Wrinkled Carbon Nanotube Thin Films for Human Physiological Signals. *Adv. Mater. Technol.* **2018**, *3*, 1700158. <https://doi.org/10.1002/admt.201700158>.

170. Devi, R.; Gill, S.S. Performance Investigation of Carbon Nanotube Based Temperature Compensated Piezoresistive Pressure Sensor. *Silicon* **2022**, *14*, 3931–3938. <https://doi.org/10.1007/s12633-021-01153-w>.
171. Zheng, J.; Zhang, H.; Xiao, G.; et al. Superhydrophobic cotton-based piezoresistive pressure sensor for detecting human motions. *Sens. Actuators A Phys.* **2022**, *347*, 113956. <https://doi.org/10.1016/j.sna.2022.113956>.
172. Xia, Y.; Huang, P.; Lin, X.; et al. The piezoresistive pressure sensors based on ITO nanocrystalline-plant fiber composite. *Sci. China Mater.* **2023**, *66*, 3922–3930. <https://doi.org/10.1007/s40843-023-2534-1>.
173. Zhou, Y.; Zhao, L.; Tao, W.; et al. All-Nanofiber Network Structure for Ultrasensitive Piezoresistive Pressure Sensors. *ACS Appl. Mater. Interfaces* **2022**, *14*, 19949–19957. <https://doi.org/10.1021/acsami.1c24257>.
174. Wu, J.; Li, H.; Lai, X.; et al. Conductive and superhydrophobic F-rGO@CNTs/chitosan aerogel for piezoresistive pressure sensor. *Chem. Eng. J.* **2020**, *386*, 123998. <https://doi.org/10.1016/j.cej.2019.123998>.
175. Kouediatouka, A.N.; Wang, J.; Mawignon, F.J.; et al. Carbon nanotube/liquid metal hybrid coating-based flexible pressure piezoresistive sensors. *Chem. Eng. J.* **2024**, *481*, 148637. <https://doi.org/10.1016/j.cej.2024.148637>.
176. Lu, H.; Chen, B.; Lai, X.; et al. Porous reduced graphene oxide@multi-walled carbon nanotubes/polydimethylsiloxane piezoresistive pressure sensor for human motion detection. *Mater. Today Nano* **2024**, *28*, 100512. <https://doi.org/10.1016/j.mtnano.2024.100512>.
177. Wang, M.; Wang, G.; Zheng, M.; et al. High-performance flexible piezoresistive pressure sensor based on multi-layer interlocking microstructures. *J. Mater. Chem. A* **2024**, *12*, 22931–22944. <https://doi.org/10.1039/d4ta03758h>.
178. Pan, H.; Xie, G.; Pang, W.; et al. Surface Engineering of a 3D Topological Network for Ultrasensitive Piezoresistive Pressure Sensors. *ACS Appl. Mater. Interfaces* **2020**, *12*, 38805–38812. <https://doi.org/10.1021/acsami.0c11658>.
179. Wang, H.; Xu, H.; Zhang, Z.; et al. Fire and explosion characteristics of vent gas from lithium-ion batteries after thermal runaway: A comparative study. *eTransportation* **2022**, *13*, 100190. <https://doi.org/10.1016/j.etrans.2022.100190>.
180. Golubkov, A.W.; Scheidl, S.; Planteu, R.; et al. Thermal runaway of commercial 18650 Li-ion batteries with LFP and NCA cathodes-impact of state of charge and overcharge. *RSC Adv.* **2015**, *5*, 57171–57186. <https://doi.org/10.1039/c5ra05897j>.
181. Ma, B.; Lin, C.; Liu, L.; et al. Venting Characteristics and Flammability Limit of Thermal Runaway Gas of Lithium Ion Battery. *Energy Storage Sci. Technol.* **2022**, *11*, 1592–1600. <https://doi.org/10.19799/j.cnki.2095-4239.2021.0618>.
182. Essl, C.; Golubkov, A.W.; Gasser, E.; et al. Comprehensive Hazard Analysis of Failing Automotive Lithium-Ion Batteries in Overtemperature Experiments. *Batteries* **2020**, *6*, 30. <https://doi.org/10.3390/batteries6020030>.
183. Koch, S.; Fill, A.; Birke, K.P. Comprehensive gas analysis on large scale automotive lithium-ion cells in thermal runaway. *J. Power Sources* **2018**, *398*, 106–112. <https://doi.org/10.1016/j.jpowsour.2018.07.051>.
