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PROPERTIES AND RECENT PROGRESS IN OXIDE BASED THERMOELECTRIC MATERIALS

[1]CHINCHU.Y.M, [2]Dr.T. BEENA

[1]Research Scholar (20113162132020), Department of Physics,
Scott Christian College (Autonomous), Affiliated to Manonmanium Sundaranar University Nagercoil,
[2]Department Of Physics, Scott Christian College (Autonomous) Affiliated to Manonmanium Sundaranar University) Nagercoil, Tamil Nadu

Corresponding Author's Email: chinchukayal03@gmail.com

Abstract

Advanced thermoelectric materials that can be used efficiently for energy conversion have received significant research interest for the last decade because of the mounting demand for sustainable and eco-friendly energy technologies. The main advantage of the thermoelectric materials is their capability to directly convert the waste heat into electrical energy which makes them highly promising for the recovery of waste heat from industrial processes, automotive systems and power generation applications. Oxide-based thermoelectric materials are interesting due to their high abundance, low cost, low mass density, excellent chemical and thermal stability, non-toxicity, and capability to work at higher temperatures in oxidizing conditions, among the different classes of thermoelectric materials. Although they are useful,

high thermoelectric efficiency is still hard to attain because of the interdependence of electrical conductivity, Seebeck coefficient and thermal conductivity. This review gives a thorough overview of the basic properties of oxide-based thermoelectric materials and the methods used to optimize these transport properties to improve the thermoelectric properties. Different synthesis and fabrication methods such as solid-state reaction, sol-gel, polymer solution, pressure-less sintering and spark plasma sintering are discussed and their effects on the material properties are explored. The developments of the systems that have been extensively studied, such as $Ca_3Co_4O_9$, $SrTiO_3$ and $CaMnO_3$, over the last years are also summarized, including the effect of element doping and microstructural engineering. In addition, the review identifies the recent progress, current challenges and future research trends to enhance the figure of merit (ZT) and further extend the application of thermoelectric oxide materials to efficient and sustainable energy harvesting.

Keywords

Thermoelectric, Seebeck coefficient, electrical conductivity, Powerfactor, Thermal conductivity

INTRODUCTION

There are several issues with energy use in the globe today. Social and political instability is sharply increasing as a result of the global demand for energy. Over 60% of the energy lost globally is converted to heat. On the other hand, there is a growing demand for greenhouse gases especially CO_2 in the environment (1,2). Similarly, the effects of using fossil fuels on the ecosystem and climate change are become more concerning. Challenges to develop alternative technologies that can convert waste heat in to electrical energy plays key role in current days (3-5). It can reduce our dependent on fossil fuels and reduces greenhouse gas emission. Scientist worldwide are in search of such materials that can help to meet the increasing energy demands with minimal environmental impact(6-8). In several fields, materials with the ability to directly and reversibly transform thermal energy into electrical energy have sparked attention. Materials that possess these properties are called thermoelectric materials (TE). Home heating, automotive exhaust and industrial process can use TE materials(9-15). High-efficiency TE materials must be developed immediately for waste heat recovery, as this will have significant positive effects on the economy and the environment(16-25). It is highly applicable for remote applications in case of absence of any compressors or pumps especially

in space craft. Heat lost in engine coolant or exhaust gas can be used to produce electricity by using TE(26-35).

THERMOELECTRIC MATERIALS

Environmentally friendly energy conversion materials that are compact, highly reliable, pollutant-free, and feasible throughout a broad temperature range are called thermoelectric materials (36-42). Thermoelectric materials can be used to turn the vast amounts of waste heat produced by industrial processes, vehicle exhaust, and home heating into energy. It is critical to develop high-efficiency thermoelectric materials for waste heat recovery because they will have significant positive effects on the economy and the environment (43-54).

PROPERTIES OF TE:

To carry out such thermoelectric conversion, good TE materials should possess a few special qualities. The figure of merit (ZT), which is defined as the conversion efficiency of TE material, $ZT = \frac{S^2\,\sigma T}{K}$. S,σ,T and k are Seebeck coefficient, electrical conductivity, Temperature and Thermal conductivity. $S^2\,\sigma$ is the power factor. The relationship between Seebeck coefficient can be expressed as $S = \frac{8\pi^2 {K_B}^2}{3eh^2} m^* T\left(\pi/3n\right)^{2/3}$ Where k_B, e, h, m^* and n are Boltzmann constant, carrier charge, Planck's constant, effective mass and carrier concentration. Low thermal conductivity and high electrical conductivity are necessary to optimise ZT material's thermopower.

