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Review Article

Review of Development Status of Bi_2Te_3-Based Semiconductor Thermoelectric Power Generation

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Semiconductor thermoelectric power generation is a new type of energy-saving and environment-friendly power generation technology, which directly converts heat energy into electrical energy by using the characteristics of semiconductor thermoelectric materials and has broad application prospects. This paper introduces the basic principles of thermoelectric materials and semiconductor thermoelectric power generation. The research status and progress of Bi_2Te_3-based semiconductor materials and thermoelectric generators in recent years are also introduced, respectively. Then, the paper emphasizes the research status of low temperature difference semiconductor power generation and points out the future development directions.

1. Introduction

Thermoelectric power generation technology has many advantages, such as simple structure, sturdy and durable, no moving parts, no noise, long service life, environmental protection, and so on. The main applications include aerospace and military fields, transportation, industrial waste heat recovery and power generation, the use of semiconductor thermoelectric power generation for lighting power in high-altitude weather stations, remote mountainous areas, border posts and other places, transport pipeline across the desolate area of natural gas and oil, the use of fuel oil or natural gas combustion heat, thermoelectric power generation device as a metal cathode protection power and oil and gas transport state detection, communication, and control system power supply. Therefore, the thermoelectric power generation technology has a broad research space, which is of great practical significance.

At present, the biggest problem of semiconductor thermoelectric generation technology is the low efficiency of its thermoelectric conversion, which is only 5%–7% [1], and far below those of hydropower, thermal power, nuclear power, wind power, and photovoltaic power. In order to achieve stable and optimal performance of thermoelectric generator, the researches on thermoelectric generation technology at home and abroad mainly focus on two aspects: (1) analysis in development and performance of thermoelectric materials, aiming to improve the thermoelectric merit value coefficient (ZT) of semiconductor. (2) Research of thermoelectric generator, aiming to improve power generation efficiency and output power.

2. Performance of Thermoelectric Materials and Technical Principle of Thermoelectric Power Generation

The study of thermoelectric materials began in the early 20th century. In 1911, Altenkirch proposed that dimensionless figure of ZT value can represent performance of thermoelectric materials and pointed out that when the ZT value reached 3 [2], thermoelectric conversion technology can compete with conventional power generation technology; $ZT = \alpha^2\sigma T/\lambda$, where α, σ, and λ are, respectively, Seebeck coefficient (thermoelectric power), electrical conductivity, and thermal conductivity of the thermoelectric material and T is the thermodynamic temperature. The $\alpha^2\sigma$ determines the electrical performance of the material, the λ determines the thermal transportation performance of the material [3, 4], and the electrical performance and thermal transportation performance are correlated, both of which are the functions of carrier concentration [5]. To improve *ZT* value is complicated and coordinated control of electrical performance and thermal transportation performance is required [6]. Since 1950s, the thermoelectric performances of the large number of materials have been studied, and it has been proved that the thermoelectric performances of different materials in different temperature zones are different.

At present, the research on the thermoelectric performance of semiconductor materials mainly focuses on the high-temperature region, while the research on the low-temperature region is less. Among them, the thermoelectric performance of Bi_2Te_3-based thermoelectric materials in the temperature range of 200 K to 500 K (including n type and p type; modified by doping) in the field of semiconductor alloys is the best [7, 8]; the *ZT* value at room temperature (300 K to 400 K) is closer to the “alloy limit value” [9], but the power generation efficiency is low. At present, thermoelectric power generation modules based on bulk Bi_2Te_3-based materials are more used for micro-environmental cooling and local precise temperature control using the Peltier effect (the inverse effect of the Seebeck effect) [10, 11].

The basic principle of thermoelectric power generation is to use the Seebeck effect of the thermoelectric material. Connecting one end of p type thermoelectric materials and one end of n type thermoelectric materials to form a PN junction, and the PN junction is placed between the cold and the heat sources to make it in a temperature-difference environment [12]. Due to thermal excitation, the hole (electron) concentration of the heat source end of the p(n)-type material is higher than that of the cold end, and holes and electrons are diffused from the heat source end to the cold end by the hole (electron) concentration gradient to form electromotive force; potential load connection between electromotive force can produce current. Thermoelectric generator (TEG) exposes two materials to different temperatures to complete the power generation process (Figure 1) [13]. The formation of a PN junction electromotive force is very small; a lot of such PN junction synthesis thermoelectric generator can get high enough voltage.

