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Thermally Stable Battery-Like Memory for Emerging Computing Applications and Future

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Abstract*: This project aims to develop a lot- based power theft detection system to identify unauthorized energy usage. Using smart energy meters, sensors, and a centralized control unit, the system monitors energy flow and compares consumption with billed usage. Discrepancies trigger real-time alerts, enabling authorities to take quick action. Smart meters installed at each lot send consumption data to the control unit, where an algorithm detects deviations. This helps reduce revenue losses, improve power quality and efficiency, and ensure reliable electricity distribution.*

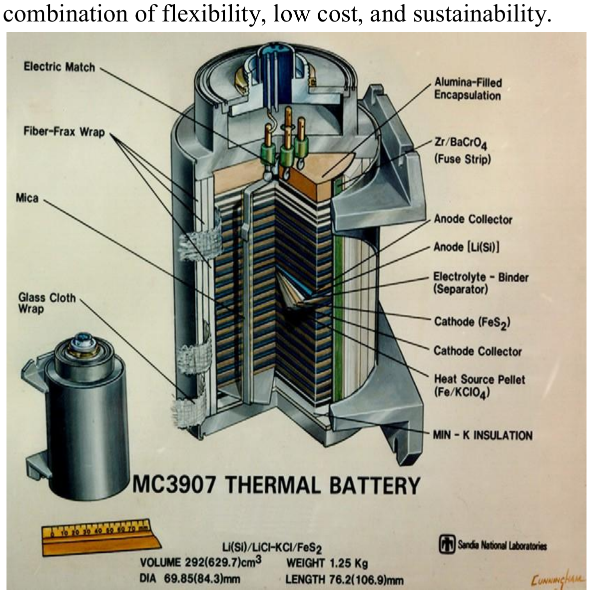
Keywords: LIBs, SSEs, LiPON, LTO, ML, AIMD

I. INTRODUCTION

Thermal batteries are a reliable and robust power source used in various military and space applications. Due to their ability to provide high power density and long shelf life, thermal batteries have become a crucial component in guided missiles, ordnance devices, torpedoes, and space exploration. This chapter provides an overview of thermal batteries, their applications, design, and performance characteristics, highlighting their importance in modern military and space technologies.

The emergence of paper-based electronics has revolutionized the field of flexible and portable devices. Paper, with its unique combination of low cost, biocompatibility, and high surface area, has become an attractive substrate for various electronic applications. Recently, researchers have explored the integration of paper-based energy storage devices, including batteries and supercapacitors, to power these devices. This review aims to provide a comprehensive overview of the current state of paper-based and paper-like batteries and energy storage devices, highlighting their operating principles, materials, and potential applications.

Supercapacitors are energy storage devices that have attracted significant attention in recent years. Paper-based supercapacitors offer a unique combination of flexibility, low cost, and sustainability.



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Advantages of Li-ion Batteries

1. High energy and power density
2. Low reduction potential, allowing for high cell potential
3. Lightweight and small ionic radius, enabling high gravimetric and volumetric capacity and power density

Limitations and Concerns

1. Cost: Li-ion batteries are expensive, particularly for large-scale applications like transportation and grid storage
2. Potential shortage of Li and transition metals
3. Limited mobility of multivalent cations, hindering alternative chemistries

Thermal Batteries

Overview

Thermal batteries are reliable, rugged, and robust power sources used in various applications, including artillery shells, earth-penetrator weapons, and renewable energy systems.

Advantages

1. High reliability and longevity (up to 25 years)
2. Ability to operate in extreme environments (high-spin, shock, and temperature)
3. High power density and energy efficiency

Limitations

1. High cost
2. Limited availability of certain materials (e.g., Li, Fe)
3. Heat generation during operation

Key Components

1. Anode (e.g., Li-Si)
2. Cathode (e.g., FeS2)
3. Electrolyte (e.g., LiCl-KCl eutectic)
4. Separator (e.g., MgO powder)
5. Pyrotechnic heat source (e.g., Fe-KClO4)

Historical Development

1. Early technology: cup-and-cover approach
2. Pellet technology (1960s): improved electrolyte immobilization and safety
3. Modern developments: all-pellet thermal batteries, advanced materials, and designs