184. Fernandes, Y.; Bry, A.; de Persis, S. Identification and quantification of gases emitted during abuse tests by overcharge of a commercial Li-ion battery. *J. Power Sources* **2018**, *389*, 106–119. <https://doi.org/10.1016/j.jpowsour.2018.03.034>.
185. Lammer, M.; Königseder, A.; Hacker, V. Holistic methodology for characterization of the thermally induced failure of commercially available 18650 lithium ion cells. *RSC Adv.* **2017**, *7*, 24425–24429. <https://doi.org/10.1039/c7ra02635h>.
186. Yuan, L.; Dubaniewicz, T.; Zlochower, I.; et al. Experimental study on thermal runaway and vented gases of lithium-ion cells. *Process Saf. Environ. Prot.* **2020**, *144*, 186–192. <https://doi.org/10.1016/j.psep.2020.07.028>.
187. Tomić, M.; Šetka, M.; Vojkúvka, L.; et al. VOCs Sensing by Metal Oxides, Conductive Polymers, and Carbon-Based Materials. *Nanomaterials* **2021**, *11*, 552. <https://doi.org/10.3390/nano11020552>.
188. Luan, S.; Hu, J.; Ma, M.; et al. The enhanced sensing properties of MOS-based resistive gas sensors by Au functionalization: A review. *Dalton Trans.* **2023**, *52*, 8503–8529. <https://doi.org/10.1039/d3dt01078c>.
189. Liu, D.; Huan, C.; Wang, Z.; et al. Conductive polymer based hydrogels and their application in wearable sensors: A review. *Mater. Horiz.* **2023**, *10*, 2800–2823. <https://doi.org/10.1039/d3mh00056g>.
190. Zhou, T.; Zhang, T. Recent Progress of Nanostructured Sensing Materials from 0D to 3D: Overview of Structure–Property–Application Relationship for Gas Sensors. *Small Methods* **2021**, *5*, 2100515. <https://doi.org/10.1002/smt.202100515>.
191. Liu, X.; Ma, T.; Pinna, N.; et al. Two-Dimensional Nanostructured Materials for Gas Sensing. *Adv. Funct. Mater.* **2017**, *27*, 1702168. <https://doi.org/10.1002/adfm.201702168>.
192. Goel, N.; Kunal, K.; Kushwaha, A.; et al. Metal oxide semiconductors for gas sensing. *Eng. Rep.* **2023**, *5*, e12604. <https://doi.org/10.1002/eng.2.12604>.
193. Tanvir, N.B.; Yurchenko, O.; Wilbertz, C.; et al. Investigation of CO₂ reaction with copper oxide nanoparticles for room temperature gas sensing. *J. Mater. Chem. A* **2016**, *4*, 5294–5302. <https://doi.org/10.1039/c5ta09089j>.
194. Kim, H.J.; Lee, J.H. Highly sensitive and selective gas sensors using p-type oxide semiconductors: Overview. *Sens. Actuators B Chem.* **2014**, *192*, 607–627. <https://doi.org/10.1016/j.snb.2013.11.005>.
195. Yu, Y.; Xia, Y.; Zeng, W.; et al. Synthesis of multiple networked NiO nanostructures for enhanced gas sensing performance. *Mater. Lett.* **2017**, *206*, 80–83. <https://doi.org/10.1016/j.matlet.2017.06.119>.
196. Kim, D.Y.; Kang, H.; Choi, N.J.; et al. A carbon dioxide gas sensor based on cobalt oxide containing barium carbonate. *Sens. Actuators B Chem.* **2017**, *248*, 987–992. <https://doi.org/10.1016/j.snb.2017.02.160>.

197. Bolli, E.; Bellucci, A.; Mastellone, M.; et al. Engineered SnO₂-based thin films for efficient CO₂ gas sensing at room temperature. *Appl. Surf. Sci.* **2025**, *683*, 161795. <https://doi.org/10.1016/j.apsusc.2024.161795>.
198. Abdulsattar, M.A.; Jabbar, R.H.; Fadhel, H.M.; et al. SnO₂ nanocluster interaction with noble and environmental gases: A DFT study. *Struct. Chem.* **2022**, *33*, 71–79. <https://doi.org/10.1007/s11224-021-01823-w>.
199. Alam, M.; Pooja, P.; Aamir, M.; et al. The Recent Development in Chemoresistive-Based Heterostructure Gas Sensor Technology, Their Future Opportunities and Challenges: A Review. *Membranes* **2022**, *12*, 555. <https://doi.org/10.3390/membranes12060555>.
