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Park et al.

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(54) **THERMOELECTRIC CONVERSION MATERIAL AND PRODUCING METHOD THEREOF, AND THERMOELECTRIC CONVERSION ELEMENT USING THE SAME**

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H01L 35/16 (2006.01)

(Continued)

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CPC **H01L 35/18** (2013.01); **H01B 1/08** (2013.01); **H01L 31/0272** (2013.01); (Continued)

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See application file for complete search history.

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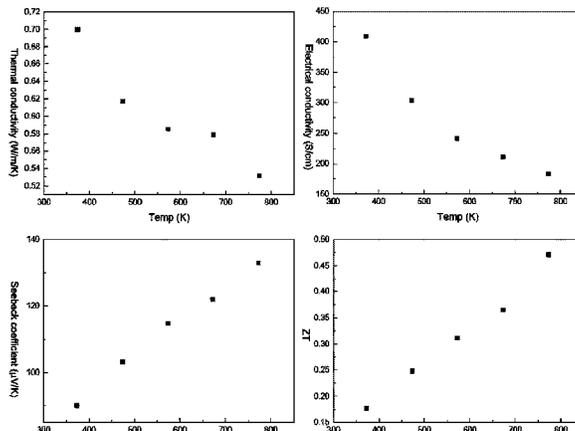
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(57) **ABSTRACT**

Thermoelectric conversion materials, expressed by the following formula: $Bi_{1-x}M_xCu_{1-w}O_{a-y}Q1_yTe_{b-z}Q2_z$. Here, M is at least one element selected from the group consisting of Ba, Sr, Ca, Mg, Cs, K, Na, Cd, Hg, Sn, Pb, Mn, Ga, In, Tl, As and Sb; Q1 and Q2 are at least one element selected from the group consisting of S, Se, As and Sb; x, y, z, w, a, and b are $0 \leq x < 1$, $0 < w < 1$, $0.2 < a < 4$, $0 \leq y < 4$, $0.2 < b < 4$, $0 \leq z < 4$ and $x+y+z > 0$. These thermoelectric conversion materials may be used for thermoelectric conversion elements, where they

(Continued)



may replace thermoelectric conversion materials in common use, or be used along with thermoelectric conversion materials in common use.

14 Claims, 13 Drawing Sheets

Related U.S. Application Data

application No. 13/531,186, filed on Jun. 22, 2012, now Pat. No. 8,715,538, which is a continuation of application No. 12/906,917, filed on Oct. 18, 2010, now Pat. No. 8,226,843, which is a continuation of application No. PCT/KR2008/007041, filed on Nov. 28, 2008.

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H01L 31/0272 (2006.01)
H01L 31/032 (2006.01)
H01L 31/072 (2012.01)
H01L 31/0725 (2012.01)

