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A Review: Halide Perovskites Materials For Energy Storage Sup

Abstract

Due to the increasing global energy demand, it is essential to develop materials for energy conversion and storage in a coordinated manner. Modern energy systems rely heavily on energy storage technologies, which are vital for efficiently capturing, storing, and releasing energy to accommodate varying demands. Supercapacitors, in particular, have become highly significant because of their high power density, fast charging and discharging abilities, and extended cycle life, making them perfect for applications that require rapid energy bursts and frequent cycling. Recently, halide perovskites have transformed energy applications, especially in solar cells and light-emitting devices. These materials are highly valued for their outstanding optoelectronic properties, ease of production, and adjustable band gaps, leading to their swift integration into next-generation energy harvesting and storage systems. Collectively, the progress in supercapacitors and halide perovskites is propelling innovation towards more efficient, sustainable, and adaptable energy solutions.

Halide perovskites, traditionally recognised for their outstanding optoelectronic properties in solar cells, have recently attracted considerable attention as promising materials for energy storage applications, including supercapacitors. Their ABX3 crystal structure, where A is a cation (often organic or inorganic), B is a metal cation (commonly lead or tin), and X is a halide anion (Cl, Br, I), enables tunable optoelectronic characteristics and high charge-carrier mobility. These properties contribute to improved charge storage capability and rapid charge–discharge cycles in supercapacitor systems. This article reviews recent progress in halide perovskite-based energy storage systems, with a particular focus on

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supercapacitors

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Introduction

The increasing pollution from fossil fuels and the continuous energy crises have raised demand for renewable energy sources in recent years. The perovskite structure is a particular crystal structure that distinguishes perovskite materials from other crystalline substances. The general chemical formula of perovskite is ABX_3 where (A=Cs+, $CH_3NH_3^+$, CH $(NH_2)^{2+}$, B=Pb^{2+},Sn^{2+}, X=Cl, Br, I) (Sharif, Rabia, et al. 2023) Perovskite materials have unique features due to their unusual structure, which makes them very attractive and adaptable for a range of applications such as supercapacitors and batteries (Kim, Jin Young, et al. 2020). Perovskites have also been used as photodetectors, lasers, and catalysts (Chen, et al. 2023).

Due to their high power density, supercapacitors (SCs) or ultracapacitors, one type of ESS, have garnered a lot of attention and been used in a number of applications during the past ten years (Sharma, et al. 2023),

Long cycle life and quick charging and draining capabilities. Because SCs have better energy and power densities than batteries and capacitors, they effectively close the gap between the two (Guo, Wenfeng, et al. 2017; Pershaanaa, M., et al. 2022).The types of charge storage methods and electrode materials distinguish the two types of ultracapacitors known as EDLCs (electric double-layer capacitors) and pseudocapacitors. A pseudocapacitor uses either metal oxides or conducting polymer electrode material to store charge through an oxidation-reduction mechanism (Saini, S., & Chand, P. 2022). In the case of EDLCs, charge is electrostatically stored due to ion adsorption at the electrode-electrolyte interface (EEI) (Sharma, S., & Chand, P. 2023) Applications for carbon-bearing electrodes include graphene, activated carbon (Yadav, Mahendra Singh, et al. 2021), carbon aerogels and carbon nanotubes.The advantages of EDLCs and class pseudocapacitors, both of which have high power and energy (Abdah, Muhammad Amirul Aizat Mohd, et al. 2020) are a component of hybrid supercapacitors. The supercapacitor taxonomy is clearly displayed in Figure .1 (Kambale, S. V., & Lokhande, B. J. 2023)

