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Review article

Oxide thermoelectric materials: A review of emerging strategies for efficient waste heat recovery

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HIGHLIGHTS

- Oxide thermoelectrics enable efficient waste heat recovery with high stability.
- BiCuSeO achieves ZT of 1.5 at 923 K via texturation and dual-doping.
- Nb-doped $SrTiO_3$ reaches ZT of 1.42 at 1050 K with graphite inclusions.
- Nanostructuring and doping enhance ZT in ZnO, $Ca_3Co_4O_9$, and In_2O_3.
- High-entropy oxides reduce thermal conductivity for improved performance.

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ABSTRACT

In response to the escalating global energy demand and the environmental impact of fossil fuels, oxide thermoelectric materials have emerged as promising candidates for waste heat recovery due to their stability, non-toxicity, and capacity for high-temperature applications. This comprehensive review evaluates critical advances in oxide-based thermoelectrics, focusing on p-type ($Ca_3Co_4O_9$, BiCuSeO) and n-type (ZnO, $SrTiO_3$, $CaMnO_3$, In_2O_3) materials. Key challenges in achieving high thermoelectric performance, such as balancing the Seebeck coefficient, electrical conductivity, and thermal conductivity, are addressed through diverse strategies including doping, compositional tuning, nanostructuring, and interface engineering. Notable achievements include a ZT of 1.42 at 1050 K in Nb-doped $SrTiO_3$ with graphite inclusions, a ZT of 0.9 in nonstoichiometric $Ca_3Co_4O_9$, and a ZT of 0.47 at 1223 K in Ce-doped In_2O_3 through defect engineering. BiCuSeO stands out with a ZT of 1.5 at 923 K, achieved via three-step texturation and dual-doping, demonstrating its potential for mid-to-high-temperature applications. Innovations such as high-entropy oxide compositions, two-dimensional electron gas systems, and advanced synthesis techniques like spark plasma sintering and solvothermal synthesis have shown remarkable potential for ZT improvement across these materials. This review highlights a multi-faceted approach to improving thermoelectric efficiency and outlines strategic pathways for scalable, eco-friendly thermoelectric applications in energy harvesting and industrial heat recovery.

1. Introduction

The global energy demand is a significant concern due to decreasing availability of natural energy resources and the environmental impacts of pollution and global warming. This situation has prompted researchers to explore alternative and sustainable energy harvesting techniques. One eco-friendly and effective approach involves converting waste heat or ambient heat into useable energy. This process is based on the Seebeck effect, a phenomenon where a voltage is generated across a solid when it is subjected to a temperature gradient [1,2]. Thermoelectric materials are promising for solid-state energy generation, capable of converting substantial waste heat from vehicles and industries into electricity. Average temperature (T *m*), the hot side temperature (T *h*), cold side temperature(T *c*), and the efficiency of energy

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