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Figure 1

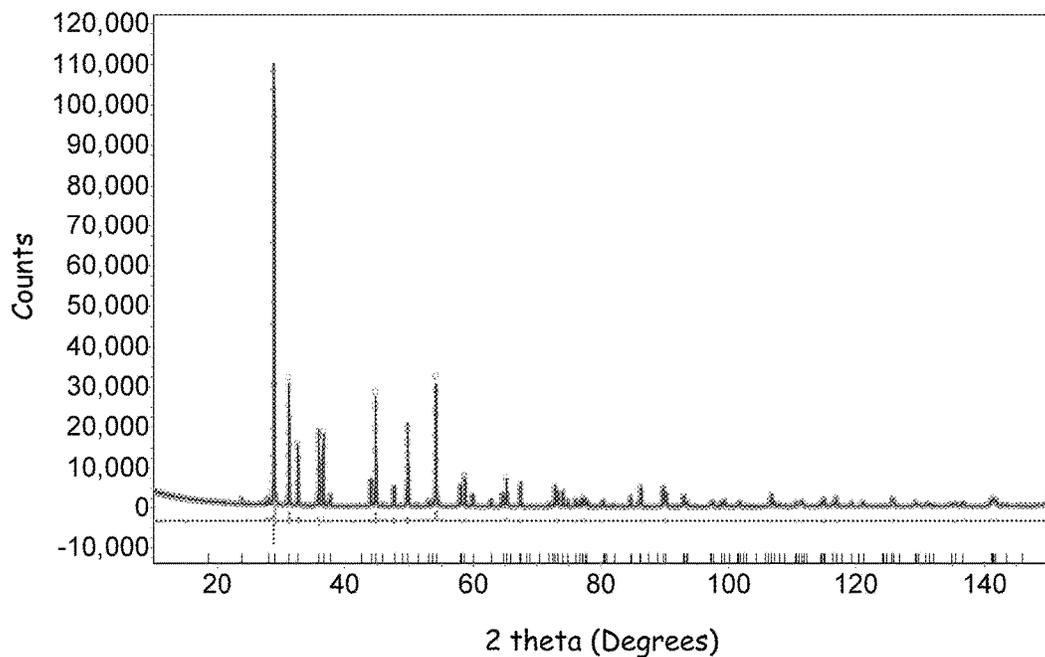


Figure 2

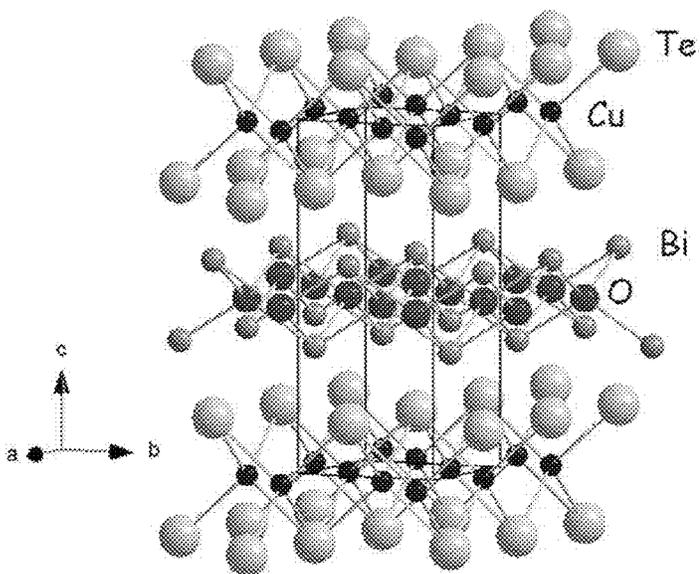


Figure 3

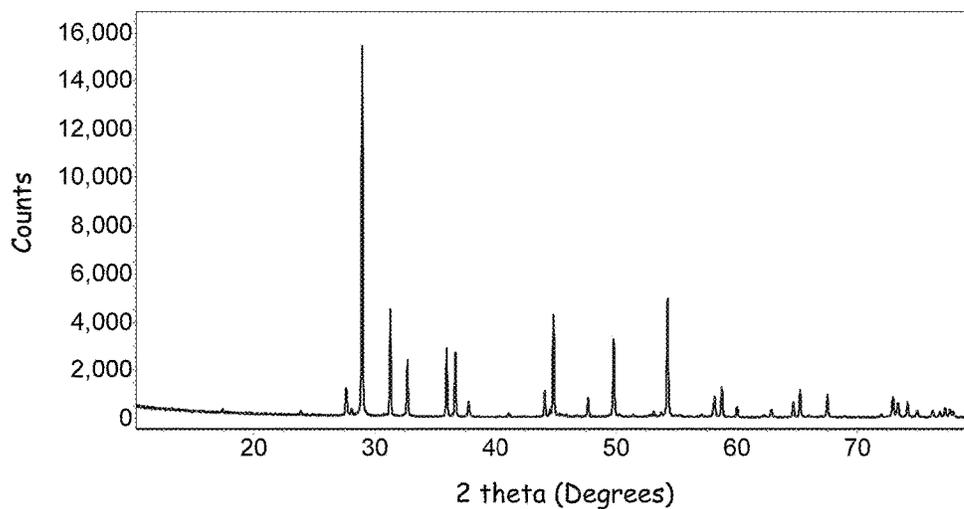


Figure 4