200. Musa, A.M.M.; Rasadujjaman, M.; Gafur, M.A.; et al. Synthesis and characterization of dip-coated ZnO–CuO composite thin film for room-temperature CO₂ gas sensing. *Thin Solid Films* **2023**, *773*, 139838. <https://doi.org/10.1016/j.tsf.2023.139838>.
201. Bhowmick, T.; Ghosh, A.; Nag, S.; et al. Sensitive and selective CO₂ gas sensor based on CuO/ZnO bilayer thin-film architecture. *J. Alloys Compd.* **2022**, *903*, 163871. <https://doi.org/10.1016/j.jallcom.2022.163871>.
202. Han, D.; Liu, L.; Liu, Z.; et al. Polyethyleneimine/polyethylene-glycol/Ti₃C₂T_x composites for ultrasensitive room-temperature CO₂ sensing. *Sens. Actuators B Chem.* **2023**, *393*, 134221. <https://doi.org/10.1016/j.snb.2023.134221>.
203. Bouachma, S.; Ayouz-Chebout, K.; Kechouane, M.; et al. Synthesis of PSi-n/CuO-p/Cu₂O-n heterostructure for CO₂ gas sensing at room temperature. *Appl. Phys. A* **2022**, *128*, 69. <https://doi.org/10.1007/s00339-021-05167-4>.
204. Hamada, T.; Sugiyama, M. Fabrication of solar cells with CO₂ gas sensing capabilities based on a NiO/ZnO p-n junction for developing self-powered gas sensors. *Jpn. J. Appl. Phys.* **2022**, *61*, 054002. <https://doi.org/10.35848/1347-4065/ac541f>.
205. Taheripour, M.; Nasresfahani, S.; Yasrebi, N.; et al. Impact of Ag₂O on the gas sensing properties of the star-shaped BaTiO₃/ZnO heterostructures. *Ceram. Int.* **2024**, *50*, 48373–48383. <https://doi.org/10.1016/j.ceramint.2024.09.186>.
206. Panday, M.; Upadhyay, G.K.; Purohit, L.P. Sb incorporated SnO₂ nanostructured thin films for CO₂ gas sensing and humidity sensing applications. *J. Alloys Compd.* **2022**, *904*, 164053. <https://doi.org/10.1016/j.jallcom.2022.164053>.
207. Taha, I.; Abdulhamid, Z.M.; Straubinger, R.; et al. Ga-doped ZnO nanoparticles for enhanced CO₂ gas sensing applications. *Sci. Rep.* **2024**, *14*, 29712. <https://doi.org/10.1038/s41598-024-81279-0>.
208. Jaiswal, S.N.; Pandey, B.P.; Kumar, D.; et al. Improved gas sensing properties of copper-doped MoSe₂ monolayers: A first-principles study on CO₂ and NO₂ adsorption. *Phys. Scr.* **2024**, *99*, 125907. <https://doi.org/10.1088/1402-4896/ad8a03>.
209. Tangirala, V.K.K.; Hernandez Zanabria, A.G.; Gomez Pozos, H.; et al. CO₂ detection using In and Ti doped SnO₂ nanostructures: Comparative analysis of gas sensing properties. *Ceram. Int.* **2024**, *50*, 54240–54255. <https://doi.org/10.1016/j.ceramint.2024.10.281>.
210. Liu, X.; Shao, H.; Li, N.; et al. Achieving bi-function of enhanced CO₂ gas sensing and orange-red light emission of La₂O₂CO₃ 1D nanostructures via Eu³⁺ doping. *J. Alloys Compd.* **2025**, *1010*, 177641. <https://doi.org/10.1016/j.jallcom.2024.177641>.
211. Yagüe, J.L.; Borrós, S. Conducting Plasma Polymerized Polypyrrole Thin Films as Carbon Dioxide Gas Sensors. *Plasma Process. Polym.* **2012**, *9*, 485–490. <https://doi.org/10.1002/ppap.201100169>.
212. Gupta, M.; Hawari, H.F.; Kumar, P.; et al. Functionalized Reduced Graphene Oxide Thin Films for Ultrahigh CO₂ Gas Sensing Performance at Room Temperature. *Nanomaterials* **2021**, *11*, 623. <https://doi.org/10.3390/nano11030623>.
213. Kumar, P.; Hawari, H.F.; Gupta, M.; et al. Comparative investigation of surface-electrical properties of functionalized graphene and MXene thin films for CO₂ gas sensing. *J. Mater. Sci.* **2024**, *59*, 22132–22148. <https://doi.org/10.1007/s10853-024-10440-x>.
