Review of Recent Progresses in Thermoelectric Materials

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Abstract Thermoelectric (TE) technology facilitates the direct conversion of heat into electricity and vice versa. Thermoelectric materials attract researchers since they facilitate a promising green energy solution in the form of solid-state cooling and power generation. However, the low energy conversion efficiency restricts the use of TE materials in real-world applications. Developing highly efficient thermoelectric materials is necessary to benefit the environment as well as the economy. The performance of a particular TE material is generally evaluated by the dimensionless figure of merit (*ZT*). Recent years have witnessed progress with new techniques in maximizing the *ZT* values of various thermoelectric materials. In this review, we summarize recent development in thermoelectric materials for a specific temperature range, which has been developed to improve their maximum *ZT* value up to 95% at the same temperature.

Keywords Thermoelectric materials · Thermoelectric performance · Dimensionless figure of merit · Seebeck coefficient

1 Introduction

The environmental issues resulting from unsustainable consumption of fossil fuels are well known. Thermoelectric (TE) devices are compact, noiseless, and environmentally friendly and exhibit a leading potential for sustainable development. The thermoelectric module is a p-type and n-type semiconductor element-based solid-state device that converts the thermal energy with temperature difference into electric power (known as Seebeck effect) and also capable of converting electrical energy into temperature gradient (known as Peltier effect). Based on the directions of energy

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conversion, these devices are termed as thermoelectric coolers (TEC) and thermoelectric generator (TEG). Thermoelectric generators allow obtaining electricity from any heat source, which shows fantastic application potential. From micro-scale applications to large-scale applications, thermoelectric coolers offer a futuristic role in cooling systems as they work without any moving element involving working fluid.

2 Background

Thermoelectricity is based on two primary thermoelectric effects; the Seebeck effect and the Peltier effect. According to the Seebeck effect, an electromotive force emerges through the electrical circuit consisting of p-type and n-type semiconductor materials and connected in series when contacts are maintained at different temperatures. According to the Peltier effect, if the electric current passes through the circuit of p-type and n-type semiconductor materials, interconnected in series, heat flows from one side to the other side. So, one side of the thermoelectric module is cooled while the other side gets heated.

The performance of any thermoelectric material is generally recognized by the figure of merit (Z). Z depends on three essential material parameters: Seebeck coefficient (S), electrical conductivity (σ), and thermal conductivity (κ) and usually expressed in the dimensionless form at an absolute temperature (T). The dimensionless figure of merit (ZT) is defined as $ZT = S^2\sigma T/\kappa$. Alternatively, ZT is also defined as $(S^2/\rho\kappa)\,T$, where ρ is the electrical resistivity. A large power factor (S^2/ρ) is required to enhance thermoelectric performance. A good thermoelectric material should possess a large Seebeck coefficient (S), low thermal conductivity (σ), and high electrical conductivity (κ). The conversion efficiency of TE devices is directly related to the dimensionless figure of merit of their constituting materials. Thus, a high value of the figure of merit is highly desirable.

3 Recent Progresses to Enhance *ZT* of Thermoelectric Materials

In recent years, researchers applied new approaches and techniques in maximizing the ZT values of various thermoelectric materials. The available thermoelectric materials exhibit varying performance in the different temperature ranges. Improvement in each available thermoelectric material is a focused goal of researchers for a sustainable alternative of conventional energy converters. Earlier, the performance of the semiconductors used in TE applications was dependent on the available pure and perfect single crystals. However, these materials can be doped by adding small quantities of impurities. These impurities act as the electron donor for the parent materials. Most traditional semiconductors have cubic structures, whereas anisotropic crystals

are used for TE applications. The task of designing high-performance thermoelectric materials is to adjust the physical parameters of interconnected S, σ, and κ for a crystalline structure. Thermoelectric transport includes the flow of thermal energy and charge. The energy of phonons (vibrational waves of atoms) represents the thermal energy. Electron scattering on phonons creates electrical resistance. Through incorporating some new scattering mechanisms, nanostructures provide an opportunity to sever the connection between electric and thermal transport. The lattice thermal conductivity needs to be reduced for improvement in TE performance. Mass fluctuations increase through vacancies, and interstitial atoms result in higher phonon scattering that can lead to better TE performance. Sintering of bulk materials and melting production are the techniques used for research efforts to get improved TE materials. This work summarizes recent approaches to enhance the *ZT* of various thermoelectric materials. There is a wide variety of elements and compounds which can be categorized as thermoelectric materials. It is to be noted that every thermoelectric material exhibits different performance at different temperatures. Hence, it is not possible to recommend a single TE material that is suitable for all practical ranges of temperature in real-world applications. Thus in the present study, the authors have classified the TE materials based on their suitability for low-, medium-, and high-temperature applications.