Performance Characteristics

1. High specific power and energy density
2. Fast activation times (under 40 ms)
3. Long shelf life (up to 25 years)

History of Thermal Batteries

The development of thermal batteries began in Germany during World War II. The batteries were used to power the guidance systems of V2 rockets. After the war, the technology was brought back to the United States, where it was further developed and adapted for use in various military applications. [6]

Technology of Thermal Batteries

Thermal batteries use a unique electrolyte system that is designed to operate at high temperatures. The electrolyte system typically consists of a lithium chloride-potassium chloride eutectic that melts at 352°C. The battery also includes a thermal management system that is designed to maintain the operating temperature of the battery. [6]

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The increasing demand for flexible, wearable, and implantable electronics has driven the development of paper-based energy storage devices. Paper is an attractive substrate for energy storage devices due to its low cost, flexibility, and sustainability. [1]

Lithium-ion batteries (LIBs) are widely used in electric vehicles and portable electronics due to their high energy density and long cycle life. However, LIBs are prone to thermal runaway, which can lead to fires and explosions. Thermal runaway is a complex phenomenon that involves the interaction of multiple factors, including chemical reactions, heat transfer, and electrical properties. [2]

Lithium-ion batteries (LIBs) are widely used in portable electronics and electric vehicles due to their high energy density and long cycle life. However, the safety concerns associated with the use of liquid electrolytes in LIBs have motivated the development of solid-state electrolytes (SSEs). SSEs are expected to provide improved safety, stability, and energy density for LIBs. However, the discovery of new SSEs with high ionic conductivity and stability remains a significant challenge. [3]

Lithium-ion batteries (LIBs) are widely used in portable electronics and electric vehicles due to their high energy density and long cycle life. The development of new anode materials is crucial for improving the performance and safety of LIBs. Anode materials should have high capacity, high rate capability, long cycle life, and good safety. [4]

Lithium-ion batteries (LIBs) have become a vital energy storage technology due to their high energy density, long lifespan, and low self-discharge property. The increasing demand for high-energy density LIBs has driven research and development in this field. This review aims to provide an overview of the evolution of LIBs, from conventional to advanced technologies, and to discuss future perspectives. [5]

Thermal batteries have been used for over seven decades in various military and space applications. The concept of thermal batteries was first conceived and developed by German scientists during World War II. The technology was later adapted in the United States and has since been widely used in various applications. [6]

Electrochemical Batteries

Electrochemical batteries are one of the most widely studied paper-based energy storage devices. They operate on the principle of electrochemical reactions between two electrodes and an electrolyte. Paper-based electrochemical batteries have been fabricated using various materials, including zinc, manganese, and copper. [1]

Biofuel Cells

Biofuel cells are another type of paper-based energy storage device that has gained significant attention. They operate on the principle of electrochemical reactions between enzymes and fuels. Paper-based biofuel cells have been fabricated using various materials, including glucose, lactate, and ethanol. [1]