3. Research Status of Bi_2Te_3-Based Thermoelectric Materials

In order to improve the thermoelectric performance of Bi_2Te_3-based materials and broaden the application of power generation, scientists worldwide have conducted a great deal of researches. Now, the focuses of Bi_2Te_3-based thermoelectric materials studying include mainly three aspects: (1) low-dimension nanomaterials; (2) doping modification; and (3) preparation technology. The purpose is to synthesize high-performance Bi_2Te_3-based thermoelectric materials with different ideas and methods to improve their transport characteristics and greatly improve the *ZT* value of materials. The material is one of the most successful commercial available Te material, Bi-Te-based material (Table 1) [13]. It should be noted that, for Bi_2Te_3-based thermoelectric materials, the maximum ZT value is obtained only at room temperature, and ZT drops sharply with increasing temperature. Thus, the Bi-Te-based alloys are generally used near the room temperature [14].

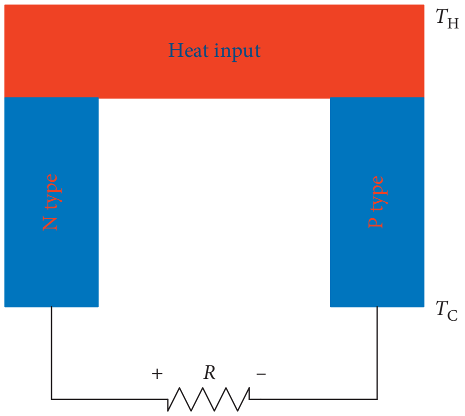

Figure 1: The schematic diagram of thermoelectric generator.

3.1. Studies on Low Dimension of Nanoscale. The theoretical research on Bi_2Te_3-based thermoelectric materials is in the process of continuous improvement. The bulk thermoelectric materials mainly use the semiclassical electron transport theory to calculate the thermoelectric efficiency of *ZT*, and the general bulk thermoelectric materials have low *ZT* values. Therefore, low-dimensional nanometer is one of the effective ways to improve the performance of thermoelectric materials.

By reducing the dimension, the thermal conductivity can be reduced and the *ZT* value can be increased, the Seebeck coefficient can be further increased, and the power generation efficiency of thermoelectric power generation can be improved. In recent years, the research on nanostructure Bi_2Te_3-based thermoelectric materials, especially superlattice structures and nanowires has been very active [8]. In 1993, Hicks and Dresselhaus predicted for the first time that the thermoelectric performance of one-dimensional (line) or two-dimensional (slice) systems was greatly improved compared to three-dimensional (block) materials [32, 33]. Venkatasubramanian and others have developed the superlattice nano-thin film (2D) [27]. Bejenari et al. found that the maximum *ZT* values of p type Bi_2Te_3 nanotubes (1D) at the test temperatures of 310 K, 390 K, 480 K, and 30 nm × 30 nm, 15 nm × 15 nm and 7 nm × 7 nm were 1.3, 1.6 and 2.8, and the *ZT* values can reach 1.2, 1.3 and 1.7 even at room temperature [34]. However, the maximum value of *ZT* increases while gradually moving temperature to the high zone. Zhao Xin-Bing et al. synthesized the La-doped Bi_2Te_3 flower-like nanoparticles (0D) by hydrothermal method in Zhejiang University [35]. The *ZT* value at 480K was 0.58. In the past few years, low-dimensional and nanostructured Bi_2Te_3-based thermoelectric materials have been synthesized by various synthetic methods. The thermoelectric properties shown in Table 2 [8].

Table 1: The value of ZT of the Bi-Te-based material (reproduced from [13] with permission).