1.Electrical conductivity:

Electrical conductivity is given by, $\sigma = ne\mu$. Where μ and n are carrier mobility and carrier concentration Strongly doped semiconductors with carrier concentrations between 1019 and 1021 cm3 are good TE materials. One kind of carrier should be chosen to guarantee a high Seebeck coefficient; mixing carriers can reduce thermopower. To obtain a single kind of carrier, materials with sufficient doping and energy bandgaps that allow for a good separation between n-type and p-type are selected. Consequently, semiconductors with an energy bandgap of less than 1 eV that are extensively doped are effective TE materials.

2.Effective mass:

Another contradiction arises from the charge carriers' effective mass, since a large effective mass results in limited electrical conductivity and high thermopower. The m^* refers to the density of states effective mass, which increases with flat, narrow bandgap with density of states at the Fermi surface,$\sigma = \frac{ne^2\tau}{m^*}$. Electrical conductivity results from heavy carriers moving with stronger velocities and, consequently, small mobilities, as m* is linked to n. Effective mass and mobility have a complicated relationship that is influenced by anisotropy, electronic structure, and scattering mechanisms. Effective mass and the dominating charge carriers must be balanced in order to strike a compromise between high mobility and high effective mass.

3.Thermal conductivity:

Thermal conductivity in the thermoelectric materials comes from two sources

(1) Electron and hole transporting heat (k_e)
(2) Phonons travelling through the lattices(k_l)

$$k = k_l + k_e$$

$$k_e = LenuT$$

Since k_e is linearly proportional to electrical conductivity, decreasing k affect the electrical conductivity Lattice thermal conductivity is tuned to change thermal conductivity since reducing k has little to no improvement in ZT.

PHONON-GLASS-ELECTRON CRYSTAL

As ZT difficulty increases, the complex parameter relationship gets closer. A "phonon-glass-electron-crystal (PGEC)" model is a necessary component of high-quality thermoelectric materials. The characteristics of thermoelectric materials are described by this model. An ideal thermoelectric material is said to have both crystal-like electrical characteristics and glass-like thermal conductivity. The lattice thermal conductivities of glasses are poor. The idea of lowest thermal conductivity arises from the perception that thermal conductivity in glass is a random travel of energy through the lattice rather than quick transit via phonons. However, because they lack the necessary electron-crystal characteristics, they perform poorly as thermoelectrics. Thus, crystalline materials that scatter phonons without substantially altering electrical conductivity are good thermoelectric material. For a thermoelectric material to be capable of

such a conversion process, it must possess specific characteristics. The thermoelectric materials' conversion efficiency is correlated with the figure of merit (ZT), which is defined as

$$ZT = S^2\sigma T\ k$$

where, S → Seebeck coefficient (μV/K)

σ → Electrical conductivity ($\Omega^{-1}cm^{-1}$)

k → Thermal conductivity ($Wm^{-1}\ k^{-1}$)

T → Temperature (K)

$S^2\sigma$ → Power factor

RESEARCH PROGRESS ON THERMOELECTRIC MATERIALS

The 1950s saw remarkable advancements in the field of thermoelectrics. Bi2Te3, PbTe, and SnGe bulk thermoelectric materials are examples of the first generation of thermoelectric materials that were created for room temperature applications. In 1960, solid solution formation and doping control were the main strategies for raising ZT. Global interest in the field of thermoelectrics was low between 1960 and 1990 (55-59).

With ZT~ 1, the alloy family kept the best commercial material. Two distinct strategies have been developed over the last 20 years to find the next generation of high-performance thermoelectric materials. One is the synthesis and application of low dimensional thermoelectric material systems, and the other is the discovery and use of novel families of bulk materials with intricate crystal structures. High ZT~2.4 at 300K has been recorded by Bi2/Sb2Te3. However, at high temperatures, these substances become unstable and poisonous. As a result, the focus of the research had somewhat changed to oxides. Oxides' high chemical and thermal stability makes it possible to apply a significant temperature gradient across materials in air (60).

Oxides are distinguished by their structural, compositional, and chemical versatility. Oxides are inexpensive and environmentally benign. Metal oxides were not thought to have good TE at first, but studies on transition metal oxides showed promising results because of their strong electronic correlation, narrow bands, which resulted in strong spin and orbital fluctuations, and high degeneracy, which can occur in the d-electrons and is beneficial for enhancing TE. The most common oxide materials are p-type Ca3Co4O9, n-type ZnO, SrTiO3, and CaMnO3.

The various manufacturing techniques employed and the potent thermoelectric outcomes attained in these materials in recent years are discussed in this review.