214. Karthik, T.V.K.; Martínez-García, H.; Ortiz-Chi, F.; et al. CO₂ gas sensing properties of graphitic carbon nitride (g-C₃N₄) thin films. *Diam. Relat. Mater.* **2023**, *133*, 109736. <https://doi.org/10.1016/j.diamond.2023.109736>.
215. Shehzad, K.; Shah, N.A.; Amin, M.T.; et al. Synthesis of SnO₂ nanowires for CO, CH₄ and CH₃OH gases sensing. *Int. J. Distrib. Sens. Netw.* **2018**, *14*, 1550147718790750. <https://doi.org/10.1177/1550147718790750>.
216. Joy, R.; Han, Z.; Xu, K.; et al. DFT investigation of gas sensing characteristics of Au-doped vanadium dioxide. *Phys. Lett. A* **2020**, *384*, 126823. <https://doi.org/10.1016/j.physleta.2020.126823>.
217. Dong, M.; Wu, Y.; Zhou, S.; et al. A Study Based on the First-Principle Study of the Adsorption and Sensing Properties of Mo-Doped WSe₂ for N₂O, CO₂, and CH₄. *Chemosensors* **2024**, *12*, 192. <https://doi.org/10.3390/chemosensors12090192>.
218. Qian, G.; Peng, Q.; Zou, D.; et al. First-Principles Insight into Au-Doped MoS₂ for Sensing C₂H₆ and C₂H₄. *Front. Mater.* **2020**, *7*, 22. <https://doi.org/10.3389/fmats.2020.00022>.
219. Wang, Y.; Zhang, H.; Cao, J. Synthesis and low temperature methane sensing performance of Pd modified In₂O₃ microspheres. *Mater. Chem. Phys.* **2022**, *279*, 125749. <https://doi.org/10.1016/j.matchemphys.2022.125749>.
220. Li, X.; Hu, H.; Tan, T.; et al. Enhancing Methane Gas Sensing through Defect Engineering in Ag–Ru Co-doped ZnO Nanorods. *ACS Appl. Mater. Interfaces* **2024**, *16*, 26395–26405. <https://doi.org/10.1021/acsami.4c03252>.
221. Leangtanom, P.; Wisitsoraat, A.; Jaruwongrungrsee, K.; et al. Highly sensitive and selective ethylene gas sensors based on CeO_x-SnO₂ nanocomposites prepared by a Co-precipitation method. *Mater. Chem. Phys.* **2020**, *254*, 123540. <https://doi.org/10.1016/j.matchemphys.2020.123540>.

222. Shaalan, N.M.; Hamad, D.; Saber, O. Co-Evaporated CuO-Doped In₂O₃ 1D-Nanostructure for Reversible CH₄ Detection at Low Temperatures: Structural Phase Change and Properties. *Materials* **2019**, *12*, 4073. <https://doi.org/10.3390/ma12244073>.
223. Afrin, R.; Shah, N.A. Room temperature gas sensors based on carboxyl and thiol functionalized carbon nanotubes buckypapers. *Diam. Relat. Mater.* **2015**, *60*, 42–49. <https://doi.org/10.1016/j.diamond.2015.10.010>.
224. Aldalbahi, A.; Feng, P.; Alhokbany, N.; et al. Synthesis and characterization of hybrid nanocomposites as highly-efficient conducting CH₄ gas sensor. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2017**, *173*, 502–509. <https://doi.org/10.1016/j.saa.2016.09.009>.
225. Chen, H.; Wang, H.; Miao, S.; et al. Temperature-Responsive Electrodes Enabled by Poly(3-Alkylthiophene)s with Tailored Branches. *Adv. Sustain. Syst.* **2025**, *9*, e01198. <https://doi.org/10.1002/adsu.202501198>.
226. Chen, H.; Miao, S.; Li, H.; et al. Molecular Engineering of Poly(3-Alkylthiophene)s with Enhanced Positive Temperature Coefficient Effects for Intrinsically Safe Lithium-Ion Batteries. *ChemSusChem* **2025**, *18*, e202500398. <https://doi.org/10.1002/cssc.202500398>.
227. Miao, S.; You, Y.; Wang, Z.; et al. Non-flammable electrolytes for high-safety sodium-ion batteries. *Chem. Soc. Rev.* **2025**, *54*, 9289–9316. <https://doi.org/10.1039/d5cs00236b>.