Authors	Published year	Material	ZT	Temperature (K)
Tan et al. [15]	2014	$Bi_2Se_{0.5}Te_{2.5}$	1.28	Room temperature
Yeo and Oh [16]	2014	$(Bi,Sb)_2Te_3$	1.41	Room temperature
Tan et al. [17]	2014	$Bi_2Te_{2.7}Se_{0.3}$	1.27	Room temperature
Chen et al. [18]	2014	$Bi_{0.4}Sb_{1.6}Te_3$	1.26	Room temperature
Fan et al. [19]	2014	p type $(Bi,Sb)_2Te_3$	1.17	323
Tan et al. [20]	2014	Bi2(Te,Se)3	1.01	Room temperature
Xu et al. [21]	2012	p type$(Bi_{0.26}Sb_{0.74})_2Te_3$ + 3%Te ingots	1.12	Room temperature
Jiang et al. [22]	2005	Bi-Sb-Te materials	1.15	350
Hong et al. [23]	2003	$(Bi_2Te_3)_{0.25}(Sb_2Te_3)_{0.75}$	1.80	723
Kim et al. [24]	2002	$Bi_2Te_{2.85}Se_{0.15}$	2.38	773
Park et al. [25]	2002	$Bi_{0.5}Sb_{1.5}Te_3$	1.93	693
Yang et al. [26]	2001	Bi_2Te_3-Sb_2Te_3	1.26	420
Venkatasubramanian et al. [27]	2001	p type Bi_2Te_3/Sb_2Te_3	1.67	723
Yang et al. [28]	2000	95%Bi_2Te_3-5%Bi_2Se_3	1.77	693
Miura et al. [29]	2000	90%Bi_2Te_3-5% Sb_2Te_3-5% Sb_2Se_3	1.87	713
Seo et al. [30]	1997	$(Bi_2Se_3)_x(Bi_2Te_3)_{1-x}$	1.62	693
Seo et al. [30]	1997	Bi_2Te_3	1.86	693
Seo et al. [31]	1996	$Bi_2Te_{2.85}Se_{0.15}$	2.4	300

Table 2: Thermoelectric properties of low-dimensional and nanostructured materials synthesized by various synthetic methods in the past years (reproduced from [8] with permission).

Material system	Carrier type	ZT	K ($Wm^{-1}K^{-1}$)	T (K)	Synthetic method
BiSbTe	p	1.2	—	RT	HEBM + HP
BiSbTe	p	1.4	—	373	HEBM + HP
BiSbTe	p	1.3	—	373	HEBM + HP
BiSbTe	p	1.4	—	373	HEBM + HP
$Bi_2Te_{2.7}Se_{0.3}$	n	1.04	—	498	HEBM + HP
$(Bi,Sb)_2Te_3$	p	1.5	—	390	MS + SPS
$(BiSb)_2Te_3$	p	1.47	0.26	440	HS + HP
$Bi_{0.52}Sb_{1.48}Te_3$	p	1.56	0.26	300	MS + SPS
Bi_2Te_3	n	1	0.3	450	HS + HP
$Bi_{0.4}Sb_{1.6}Te_3$	p	1.5	0.16	RT	MS + HP
$Bi_{0.4}Sb_{1.6}Te_3$	p	1.8	—	316	MS + HP

3.2. Studies on Doping Modification. In order to improve the thermoelectric performance of Bi_2Te_3-based thermoelectric materials, another effective way is to incorporate semimetal into the base thermoelectric materials. Dou et al. improved their *ZT* values to 1.12 and 1.27 at about 303 K and 363 K by doping amorphous (SiO_2) to $(Bi_2Te_3)_{0.2}(Sb_2Te_3)_{0.8}$ bulk, which increased by 27% and 20%, respectively [36]. HWang et al. used wet chemical method to embed nano-metal particles in the p type $Bi_{0.5}Sb_{1.5}Te_3$ bulk, which made *ZT* value reach the maximum of 1.47 at near room temperature [37]. Wu et al. synthesized $R_{0.2}Bi_{1.8}Se_{0.3}Te_{2.7}$ which is doped with Ce, Y, and Sm, respectively, by hydrothermal method [38]. It was found that the Seebeck coefficients of both Ce and Y exceeded that of the two elements at temperatures higher than 400 K undoped materials, but the effect is not satisfactory at low temperatures. Subsequently, they studied the effect of different doping concentrations on the $CexBi_1$-$xSe_{0.3}Te_{2.7}$ samples [39]. When the value of x was 0.1, the Seebeck coefficients of the samples were greatly improved at the measurement temperature less than 480K, and the maximum *ZT* value was 1.22 at 386 K. By cryogenic growth, Venkatasubramanian et al. prepared the superlattice nano-thin films (2D) of the p type Bi_2Te_3 or Sb_2Te_3 and n type Bi_2Te_3or $Bi_2Te_{2.83}Se_{0.17}$, and their *ZT* values reached 2.4 and 1.4, respectively, at room temperature [27]. Conventional doping is generally doped with Sb and Se elements. Different doping components change the thermoelectric properties of Bi_2Te_3 materials (Table 3) [40].