1.**$Ca_3Co_4O_9$ (CCO):**

CCO is a p-type semiconducting material well known for its electronic, magnetic and elctro-optic properties. In the family of Cobalite, CCO has gained a special place due to its misfit layered structure. Its crystal structure consists of two different CdI_2 – type monoclinic structures. The middle layer consists of Ca and O. The others contain Ca and O. The substructure has the composition of Ca_2CoO_3 and is usually referred to as rock salt structure Various techniques has been used to prepare CCO nanoparticles. The thermoelectric properties also show variation depending upon the fabrication techniques used and conditions of annealing and sintering. Various techniques used for the fabrication and their outcomes are given in this article.

i)Solid state reaction method:

The simplest yet effective method for the fabrications of CCO nanomaterials is the solid-state reaction method. $CaCo_3$ and CO_3O_4 are mixed for 5 mints at 400rpm in agetate ball. The powder obtained is heated at 850 ˚C for 8 hours by varying the concentrations (x=1,10,20). Spark plasma sintering is processed. Decomposition of $Ca_3CO_4O_9$ to $Ca_3CO_2O_6$ is studied using TGA analysis, which shows two peaks at 911 and 965 ˚C. All samples are *p*-type conductors with positive Seebeck coefficient. Electrical conductivity also shows increment with temperature and a higher ZT is obtained for pure CCO than the doped one. $CaCo_3$ and CO_3O_4 are mixed and calcined for 20 hours at 700 ˚C. Pellets prepared were annealed at 900 ˚C for 20 hours. Again, grounded and wood powders [1,1.05,0.15,0.25] were added to 1gm of CCO. The samples were sintered at different temperatures of 500 ˚C and 900 ˚C for 6 hours and 18 hours respectively. Structural analysis and thermoelectric studies were carried for all samples. Seebeck coefficient varies from 18 μV/k to 144 μV/k for x=0 and 0.15 at 800K. Among all the samples CCO[0.15] shows high thermeoelctric properties attaining ZT=1.19 at 800K

ii) Pressure less sintering method:

Zirconia grinding media are used to combine CaCo3 and CO3O4 with water. It is calcined twice at 900 ˚C for 15 hours after drying. Samples were chilled to 900 ˚C and then annealed at 900 ˚C for 12, 24, and 72 hours after being fired in air at 1000–1300 ˚C for 6 hours. At 890 ˚C and 940 ˚C, TGA displays two peaks, signifying the breakdown into Ca3CO2O6 and CaO at 940 ˚C. The electrical conductivity of the 920 ˚C sample is 56 S/cm at 100 ˚C, and the Seebeck

coefficient progressively rises from 130 to 160 μV/k within the measured temperature range of 100-670 ˚C. At 600 ˚C, a ZT of 0.06 is recorded.

iii)Polymer solution method

$Ca[CH_3CO_2].{}^1/_2H_2O$ +$[Co(CH_3CO_2)_2.4H_2O$ were added in the distilled H_2O. Polyethyleneimine was added to the above solution. Partial evaporation take place in a rotary evaporator. The powder obtained was thermally heated twice at 750 and 800 ˚C for 12h and pelletized. Pellets prepared were annealed in air at 900 ˚C and 960 ˚C indicating the formation of $Ca_3CO_2O_6$. XRD studies reveals that $Ca_3CO_4O_9$ is the major phase accompanied by Cao, $Ca_yCo_{1-y}O$ and $Ca_3CO_2O_6$ for samples annealed for 24h. For further annealing time, number of secondary phases got decreased. Electrical resistivity got decreased with increase in temperature. The minimum resistivity values at room temperature is 15mΩcm for 96h annealed sample. For as prepared sample, Seebeck coefficient varies from 80 to $550MvK^{-1}$ for 400 and 800 ˚C.

iv) Sol-gel method

$Ca(No_3)_2$ and $Co(No_3).2.6H_2O$ and citric acid were dissolved in distilled water with a metal ion concentration of 0.2~0.3 mol/liter solution was stirred and heated at 70 ˚C for 3h. The dried gel was grinned and calcined at different temperatures from 400 to 800 ˚C sintered by using SPS and CS techniques. XRD reveals that CCO appears when calcined at 600 ˚C as temperature is increased pure phase is obtained at 800 ˚C. TGA reveals peaks at 251 ˚C, 377 ˚C ,627 ˚C, and heavy one at 763 ˚C, sharp endothermic peak exhibit at 956 ˚C. electrical conductivity at room temperature for CS sample is 34S/cm and increased for 700 ˚C. Power factor of CS and SPS are noted as $3.51e^{-4}$ and 1.15 e^{-4} W/m^2s at 700 ˚C. ZT values are noted as 0.16 and 0.052 at 700 ˚C.

