

Review: Lead Sulfide (PbS) Thermoelectric PropertiesSalah Uddin*

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Abstract

This article presents lead sulfide (PbS) as a notable thermoelectric material for converting heat into electricity. PbS exhibits a high thermoelectric figure of merit (ZT) of 1.7 at 900 K, showcasing its efficiency in thermoelectric modules with conversion efficiencies exceeding 11% at 585 K. Crystal structure, electronic properties, and synthesis methods, particularly nanoparticle synthesis techniques, are discussed. The significance of doping and nanostructuring for enhancing thermoelectric efficiency is highlighted, alongside factors like alloying and effective mass reduction. Applications range from waste heat recovery to space missions and solar converters, leveraging PbS's stability and high efficiency. Limitations such as lead toxicity and narrow bandgap are acknowledged. Future research aims at lead-free alternatives, bandgap engineering, and exploring PbS's multi-functional capabilities in energy technologies.

Keywords: Figure of Merit, Doping, Nanostructuring, Seebeck Coefficient, Bandgap

1. Introduction

Thermoelectric materials are substances that can convert heat directly into electricity (thermoelectric power generation) or vice versa (thermoelectric cooling). This phenomenon is based on the Seebeck effect, where a temperature difference across the material generates a voltage difference, creating an electric current. Conversely, applying an electric current can create a temperature difference, leading to cooling effects (Peltier effect) [1-8]. Key characteristics of thermoelectric materials include Seebeck Coefficient, Electrical Conductivity, Thermal Conductivity and Figure of Merit (ZT) which is a dimensionless number indicating the overall thermoelectric performance [9-15]. The equation for ZT is expressed as: $ZT = S^2 \sigma T / \kappa$ can also be applied to PbS to further enhance its thermoelectric performance by reducing thermal conductivity and enhancing electrical transport properties. Moreover, lead and sulfur are abundant and cost-effective elements, making PbS an attractive choice for large-scale energy applications [6,15].

Overall, PbS stands out as a promising thermoelectric material due to its favorable properties, cost-effectiveness, versatility, and potential for continued advancements in thermoelectric technology. It can be compared with the oxide-based material investigation for the advanced research technology [16-24]. In

this review article, we intend to study future smooth research investigations, such as electrostatic spray deposition (ESD) and arc melting sintering process advancement for material fabrication processes. However, it should be noted that Abbas et al. [25-36] have developed the material characteristics considering thermodynamic and transport dynamics investigation routes. This group has been keeping the Fortran code language for the bulk of the phenomenon investigation. Their procedure may be employed for the PbS investigation process. Other research activities also addressed different research routes considering IoT- and AI-based research [37-50]. Large-scale AI methods may also be a significant area of research for PbS [37-50].

2. Methods

The synthesis of PbS nanoparticles can be achieved through various methods tailored to control particle size, structure, and properties. One such method is the Surfactant-Free Microemulsion Scheme (CID-SFME), which utilizes a microemulsion system without surfactants. This method is notable for producing small PbS nanoparticles in the quantum-dot regime, typically ranging from 13.17 to 26.91 nm. The quantum confinement effect in CID-SFME leads to a reduction in the band gap as particle size increases, making it suitable for applications like photodetectors. Additionally, CID-SFME offers the advantage of simplicity by

eliminating the need for capping agents [9].

Another method, the Chemical Reaction with Thiourea, involves a straightforward chemical reaction between lead acetate and thiourea at room temperature. This method is convenient and commonly used for fundamental studies due to its ease of implementation. Characterization techniques such as EDAX, XRD, TEM, UV-VIS-NIR spectroscopy, and photoluminescence are typically employed to study the synthesized PbS nanoparticles. While the Thiourea method may not offer the same level of precise particle size control as CID-SFME or quantum dot synthesis, it serves as a benchmark for nanoparticle synthesis and analysis [10].

The Solution-Based Method for Quantum Dots (QDs) represents another approach focusing on solution-based synthesis of PbS

quantum dots with the assistance of chemicals to limit nanocrystal size to quantum levels. This method leverages quantum confinement effects, resulting in discrete energy levels within the nanocrystals. As a result, PbS quantum dots exhibit size-dependent optical and electronic behavior, making them ideal for optoelectronic devices such as solar cells and LEDs. The Quantum Dot Synthesis method offers precise control over nanocrystal size and tailored optoelectronic properties, albeit potentially involving more intricate processes compared to other methods [11].

3. Results and Discussion

Lead sulfide (PbS), commonly known as galena, has a rich history dating back to ancient times. It was primarily used as a dark pigment in civilizations such as ancient Egypt, Greece, and Rome.

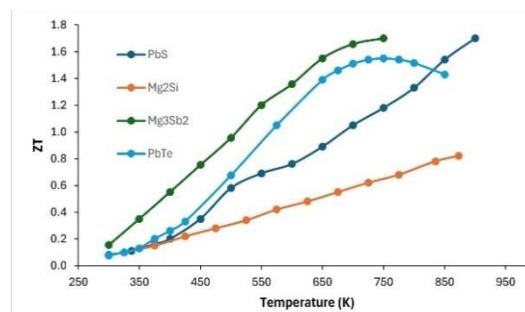


Figure 1: Figure of Merit (ZT) vs Temperature for Various Thermoelectric Materials [3-6].

