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Recent trends and future perspectives of thermoelectric materials and their applications

 Pavithra Baskaran and Mani Rajasekar *

This review explores the ever-evolving landscape of thermoelectric materials, focusing on the latest trends and innovations in ceramics, thermally conductive gel-like materials, metals, nanoparticles, polymers, and silicon. Thermoelectric materials have garnered significant attention for their capability to convert waste heat into electrical power, positioning them as promising candidates for energy harvesting and cooling applications. This review distinguishes itself by highlighting recent advancements in synthesis methods, advanced doping strategies, and nanostructuring techniques that have markedly enhanced material performance. It provides a comprehensive analysis of the controlled properties concerning their synthesis parameters, such as electrical conductivity, Seebeck coefficient, and thermal conductivity. Furthermore, this work delves into the emerging applications of thermoelectric devices across diverse fields, including automotive, aerospace, wearable electronics, and industrial waste heat recovery. By offering forward-looking insights, this review outlines thermoelectric devices' challenges and future prospects, underscoring their potential to contribute to sustainable energy solutions and efficient thermal management systems. By integrating current trends with future projections, this review offers a timely and comprehensive roadmap for researchers and engineers dedicated to advancing next-generation thermoelectric technologies.

1. Introduction

Recent years have witnessed a surge of interest in thermoelectric devices and their applications, driven by the pressing need for sustainable energy solutions and efficient thermal management systems.¹ Thermoelectric materials have become more attractive as potential solutions to these problems because of their exceptional capacity to transform waste heat into useful electrical power. This paper aims to provide a comprehensive overview of the recent trends in thermoelectric devices and their diverse applications across various industries, while also delving into the future prospects and potential impact of these advancements. The field of thermoelectric materials and devices has undergone significant evolution, marked by a growing emphasis on enhancing performance, scalability, and applicability.^{2–4} Recent advancements in materials science have led to the development of novel thermoelectric materials, including nanostructured materials, organic and hybrid materials, and the utilization of advanced manufacturing techniques. These innovations have opened new avenues for improving the efficiency and cost-effectiveness of

thermoelectric devices, thereby expanding their potential applications.^{5–7}

One of the key future prospects in the realm of thermoelectric devices lies in the continued refinement of materials and manufacturing processes to achieve higher thermoelectric conversion efficiencies. The pursuit of materials with enhanced thermoelectric properties, such as high thermoelectric figure of merit (ZT), remains a focal point for researchers and industry stakeholders. Additionally, the exploration of scalable and cost-effective manufacturing methods holds promise for enabling the widespread adoption of thermoelectric technology in diverse settings.^{8–10} The potential applications of thermoelectric devices span a wide spectrum of industries, each presenting unique opportunities for leveraging waste heat recovery and efficient thermal management. In the automotive sector, thermoelectric generators offer the prospect of harnessing waste heat from exhaust systems to power vehicle electronics and reduce fuel consumption. Similarly, in aerospace applications, thermoelectric devices hold the potential to enhance energy efficiency and provide reliable power sources for critical systems. The integration of thermoelectric modules in wearable electronics presents an intriguing avenue for self-powered, energy-autonomous wearable devices, catering to the burgeoning demand for portable and sustainable technologies. Furthermore, in industrial settings, thermoelectric systems offer the prospect of recovering waste heat from various

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Recent Trends In Thermoelectric Materials Research

Minjie Lin



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Recent Trends in Thermoelectric Materials Research Albert C. Beer, Robert K. Willardson, 1966 **Recent Trends in Thermoelectric Materials Research: Part Three** , 2001-01-03 Since its inception in 1966 the series of numbered volumes known as Semiconductors and Semimetals has distinguished itself through the careful selection of well known authors editors and contributors The Willardson and Beer series as it is widely known has succeeded in producing numerous landmark volumes and chapters Not only did many of these volumes make an impact at the time of their publication but they continue to be well cited years after their original release Recently Professor Eicke R Weber of the University of California at Berkeley joined as a co editor of the series Professor Weber a well known expert in the field of semiconductor materials will further contribute to continuing the series tradition of publishing timely highly relevant and long impacting volumes Some of the recent volumes such as Hydrogen in Semiconductors Imperfections in III V Materials Epitaxial Microstructures High Speed Heterostructure Devices Oxygen in Silicon and others promise that this tradition will be maintained and even expanded Thermoelectric materials may be used for solid state refrigeration or power generation applications via the large Peltier effect in these materials To be an effective thermoelectric material a material must possess a large Seebeck coefficient a low resistivity and a low thermal conductivity Due to increased need for alternative energy sources providing environmentally friendly refrigeration and power generation thermoelectric materials research experienced a rebirth in the mid 1990 s Semiconductors and Semimetals Volume 71 Recent Trends in Thermoelectric Materials Research Part Three provides an overview of much of this research in thermoelectric materials during the decade of the 1990 s New materials and new material concepts such as quantum well and superlattice structures gave hope to the possibilities that might be achieved An effort was made to focus on these new materials and not on materials such as BiTe alloys since such recent reviews are available Experts in the field who were active researchers during this period were the primary authors to this series of review articles This is the most complete collection of review articles that are primarily focussed on new materials and new