DOPING:

a) Bi doping

Bi doped CCO is prepared by using chemical sol-gel method. Bi doped CCO is prepared by using chemical sol-gel method. $Ca(NO_3)_2.4H_2O$ + $Ca(NO_3)_2.6H_2O$ + Bi $(NO_3)_2.5H_2O$. Ethylene glycol and polyethylene glycol is used to polymerize the solution. Nitric acid is added and stirred at 353k and gel is prepared and calcined at 923k for 4h and pellets are sintered at 1233k for 9h in a furnace with oxygen flow. Power factor of 22.5 and 23.8 is obtained for concentration of 0.2 and 0.3 of Bi. ZT of 0.16 at ZT of 0.16 at 823k is obtained for Bi doped with CCO prepared by spark plasma sintering method

b) Lanthanum doped

$Ca(NO_3)_2.4H_2O$ + $Ca(NO_3)_2.6H_2O$ + $La(NO_3)_2$ are mixed and dissolved in distilled water. Precursors are calcined in a muffle furnace at 650,700 and 750˚C for 5h to produce CCO powders of CCO/LaCCO 650 reveal weak signal corresponds to $CaCo_2O_4$.No other phases was observed confirming the entry of La elements into the lattice of CCO. Power factor exhibits positive co-ordination with the temperature. LaCCO 700-900 having high power factor of 204.25$\mu Wm^{-1}k^{-2}$ at 600 ˚C three times higher than CCO. Improvement of K in 950 ˚C is due to density improvement compared with 900 ˚C samples. ZT reached 0.25 at 600 ˚C

c) Silver doping:

Silver doped CCO is prepared by using ball milling process and calcined at 1173K for 24h in air twice with an intermediate grinding. The prepared CCO mixed with different proportion of AgNPS [0,0.5,1.0,1.5,2.0]. XRD shows that all the samples are single phase. As AgNPS content grows higher impurity phase of CCO appears in XRD pattern. For pure CCO and AgNPS(0.2), conductivity of 74 S/cm and 85 S/cm is obtained at 700 K.

ZT of 0.1 at 700K is obtained.

d) Ba,La and Ag doped

Citrate sol-gel synthesis followed by spark plasma sintering is used for preparing $Ca_{2.9}M_{0.1}Co_4O_9$[M=Ca,Ba,La,Ag]. Ca,Ba,La,Ag and Co were dissolved in an aqueous solution of citric acid. Ethylene glycol was added and solution was heated under continuous stirring at 358K in order to form precursor gel. The gel was dried at 393K in air for 24h and then heated at 1073K for 8h. Activation energy

2.$SrTiO_3$

In following years, the studies based on $SrTiO_3$ materials has expanded in wide range of fields. High power factor of 1.8 $Wm^{-1}K^{-1}$ is achieved for heavily La doped single crystal STO which increased the study of TE properties of STO. The electronic transport in $SrTiO_3$ can be tuned over a wide range of physical properties. The electrical conductivity of n-type STO materials can be achieved over a very broad range. Effective doping helps in achieving high ZT.

a) Pr doped $SrTiO_3$

$SrCO_3$ is added with Pr_2O_3 and TiO_2 mixed and made into pellets and calcined at 1300-1400 ˚C.The pellets are grinded, wrapped in graphite foil and again sintered by using SPS. Powerfactor of 1.3$Wm^{-1}k^{-1}$ and 2 $Wm^{-1}k^{-1}$ is observed at 500 ˚C and 100 ˚C.

b) La doped $SrTiO_3$

La_2O_3 is mixed with TiO_2 and $SrCo_3$ using planetary ball milling for 60 mints and calcined at 1100 ˚C for 7 h in alumina crucible grounded and served. Pellets are sintered at 1500 ˚C. La

doped $SrTiO_3$ is prepared using SPS at 925,1100 and 1200 ˚C. High ZT of 0.2 is reported for sample sintered and annealed at 500 ˚C. This is due to the high conductivity from 750 Scm^{-1} to 400 Scm^{-1}.

c) Nb doped $SrTiO_3$

Nb doped $SrTiO_3$ is prepared by taking $SrCo_3$, La_2Co_3 and TiO_2 as starting materials mixed using an attriation mill for 60 min. calcined at 1373K for 3h. Pellets were prepared using 200 Mpa. Sintering at air/N_2. ($Sr_{1-3x/2}$ La_x TiO_3) ZT is calculated for varying x. Highest ZT of 0.41 is calculated for x=0.125-0.175.

d) Titanium nitrate and Y

Y doped $SrTiO_3$ is prepared from calcination of Strontium Carbonate + Yittrium Oxide +Titanium oxide. Y doped $SrTiO_3$ and TIN powders is mixed. Pelletrized under 47MPa and sintered at 1573K for 2hrs ZT of 0.26 at 1073 K.

e) La,Dy

La_2 + $SrCO_3$ +TiO_2 +Dy_2O_3 is mixed ball milled for 12 hrs. and dried pressed and pelletized, calcined at 1350 ˚C for 6hr in air. Pellets are smashed to fine powders, again pelletized and sintered at 1460 ˚C for 4 h to get $La_{1-x}Dy_{0.1+x}Sr_{0.8}TiO_3$[x=0.02,0.05,0.08,0.10]. highest power factor of 1.9 e^3 is obtained at 303 K.

f) Rare Earth

Multiple dopants method is also used to enhance the thermoelectric properties of $SrTiO_3$. Rare earth elements Y, La, Sm, Gd,Dy are doped simultaneously with $SrTiO_3$.