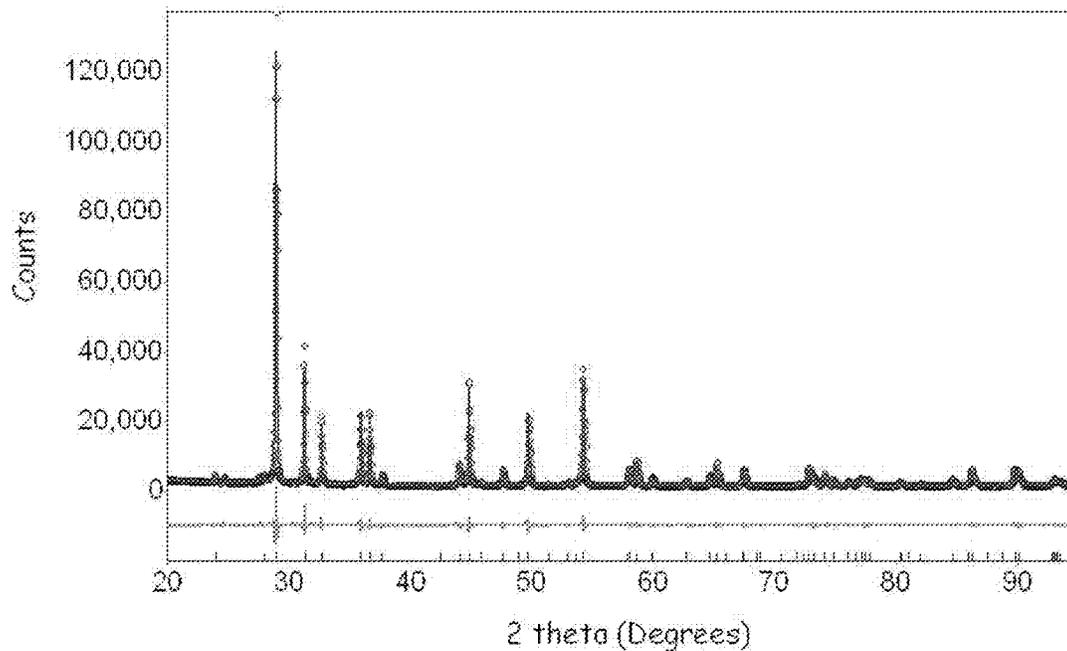


Figure 5

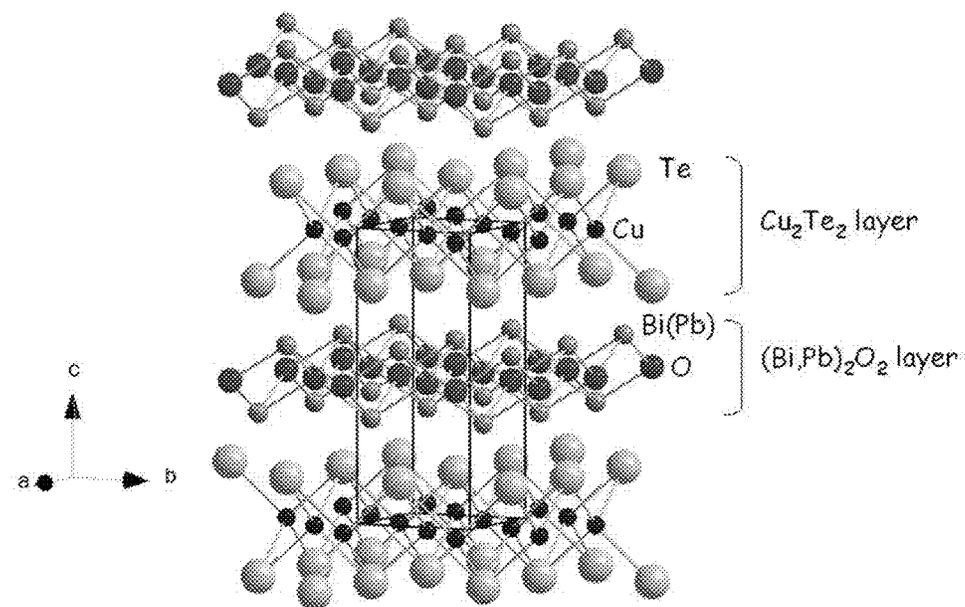


Figure 6

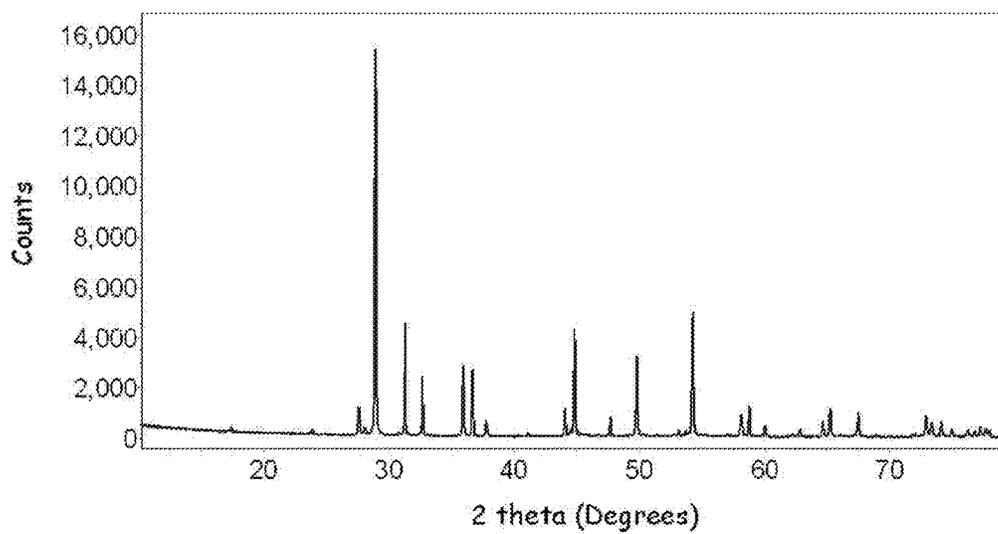


Figure 7

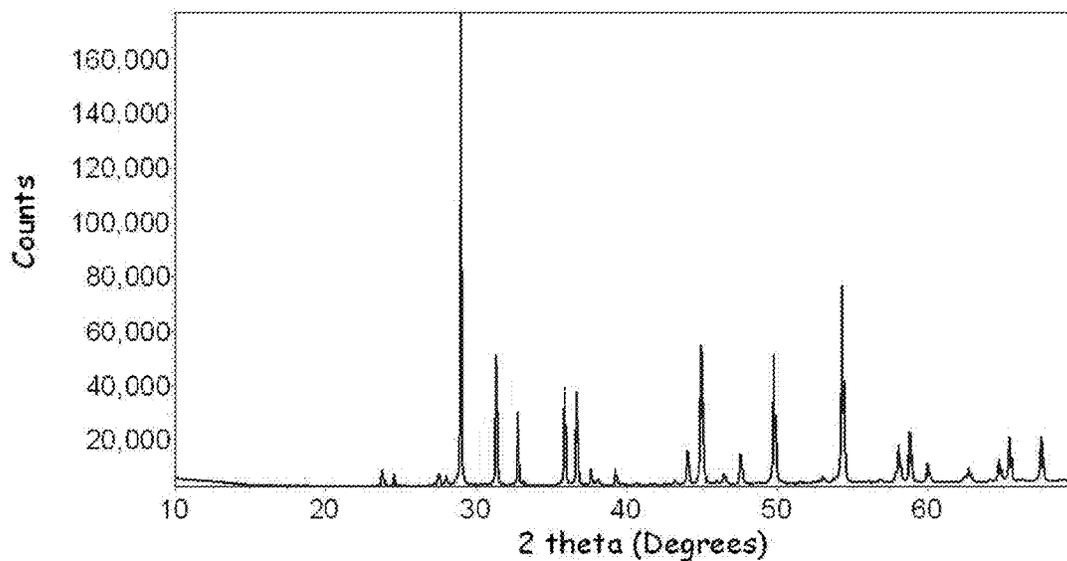


Figure 8