3.1 Low-Temperature Thermoelectric Materials (300–500 K)

Bi_2Te_3 and its alloys with *ZT* values of around 0.9–1.0 are considered prominent TE materials at room temperature and widely used for practical thermoelectric applications [1, 2]. Hu et al. demonstrated that the porous structure affects thermoelectric performance [3]. As porosity increased, electrical and thermal conductivity decreased significantly. Reducing thermal conductivity compensates for the deterioration in electrical conductivity and improves the *ZT* value. A sample premixed with five wt percent NH_4HCO_3 was reported with 1.1 value of maximum *ZT* at temperature 343 K. This was around 20% better than that of the entirely dense sample with 0.92 value of *ZT*. Bi-containing Sb_2Te_3 and the related alloys with a high thermoelectric figure of merit can be futuristic options to use in thermoelectric devices. $Sb_{2-x}Bi_xTe_3$ samples were milled, pressed, and annealed under vacuum for 3 h at 250 °C by Adam et al. [4]. Bi was added to the binary Sb_2Te_3 system. An increased Seebeck coefficient and power factor were obtained for $Sb_{1.65}Bi_{0.35}Te_3$ with the reduced value of thermal conductivity. Subsequently, a high *ZT* of 1.14 at 400 K was achieved. The sample composition of $(Bi_2Te_3)_{0.15} + (Sb_2Te_3)_{0.85}$ was prepared to shift maximum *ZT* to the high-temperature zone by Madavali et al. [5]. The maximum *ZT* values of 1.3 and 1.07 were reported at 400 K and 300 K, respectively.

Tellurium is the prevailing thermoelectric material utilized in low to medium range of temperature. However, it contains an inferior thermoelectric efficiency with a low value of *ZT*. An enhancement in the performance of amorphous silicon has

been reported by Banerjee et al. [6]. They applied the method of arsenic ion implantation. The low-temperature dopant activation was done. It was observed that the *ZT* value of amorphous silicon (a-Si) thin films could be enhanced by seven orders at room temperature. Arsenic doping at low-temperature results in the enhancement of electrical conductivity. Empowering a-Si as a conspicuous TE material may be useful for sustainable energy applications at room temperature with maximum *ZT* up to 0.77. The magneto-thermoelectric figure of merit (*ZT*) in 3-D Dirac semimetal Cd_3As_2 crystal was reported by Wang et al. [7]. The magnetic field very effectively reduces electric conductivity and thermal conductivity. A maximum *ZT* value of 1.1 was obtained at 350 K temperature under 7 T of the magnetic field.

A hypothesis of thermoelectric transport properties in 2-D semiconducting quantum well structures is built up by Yelgel et al. [8]. Within the temperature range 50–600 K, computations are performed for n-type 0.1 wt% CuBr-doped $Bi_2Se_3/Bi_2Te_3/Bi_2Se_3$ and also for p-type 3 wt% Te-doped $Sb_2Te_3/Bi_2Te_3/Sb_2Te_3$ quantum well frameworks. It is discovered that diminishing the well thickness pronouncedly affects upgrading the *ZT* value. At 350 K temperature, the maximum *ZT* value of 0.97 is obtained for $Bi_2Se_3/Bi_2Te_3/Bi_2Se_3$. At 440 K temperature, the maximum *ZT* value of 1.945 is obtained for $Sb_2Te_3/Bi_2Te_3/Sb_2Te_3$. $CaMnO_3$ has a generally high Seebeck coefficient; however, the electrical conductivity (σ) is quite low (within the temperature range 300–1000 K). Hence, an un-doped material brings a low power factor ($S^2\sigma$). The bismuth doping of $Ca_{1-x}Bi_xMnO_3$ has been reported by Paengson et al. [9]. With x range of 0-0.05, TE materials were setup. The solid-state reaction and hot pressing techniques were used. Bi doping increased carrier concentration for all samples with different x. The electrical resistivity diminished with expanding bismuth content. The maximum *ZT* value of 0.065 at 473 K was found for $Ca_{0.97}Bi_{0.03}MnO_3$. It is worth mentioning that the *ZT* value was increased by 95% at the same temperature compared to $CaMnO_3$. Bi_2Te_3 and the family of similar compounds potentially satisfy the thermoelectric efficiency levels at low temperatures. However, the dimensionless figure of merit values decreases severely at a temperature over 450 K. The bulk $Bi_{1.9}Lu_{0.1}Te_3$ samples with diverse micro-grained particles were fabricated using cold isolated pressing (CIP) with annealing at high temperature and secondly by spark plasma sintering (at 653 and 683 K) by Yaprintsev et al. [10]. The maximum *ZT* ~ 0.9 for 450–500 K range of temperature range is obtained.