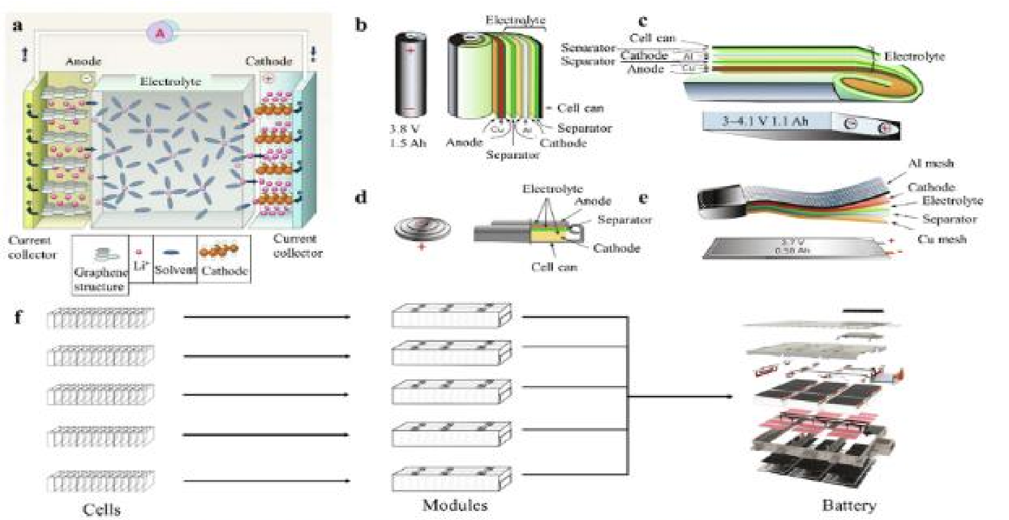

Fig. 1. (a) Schematic diagram of the fundamental structure of a LIB cell, which is the same for different cell types [36]. Copyright (2011) American Association for the Advancement of Science [36]. Cell types: (b) cylindrical cell; (c) prismatic cell; (d) coin cell; (e) pouch cell. Copyright (2001) Macmillan Magazines Ltd [41]. (f) Schematic diagram of the relationship between cell, module, and battery.

Lithium-Ion Batteries

Lithium-ion batteries are a type of paper-based energy storage device that has been widely studied. They operate on the principle of electrochemical reactions between lithium ions and electrodes. Paper-based lithium-ion batteries have been fabricated using various materials, including graphite, lithium cobalt oxide, and lithium iron phosphate. [1]

Supercapacitors

Supercapacitors are a type of paper-based energy storage device that has gained significant attention. They operate on the principle of electrostatic double-layer capacitance and electrochemical pseudocapacitance. Paper-based supercapacitors have been fabricated using various materials, including carbon nanotubes, graphene, and conducting polymers. [1]

Nanogenerators

Nanogenerators are a type of paper-based energy storage device that has been widely studied. They operate on the principle of piezoelectric or triboelectric effects. Paper-based nanogenerators have been fabricated using various materials, including zinc oxide, lead zirconate titanate, and polyvinylidene fluoride. [1]

Causes of Thermal Runaway

Thermal runaway in LIBs can be caused by a variety of factors, including undesirable chemical reactions, mechanical abuse, and electrical abuse. [2]

Undesirable Chemical Reactions

Undesirable chemical reactions can occur in LIBs due to the decomposition of the electrolyte, the oxidation of the anode, and the reduction of the cathode. These reactions can release heat and gas, which can lead to thermal runaway. [2]

Mechanical Abuse

Mechanical abuse, such as crushing or puncturing, can cause internal short circuits in LIBs, which can lead to thermal runaway. [2]

Electrical Abuse

Electrical abuse, such as overcharging or over-discharging, can cause heat buildup in LIBs, which can lead to thermal runaway. [2]

Safety Issues

LIBs are prone to a variety of safety issues, including thermal shock, local heating, and oxygen release. [2]

Thermal Batteries Overview

Thermal batteries are reliable, rugged, and robust power sources used in various applications, including artillery shells, earth-penetrator weapons, and renewable energy systems.

Historical Development

1. Early technology: cup-and-cover approach
2. Pellet technology (1960s): improved electrolyte immobilization and safety
3. Modern developments: all-pellet thermal batteries, advanced materials, and designs

Performance Characteristics

1. High specific power and energy density
2. Fast activation times (under 40 ms)
3. Long shelf life (up to 25 years)

Applications

1. Military: artillery shells, earth-penetrator weapons
2. Renewable energy: grid storage, wind, solar, geothermal
3. Aerospace: satellite power systems

To improve the safety of LIBs, we recommend the following:

1. Improved thermal management: LIBs should be designed with improved thermal management systems to prevent heat buildup and thermal runaway. [2]
2. Enhanced mechanical protection: LIBs should be designed with enhanced mechanical protection to prevent internal short circuits and thermal runaway. [2]

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3. Improved electrical protection: LIBs should be designed with improved electrical protection to prevent overcharging and over-discharging. [2]

4. Regular maintenance: LIBs should be regularly maintained to prevent degradation and thermal runaway. [2]

Representation of Compositional and Structural Information

The representation of compositional and structural information of SSEs is crucial for the development of ML models. Several approaches have been used to represent this information, including domain-knowledge-based chemical features, physics-based descriptors, and deep learning-based feature extraction. [3]

Domain-Knowledge-Based Chemical Features

Domain-knowledge-based chemical features are hand-crafted descriptors that are based on the chemical and physical properties of SSEs. These descriptors can be used to represent the compositional and structural information of SSEs. For example, Sendek et al. used a set of 40 empirical features to model the conductivity of Li-containing compounds. [3]