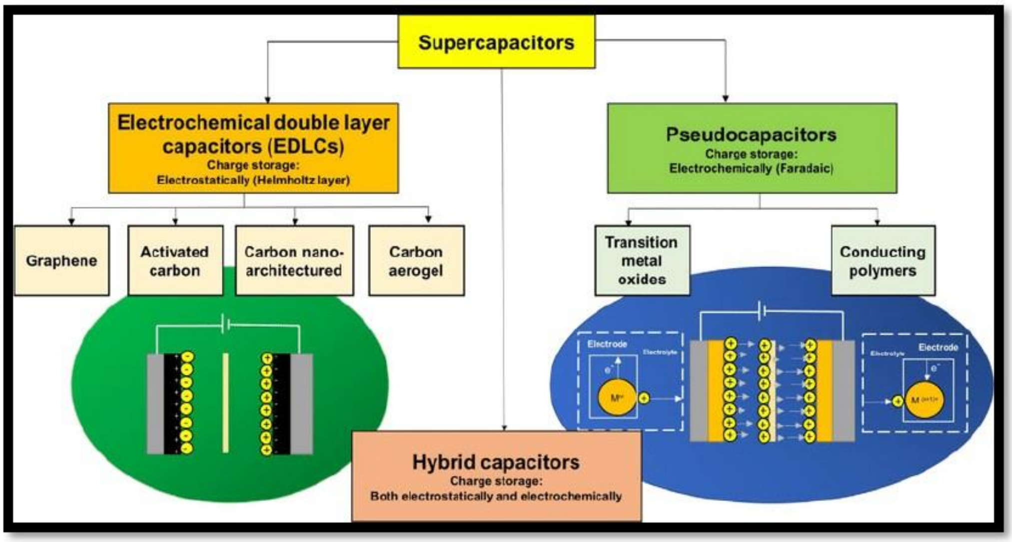

Fig.1. Taxonomy of Electrochemical Supercapacitors.

1.1 Overview of Supercapacitors and Their Importance

In the past ten years, supercapacitors have drawn a lot of attention from researchers because of their high power density, quick charge-discharge rate, and long cycling stability (Li, Huan, et al. 2016). Supercapacitor are a new form of energy storage technology that shows promise for use in several applications. Supercapacitor are more important than other options because to their superior power density and storage capabilities. the other modern energy storage devices because of its various benefits, which include their varied operating temperature, high power density, long life cycle, high specific capacitance, excellent performance, and environmental friendliness. They may also be filling the gaps between conventional condensers and batteries because they have been rapidly charged with rapid power delivery (Thiagarajan, K., et al. 2017). Supercapacitor are divided into two categories based on the charge storage mechanism: pseudocapacitors and electric double-layer (EDL) capacitors (Wang, Jinhui, et al. 2019).

1.2 The Role of Halide Perovskites in Energy Storage

Halide perovskite used as energy storage materials such as supercapacitor because halide perovskite materials have shown a number of innovative characteristics, such as exceptional ambipolar charge carrier behaviors (such strong carrier mobility and long diffusion duration), high defect tolerance, high photoluminescence yield (PLQY), and bandgap tunability (Cho, Himchan, et al. 2018), MHPs' superior ion diffusion qualities are causing them to flourish in the field of energy storage applications (Wang, Yonggang, et al. 2010).

2. Structure of Halide Perovskites

2.1 Structure and Composition of Halide Perovskites

A monovalent cation (like methylammonium), a divalent metallic cation (like lead and tin), and a halogen monovalent anion (like F, Cl, Br, and I) make up the common ABX_3 formula shared by the halide perovskites. Corner-shared octahedra create the ABX3 halide perovskites, resulting in an extensive network within the crystal structure. Crystal structure of halide perovskites show in figure 2 (Kim, Hyojung, et al. 2018;Jung, H. S., & Park, N. G. 2015).

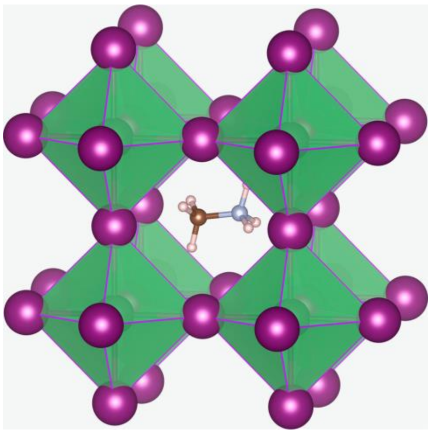

Fig:-2 Crystal structure of halide perovskites.