The summary of recent *ZT* improvements of thermoelectric materials at low temperatures discussed in this study is presented in Table 1.

3.2 Medium-Temperature Thermoelectric Materials (500–900 K)

CuAgSe exhibits excellent potential due to its fantastic carrier mobility. It also has low thermal conductivity. To prepare monodisperse CuAgSe nanocrystals, a scalable

Table 1 Summary of recent *ZT* improvements of TE materials at low temperatures

Researchers	Year	Thermoelectric material	Method for properties enhancement	Impact on *ZT* performance
Hu et al.	2020	$Bi_{0.4}Sb_{1.6}Te_3$	Pre-mixing with NH_4HCO_3	• Max. Dimensionless figure of merit (ZT_{max}) of 1.11 at 343 K • 20% increment in ZT_{max} as compared with fully dense material
Adam et al.	2020	Sb_2Te_3	Bi-containing	ZT_{max} value of 1.14 at 400 K for Sb_2Te_3
Madavali et al.	2018	$(Bi_2Te_3)_x + (Sb_2Te_3)_{1-x}$	Increasing Sb_2Te_3 content	• ZT_{max} value of 1.3 at 400 K • ZT_{max} value of 1.07 at 300 K
Banerjee et al.	2018	Amorphous silicon	Arsenic doping	*ZT* around ~0.64 ± 0.13 at room temperature
Wang et al.	2018	Cd_3As_2	Enhancement by the magnetic field	ZT_{max} value of 1.1 at 350 K
Yelgel and Srivastava	2014	$Bi_2Se_3/Bi_2Te_3/Bi_2Se_3$ and $Sb_2Te_3/Bi_2Te_3/Sb_2Te_3$	By varying the well thickness+	$ZT_{max} = 0.97$ at 350 K for $Bi_2Se_3/Bi_2Te_3/Bi_2Se_3$ and $ZT_{max} = 1.945$ at 440 K for $Sb_2Te_3/Bi_2Te_3/Sb_2Te_3$
Paengson et al.	2017	$CaMnO_3$	Bi doping and hot pressing of $CaMnO_3$	• ZT_{max} value of 0.065 at 473 K for $Ca_{0.97}Bi_{0.03}MnO_3$ • 95% increment in ZT_{max} as compared with un-doped material
Yaprintsev et al.	2017	$Bi_{1.9}Lu_{0.1}Te_3$	Fabrication by cold isostatic pressing and SPS	ZT_{max} value ~0.9 for 450–500 K

colloidal synthesis has been reported by Zuo et al. [11]. The gathered powder test was cleaned by a non-sulfur substance of $NaNH_2$. It was done to expel the organic ligands from the surface. After that, annealing process was also done. A 0.68 value of maximum *ZT* at 566 K was obtained. The obtained material shows the potential of TE applications for mid-range temperatures. The material before annealing exhibits a temperature- controlled transition from n-type toward p-type. This makes it suitable for thermal control transistor applications. $CoSb_3$ skutterudite is considered potential TE material for power generation. La Filler atoms are used to minimize lattice thermal conductivity for the skutterudite to get better TE performance [12, 13]. Bashir et al. reported a high *ZT* value of 1.15 at 692 K with La and In as the $In_{0.3}La_{0.5}Co_4Sb_{12}$ skutterudite [14]. BiCuSeO contains low thermal conductivity and an average power

factor. BiCuSO was doped with Pb and effectively synthesized by high pressure by Zhu et al. [15]. BiCuSeO doped with Pb increases the carrier concentration. This Pb doping improves the power factor. The thermal conductivity is smothered by Pb doping. At 700 K temperature, the maximum *ZT* of 0.14 is achieved. Synthesization with feasible high-pressure and high-temperature techniques can increase the TE performance of Cu_2Se bulk materials. At 723 K, a high *ZT* value of 1.19 was reported for Cu_2Se synthesized at 3 GPa by Xue et al. [16]. Recently, GeTe and its derivatives have gained considerable attention as promising thermoelectric materials. Perumal et al. [17] reported a maximum *ZT* value of 2.1 for In and Bi co-doped GeTe at 723 K.