Physics-Based Descriptors

Physics-based descriptors are constructed from the known physics of properties. For example, the ionic conductivity of most solid substances follows an Arrhenius dependence on temperature. Zhu et al. analyzed the mean square displacements (MSDs) obtained from short ab initio molecular dynamics (AIMD) simulations at 800 and 1200 K for known superionic conductors. [3]

Deep Learning-Based Feature Extraction

Deep learning-based feature extraction uses deep learning models to learn the features from the data. For example, the crystal graph convolutional neural network (CGCNN) has been used to represent the crystalline structure of SSEs. [3]

Machine Learning Models

Several ML models have been used to predict the ionic conductivity of SSEs, including supervised regression, supervised classification, and unsupervised screening. [3]

Supervised Regression

Supervised regression models are trained on a dataset of SSEs with known ionic conductivity. The model learns the relationship between the compositional and structural information of SSEs and their ionic conductivity. For example, Fujimura et al. used a supervised regression model to predict the conductivity of LISICON compounds. [3]

Supervised Classification

Supervised classification models are trained on a dataset of SSEs with known ionic conductivity. The model learns to classify SSEs as either good or poor conductors. For example, Sendek et al. used a supervised classification model to screen 12000+ Li-containing compounds. [3]

Unsupervised Screening

Unsupervised screening models are used to identify patterns in the data without prior knowledge of the ionic conductivity of SSEs. For example, Zhu et al. used an unsupervised screening model to identify potential SSEs with high ionic conductivity. [3]

Challenges and Opportunities

Despite the recent advances in ML guided discovery of SSEs, there are still several challenges and opportunities in the field. [3]

Challenges

1. Data scarcity: The availability of high-quality data on SSEs is limited, which makes it challenging to develop accurate ML models. [3]

2. Complexity of SSEs: SSEs are complex materials with multiple components and phases, which makes it challenging to develop accurate ML models. [3]

3. Interpretability of ML models: The interpretability of ML models is limited, which makes it challenging to understand the underlying physics of SSEs. [3]

Opportunities

1. Integration of ML with experiments: The integration of ML with experiments can accelerate the discovery of new SSEs. [3]

2. Development of new ML models: The development of new ML models can improve the accuracy and interpretability of ML models. [3]
3. Application of ML to other energy storage materials: The application of ML to other energy storage materials can accelerate the discovery of new materials. [3]

Graphitic Carbons

Graphitic carbons are widely used as anode materials for LIBs due to their high capacity, high rate capability, and long cycle life. However, graphitic carbons have some disadvantages, such as low volumetric capacity and high cost. [4]

Hard Carbons

Hard carbons have small graphitic grains with disordered orientation, which makes them less susceptible to exfoliation. Hard carbons also have nanovoids between the grains, which results in reduced and isotropic volume expansion. However, hard carbons have some disadvantages, such as low density and high irreversible capacity loss. [4]

Lithium Titanium Oxide (LTO)

Lithium titanium oxide (LTO) is a promising anode material for LIBs due to its high safety, high rate capability, and long cycle life. LTO has a "zero strain" intercalation mechanism, which results in a small voltage hysteresis and high stability. [4]

Conversion Materials

Conversion materials are a type of anode material that undergoes a conversion reaction with lithium ions. Conversion materials have high capacity and high rate capability, but they also have some disadvantages, such as large volume change and high irreversible capacity loss. [4]

Alloying Materials

Alloying materials are a type of anode material that undergoes an alloying reaction with lithium ions. Alloying materials have high capacity and high rate capability, but they also have some disadvantages, such as large volume change and high irreversible capacity loss. [4]

Strategies for Improving Performance and Safety

Several strategies have been used to improve the performance and safety of anode materials, including surface modification, composite formation, and nanostructuring. Surface modification can improve the stability and rate capability of anode materials. Composite formation can improve the capacity and stability of anode materials. Nanostructuring can improve the rate capability and stability of anode materials. [4]

Evolution of LIBs

Conventional LIBs use lithium cobalt oxide ($LiCoO_2$) as the cathode material and graphite as the anode material. However, these batteries have limitations in terms of energy density and safety. Advanced LIBs, such as Li-rich transition metal oxide and Ni-rich transition metal oxide batteries, have been developed to address these limitations. [5]