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Continuum Theory and Modeling of Thermoelectric Elements Christophe Goupil,2015-12-14 Sound knowledge of the latest research results in the thermodynamics and design of thermoelectric devices providing a solid foundation for thermoelectric element and module design in the technical development process and thus serving as an indispensable tool for any application development The text is aimed mainly at the project developer in the field of thermoelectric technology both in academia and industry as well as at graduate and advanced undergraduate students Some core sections address the specialist in the field of thermoelectric energy conversion providing detailed discussion of key points with regard to optimization The international team of authors with experience in thermoelectrics research represents such institutes as EnsiCaen Universite de Paris JPL CalTech and the German Aerospace Center

Advances in Infrared Photodetectors ,2011-05-03 Semiconductors and Semimetals has distinguished itself through the careful selection of well known authors editors and contributors Originally widely known as the Willardson and Beer Series it has succeeded in publishing numerous landmark volumes and chapters The series publishes timely highly relevant volumes intended for long term impact and reflecting the truly interdisciplinary nature of the field The volumes in Semiconductors and Semimetals have been and will continue to be of great interest to physicists chemists materials scientists and device engineers in academia scientific laboratories and modern industry Written and edited by internationally renowned experts Relevant to a wide readership physicists chemists materials scientists and device engineers in academia scientific laboratories and modern industry

Advances in Semiconductor Lasers James J Coleman,A. Catrina Bryce,Chennupati Jagadish,2012-05-02 Since its inception in 1966 the series of numbered volumes known as Semiconductors and Semimetals has distinguished itself through the careful selection of well known authors editors and contributors The Willardson and Beer Series as it is widely known has succeeded in publishing numerous landmark volumes and chapters Not only did many of these volumes make an impact at the time of their publication but they continue to be well cited years after their original release Recently Professor Eicke R Weber of the University of California at Berkeley joined as a co editor of the

series **Silicon-Germanium Strained Layers and Heterostructures** M. Willander, Suresh C. Jain, 2003-10-02 The study of Silicon Germanium strained layers has broad implications for material scientists and engineers in particular those working on the design and modelling of semi conductor devices Since the publication of the original volume in 1994 there has been a steady flow of new ideas new understanding new Silicon Germanium SiGe structures and new devices with enhanced performance Written for both students and senior researchers the 2nd edition of Silicon Germanium Strained Layers and Heterostructures provides an essential up date of this important topic describing in particular the recent developments in technology and modelling Fully revised and updated 2nd edition incorporating important recent breakthroughs and a complete literature review The extensive bibliography of over 400 papers provides a comprehensive and coherent overview of the subject Appropriate for students and senior researchers Quantum Efficiency in Complex Systems, Part I, 2010-12-14 Since its inception in 1966 the series of numbered volumes known as Semiconductors and Semimetals has distinguished itself through the careful selection of well known authors editors and contributors The Willardson and Beer Series as it is widely known has succeeded in publishing numerous landmark volumes and chapters Not only did many of these volumes make an impact at the time of their publication but they continue to be well cited years after their original release Recently Professor Eicke R Weber of the University of California at Berkeley joined as a co editor of the series Professor Weber a well known expert in the field of semiconductor materials will further contribute to continuing the series tradition of publishing timely highly relevant and long impacting volumes Some of the recent volumes such as Hydrogen in Semiconductors Imperfections in III V Materials Epitaxial Microstructures High Speed Heterostructure Devices Oxygen in Silicon and others promise that this tradition will be maintained and even expanded Reflecting the truly interdisciplinary nature of the field that the series covers the volumes in Semiconductors and Semimetals have been and will continue to be of great interest to physicists chemists materials scientists and device engineers in modern industry

Thin-Film Diamond II Christopher Nebel, 2004-04-19 Part II reviews the state of the art of thin film diamond a very promising new semiconductor that may one day rival silicon as the material of choice for electronics Diamond has the following important characteristics it is resistant to radiation damage chemically inert and biocompatible and it will become the material for bio electronics in vivo applications radiation detectors and high frequency devices Thin Film Diamond II is the first book to summarize state of the art of CVD diamond in depth It covers the most recent results regarding growth and structural properties doping and defect characterization hydrogen in and on diamond as well as surface properties in general applications of diamond in electrochemistry as detectors and in surface acoustic wave devices Accessible by both experts and non experts in the field of semi conductors research and technology each chapter is written in a tutorial format Assisting engineers to manufacture devices with optimized electronic properties Truly international this volume contains chapters written by recognized experts representing academic and industrial institutions from Europe Japan and the US Quantum