The synthesization of a group of TiNiSn-based alloys has been performed by Chen et al. [18]. It was done by way of an easy solid-state reaction followed by the SPS method. The amount and mixture of the heterogeneous phase were precisely managed, which results in a successful decrement of thermal conductivity (up to 2.3–3.0 $Wm^{-1}K^{-1}$). Besides, TE figure of merit was enhanced up to 0.49 at 750 K temperature. Silicon–germanium-based alloys are appealing. For radioisotope thermoelectric power generation at an excessive temperature (more than 1000 °C), they offer a good choice of TE material. On the other side, mesostructured $In_{0.25}Co_4Sb_{12}$ and $In_{0.25}Yb_{0.05}Co_4Sb_{12}$ samples have been synthesized by Benyahia et al. [19]. The samples were fabricated through melting and annealing. Then, the ball-milling procedure was applied to minimize size and sintered through the SPS method. With a mean grain size of 400 nm, a maximum dimensionless figure of merit of 1.4 at 750 K temperature is obtained. It was achieved in the BM $In_{0.25}Co_4Sb_{12}$ + 0% CeO_2. TiNiSn-based half-Heusler (HH) alloys are widely studied. These thermoelectric materials show a high-temperature stabilization. However, the thermal conductivity is constantly enormously high, and hence, further *ZT* enhancement is difficult. SiC nanoparticles were brought into the matrix of $Pb_{0.98}Na_{0.02}Te$ doped with SrTe by Ai et al. [20]. The increased Seebeck coefficient and decreased electrical conductivity resulted in a remarkable peak *ZT* of 1.73 at 750 K.

Copper selenide is a promising thermoelectric material because of its fantastic electrical properties. A hydrothermal technique to incorporate astounding β-$Cu_2Se_{1-x}I_x$ nanopowder with a cost-effective minimum consumption of energy is reported by Wang et al. [21]. The nanopowder with different levels of doped iodine was used. Utilizing this straightforward and modest methodology, an improved *ZT* of 1.13 is obtained at a temperature of 773 K in iodine-doped Cu_2Se ($x = 0.03$) pellets after hot squeezing. Recently, the synthesis of p-type SiGe with boron using varied proportion is reported by Murugasami et al. [22]. The material was sintered through the spark plasma sintering technique. Doped with $B_{1.5}$ at.% synthesized SiGe alloy exhibits the enhanced *ZT* of 0.525 at 800 °C temperature. A considerable improvement of approximately 9.38% is obtained. Recently, the enhancement of skutterudite performance is reported by Yang et al. [23]. Tellurium-doped skutterudite has been shown to have promising TE properties using nano-micro-level pores. Cobalt, antimony, and tellurium powders were utterly blended with a nominal composition of $Co_4Sb_{11.5}Te_{0.5}$. Then, the material was stacked into carbon cauldrons and kept inside quartz tubes below vacuum for heating. The acquired ingots were ground into powders utilizing two successive methods, first by a mortar and then

by ball milling below vacuum. The two powders (without ball milling and with ball milling) with different proportions were blended, and after that, sintered using spark plasma sintering technique. The annealing process below vacuum was also done on the obtained bulk material. The authors reported that annealed nanoparticles carry some randomly allotted nanopores with a range of sizes from 200 nm to 2 μm. The development of these nanosized pores is due to strain during sintering. The thermal conductivity drops drastically which is a desired effect. A 1.2 value of the maximum dimensionless figure of merit is obtained for the annealed material at a temperature of 800 K. A significant increment of approx. 35% was reported. The thermoelectric properties of n-type-doped Mg_2 $(Si_{0.4}Sn_{0.6})_{1-y}$ Bi_y solid solutions are investigated theoretically by Yelgel [24]. From 300 to 800 K temperature range, the selected y range is 0.005–0.06 for doping Bi with available experimental data. It was found that an appropriate y can increase *ZT*. The maximum *ZT* is obtained with y = 0.03 at 800 K and values 1.82.

