RSC Advances

REVIEW

Cite this: RSC Adv., 2024, 14, 21706

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.

Received 17th May 2024
Accepted 3rd July 2024

DOI: 10.1039/d4ra03625e

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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.[2–5] 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.[6–8]

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.[9–11] 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

Tomasz Dietl,David D. Awschalom,Maria Kaminska,Hideo Ohno

Recent Trends In Thermoelectric Materials Research:

Recent Trends in Thermoelectric Materials Research III Terry M. Tritt,2001 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 concepts that is existence to date *Recent Trends in Thermoelectric Materials Research, Part Two* ,2000-10-25 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

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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 concepts that is existence to date

Thermoelectric Power in Nanostructured Materials

Kamakhya Prasad Ghatak,Sitangshu Bhattacharya,2010-07-20 This is the first monograph which solely investigates the thermoelectric power in nanostrcutured materials under strong magnetic field TPSM in quantum confined nonlinear optical III V II VI n GaP n Ge Te Graphite PtSb2 zerogap II V Gallium Antimonide stressed materials Bismuth IV VI lead germanium telluride Zinc and Cadmium diphosphides Bi2Te3 Antimony and carbon nanotubes III V II VI IV VI and HgTe CdTe superlattices with graded interfaces and effective mass superlattices under magnetic quantization the quantum wires and dots of the aforementiond superlattices by formulating the approprate respective carrier energy spectra which in turn control the quantum processes in quantum effect devices The TPSM in macro quantum wire and quantum dot superlattices of optoelectronic materials in the presence of external photo excitation have also been studied on the basis of newly formulated electron dispersion laws This monograph contains 150 open research problems which form the very core and are useful for PhD students and researchers in the fields of materials science solid state sciences computational and theoretical nanoscience and technology nanostructured thermodynamics and condensed matter physics in general in addition to the graduate courses on modern thermoelectric materials in various academic departments of many institutes and universities

Recent Trends in Thermoelectric Materials Research ,2001 *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

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Thermoelectricity and Advanced Thermoelectric Materials Ranjan Kumar,Ranber Singh,2021-06-03 Thermoelectricity and Advanced Thermoelectric Materials reviews emerging thermoelectric materials including skutterudites clathrates and half Heusler alloys In addition the book discusses a number of oxides and silicides that have promising thermoelectric properties Because 2D materials with high figures of merit have emerged as promising candidates for thermoelectric applications this book presents an updated introduction to the field of thermoelectric materials including recent advances in materials synthesis device modeling and design Finally the book addresses the theoretical difficulties and methodologies of computing the thermoelectric properties of materials that can be used to understand and predict highly efficient thermoelectric materials This book is a key reference for materials scientists physicists and engineers in energy Reviews the most relevant emerging thermoelectric materials including 2D materials skutterudites clathrates and half Heusler alloys Focuses on how electronic structure engineering can lead to improved materials performance for thermoelectric energy conversion applications Includes the latest advances in the synthesis modeling and design of advanced thermoelectric materials **Recent Trends in Thermoelectric Materials Research, Part Two** ,2000-10-27 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 70 Recent Trends in Thermoelectric Materials Research Part Two 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 concepts that is existence to date *Spintronics* Tomasz Dietl,David D. Awschalom,Maria Kaminska,Hideo Ohno,2009-02-12 This new volume focuses on a new exciting field of research Spintronics the area also known as spin based electronics The ultimate aim of researchers in this area is to develop new devices that exploit the spin of an electron instead of or in addition to its electronic charge In recent years many groups worldwide have devoted huge efforts to research of spintronic materials from their technology through characterization to modeling The resultant explosion of papers in this field and the solid scientific results achieved justify the publication of this volume Its goal is to summarize the current level of understanding and to highlight some key results and milestones that have been achieved to date Semiconductor spintronics is expected to lead to a new generation of transistors lasers and integrated magnetic sensors that can be used to create ultra low power high speed memory logic and photonic devices In addition development of novel devices such as spin polarized light emitters spin field effect transistors integrated sensors and high temperature electronics is anticipated Spintronics has emerged as one of the fastest growing areas of research This text presents an in depth examination of the most recent technological spintronic developments Includes contributions from leading scholars and industry experts *Recent Trends in Thermoelectric Materials Research, Part Two* ,2000-10-27 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 70 Recent Trends in Thermoelectric Materials Research Part Two 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

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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 Electronic Ceramics, Volume 28, Issue 8* Clive Randall,Hua-Tay Lin,Kunihito Koumoto,Paul Clem,2007-11-09 Papers from The American Ceramic Society s 31st International Conference on Advanced Ceramics and Composites held in Daytona Beach Florida January 21 26 2007 Topics include advances in dielectric piezoelectric and ferroelectric materials electroceramic materials for sensors thermoelectric materials for power conversion applications and transparent conductive oxides *Materials for Sustainable Energy* Vincent Dusastre,2011 The search for cleaner cheaper smaller and more efficient energy technologies has to a large extent been motivated by the development of new materials The aim of this collection of articles is therefore to focus on what materials based solutions can offer and show how the rationale design and improvement of their physical and chemical properties can lead to energy production alternatives that have the potential to compete with existing technologies In terms of alternative means to generate electricity that utilize renewable energy sources the most dramatic breakthroughs for both mobile i e transportation and stationary applications are taking place in the fields of solar and fuel cells And from an energy storage perspective exciting developments can be seen emerging from the fields of rechargeable batteries and hydrogen storage

