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Mini Review

Thermoelectric Materials Based on Lead Telluride and Prospects for their Practical Application

Yuriy Pavlovskyy[1]* and Nadiya Pavlovska[2]

[1]Candidate of Physical and Mathematical Sciences, Associate Professor of the Department of Technological and Professional Education Ivan Franko Drohobych State Pedagogical University, Drohobych, Ukraine

[2]Candidate of Physical and Mathematical Sciences, Teacher of the Highest Category at Lesya Ukrainka Lyceum No. 4 of the Drohobych City Council of the Lviv Region, Drohobych, Ukraine

Abstract

Lead telluride (PbTe) is considered one of the most promising materials in thermoelectrics due to its unique thermoelectric properties. This semiconductor exhibits a high thermoelectric figure of merit (ZT) in certain temperature ranges, making it highly effective for converting heat energy into electricity. Additionally, PbTe is characterized by stability and low thermal conductivity, which further enhances the efficiency of thermoelectric devices. Another advantage of using PbTe is its relative affordability and high availability of raw materials. This makes it attractive for manufacturing mass thermoelectric devices such as thermoelectric modules for automobiles, industrial thermoelectric generators, heat recirculation, and others. The paper provides a review of works and an analysis of general approaches to semiconductor thermoelectric materials, including lead telluride.

More Information

***Address for correspondence:** Yuriy Pavlovskyy, Candidate of Physical and Mathematical Sciences, Associate Professor of the Department of Technological and Professional Education Ivan Franko Drohobych State Pedagogical University, Drohobych, Ukraine, Email: yu_pavlovskyy@ukr.net

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https://orcid.org/0000-0002-8194-6820

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Introduction

Recent achievements in the field of thermoelectrics encompass a wide range of directions, including the development of new thermoelectric materials with enhanced thermoelectric properties, optimization of manufacturing processes and design of thermoelectric devices, as well as applications in renewable energy and energy-efficient technologies [1]. Some of the most significant achievements include the development of new nanostructured materials with a high thermoelectric figure of merit (ZT), the improvement of crystal growth and film synthesis methods, and the implementation of thermoelectric devices in the electronics and automotive industries. Thermoelectrics is increasingly important in the search for new energy sources and in addressing energy efficiency issues, making it one of the most actively researched fields in modern science and technology.

Lead chalcogenides and compounds based on them find wide application in thermoelectrics. However, for the extensive utilization of lead telluride in thermoelectric applications, researchers continue to improve its production technology, optimize strengthening processes, and control its microstructure. This effort is aimed at further increasing the ZT coefficient and enhancing the efficiency of thermoelectric devices based on this material. All of this underscores the potential and prospects of using lead telluride in thermoelectric applications, which can play a significant role in the development of energy-efficient technologies and addressing energy-efficiency issues. The article provides an overview of works and analysis of general approaches to semiconductor thermoelectric materials, including lead telluride.

Discussion

The development of new technologies with energy-saving characteristics, the creation of renewable energy sources that are efficient, the utilization of thermal waste, autonomous energy sources, etc., are among the most significant and priority directions of global scientific research and are highly relevant today. Therefore, at present, the development of science and technology is undoubtedly linked to successes and progress regarding the improvement of technologies for obtaining traditional semiconductor materials, as well as issues related to the development and research of new semiconductor structures [2,3].

The efficiency of using thermoelectric semiconductor materials primarily depends on their thermoelectric figure of merit

$$Z = \frac{S^2\sigma}{\chi},$$

Where S is the Seebeck coefficient, σ is the specific electrical conductivity, χ is the thermal conductivity coefficient, as well as the possibility of this parameter reaching high values [3].