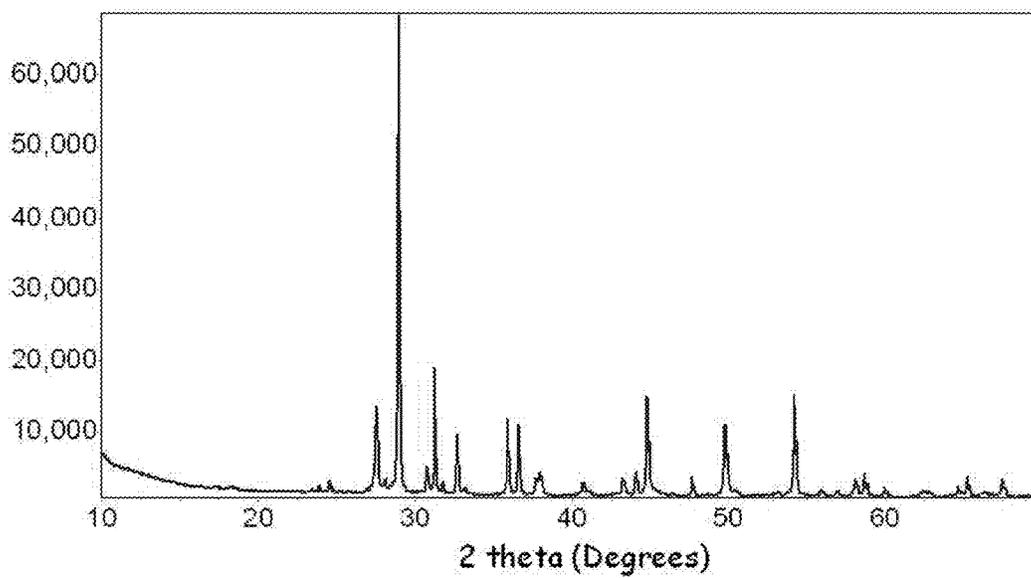


Figure 9

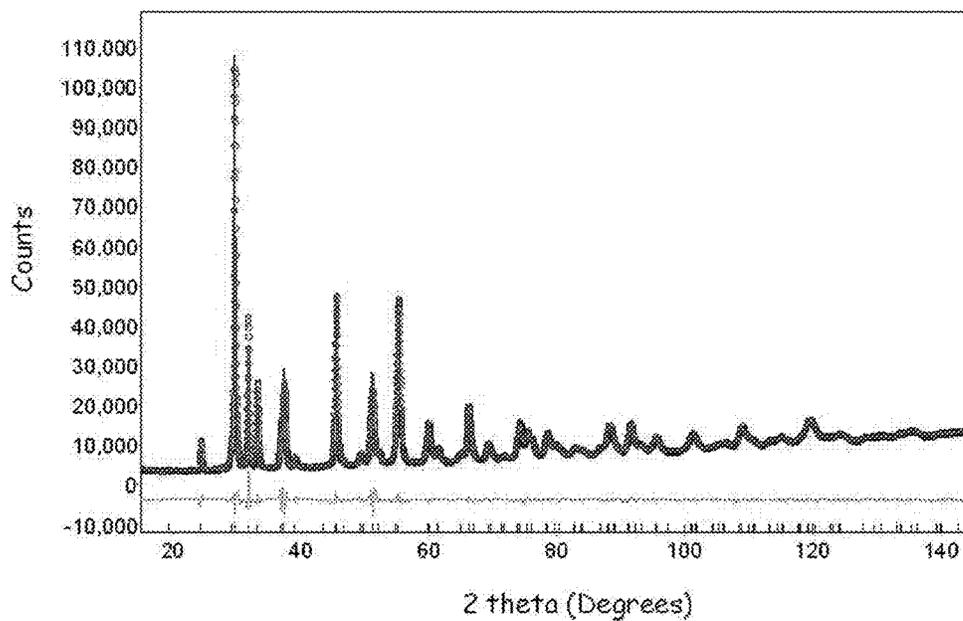


Figure 10

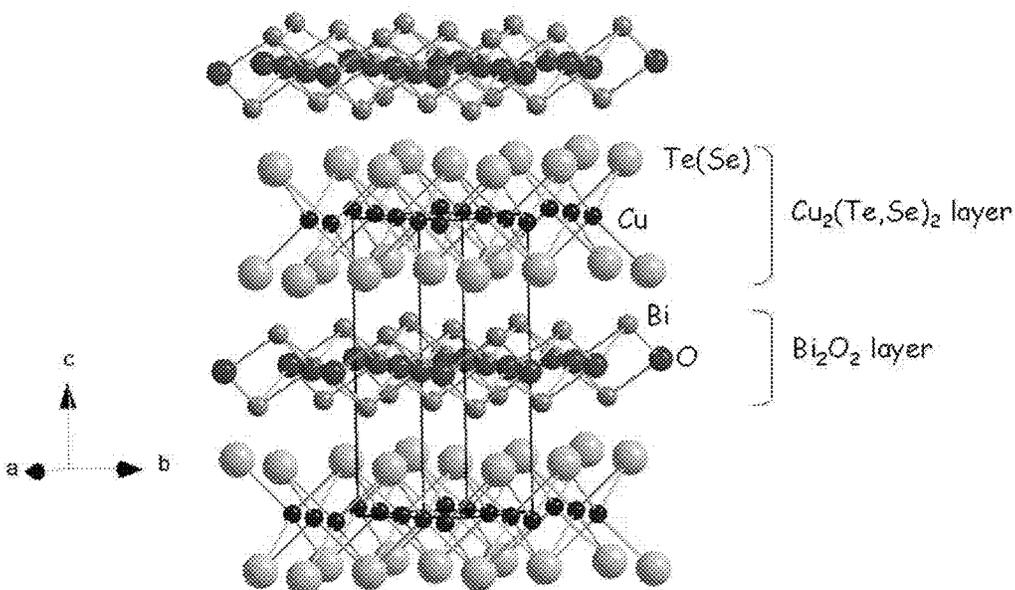


Figure 11

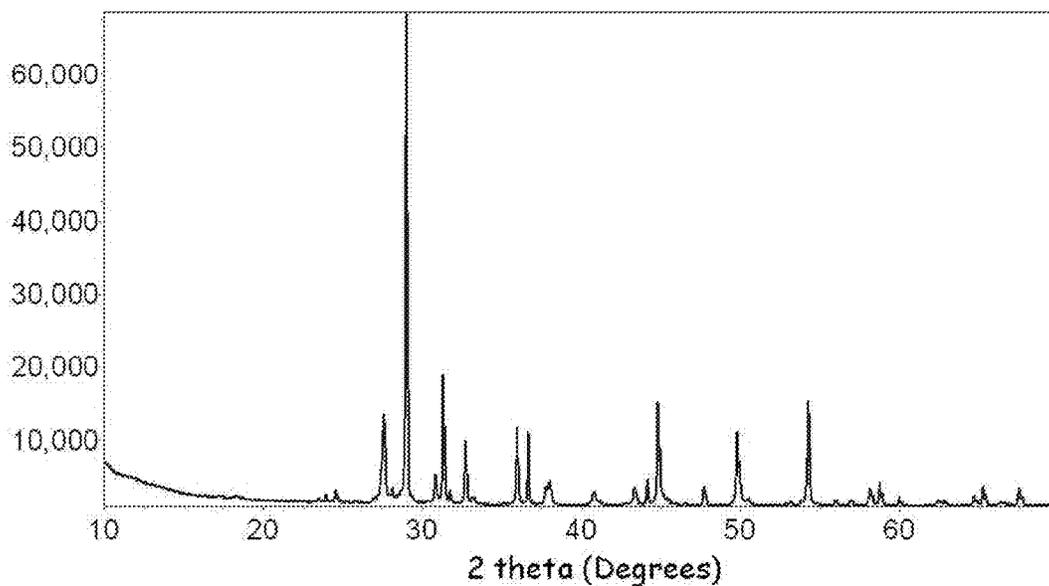
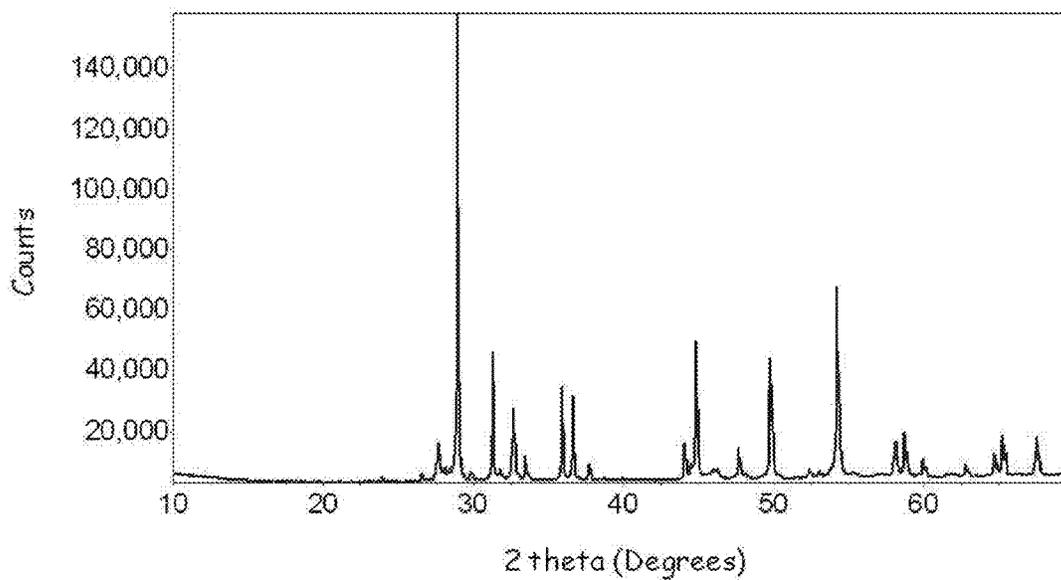