3.3. Studies on Preparation Technology Research. The research on low-dimension and doping modification of semiconductor thermoelectric materials has promoted the development of semiconductor preparation technology. However, segregation phenomenon occurs during the transformation from liquid phase to solid phase in melting and casting process, and Bi and Te in the molten state tend to volatilize, leading to the decrease of the utilization ratio and the decrease of the thermoelectric figure of merit.

The currently popular semiconductor thermoelectric materials are prepared by molecular beam epitaxy (MBE), pulsed laser deposition technology (PLD), alloying technology, hydrothermal synthesis, sputtering deposition, flash evaporation, electrochemical preparation, laser cladding, magnetron sputtering (MS), high-pressure inert gas atomization (HP-GA), and metal organic vapor deposition

Table 3: The effect of doping contents on the thermoelectric properties of Bi_2Te_3.

Materials	Doping type	Carrier type	$Z/10^{-3}$ (K)
Bi_2Te_3	—	n	2.0
Bi_2Te_3	AgI	n	2.2
Bi_2Te_3	CuI	n	2.6
$Bi_2Te_{2.7}Se_{0.3}$	AgI	n	2.3
$Bi_2Te_{2.7}Se_{0.3}$	—	n	2.4
$Bi_2Te_{2.25}Se_{0.75}$	$CuBr_2$	n	2.7
$Bi_2Te_{2.88}Se_{0.12}$	SbI_3	n	3.1
$Bi_{1.8}Sb_{0.2}Te_{2.7}Se_{0.3}$	SbI_3	n	3.2
Bi_2Te_3	Excessive Bi	p	1.6
Bi_2Te_3	Excessive Bi	p	1.5
Bi_2Te_3	—	p	1.8
$Bi_{1.5}Sb_{0.5}Te_3$	Excessive Bi	p	2.2
$Bi_{0.5}Sb_{1.5}Te_3$	Excessive Bi	p	3.1
$Bi_{1.52}Sb_{0.5}Te_{2.85}Se_{0.15}$	Excessive Bi	p	2.4
$Bi_{1.5}Sb_{0.5}Te_{2.90}Se_{0.1}$	Excessive Bi	p	3.4

(MOCVD) [41]. Table 4 shows a comparison of different preparation methods of Bi-Te-based material [42].

Table 4: Comparison of different preparation methods of Bi-Te-based material.

Preparation method	T (°C)	S (μ V·K^{-1})	$\rho(\mu\Omega\cdot m)$
ECD	400–492	−213 to −129	—
PLD	—	—	—
MBE	250–310	−180	—
MOCVD	400–492	−218	6.92
Coevaporation	300	−228 (n type) 81 (p type)	12.99 (n type) 3.23 (p type)
Flash evaporation	473	−180	27
IBS	Room temperature	−168 to −32	3.18
MS	Room temperature	59.89	1.47

4. Research Status of Thermoelectric Generator (TEG)

The first thermoelectric generator (TEG) was developed by TUX in 1947, and its power generation efficiency was only 1.5% [43]. Since then, the need for power supplies in the military space fronts has contributed to the rapid development of thermoelectric generators; the United States and the former Soviet Union are the countries that have developed and used the most TEGs of radioisotopes. TEG has been industrialized in terms of utilization of industrial waste heat [44] and automobile waste heat [45]. With the appearance of high-performance and low-dimensional thermoelectric materials, it has also promoted the development of micro-TEG which was used for power supply for microwatt [46], milliwatt low-power devices, and its electric cooling [47]. In addition, thermoelectric power generation, photovoltaic power generation, and other composite power generation system research have also been carried out [48, 49]. TEG performances are characterized by output power and thermoelectric conversion efficiency [50]. With regard to the factors affecting the performance of TEG, abundant experimental researches have been accumulated at home and abroad. The researchers mainly focus on the three aspects: (1) coupling effects of thermoelectric material; (2) module structural parameters; and (3) structural parameters of system. At present, TEG types include radioisotope temperature difference TEG, residual (waste) thermal temperature difference TEG, in-plane-type miniature TEG, cross-plane miniature TEG, and cylindrical micro-TEG. The advantages and disadvantages are shown in Table 5 [51]. Those modules that are already available or soon to be marketed are presented and summarized in Table 6 [52]. The temperature of the hot and cold end of the thermoelectric module of each stage of the multistage thermoelectric generator is interrelated, sharing a hot end and a cold end. Here is the schematic layout of thermoelectric module (Figure 2) [53].