The graphene nanoplate incorporated into Cu_2Se samples has been fabricated by Li et al. [25]. The ball-milling technique was applied. Then, sintering through the SPS method was done. The homogeneous dispersion of the carbon phase reduced the Cu_2Se particles to form an excellent dense construction. Maximum *ZT* reached a high 1.7 value at 873 K. This gives an appropriate technique to use carbon engineering to maximize TE performance for Cu_2Se and family compounds. The deliberate actuated dislocations and vacancies are compelling in diminishing the thermal conductivity of polycrystalline SnS, as reported by Asfandiyar et al. [26]. Low thermal conductivity and high electrical conductivity $Sn_{0.99}Ag_{0.005}S$ sample were obtained at 877 K. Ag doping brings high power factor, and an enhanced *ZT* of 1.1 at 877 K was recorded for $Sn_{0.99}Ag_{0.005}S$. N-type half-Heusler NbCoSn performs well in TE performance, but p-type performs poorly. Replacing Sc at Nb site may change the n-type NbCoSn to a p-type semiconductor as reported by Yan et al. [27] by changing the Fermi level, indicating that Sc is a suitable p-type dopant. ZT_{max} value of 0.13 at 879 K has been reported.

The summary of recent *ZT* improvements of thermoelectric materials at medium temperatures discussed in this study is presented in Table 2.

3.3 High-Temperature Thermoelectric Materials (>900 K)

Lead selenide (PbSe) displays a temperature-dependent Seebeck coefficient, low thermal conductivity, and low electrical resistivity. Further, it has resolved the issue that emerges to get both n- and p-type legs. A simultaneous advancement of thermal and electrical properties of p-type PbSe has been reported by Zhao et al. [28]. The density hypothesis for estimations of valence band energy levels was used. Between lead selenide and nanostructures of $CdS_{1-x}Se_x/ZnS_{1-x}Se_x$, appropriate valence band alignments were introduced. A highly enhanced dimensionless figure of merit of 1.6 at 923 K was attained at $Pb_{0.98}Na_{0.02}Se + 3\%Cds$. Due to its high TE efficiency, Si-Ge alloys are considered valuable TE materials operating at high temperatures. The effect

Table 2 Summary of recent *ZT* improvements of TE materials at medium temperatures

Researchers	Year	Thermoelectric material	Method for properties enhancement	Impact on *ZT* performance
Zuo et al.	2018	CuAgSe	Colloidal synthesis of monodisperse CuAgSe NCs	ZT_{max} value of 0.68 at 566 K
Bashir et al.	2018	$CoSb_3$	La and In filling	ZT_{max} value of 1.15 at 692 K
Zhu et al.	2018	BiCuSO	Doping with Pb	ZT_{max} value of 0.14 at 700 K
Xue et al.	2019	Cu_2Se	Synthesis with high pressure	ZT_{max} value of 1.1 at 723 K
Perumal et al.	2019	GeTe	In and Bi doping	ZT_{max} value of 2.1 at 723 K
Chen et al.	2017	TiNiSn-based half-Heusler (HH) alloys	Synthesis with solid-state reaction	ZT_{max} value of 0.49 at 750 K
Benyahia et al.	2018	$In_{0.25}Co_4Sb_{12}$	Synthesis by a melting–annealing–ball-milling–SPS method	ZT_{max} value of 1.4 at 750 K
Ai et al.	2020	PbTe	SiC dispersing and SrTe doping	ZT_{max} value of 1.73 at 750 K for $Pb_{0.98}Na_{0.02}Te$/4 mol%SrTe composite
Wang et al.	2019	Cu_2Se	Synthesis of Cu_2Se alloys doped with iodine	ZT_{max} value of 1.13 at 773 K for $Cu_2Se_{1-x}I_x$ ($x = 0.03$)
Murugasami et al.	2019	SiGe	Synthesis of SiGe alloys doped with Boron	ZT_{max} value of 0.525 at 800 °C for doped with $B_{1.5}$
Yang et al.	2019	Te-doped skutterudite ($Co_4Sb_{11.5}Te_{0.5}$)	Nanomicroporous structure in $Co_4Sb_{11.5}Te_{0.5}$ materials via annealing the nano-$Co_4Sb_{11.5}Te_{0.5}$/$Co_4Sb_{11.5}Te_{0.5}$ composites	• Max. Dimensionless figure of merit (ZT_{max}) of 1.2 at 800 K for annealed sample (N10-A100) • 33.7% increment in ZT_{max} as compared with dense material (N0)
Yelgel	2016	$Mg_2Si_{0.4}Sn_{0.6}$	Mg_2 $(Si_{0.4}Sn_{0.6})_{1-y}$ Bi solid solutions	ZT_{max} value of 1.82 at 800 K
Li et al.	2018	Cu_2Se	By graphene nanoplate incorporation	ZT_{max} value of 1.7 at 873 K
Asfandiyar et al.	2020	SnS	Intentional-induced dislocations and vacancies and Ag doping	ZT_{max} value of 1.1 at 877 K for $Sn_{0.99}Ag_{0.005}S$
Yan et al.	2020	NbCoSn	Sc substitution at the Nb site	ZT_{max} value of 0.13 at 879 K