State-of-the-Art LIBs

Several state-of-the-art LIBs have been developed, including Li–air, Li–sulfur, organic electrode, solid-state, and Li–CO_2 batteries. These batteries offer improved energy density, safety, and sustainability. [5]

Hybridized LIBs

Hybridized LIBs, such as metal halide perovskite batteries, have been developed to combine the benefits of different battery technologies. [5]

Stand-Alone Energy Devices

Stand-alone energy devices that combine energy harvesting technologies with LIBs have been developed for off-grid applications. These devices offer a sustainable and reliable energy solution. [5]

Applications of Thermal Batteries

1. Guided Missiles: Thermal batteries are used to power the guidance systems of guided missiles. [6]
2. Proximity Fuzes: Thermal batteries are used to power the proximity fuzes used in ordnance [6]devices.
3. Space Exploration: Thermal batteries have been used in various space exploration missions, including the Galileo mission to Jupiter. [6]
4. Emergency Backup Power: Thermal batteries are used to provide emergency backup power for critical systems in military aircraft. [6]

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Research is currently underway on several types of batteries, including:

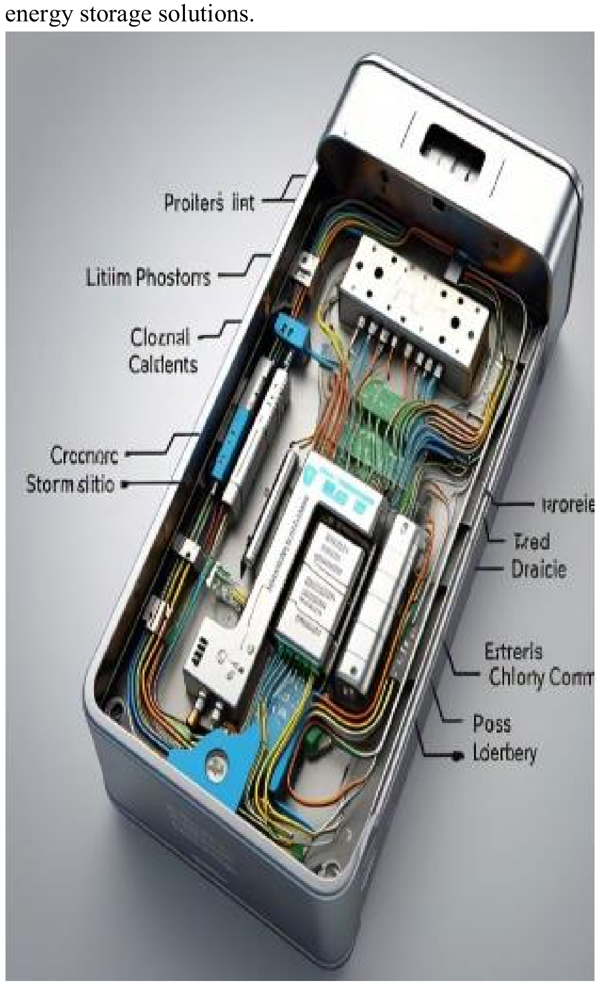
Lithium-Sulfur Batteries: These batteries have been identified as promising alternatives to traditional lithium-ion batteries due to their high energy density and abundant resources. However, challenges such as the "shuttle effect" and sluggish transformation of lithium polysulfides need to be addressed [1].

Lithium Phosphorus Oxynitride (LiPON) Batteries: LiPON has paved the way for thin-film solid-state battery technology development and has shown applications in various fields. Research is focused on understanding how different preparation methods affect the properties of LiPON [2].

Lithium Phosphorus Sulfide Chloride-Polymer Composite Batteries: These batteries are being explored for their potential to improve stability toward dendrite formation in lithium-ion solid electrolytes [3].

Solid-State Batteries: Researchers are working on developing solid-state batteries that replace the liquid electrolyte with a solid material, enhancing safety and energy density.

These emerging battery technologies aim to address the limitations of traditional lithium-ion batteries and provide more efficient, sustainable, and safe energy storage solutions.



II. CONCLUSION

While Li-ion batteries have significant advantages, their high cost and potential material shortages may limit their widespread adoption. However, the authors argue that Li shortages are unlikely in the near future, and rising prices can drive innovation and increased production.[2]

Paper-based super capacitors offer a promising technology for energy storage. Further research is needed to improve their performance, scalability, and cost-effectiveness.[1]

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