$SrTiO_3$ is mixed with TiO_2 ,Ti ,Y_2O_3, La_2O_3 ,Sm_2O_3, Gd_2O_3 and Dy_2O_3.All are mixed and are made into pellets , sintering at 80mPa and 1873K for 4hrs. Thermoelectric studies are taken for $Sr_{1-X}RxTiO_3$ by varying the concentrations from 0.05 to 0.2. ZT of $3.8 * 10^{-4}$ k^{-1} is obtained for for $Sr_{0.9}Dy_{0.1}TiO_3$ at 573 K.

3.$CaMnO_3$

Compared with, chalcogenides and skutterudites metal oxides good candidates for thermoelectric applications. due to their high thermal and chemical stability at high temperature in air, easy manufacture and low cost. But ionic bonding in metal oxides usually leads to a strong scattering of electrons by optical phonons, which results in low carrier mobility and thus generally makes for poor thermoelectric performance. For this reason, metal oxides have long been avoided in the search for good thermoelectric materials. In 1997, $Na_xCo_2O_4$, shows unexpected thermoelectric properties which made thermoelectric metal oxides highly attractive. Also, perovskite families have also been explored and considered as thermoelectric

oxides. Among them, $SrTiO_3$ is a good TE material, it's TE properties and its variations with dopants are mentioned below.

i) Solid state reaction method

La^{3+},Y^{3+},Ce^{4+} were added to replace Ca^{+} in $CaMnO_3$. Multi dopants were used to yield high efficiency by using simple solid state reaction method by taking $CaCo_3$, MnO_2, La_2O_3, CeO_2 and Y_2O_3 as mixing agents. They are mixed individually, calcined in air at 1273K for almost 12 hrs. They were pelletized and sintered at 1573k for 24 hrs. to obtain $Ca_{1-x}La_xMnO_3$, $Ca_{1-x}Ya_xMnO_3$ and $Ca_{1-x}Ce_xMnO_3$. Thermoelectric results have been noted by varying the concentrations. The minimum resistivity has been noted for x=0.12 for La and Y doped and also for x=0.06 for Ce doped. Largest Seebeck coefficient of 500 to 600μVk^{-1} is noted for $CaMnO_3$. A large ZT of is obtained for $Ca_{0.9}La_{0.1}MnO_3$ at 1000K.

ii) SAMARIUM DOPED $CaMnO_3$:

Sm doped $CaMnO_3$ is prepared by using sol-gel method. $Ca_{0.1}Sm_{0.1}MnO_3$ shows high power factor of 3.11 $\mu Wm\text{-}1k^2$ at 800˚C.

iii) Bi and Nb doped:

Bismuth and Niobium doped $CaMnO_3$ is prepared using solid state reaction method by taking $CaCO_3$ and MnO_2 as starting materials and grinded at 1373K.The prepared powders were mixed with Nb_2O_5 and Bi_2O_3 and calcined at 1373K. The powders were pelletized and sintered at 1573K for 12 hrs. $Ca_{1-x}Bi_xMn_{1-y}Nb_yO3$ is prepared. Maximum power factor is obtained for x=y=0.04 and ZT~ 0.1 at 873K.

iv) Bi doped :

By using planetary ball milling method in an ethanol medium for 5hrs. from $CaCo_3$, MnO_2 and Bi_2O_3 calcined at 117K for 10 hrs and again annealed at 1273K for 10hrs. Resultant powder was then again ball milled and pelletized. The pellets were sintered at 1423K for 10hrs and the results were studied varying the concentrations [0,0.02,0.03,0.04,0.06 and 0.10]. ZT of 0.25 is observed at 973K for x=0.03 and a high power factor of 4×10^{-4} is noted.

CONCLUSION

The global demand for sustainable energy and the energy and the environmental concern on the use of fossil fuel have imposed an impressing need for the advancement of alternative energy conversion technologies including thermoelctrics. On the road to improve thermoelectric material performance, we have established in the past years an arsenal of technical tools and ways to achieve low lattice thermal conductivity. Ther is an little overlap between lattice thermal conductivity reduction and powerfactor improvement and hence we should pay closer attention to the enhancement approaches with dual purpose. In this review

we have discussed various preparation techniques used and the powerfactors and ZT values obtained. In conclusion, thermoelectric research is an exciting field. It will also provide students of next generation with invaluable skill sets including an intimate knowledge on phonon and electron scattering. We feel that this review article is very timely and necessary in understanding the power factor of thermoelectric materials and hope that readers will find it very useful in their future research.