. **2.2 Crystal structure of 2D& 3D halide perovskites**

The An−1BnX$_{3n+1}$ layer is sandwiched between the bulky organic cations in 2D R–P or D–J layered perovskites, where n is to the perovskite slab's thickness or number of unit cells. When n = 1, a monolayered 2D structure is formed (Stoumpos, Constantinos C., et al. 2016). Compared to the ABX$_3$ varieties, 2D R–P or D–J layered perovskites have greater structural flexibility. Furthermore, in terms of stability and optoelectronics, layered 2D halide perovskites outperform their 3D counterparts, showing promise for energy-harvesting and light-emitting applications (Li, Haojin, et al. (2022; Cho, Junsang, et al. 2020).

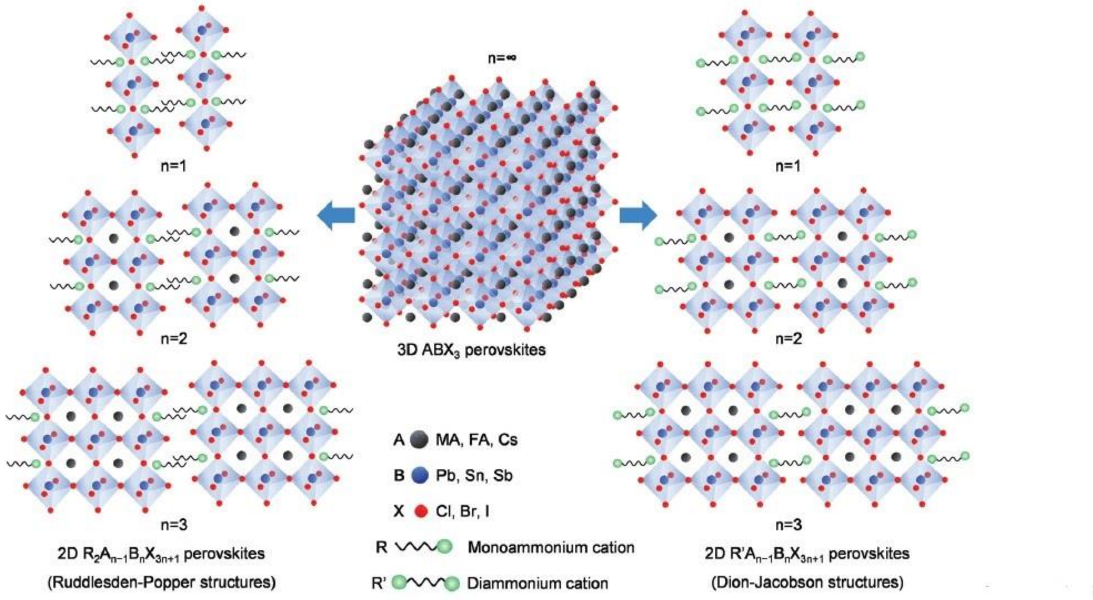

Fig:-3.Crystal structure of 2D & 3D halide perovskites

2.3 Properties of Halide Perovskites Relevant to Supercapacitors

In supercapacitors, perovskite materials can be employed as the cathode, anode, or both. The materials used for active electrodes in supercapacitors should be those that possesses a high absorption coefficient together with high ionic and electronic mobilities. Zhou et al. initially showed that the flow of free charge carriers is mostly responsible for activating the ionic conduction of methylammonium lead triiodide (MAPbI3) in an electrochemical supercapacitor and the ion kinetics (Zhou, Shuang, et al. 2016). later; solid-state HHP-based electrochemical supercapacitors with a high energy density and exceptional cyclic capacity were described by Popoola et al. They had an areal capacitance of 21.50 µF cm−2 (Popoola, Idris, et al. 2020). Many teams are striving to create new electrode materials, electrolytes, and topologies for supercapacitors in an effort to increase their charge-discharge rate, capacity, cycle lifespan, energy density, and power density (Romanitan, Cosmin, et al. 2018). Supercapacitors can be broadly classified into two types: symmetric and asymmetric. Electrode/electrolyte/separator/electrolyte/electrode structure is the typical architecture for supercapacitors (Liu, N., & Gao, Y. 2017).