Table 3 Summary of recent *ZT* improvements of TE materials at high temperatures

Researchers	Year	Thermoelectric material	Method for properties enhancement	Impact on *ZT* performance
Zhao et al.	2013	PbSe	Integration of band structure with hierarchical structuring	ZT_{max} value of 1.6 at 923 K
Muthusamy et al.	2020	Si–Ge–Au	Boron doping	ZT_{max} value of 1.63 at 973 K
He et al.	2014	Cu_2S	Cu deficiency	ZT_{max} value of 1.7 at 1000 K
Fu et al.	2015	FeNbSb	Hf doping	ZT_{max} value of 1.5 at 1200 K
Wille et al.	2019	$Yb_{14}ZnSb_{11}$	Containing RE	ZT_{max} value of 0.7 at 1275 K

on thermoelectric properties of B-doped Si-Ge-Au nanocomposites was investigated, taken as $Si_{65-x}Ge_{31}Au_4B_x$ by Muthusamy et al. [29]. At 973 K, a maximum *ZT* value of 1.63 was reported at $x = 3$. The phonon-liquid electron-crystal concept for copper sulfide with reduced thermal conductivity and higher thermoelectric performance has been proposed by He et al. [30]. A high *ZT* value of 1.7 was reported at 1000 K by using copper deficiency as $Cu_{2-x}S$ with $x = 0.03$.

Half-Heusler compounds are increasingly attracting attention because of their strong mechanical and electrical properties at high temperatures. At 1200 K, through heavier Hf doping the p-type FeNbSb heavy-band half-Heusler alloys with 1.5 value of high *ZT* was reported by Fu et al. [31]. $Yb_{14}ZnSb_{11}$ is considered for intermediate valence interest. With rare earth (RE) solution as $Yb_{14-x}RE_xZnSb_{11}$ was investigated by Wille et al. [32]. The dimensionless figure of merit was reported as high as 0.7 at 1275 K with $x = 0.5$.

The summary of recent *ZT* improvements of thermoelectric materials at high temperatures discussed in this study is presented in Table 3.

4 Conclusion

Exploring advancement in thermoelectric materials for sustainable energy solutions is the contemporary area of interest. The *ZT* value of thermoelectric materials should be enhanced for a broad range of potential applications of thermoelectric devices. From this study, it can be highlighted that:

- In the recent past, material researchers are successfully applying new approaches to upgrade the performance of available materials for a particular temperature range.

- A promising new approach is to create nanolevel and macro-level pores in tellurium doped skutterudite to enhance *ZT* by approximately 35%.
- Another interesting approach is introducing a facile method for colloidal synthesis of copper-silver selenide. With ZT_{max} value of 0.68 at temperature 566 K, this resulted as a promising candidate for TE research in the intermediate temperature range.

The significant outcomes of researchers will boost the applicability of TE devices contribution to the present world's green energy solutions. For greater commercialization of thermoelectric applications, improved materials with high values of *ZT* are required at prevailing operating temperatures. This will boost the manufacture of better performing TE modules. These advancements in *ZT* values could close the gap in performance between conventional bismuth-tellurium-based materials and newer materials. The costs to invent newer thermoelectric materials are quite different from the production cost of those materials. The costs of candidate materials, costs to process those materials into TE elements, and cost to compensate the material loss are significant for the real commercial applications of newly researched materials. The non-availability of the requisite raw materials might result in holding the production of TE devices. More extensive work on that would be useful.

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