REFERENCES

1. Snyder GJ, Toberer ES. Complex thermoelectric materials. Nat Mater. 2008;7:105-114.
2. Liu G, Chen K, Li J, Li Y, Zhou M, Li L. Combustion synthesis of Cu2SnSe3 thermoelectric materials. J Eur Ceram Soc. 2016;36(6):1-9.
3. Chen ZG, Han G, Yang L, Cheng L, Zou J. Nanostructured thermoelectric materials: current research and future challenge. Prog Nat Sci Mater Int. 2012;22(6):1-7.
4. Zhang X, Zhao LD. Thermoelectric materials: energy conversion between heat and electricity. J Materiomics. 2015;1(2):25-35.
5. Bell LE. Cooling, heating, generating power, and recovering waste heat with thermoelectric systems. Science. 2008;321(5895):1457-1460.
6. Kevin P, Malik SN, Malik MA, O'Brien P. The aerosol assisted chemical vapour deposition of SnSe and Cu2SnSe3 thin films from molecular precursors. Chem Commun. 2014;50(92):14328-14330.
7. LeBlanc S. Thermoelectric generators: linking material properties and systems engineering for waste heat recovery applications. Sustain Mater Technol. 2014;1:26-35.
8. Burton MR, Liu T, McGettrick J, Mehraban S, Baker J, Pockett A, Watson T, Fenwick O, Carnie MJ. Thin film tin selenide (SnSe) thermoelectric generators exhibiting ultralow thermal conductivity. Adv Mater. 2018;30(31):1801357.
9. Babu GS, Kumar YK, Reddy YBK, Raja VS. Growth and characterization of Cu2SnSe3 thin films. Mater Chem Phys. 2014;96:2-3.
10. Zhao LD, Tan G, Hao S, He J, Pei Y, Chi H, Wang H, Gong S, Xu H, Dravid VP, Uher C. Ultrahigh power factor and thermoelectric performance in hole-doped single-crystal SnSe. Science. 2016;353(6295):1414-1419.
11. Wang WT, Zheng ZH, Li F, Li C, Fan P, Luo JT, Li B. Synthesis process and thermoelectric properties of n-type tin selenide thin films. J Alloys Compd. 2018;763.
12. Shi X, Zheng K, Hong M, Liu W, Moshwan R, Wang Y, Qu X, Chen ZG, Zou J. Boosting the thermoelectric performance of p-type heavily Cu-doped polycrystalline SnSe via inducing intensive crystal imperfections and defect phonon scattering. Chem Sci. 2018;9(37).