3 Mechanisms of Charge Storage in Supercapacitors

Supercapacitors' capacitance is mostly caused by surface reactions of the electrode materials, such as surface faradic redox reactions (also known as pseudocapacitive behavior) and electrochemical adsorption/desorption of cations and anions at the electrode/electrolyte interface (also known as capacitive behavior; Fig. 4 shows Charge storage mechanism of supercapacitor) (Simon, P., & Gogotsi, Y. (2008; Conway, B. E. 2013). As a result, supercapacitors fall into two categories: pseudocapacitors and electrochemical double-layer capacitors (EDLCs).Porous carbon has become a popular electrode material for EDLCs in recent years. For EDLCs, transition metal oxides or conductive polymers show significantly higher specific capacitance than carbon materials and typical pseudocapacitance (Simon, P., & Gogotsi, Y. 2008; Conway, B. E. 2013;Kötz, R., & Carlen, M. J. E. A. 2000). Supercapacitors frequently use graphene, carbon nanotubes, activated carbon, conducting polymers (like polyaniline and polypyrrole), metal oxides (like manganese oxide and ruthenium oxide), and certain MOFs (metal-organic frameworks),Certain energy storage devices have the ability to alter the type of energy they store. These consist of rechargeable or Li-ion (Li-ion) batteries, fuel cells, ultracapacitors (supercapacitors), and capacitors. (Deng, Xiaoyang, et al. 2017)

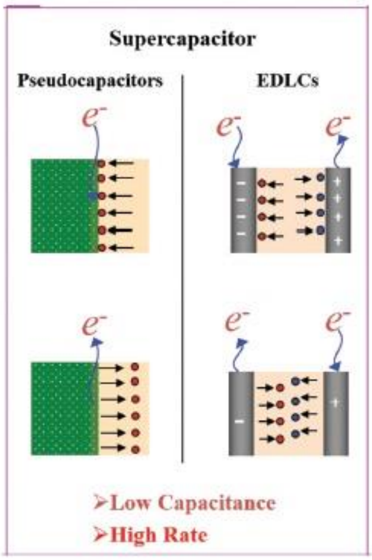

Fig:-4 Charge storage mechanism of supercapacitor

4 Recent Advances in Halide Perovskite Materials for Supercapacitors

4.1. Synthesis and Fabrication Techniques

(Tudu, Surajit, et al. 2024),states that the greatest specific capacitance, energy density, and power density of the produced $MASnCl_3$ nanocrystals (NCs) were 2050 F/g, 102 Wh/kg, and 12 kW/kg, respectively. The $MASnCl_3$ NCs' charge storage mechanism was primarily capacitive (94.16%) with a minor diffusive component (5.84%). After 1000 charge-discharge cycles, the $MASnCl_3$ NC-based supercapacitor device maintained 80.7% of its initial specific capacitance. (Yadav, A., & Bag, M. 2024), states that As a supercapacitor electrode, the $Cs_3Bi_2I_9$ halide perovskite material demonstrated a high specific capacitance (about 242 F/g) and energy density (approximately 140 Wh/kg). Out of all the halide perovskite-based supercapacitors that have been reported to date, the $Cs_3Bi_2I_9$ device exhibited the highest areal energy density (about 23 µWh/cm2).With 79% and 82% capacitance retention under 180° bending and 200 bending cycles, respectively, the Cs3Bi2I9 supercapacitor device demonstrated good flexibility. (Yadav, Ankur, et al. 2023) states that Inorganic halide perovskite-based supercapacitors with Li-ion electrolytes can achieve high energy densities of around 250 Wh/kg.Phase transitions that happen in the bulk material can be avoided by stabilizing the material structure during Li-ion intercalation by the introduction of $CsPbBr_3$ perovskite nanocrystals, which are about 10 nm in size. The employment of Li-ion electrolytes and perovskite nanocrystals can increase the performance and cyclic stability of halide perovskite supercapacitors.