4.1. Studies on Coupling Effects of Thermoelectric Material.

In consideration of Seebeck effect and Peltier effect, Yang et al. established a thermocouple analysis model and analyzed the influence of material physical parameters and its variation on the working characteristics of thermoelectric generator by numerical simulation [54]. It is pointed out that the thermal conductivity, resistivity, and Seebeck coefficient on the conversion efficiency of the generator are nonlinear, of which the thermal conductivity was the most obvious. But it ignores the effect of the Thomson effect as a secondary effect. Chen et al. pointed out that the Thomson effect significantly reduces the maximum thermoelectric conversion efficiency and the maximum output power of a thermoelectric element [55]. Furthermore, Lei et al. pointed out that the influence of Thomson heat on output power cannot be neglected under the condition of low-temperature and large temperature difference [56]. Chen et al. pointed out that the heat transfer between the heat source and the hot side of the semiconductor has a great impact on the power output and output efficiency under the influence of the three main irreversible factors of thermal conductivity, heat leakage, and Joule heat [57, 58]. Optimizing hot-side heat transfer design is necessary. However, both of their conclusions are obtained in the circumstances where the thermal conductivities are same in the cold, hot end, and heat source. There thus could be additional discussion when above circumstances do not exist. And the research is conducted only for the unit. For the system composed of a multiunit module and a multimodule system, there would be further research when the external conditions changed.

4.2. Studies on Module Structural Parameters.

Rezania designed and optimized the structure of the thermoelectric power module [59] and seeks the maximum output power of the module. The results showed that the needle thermocouple arm can effectively reduce the thermal conductivity of the module and thus improve the efficiency of thermoelectric conversion. Liu lei set up a solar TEG model and explored the influence of the factors such as heat ratio,

Table 5: Comparison of properties of different thermoelectric generators.

Thermoelectric generator type	Advantages	Disadvantages
Radioisotope temperature difference TEG	Long life, reliable performance, no environmental impact, no maintenance	High cost and low conversion efficiency
Residual (waste) thermal temperature difference TEG	Low cost, energy saving and reliable performance	Low conversion efficiency
In-plane-type miniature TEG	Large temperature difference can be established at both ends of the device	Heat is easily lost and complex manufacturing process
Cross-plane miniature TEG	High voltage can be achieved with small temperature difference	Low-temperature difference and complex manufacturing process
Cylindrical micro-TEG	Uniform large temperature difference	Complex manufacturing process

Table 6: List of TE modules and their properties (reproduced from [52] with permission).

Manufacturer	Materials	Temperature difference ΔT	Power weight	Status	Maximum temperature	Information outlook
HiZ, Thermonamic, Lairdtech, Marlow, Komatsu etc.	Bi_2Te_3	300 K	20 W 115 g	€40–€100	300°C	Scarce (rare earth), toxicity
Evident thermoelectric	Half-Heusler	500 K	15 W	Coming soon	600°C	Environmentally friendly, low cost, availability of raw, materials
Shanghai Institute of Ceramics	Skutterudites	510 K	25 W	Coming soon	600°C	Environmentally friendly, low cost, availability of raw materials
TEGMA	Skutterudites	—	—	Still in development	—	Environmentally friendly, low cost, availability of raw materials
TECTEG MFR	Calcium/Manganese oxide	750 K	12.3 W	Available	800°C	Environmentally friendly, low cost, availability of raw materials
TECTEG MFR cascade modules	Calcium/Manganese oxides with Bi_2Te_3	435 K	11 W	Available	600°C	—
TECTEG MFR hybrid modules	BiTe–PbTe	320 K	21.7 W	Available	360°C	Scarce (rare earth), toxicity
Hotblock Onboard	Silicon-based alloy	500 K	3.6 W 6 g	Available	600°C	Environmentally friendly, low cost, availability of raw materials
Romny Scientific	Magnesium silicide	—	—	Coming soon	600°C	Low \$/Watt target: 1\$/W
Alphabet energy	p type tetrahedritesnn-type magnesium silicide	300 K	9.2 W	Available	600°C	Tetrahedrite is a naturally occurring p type mineral
OTEGOCDT	Organic TEG	Small temperature gradients	—	Coming soon	130°C	Environmentally friendly, low cost, easily scalable