13. Astam A. Structural and optical characterization of Cu2SnSe3 thin films prepared by SILAR method. Thin Solid Films. 2016;615.
14. Chandra GH, Kumar K, Rao K, Uthanna S. Influence of substrate temperature and selenization temperatures of Cu2SnSe3. 2011:6925-6959.
15. Yumos M, Talib A, Yunus W, Meror M, Josephine L, Paulus W. X-ray diffraction analysis of thermally evaporated Cu2SnSe3 at different annealing temperature.
16. Boyle C, Carvillo P, Chen Y, Barbero EJ, McIntyre D, Song X. Grain boundary segregation and thermoelectric performance enhancement of bismuth doped calcium cobaltite. J Eur Ceram Soc. 2016;36(3):601-607.
17. Królicka AK, Piersa M, Mirowska A, Michalska M. Effect of sol-gel and solid-state synthesis techniques on structural, morphological and thermoelectric performance of Ca3Co4O9. Ceram Int. 2018;44(12):13736-13743.
18. Yu J, Chen K, Azough F, Alvarez-Ruiz DT, Reece MJ, Freer R. Enhancing the thermoelectric performance of calcium cobaltite ceramics by tuning composition and processing. ACS Appl Mater Interfaces. 2020;12(42):47634-47646.
19. Yu J, Freer R. Calcium cobaltite, a promising oxide for energy harvesting: effective strategies toward enhanced thermoelectric performance. J Phys Energy. 2022;4(2):022001.
20. Medina MS, Bernardi JC, Zenatti A, Escote MT. A new approach to obtain calcium cobalt oxide by microwave-assisted hydrothermal synthesis. Ceram Int. 2020;46(2):1596-1600.
21. Tahashi M, Takahashi M, Goto H. Thermoelectric performance and crystal phase of calcium cobalt oxides sintered in oxygen gas. J Am Ceram Soc. 2018;101(4):1402-1406.
22. Tahashi M, Ogawa K, Takahashi M, Goto H. Effect of compositional ratio of cobalt to calcium on crystal phase and thermoelectric properties of oxide thermoelectric material composed of sintered Ca3Co4O9/Ca3Co2O6 mixture. J Ceram Soc Jpn. 2013;121(1413):444-447.
23. Puri N, Tandon RP, Mahapatro AK. Significant enhancement in thermoelectric power factor of bulk nanostructured calcium cobalt oxide ceramics. ACS Appl Energy Mater. 2019;2(1):269-277.
24. Soffientini A, Ghigna P, Spinolo G, Boldrini S, Famengo A, Tamburini UA. Nanostructured calcium cobalt oxide Ca3Co4O9 as thermoelectric material: effect of nanostructure on local coordination, Co charge state and thermoelectric properties. J Phys Chem Solids. 2020;143:109474.
25. Tahashi M, Tanimoto T, Goto H, Takahashi M, Ido T. Sintering temperature dependence of thermoelectric performance and crystal phase of calcium cobalt oxides. J Am Ceram Soc. 2010;93(10):3046-3048.
26. Delorme F, Ovono DO, Marudhachalam P, Martin CF, Fraboulet O. Effect of precursors size on the thermoelectric properties of Ca3Co4O9 ceramics. Mater Res Bull. 2012;47(5):1169-1175.
27. Mohammed MA, Uday MB, Izman S. Effects of calcination temperature and time on the Ca3Co4O9 purity when synthesized using starch-assisted sol-gel combustion method. J Adv Ceram. 2020;9:162-172.
28. Sun WW, Fan WH, Chen SP, Li YY, Meng QS. The effect of nano-SiO2 addition on electrical properties of the thermoelectric compound Ca3Co4O9. Adv Mater Res. 2012;465:292-295.

29. Agilandeswari K, Ruban Kumar A. Synthesis, characterization, temperature dependent electrical and magnetic properties of Ca3Co4O9 by a starch assisted sol-gel combustion method.
30. Delorme F, Diaz-Chao P, Guilmeau E, Giovannelli F. Thermoelectric properties of Ca3Co4O9-Co3O4 composites. Ceram Int. 2015;41(8):10038-10043.
31. Butt S, Xu W, Farooq MU, Ren GK, Mohmed F, Lin Y, Nan CW. Enhancement of thermoelectric performance in hierarchical mesoscopic oxide composites of Ca3Co4O9 and La0.8Sr0.2CoO3. J Am Ceram Soc. 2015;98(4):1230-1235.
32. Ren S, Gou L. Thermoelectric properties of the lanthanum-doped Ca3Co4O9 prepared by a modified parallel flow co-precipitation method. Adv Appl Ceram. 2021;120(2):95-103.
33. Lin Y, Sun S, Zhang Q, Shen H, Shao Q, Wang L, Jiang W, Jiang W. Preparation of AgNPs/Ca3Co4O9 nanocomposites with enhanced thermoelectric performance. Mater Today Commun. 2016;6:44-49.
34. Zhang F, Lu Q, Li T, Zhang X, Zhang J, Song X. Preparation and thermoelectric transport properties of Ba-, La- and Ag-doped Ca3Co4O9 oxide materials. J Rare Earths. 2013;31(8):778-783.
35. Schulz T, Töpfer J. Thermoelectric properties of Ca3Co4O9 ceramics prepared by an alternative pressure-less sintering/annealing method. J Alloys Compd. 2016;659:122-126.
36. Yin Y, Saini S, Magginetti D, Tian K, Tiwari A. Thermoelectric response of porous Ca3Co4O9 prepared by an eco-friendly technique. Ceram Int. 2017;43(12):9505-9511.
37. Madre MA, Costa FM, Ferreira NM, Sotelo A, Torres MA, Constantinescu G, Rasekh S, Diez JC. Preparation of high-performance Ca3Co4O9 thermoelectric ceramics produced by a new two-step method. J Eur Ceram Soc. 2013;33(10):1747-1754.
38. Liu Y, Lin Y, Shi Z, Nan CW, Shen Z. Preparation of Ca3Co4O9 and improvement of its thermoelectric properties by spark plasma sintering. J Am Ceram Soc. 2005;88(5):1337-1340.
39. Qi X, Fan Y, Zhu D, Zeng L. Fabrication and characterization of Ca3Co4O9 nanoparticles by sol-gel method. Rare Met. 2011;30:111-115.
40. Zhang YF, Zhang JX, Lu QM, Zhang QY. Synthesis and characterization of Ca3Co4O9 nanoparticles by citrate sol-gel method. Mater Lett. 2006;60(20):2443-2446.
41. Mehdizadeh Dehkordi A, Bhattacharya S, Darroudi T, Graff JW, Schwingenschlögl U, Alshareef HN, Tritt TM. Large thermoelectric power factor in Pr-doped SrTiO3−δ ceramics via grain-boundary-induced mobility enhancement. Chem Mater. 2014;26(7):2478-2485.
42. Shenoy US, Bhat DK. Enhanced thermoelectric properties of vanadium doped SrTiO3: a resonant dopant approach. J Alloys Compd. 2020;832:154958.
43. Singh SP, Kanas N, Desissa TD, Johnsson M, Einarsrud MA, Norby T, Wiik K. Thermoelectric properties of A-site deficient La-doped SrTiO3 at 100-900 °C under reducing conditions. J Eur Ceram Soc. 2020;40(2):401-407.
44. Lu Z, Zhang H, Lei W, Sinclair DC, Reaney IM. High-figure-of-merit thermoelectric La-doped A-site-deficient SrTiO3 ceramics. Chem Mater. 2016;28(3):925-935.
45. Shoji T, Sugiyama S, Fuda K. Effect of addition of titanium nitride on thermoelectric performance of yttrium-doped strontium titanate. Mater Trans. 2011;52(8):1531-1534.
46. Wang HC, Wang CL, Su WB, Liu J, Sun Y, Peng H, Mei LM. Doping effect of La and Dy on the thermoelectric properties of SrTiO3. J Am Ceram Soc. 2011;94(3):838-842.