Nanotechnology for Energy Sustainability, 3 Volume Set Baldev Raj,Marcel Van de Voorde,Yashwant Mahajan,2017-06-19 Dieses Referenzwerk in drei handlichen B nden bietet einen detaillierten berblick ber Anwendungen der Nanotechnologie im Bereich Nachhaltigkeit in der Energieversorgung Der erste Band dieses klar strukturierten Nachschlagewerks behandelt nach der Einleitung die Themen Energieerzeugung erneuerbare Energien Energiespeicherung Energieverteilung sowie Energieumwandlung und Energy Harvesting Im zweiten Band werden auf Nanotechnologie basierte Materialen Energieeinsparung und management technologische und urheberrechtlich relevante Fragen M rkte und Umweltsanierung er rtert Der dritte Band wirft einen Blick in die Zukunft auf technologische Fortschritte und gibt Empfehlungen Ein wichtiges Handbuch f r alle Experten auf diesem Gebiet von Forschern und Ingenieuren im wissenschaftlichen Bereich bis hin zu Entwicklern in der Industrie *Thermoelectrics Handbook* D.M. Rowe,2018-10-03 Ten years ago D M Rowe introduced the bestselling CRC Handbook of Thermoelectrics to wide acclaim Since then increasing environmental concerns desire for long life electrical power sources and continued progress in miniaturization of electronics has led to a substantial increase in research activity involving thermoelectrics Reflecting the latest trends and developments

the Thermoelectrics Handbook Macro to Nano is an extension of the earlier work and covers the entire range of thermoelectrics disciplines Serving as a convenient reference as well as a thorough introduction to thermoelectrics this book includes contributions from 99 leading authorities from around the world Its coverage spans from general principles and theoretical concepts to material preparation and measurements thermoelectric materials thermoelements modules and devices and thermoelectric systems and applications Reflecting the enormous impact of nanotechnology on the field as the thermoelectric properties of nanostructured materials far surpass the performance of conventional materials each section progresses systematically from macro scale to micro nano scale topics In addition the book contains an appendix listing major manufacturers and suppliers of thermoelectric modules There is no longer any need to spend hours plodding through the journal literature for information The Thermoelectrics Handbook Macro to Nano offers a timely comprehensive treatment of all areas of thermoelectrics in a single unified reference **Encyclopedia Of Thermal Packaging - Set 1: Thermal Packaging Techniques (A 6-volume Set)** ,2012-09-25 remove This Encyclopedia comes in 3 sets To check out Set 2 and Set 3 please visit Set 2 Thermal Packaging Tools and Set 3 Thermal Packaging Applications remove Thermal and mechanical packaging the enabling technologies for the physical implementation of electronic systems are responsible for much of the progress in miniaturization reliability and functional density achieved by electronic microelectronic and nanoelectronic products during the past 50 years The inherent inefficiency of electronic devices and their sensitivity to heat have placed thermal packaging on the critical path of nearly every product development effort in traditional as well as emerging electronic product categories Successful thermal packaging is the key differentiator in electronic products as diverse as supercomputers and cell phones and continues to be of pivotal importance in the refinement of traditional products and in the development of products for new applications The Encyclopedia of Thermal Packaging compiled in multi volume sets Set 1 Thermal Packaging Techniques Set 2 Thermal Packaging Tools Set 3 Thermal Packaging Applications and Set 4 Thermal Packaging Configurations will provide a comprehensive one stop treatment of the techniques tools applications and configurations of electronic thermal packaging Each of the author written sets presents the accumulated wisdom and shared perspectives of a few luminaries in the thermal management of electronics Set 1 Thermal Packaging TechniquesThe first set of the Encyclopedia Thermal Packaging Techniques focuses on the technology building blocks used to assemble a complete thermal management system and provide detailed descriptions of the underlying phenomena modeling equations and correlations as well as guidance for achieving the optimal designs of individual building blocks and their insertion in the overall thermal solution Specific volumes deal with microchannel coolers cold plates immersion cooling modules thermoelectric microcoolers and cooling devices for solid state lighting systems as well as techniques and procedures for the experimental characterization of thermal management components These building blocks are the essential elements in the creation of a complete cost effective thermal management system The four sets in the Encyclopedia of Thermal Packaging

will provide the novice and student with a complete reference for a quick ascent on the thermal packaging learning curve the practitioner with a validated set of techniques and tools to face every challenge and researchers with a clear definition of the state of the art and emerging needs to guide their future efforts This encyclopedia will thus be of great interest to packaging engineers electronic product development engineers and product managers as well as to researchers in thermal management of electronic and photonic components and systems and most beneficial to undergraduate and graduate students studying mechanical electrical and electronic engineering

Recent Trends In Thermoelectric Materials Research Book Review: Unveiling the Magic of Language

In an electronic era where connections and knowledge reign supreme, the enchanting power of language has be much more apparent than ever. Its ability to stir emotions, provoke thought, and instigate transformation is really remarkable. This extraordinary book, aptly titled "**Recent Trends In Thermoelectric Materials Research**," written by a very acclaimed author, immerses readers in a captivating exploration of the significance of language and its profound affect our existence. Throughout this critique, we shall delve to the book is central themes, evaluate its unique writing style, and assess its overall influence on its readership.

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Recent Trends In Thermoelectric Materials Research Introduction

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