The coefficient of thermoelectric efficiency or the coefficient of thermoelectric conversion ZT allows you to make a proper assessment of the efficiency of the thermoelectric material at different temperatures T [3]

$$ZT = \frac{S^2\sigma T}{\chi}.$$

When it comes to increasing the thermoelectric efficiency coefficient, it should be understood that optimizing the entire set of parameters cannot be achieved solely by increasing or minimizing one of the variables. High Seebeck coefficient, as well as significant electrical and thermal conductivity, are essential for highly efficient thermoelectric materials. To obtain a material with the highest possible effective electrical and thermal conductivity, it is necessary to optimize these parameters independently of each other.

For thermoelectric materials, the value of the dimensionless thermoelectric figure of merit is equally important. Therefore, when the parameter $ZT \approx 1$, it should be noted that these materials will have considerable value for practical applications. With a value of $ZT \approx 2$-3, the efficiency coefficient would be approximately 20, which would naturally increase the demand for these materials (at T = 300 K). Moreover, with a dimensionless thermoelectric figure of merit $ZT \approx 3$-4, thermoelectric converters would have the potential to be competitive even with electric generators. With the help of the electronic subsystem (assuming $P = S^2\sigma$ – power coefficient), it is possible to determine the thermoelectric power coefficient as well as electrical conductivity. As for thermal conductivity, this parameter is determined by both the electronic and phonon subsystems, namely $\chi = \chi_{el} + \chi_{ph}$, where χ is the overall thermal conductivity coefficient, and χ_{el} and χ_{ph} are electronic and phonon thermal conductivity, respectively. However, the issue with modern traditional thermoelectric materials such as Bi_2Te_3, PbTe, PbSe, and PbS, remains their relatively low thermoelectric efficiency coefficient $ZT \sim 0.6$ [1,4]. Therefore, many researchers and scientists are engaged in the search for new materials or improving the properties of already known thermoelectric materials to obtain a high ZT value.

Among the thermoelectric materials already used for the manufacture of electric power generators, lead telluride (PbTe) should be noted. PbTe is a promising and effective semiconductor material for the medium temperature region (500 - 750)K [5]. For the creation of thermoelectronic energy converters, photo-receiving devices, as well as emitting structures of the mid- and far-infrared range of the optical spectrum, lead telluride is the basic and main material. Among other thermoelectric materials, PbTe is distinguished by its properties: the value of the energy spectrum ($N = 4$); lattice thermal conductivity has a rather low value ($\chi_{latt} = 2.09 \cdot 10^{-2}$ W·K^{-1}·cm^{-1}); the mobility of electron charge carriers is quite high ($\mu_e \approx 10^3$ cm^2·V^{-1}·s^{-1}); the value of μ_e/χ is one of the largest. At such values of these quantities, the maximum value of the thermoelectric factor ($Z_{\max}$) tends to increase [6,7].

Many experimental studies of lead telluride and thin films based on it are given in literary sources [8-10], but there is no information about the entire complex of thermoelectric characteristics of this material, only individual properties are studied. Therefore, the next task should be to optimize the set of thermoelectric, structural, and micromechanical characteristics, properties, and parameters of this semiconductor material.

So, it is possible to formulate the main criteria that are basic for highly efficient thermoelectric materials:

- Weighted value of $\frac{\mu m^{*3/2}}{\chi}$ (m^* – effective mass of media);
- Significant doping of the material (up to a concentration of 10^{19} - 10^{20} cm^{-3}), we are talking about donor and acceptor impurities that have the required solubility in this material;
- A rather high effective mass of charge carriers, for the value of μ/χ, which is characteristic for a broad plan of the energy spectrum;
- A weak decline in the mobility of charge carriers within the limits of medium and high-temperature indicators, which leads to the corresponding temperature dependence of Z;
- The width of the band gap is not very small, but it prevents the premature appearance of effects associated with intrinsic conductivity (namely, bipolar diffusion). This helps to maintain high values of the efficiency of the thermoelectric material within high temperatures and expands its interval (in other words, as the temperature increases, the value of the ΔE parameter will also increase).

Lead telluride and lead selenide (PbTe and PbSe) have these properties.