47. Muta H, Kurosaki K, Yamanaka S. Thermoelectric properties of reduced and La-doped single-crystalline SrTiO3. J Alloys Compd. 2005;392(1-2):306-309.
48. Dylla MT, Kuo JJ, Witting I, Snyder GJ. Grain boundary engineering nanostructured SrTiO3 for thermoelectric applications. Adv Mater Interfaces. 2019;6(15):1900222.
49. Muta H, Kurosaki K, Yamanaka S. Thermoelectric properties of rare earth doped SrTiO3. J Alloys Compd. 2003;350(1-2):292-295.
50. Shi XL, Wu H, Liu Q, Zhou W, Lu S, Shao Z, Dargusch M, Chen ZG. SrTiO3-based thermoelectrics: progress and challenges. Nano Energy. 2020;78:105195.
51. Mary SB, Rajesh AL. Influence of trivalent lanthanides substitution on the thermoelectric properties of nanostructured Ca1−xLnx3+MnO3−δ (Ln3+ = Sm, Ce, La; x = 0, 0.1). J Mater Sci Mater Electron. 2020;31(8):6479-6487.
52. Mary SB, Francis M, Sathe VG, Ganesan V, Rajesh AL. Enhanced thermoelectric property of nanostructured CaMnO3 by sol-gel hydrothermal method. Phys B Condens Matter. 2019;575:411707.
53. Wang Y, Sui Y, Wang X, Su W. Effects of substituting La3+, Y3+ and Ce4+ for Ca2+ on the high temperature transport and thermoelectric properties of CaMnO3. J Phys D Appl Phys. 2009;42(5):055010.
54. Park JW, Kwak DH, Yoon SH, Choi SC. Thermoelectric properties of Bi, Nb co-substituted CaMnO3 at high temperature. J Alloys Compd. 2009;487(1-2):550-555.
55. Kabir R, Tian R, Zhang T, Donelson R, Tan TT, Li S. Role of Bi doping in thermoelectric properties of CaMnO3. J Alloys Compd. 2015;628:347-351.
56. Torres SDO, Thomazini D, Balthazar GP, Gelfuso MV. Microstructural influence on thermoelectric properties of CaMnO3 ceramics. Mater Res. 2020;23:e20200169.
57. Mouyane M, Itaalit B, Bernard J, Houivet D, Noudem JG. Flash combustion synthesis of electron doped-CaMnO3 thermoelectric oxides. Powder Technol. 2014;264:71-77.
58. Zhang FP, Lu QM, Zhang X, Zhang JX. Electrical transport properties of CaMnO3 thermoelectric compound: a theoretical study. J Phys Chem Solids. 2013;74(12):1859-1864.
59. Maneesai K, Khammahong S, Siripoom P, Phrompet C, Sriwong C, Maensiri S, Ruttanapun C. Fabrication and thermoelectric conversion of thermoelectric concrete brick with buried unileg N-type CaMnO3 thermoelectric module inside. Sci Rep. 2023;13(1):916.
60. Zhang FP, Lu QM, Zhang X, Zhang JX. First principle investigation of electronic structure of CaMnO3 thermoelectric compound oxide. J Alloys Compd. 2011;509(2):542-545.