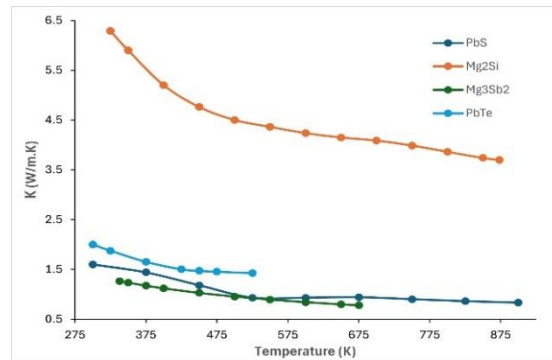


Figure 2: Thermal Conductivity (κ) vs Temperature for Various Thermoelectric Materials [3-6].

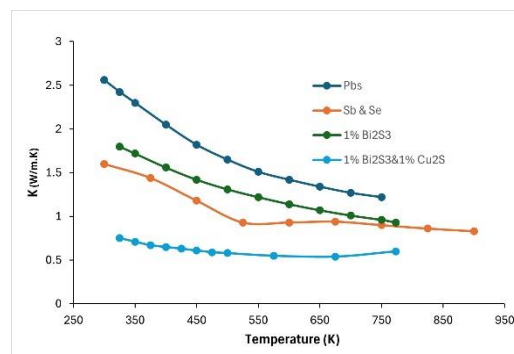


Figure 3: Thermal Conductivity (κ) vs Temperature [3,8].

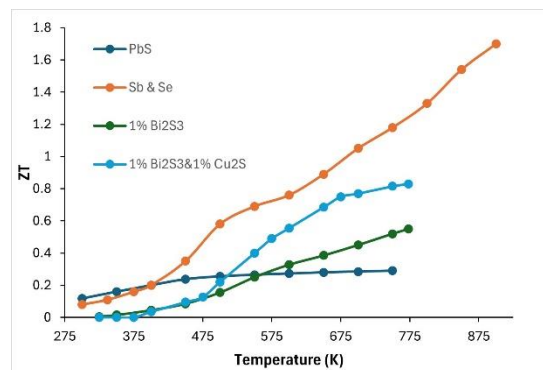


Figure 4: Figure of Merit (ZT) vs Temperature [3,8].

However, PbS's significance extends beyond art. In the 19th century, Thomas Johann Seebeck's discovery of the Seebeck effect—the generation of a voltage across a temperature gradient in certain materials—marked the beginning of systematic thermoelectric study. PbS emerged as a semiconductor material with a notable Seebeck coefficient, setting the stage for further exploration. From Figures 1 and 2, it is evident that PbS exhibits promising thermoelectric properties, particularly at higher temperatures, due to its steadily increasing ZT and low thermal conductivity. This combination suggests that PbS can be effectively used in high-temperature thermoelectric devices, providing a balance of good thermoelectric performance and stability.

PbS-based materials became attractive for thermoelectric power generation due to their cost-effectiveness and widespread availability. However, their high lattice thermal conductivities posed challenges. Researchers focused on enhancing PbS's thermoelectric properties by doping it with various elements. This approach aimed to increase electrical conductivity while preserving or improving the Seebeck coefficient. Notably, efforts to reduce lattice thermal conductivity—such as introducing zigzag nanoprecipitates—significantly boosted overall thermoelectric efficiency.

Lead sulfide (PbS) exhibits promising thermoelectric characteristics, including high electrical conductivity and a tailorable bandgap. Furthermore, its abundant nature and low cost make it an attractive candidate for large-scale applications. It has fascinating thermoelectric properties, especially when doped with elements like Bi₂S₃ and Cu₂S. The process of synthesizing hierarchical PbS powders using the hydrothermal method and then consolidating them into bulk ceramics via spark plasma sintering (SPS) is quite intriguing.

For instance, PbS doped with 1% Bi₂S₃ displayed a moderate Seebeck coefficient, high electrical conductivity, and low thermal conductivity, resulting in a maximum figure of merit (ZT) of 0.55 at 773 K. Furthermore, co-doping with 1% Bi₂S₃ and 1% Cu₂S resulted in an improved power factor and reduced thermal conductivity at elevated temperatures, achieving a ZT value of 0.83 at 773 K [8].

4. Conclusions

Lead sulfide (PbS) exhibits exceptional thermoelectric efficiency. Its high ZT of 1.7 at 900 K and over 11% conversion efficiencies at 585 K underscore its potential in energy conversion. Despite challenges like lead toxicity and a narrow bandgap (0.41 eV), PbS's cost-effectiveness, stability, and versatile applications in energy conversion are evident. Future efforts should target lead-free options, wider bandgaps, and structural enhancements for broader applications. With ongoing research, PbS holds great promise for driving advancements in thermoelectric technology towards more sustainable and efficient energy conversion solutions.

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