5 Performance Metrics

5.1 Specific Capacitance

(Zhou, Jin, et al. 2015) produced N-doped hierarchical porous carbon materials by precarbonization and KOH activation using m-aminophenol formaldehyde resin as a carbon and N source. With high specific capacitance retention of 94.1% after 10,000 cycles and a specific capacitance of 271.5 F g^{-1} under 0.2 A g^{-1}, it demonstrated good electrochemical performance when used as a supercapacitor electrode material. (Wang, Zhao, et al. 2014) created activated mesoporous carbons (AMCs) by activating phenolic resin-based carbon with KOH. The mass ratio of KOH/carbon could be changed to produce AMCs with 1118 m^2 g^{-1} of specific area. In 1 M H_2SO_4, the capacitance demonstrated a high specific capacitance of 260 F g^{-1} under 1 A g^{-1} and 163 F g^{-1} under 20 A g^{-1}. Additionally, the capacitance did not decrease after 10,000 cycles at 2 A g^{-1}.

(Yadav, A., & Bag, M. 2024) from $CsPbI_3$ to $FAPbI_3$, the specific capacitance rises as the surface area increases. Out of the three halide perovskite materials that were examined, $FAPbI_3$ had the highest specific capacitance and $CsPbI_3$ had the lowest. Because of the strong ionic mobility of the $FAPbI_3$ material, the solid-state asymmetric supercapacitor based on this material was able to reach a specific areal capacitance of over 72 mF cm^{-2}, which is at least six times higher than the devices based on $CsPbI_3$.

6 Energy Density and Power Density

(Yadav, Ankur, et al. 2022).stats that the maximum energy density of around 22 Wh kg^{-1} and power density of 600 W kg^{-1} for the supercapacitor were achieved with a particular ratio of bromide to iodide in the perovskite material. In comparison to pure halide perovskites, the mixed halide perovskite exhibited a much reduced charge transfer resistance (40.5 Ω cm^{-2}) and a significantly better ionic conductivity (3.2×10^{-13} m^2 s^{-1}). The overall stability and Coulombic efficiency of the device were reduced when the iodide content of the mixed halide perovskite was increased.

7 Future Perspectives and Research Directions

The future of halide perovskites in energy storage supercapacitors holds significant promise, driven by their unique structural and electronic properties. One key area for advancement is enhancing the environmental stability of these materials. Research should focus on developing eco-friendly synthesis routes and robust encapsulation techniques to mitigate moisture sensitivity and thermal degradation, thereby extending device lifetimes and enabling practical applications. Scaling up fabrication processes while maintaining material quality and performance is critical for commercialization.This includes refining solution processing and vapor deposition methods to produce uniform, defect-free perovskite films or nanostructures at industrial scales. Additionally, integrating halide perovskites with flexible substrates and solid-state electrolytes can pave the way for wearable and portable supercapacitor devices.

Hybrid systems that combine halide perovskites with carbon-based materials, conductive polymers, or metal oxides warrant further exploration to synergistically enhance capacitance, power density, and cycling stability. Investigating novel architectures, such as three-dimensional nanostructures and multilayer composites, may unlock superior charge storage capabilities and faster ion transport. Fundamental studies on ion migration dynamics within the perovskite lattice and the role of halide ions in pseudocapacitive behavior will deepen understanding and guide targeted material engineering. Research should also address the environmental impact and recyclability of perovskite-based supercapacitors, aligning with sustainability goals.

Overall, interdisciplinary efforts combining materials science, electrochemistry, and device engineering will be essential to realize the full potential of halide perovskites in next-generation energy storage technologies, facilitating their transition from laboratory research to real-world applications.

Conclusions

Halide perovskites have demonstrated considerable potential as advanced materials for energy storage supercapacitors due to their distinctive structural, electronic, and ionic properties. Their tunable composition and high ionic conductivity enable efficient charge storage mechanisms, including electric double-layer capacitance and pseudocapacitance. Despite challenges related to environmental stability, moisture sensitivity, and ion migration, ongoing research in synthesis methods, material engineering, and hybrid system integration is progressively addressing these limitations. Advances in scalable fabrication techniques and novel device architectures further support the practical application of halide perovskite-based supercapacitors. Continued interdisciplinary efforts focusing on stability enhancement, eco-friendly processing, and performance optimization are essential to transition these materials from laboratory-scale studies to commercial energy storage solutions, promising a new generation of high-performance, flexible, and sustainable supercapacitors.

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