In addition to the already mentioned criteria, which are required for the study of thermoelectric materials and thin films, in particular PbTe, it is possible to determine the main technological conditions that are necessary for their effective use and prospects for their use in various thermoelements, even when these thermoelements have a number of available favorable parameters.

Such technological conditions include:

- Good mechanical properties of the material (nano- and micro-hardness) and the ability to withstand temperature cycling processes (heating and cooling), corresponding to the real operating conditions of the thermoelectric generator;
- The nature of the materials should prevent irreversible physicochemical reactions. Specifically, attention should be paid to the melting temperature of the thermoelectric material, as irreversible phenomena often occur at temperatures close to the material's melting point, making it unsuitable for use in such conditions. Therefore, the melting temperature should be 200 K - 300 K higher than the temperature of the hot junction of the thermocouple, which includes the material;
- High radiation resistance of the selected thermoelectric materials in case nuclear reactors are used as heat sources in thermogenerators.

It should be noted that the thermoelectric factor of material Z will mostly be small, regardless of the optimal parameters of thermoelectric materials, such as the concentration of electron charge carriers and temperature, with significant lattice conductivity. In this case, the future research of scientists will obviously relate to the search for thermoelectric materials that will have a low lattice thermal conductivity.

Conclusion

The provided review of works and analysis of general approaches to semiconductor thermoelectric materials unequivocally indicates that for the range of so-called intermediate temperatures (500 K - 850 K), the most effective material is undoped non-stoichiometric lead telluride. At the same time, important questions arise concerning both the physical and chemical nature of the material and the study of all details of the technological process for manufacturing thermoelectric material.

References

1. d'Angelo M, Galassi C, Lecis N. Thermoelectric Materials and Applications: A Review. Energies. 2023; 16:17; 6409-6459.
2. Anatychuk LI, Luste OJ, Kuz RV, Strutinsky MN. Inverse problems of Thermoelectricity. Journal of Electronic Materials. 2011; 40;856-861.
3. Bylina IS. Mechanisms of Structure and Thermoelectric Properties of Vapor-Phase Condensates Solid Solution PbTe-Bi_2Te_3 on Ceramics. Physics and Chemistry of Solid State. 2015; 16:1; 83-92.
4. Ahmad S, Mahanti SD, Hoang K, Kanatzidis MG. Ab initio studies of the electronic structure of defects in PbTe. Phys. Rev. B. 2006; 74:15; 155205-155210.
5. Popescu A, Woods LM. Enhanced thermoelectricity in composites by electronic structure modifications and nanostructuring. Appl. Phys. Lett. 2010; 97:5; 052102-052108.
6. Kim W, Zide J, Gossard A, Klenov D, Stemmer S, Shakouri A, Majumdar A. Thermal conductivity reduction and thermoelectric figure of merit increase by embedding nanoparticles in crystalline semiconductors. Phys Rev Lett. 2006 Feb 3;96(4):045901. doi: 10.1103/PhysRevLett.96.045901. Epub 2006 Feb 2. PMID: 16486849.
7. Niua J, Shen H, Li X, Xu W, Wang H, Li LS. Controlled synthesis of high-quality PbSe and PbTe nanocrystals with the one-pot method and their self-assemblies. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2012; 406:38-43.
8. Gao X, Daw MS. Investigation of band inversion in (Pb, Sn) Te alloys using ab initio calculations. Physical Review: B. 2008; 77:3; 033103-03318.
9. Hummer K, Gruneis A, Kresse G. Structural and electronic properties of lead chalcogenides from first principles. Physical Review: B. 2007; 75:19;195211-195218.
10. Levytskyi SN, Boyko MI, Vlasenco OI, Kryskov TA. Improvement of Technologies of Synthesis of $A^{IV}B^{VI}$ Semiconductors and Solid Solution on Their Basis. Physics and Chemistry of Solid State. 2011; 12:4;1039-1041.