section area, and length variation on system performance [60]. It was found that the change of heat ratio and the length of the thermoelectric unit had a significant impact on the performance, but the change of the section area's influence was weak. Mao-de Li studied the influence of thermal contact resistance and contact resistance in small TEG generator and showed the impact of the contact resistance and contact resistance on the TEG cannot both be ignored [61]. D'angelo [62] and Mccarty [63] further analyzed the influence of the geometrical size, contact resistance and thermal contact resistance, and endpoint temperature difference on the performance of single module generator and optimized the length and quantity of the thermoelectric units. Chen et al. optimized the distribution of heat exchanger area of TEG single module and analyzed the influence of the number of thermoelectric units on the optimal current [64]. Al-merbati et al. simulated and optimized the thermal compressive stress of the thermoelectric module [65]. Chen used finite element method to solve the steady heat transfer under the condition of three-dimensional thermoelectric coupling physical model, considered the temperature characteristic of the thermoelectric material physical parameters, and optimized the structure of thermoelectric power generation module including thermoelectric unit length, area and thickness of the thermal conductivity on output power, and efficiency of energy

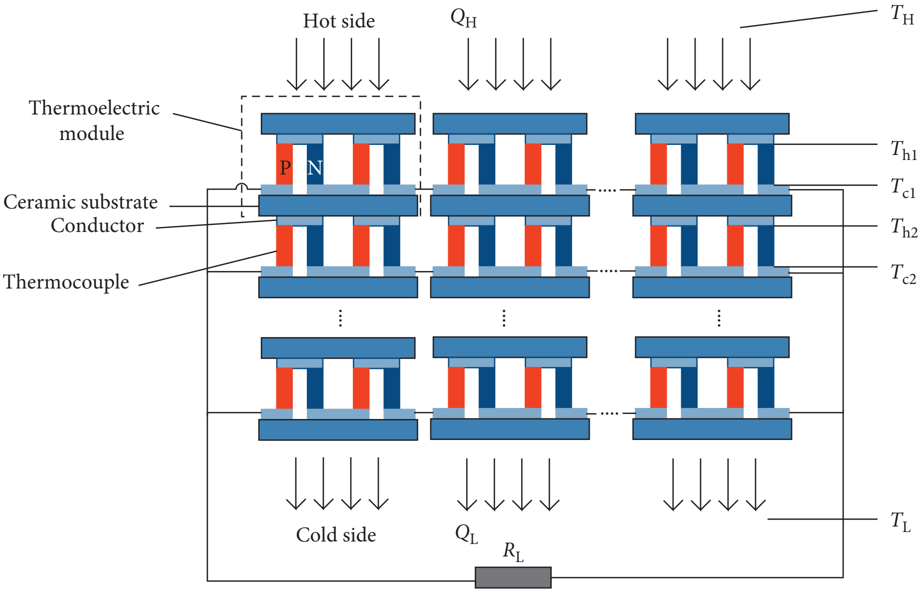

Figure 2: Schematic layout of thermoelectric module.

conversion [66]. And it is pointed that the thickening of the thermal conductive substrate will reduce the output power and efficiency of energy conversion.