Figure 12



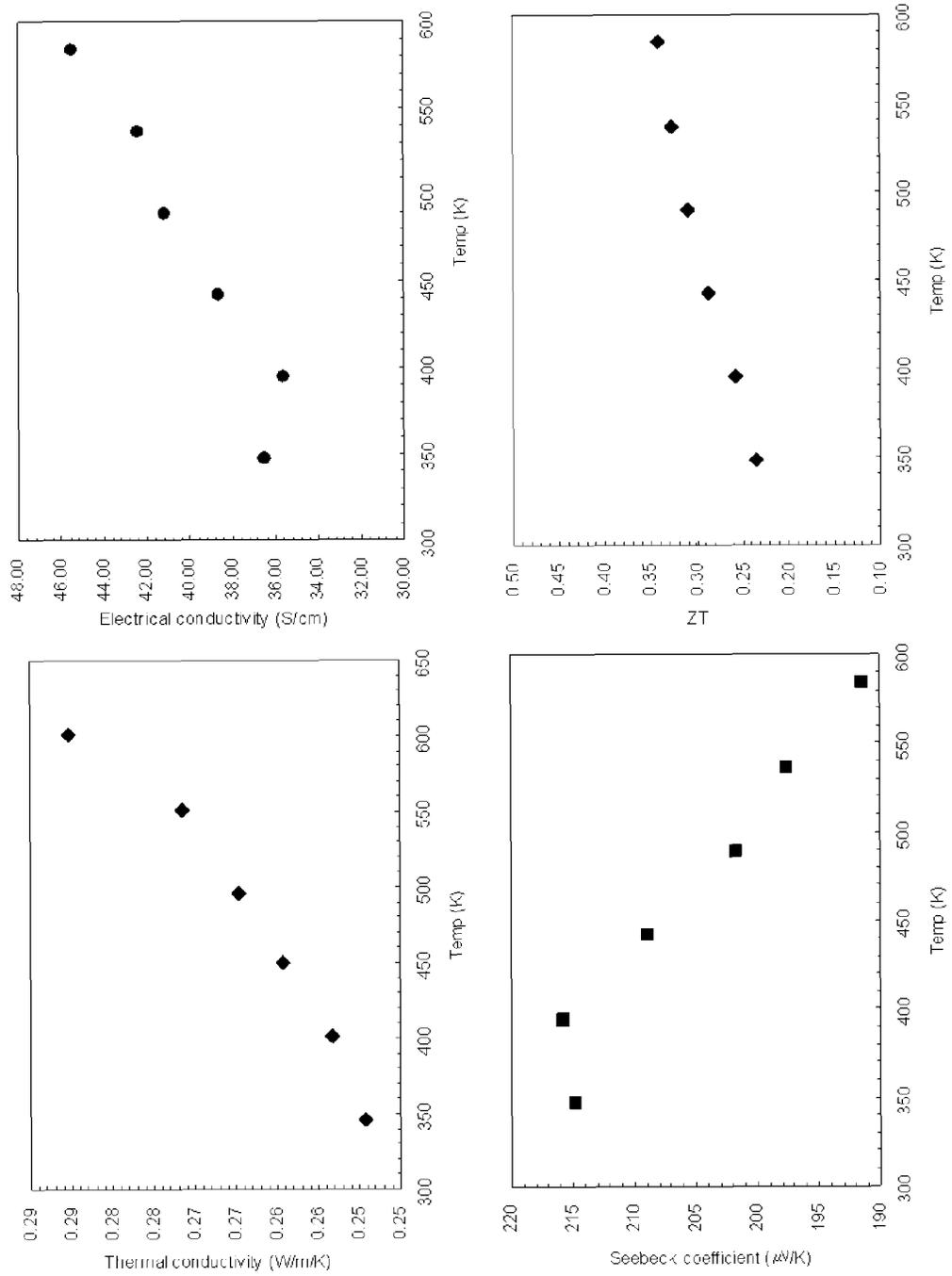


Figure 13