Efficiency in Complex Systems, Part II: From Molecular Aggregates to Organic Solar Cells, 2011-11-23 Since its inception in 1966 the series of numbered volumes known as Semiconductors and Semimetals has distinguished itself through the careful selection of well known authors editors and contributors The Willardson and Beer Series as it is widely known has succeeded in publishing numerous landmark volumes and chapters Not only did many of these volumes make an impact at the time of their publication but they continue to be well cited years after their original release Recently Professor Eicke R Weber of the University of California at Berkeley joined as a co editor of the series Professor Weber a well known expert in the field of semiconductor materials will further contribute to continuing the series tradition of publishing timely highly relevant and long impacting volumes Some of the recent volumes such as Hydrogen in Semiconductors Imperfections in III V Materials Epitaxial Microstructures High Speed Heterostructure Devices Oxygen in Silicon and others promise that this tradition will be maintained and even expanded Reflecting the truly interdisciplinary nature of the field that the series covers the volumes in Semiconductors and Semimetals have been and will continue to be of great interest to physicists chemists materials scientists and device engineers in modern industry Written and edited by internationally renowned experts Relevant to a wide readership physicists chemists materials scientists and device engineers in academia scientific laboratories and modern industry

Semiconducting Chalcogenide Glass I Robert Fairman, Boris Ushkov, 2004-05-10 Chalcogenide glass is made up of many elements from the Chalcogenide group The glass is transparent to infrared light and is useful as a semiconductor in many electronic devices For example chalcogenide glass fibers are a component of devices used to perform laser surgery This book is a comprehensive survey of the current state of science and technology in the field of chalcogenide semiconductor glasses While the majority of the book deals with properties of chalcogenide glass chapters also deal with industrial applications synthesis and purification of chalcogenide glass and glass structural modification The first individual or collective monograph written by Eastern European scientists known to Western readers regarding structural and chemical changes in chalcogenide vitreous semiconductors CVS Chapters written by B G Kolomiets who discovered the properties of chalcogenide glass in 1955 Provides evidence and discussion for problems discussed by authors from opposing positions

International Conference on Thermoelectrics, 2001 **Thermoelectric Materials**, 2003 Thermoelectric Materials 2001 - Research and Applications: Volume 691 Materials Research Society. Meeting, 2002-05 This book provides a benchmark for the state of the field of thermoelectric materials research and development Highlights of the volume include results on superlattices that show a $ZT \approx 2.4$ at room temperature in p type Bi_2Te_3 Sb_2Te_3 superlattice thermoelectrics In addition preliminary results on p n couple devices from these superlattices indicate fast acting spot cooling in addition to improved performance Thermoelectric materials are utilized in a wide variety of applications related to solid state refrigeration or small scale power generation The book focuses on traditional thermoelectric materials new materials as well as developments in device engineering Many papers presented here revolve around either maximizing the numerator of Z called

the power factor or by minimizing ZT . Topics include guidance to advanced thermoelectric research skutterudites new materials approaches and measurements clathrates chalcogenides devices thermoelectric materials and devices research and development nanowires and oxides

Thermoelectric Materials 2003: Volume 793 G. S. Nolas, 2004-03-17 The measure of a thermoelectric material is given by the material's figure of merit. For over three decades the best thermoelectric materials had a $ZT < 1$. Recently however there are reports of new methods of materials synthesis that result in improvements beyond this performance. In addition rapid characterization as well as faster theoretical modeling of thermoelectric materials has resulted in a more rapid evaluation of new materials. This book offers a look at these results and provides a benchmark for the current state in the field of thermoelectric materials research and development. The focus is on new and innovative directions that will lead to the next generation thermoelectric materials for small scale refrigeration and power generation applications. The book emphasizes the multidisciplinary nature of the research needed to advance the science and technology of the field. Both theoretical and experimental studies are featured. Topics include low dimensional systems and nanocomposites devices oxides skutterudites complex bulk materials and measurements novel approaches and thermoelectric materials and technology

Semiconductors and Semimetals Robert K. Willardson, 2003

Advanced Semiconductor and Organic Nano-Techniques - Part I Hadis Morkoc, 2003 Physical sciences and engineering as well as biological sciences have recently made great strides in their respective fields. More importantly the cross fertilization of ideas paradigms and methodologies have led to the unprecedented technological developments in areas such as information processing full colour semiconductor displays compact biosensors and controlled drug discovery to name a few. Top experts in their respective fields have come together to discuss the latest developments and the future of micro nano electronics. They investigate issues to be faced in ultimate limits such as single electron transistors zero dimensional systems for unique properties thresholdless lasers electronics based on inexpensive and flexible plastic chips cell manipulation biosensors DNA based computers quantum computing DNA sequencing chips micro fluidics nanomotors based on molecules molecular electronics and recently emerging wide bandgap semiconductors for emitters detectors and power amplifiers. Contributions from top experts in this field. Covers a wide range of topics

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