4.3. Studies on Structural Parameters of System. Yu has established a three-dimensional model of thermoelectric monocouples composed of single PN junctions on ANSYS and studied the effect of different insulating filler and height of finned heat exchanger on temperature of H/C side in thermoelectric unicouple and output voltage [67]. Pan studied the structural parameters and the inversibility by establishing TEG model and discussed the optimal conditions of TEG output power at a given temperature [68]. Jiang et al. improved the overall performance of the waste heat generation system by optimizing the spacing between the multitemperature generation modules and the thickness of the substrate [69]. Montecucco et al. found that using appropriate series-parallel mode and certain load pressure between modules will be beneficial to improve the output performance of the thermoelectric system [70]. The research of He [71] and Su [72] showed that the irreversible heat transfer performances among the cold ending, the hot ending, the heat dissipation, and the heat collection device were directly or indirectly affected by the output performance of the thermoelectric power generation module. Its performance is mainly based on the temperature gradient and thermal performance of the cooling device between the heat and the cooling device. Chen et al. pointed out that the load resistance should be slightly bigger than the internal resistance when TEG is in optimal working state and is implementation-specific [57]. Ren et al. pointed out that the load resistance of the power supply circuit has obvious influence on the temperature distribution of the thermoelectric element of the generator and can cause the shift of the maximum output power of the generator [73]. Ou proposed that under the large temperature difference environment, the efficiency and output power of the thermoelectric power generation system are simulated by the variable physical model, it is verified that the variable physical model has higher computational accuracy than the conventional physical model [74].

5. Research of Semiconductor Power Generation under Small Temperature Difference

For now, the application of semiconductor thermoelectric power generation is mainly in large temperature difference environments; relatively speaking, the utilization of thermoelectric power generation in small temperature difference is fewer. By using small temperature difference, Qian [75] and Qu [58] have studied the bad condition of semiconductor thermoelectric power generation technology, and some operation rules were found to some extent. Li analyses the performance of semiconductor materials under small temperature difference from a perspective of exergy, put forward to getting exergy efficiency as evaluation parameters, and found that with the decrease of the temperature difference, the efficiency of semiconductor thermoelectric generator decreases obviously, but basically exergy efficiency stays stable [76]. Yang constructed the dynamic model and test bed of low-temperature thermoelectric power generation and analyzed the influence of certain factors (such as the influence of cold and hot source temperature, heat transfer performance, load resistance) on maximum output and system efficiency of TEG [77]. Although the study involved the use of low-temperature difference, the low-temperature difference in low-temperature zone was not studied. Most of the researches on the use of the low-temperature difference electric generation in low-temperature zone are the study on Cold Energy Generation with Liquefied Natural Gas (LNG, the temperature about −162°C). Zhao Yulong et al. applied the thermoelectric power generation technology to the LNG air temperature vaporizer, designed the new finned tube with the thermoelectric generator, and carried out the modeling and calculation [78]. The results showed that the new finned tube has better performance. Zheng Jiang et al. put forward the concept of using TEG to recover the waste heat of automobile engines (EGs) and the cold energy of low-temperature fuel, pointing out two characteristics based on the low-temperature zone where the cold source is located and the big difference between EG and temperature. The thermoelectric conversion efficiency of TEG is higher than the normal value [79]. Ke [80] and Jia [81] all studied the thermoelectric power generation of LNG low-temperature semiconductor and analyzed influencing factors of the related performance. The low-temperature thermoelectric properties of a certain P- or n type Bi_2Te_3 material prepared by Jiang Mingbo et al. were measured by liquid nitrogen which simulated LNG within the temperature range of 80 K–300 K, and the study of cold energy power generation device was carried out, so as to prove the feasibility of using Bi_2Te_3 for cold energy power generation [82].

6. Conclusions

The development of semiconductor thermoelectric power generation technology provides a broad prospect for solving the problems of energy shortage and environmental pollution. At present, the research of Bi_2Te_3-based semiconductor thermoelectric power generation technology mainly focuses on the development of high-performance thermoelectric materials and reliable thermoelectric power generation. Although scholars at home and abroad have done a substantial amount of research work, the efficiency of semiconductor thermoelectric generation is still lower than that of conventional power generation, especially, there is less research on power generation under small temperature difference in low-temperature zone.

In general, there are three main directions of the development of semiconductor thermoelectric power generation:

(1) To improve the performance of Bi_2Te_3-based semiconductor thermoelectric materials by doping, low dimensional, and nano-scale

(2) By means of simulation and experiment to optimize the relative parameters of thermoelectric generator and achieve the goal of improving efficiency and output power

(3) To expand the application field and focus on the research of thermoelectric power generation under small temperature difference and poor heat source

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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