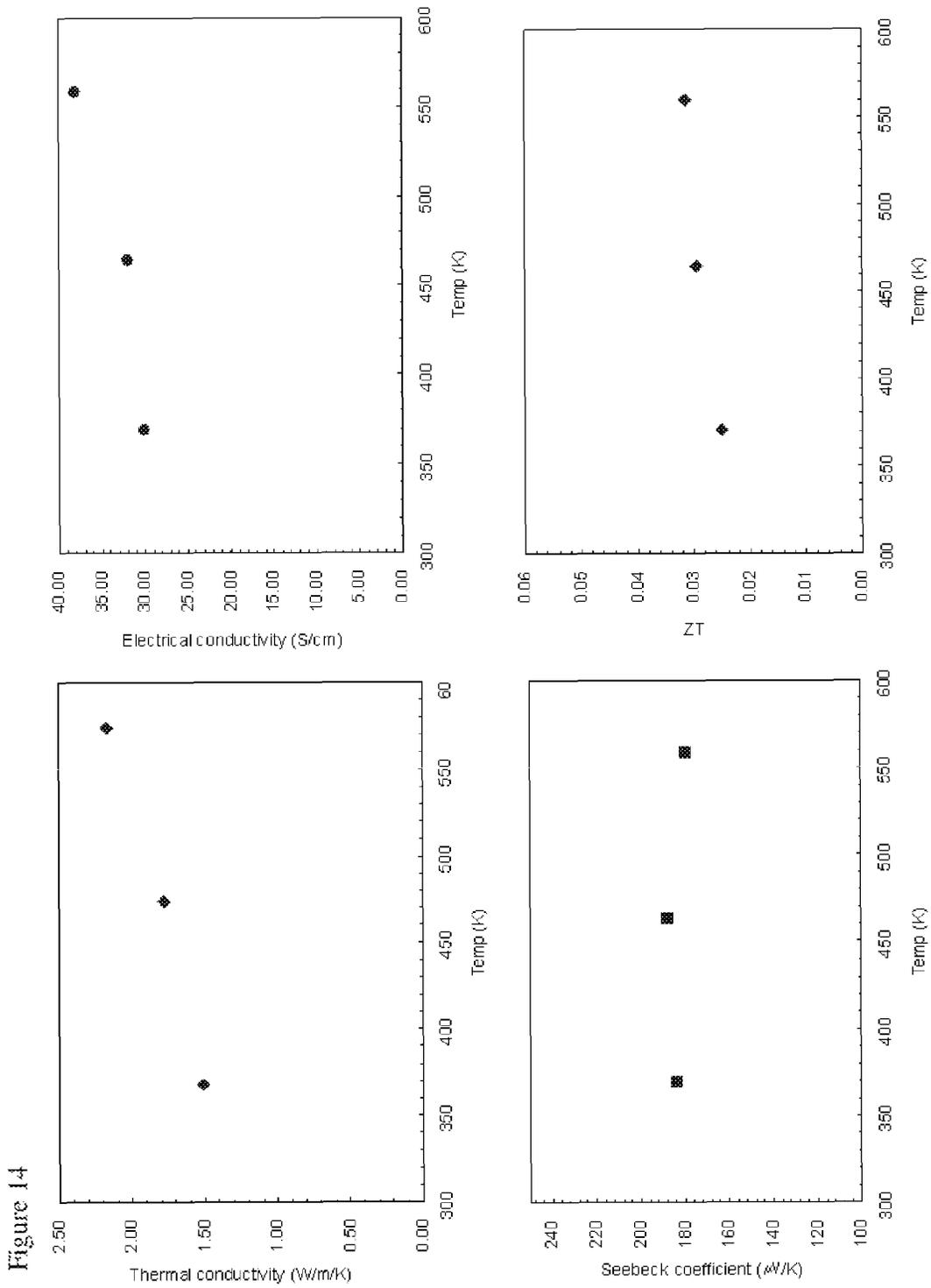
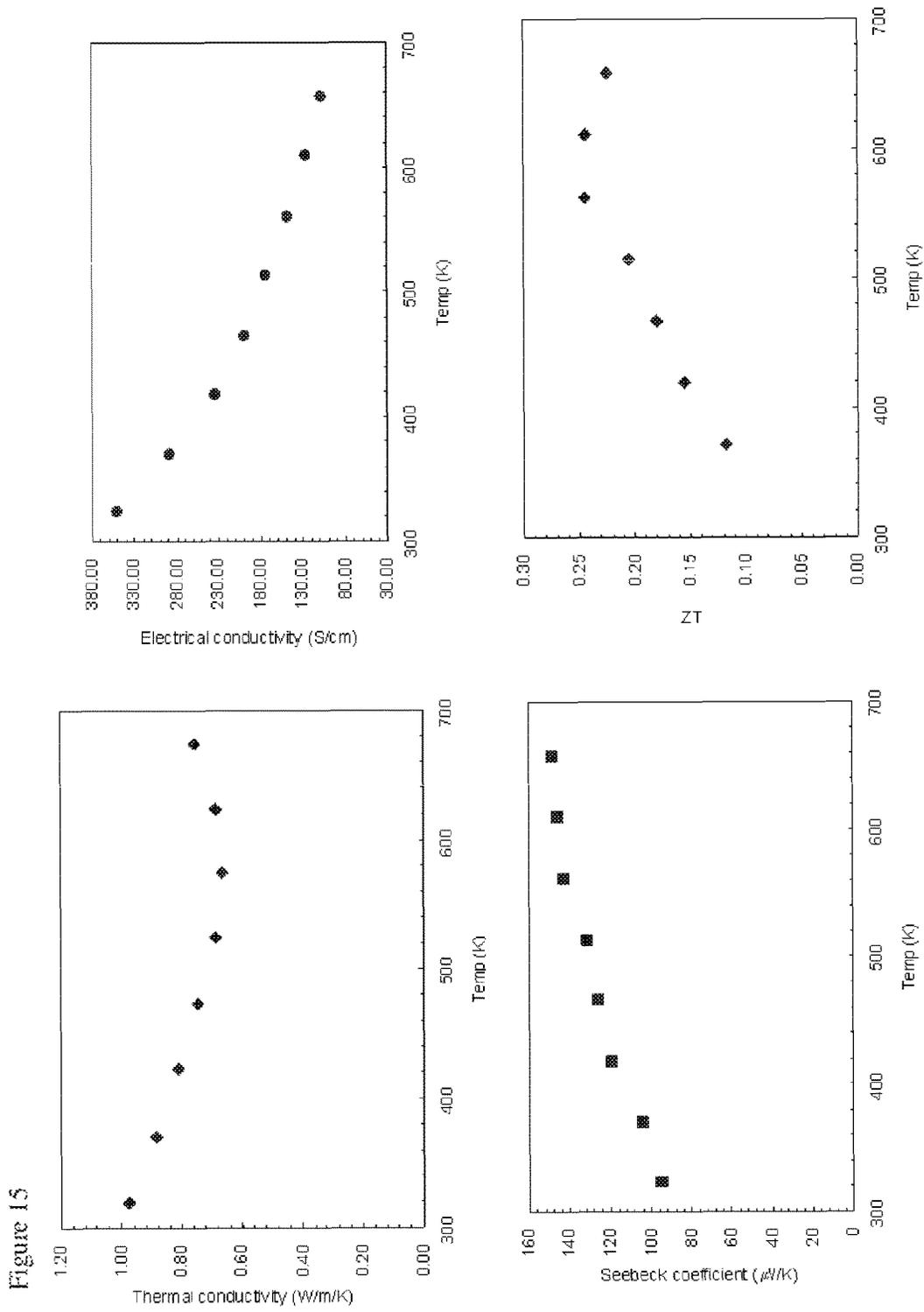


Figure 14



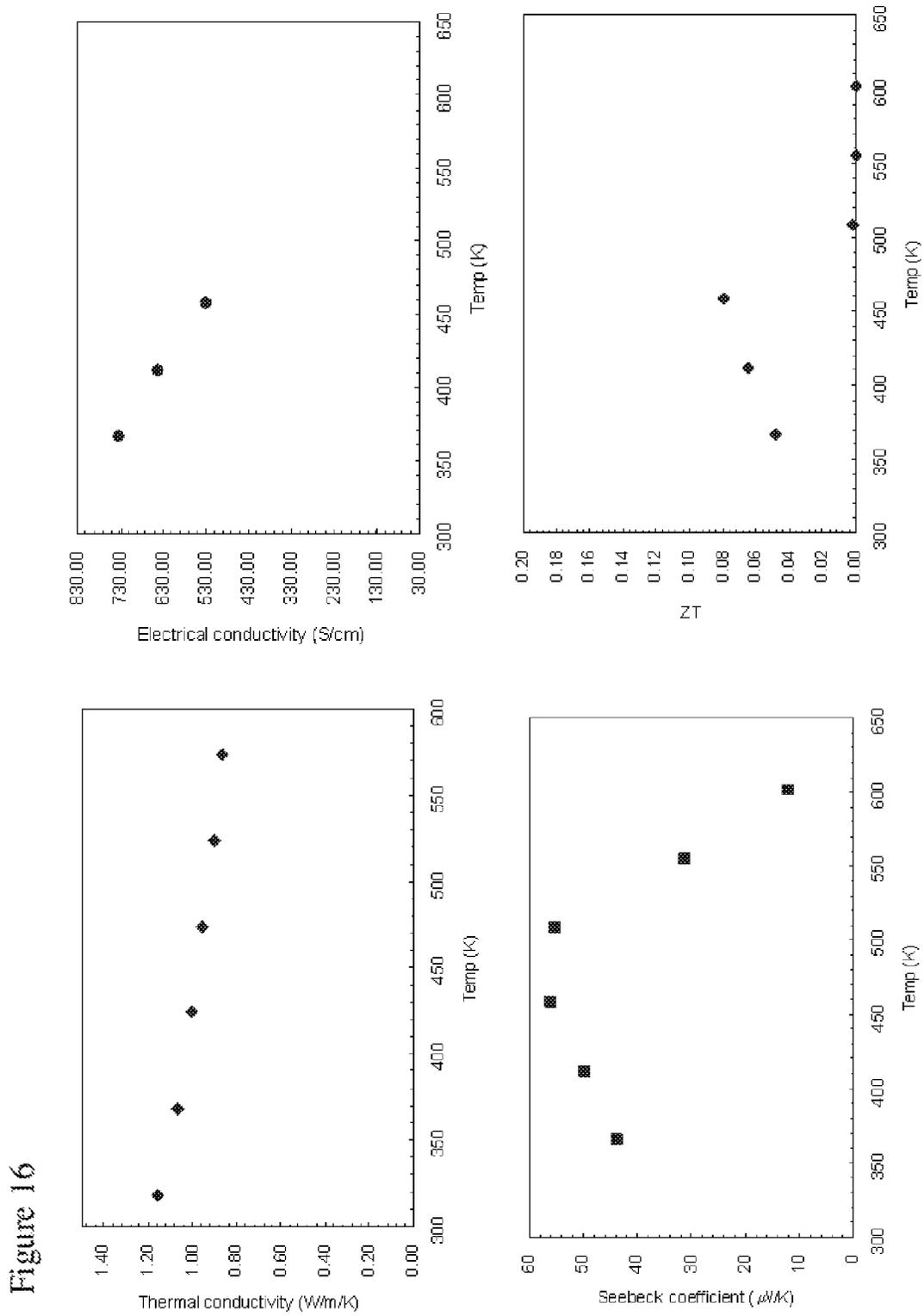
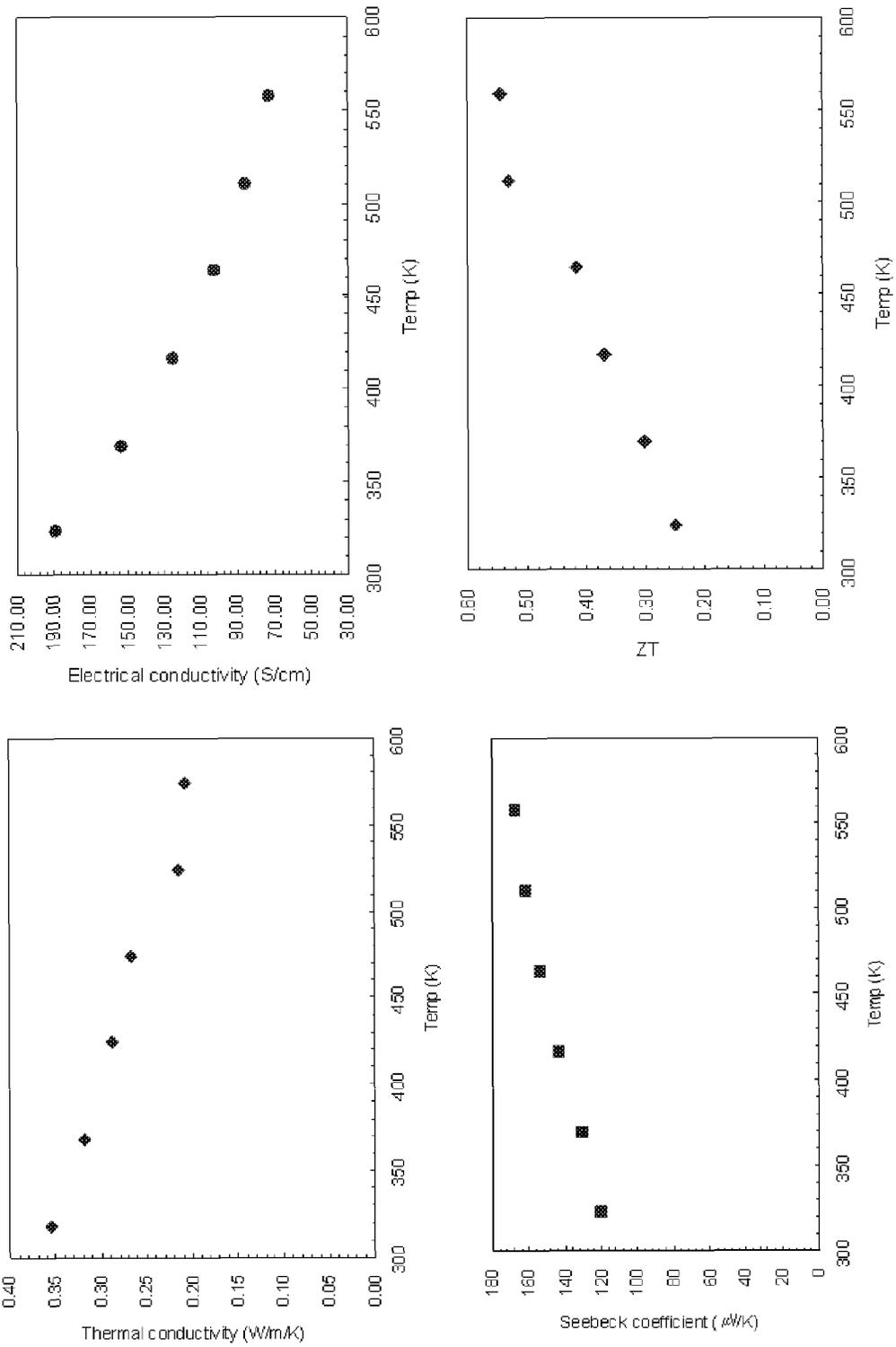


Figure 16

Figure 17



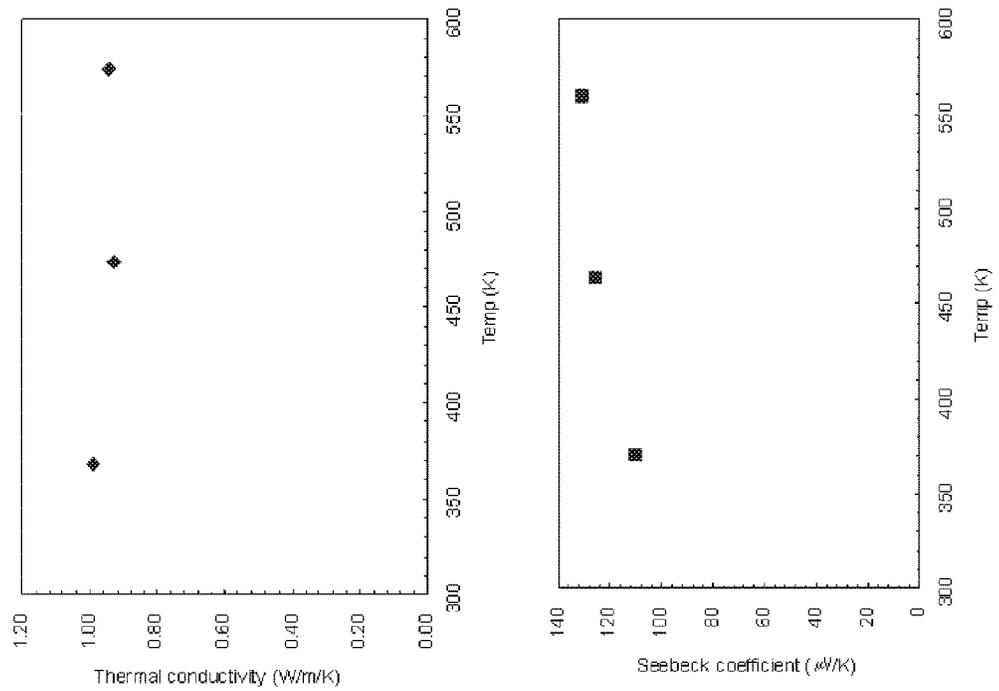
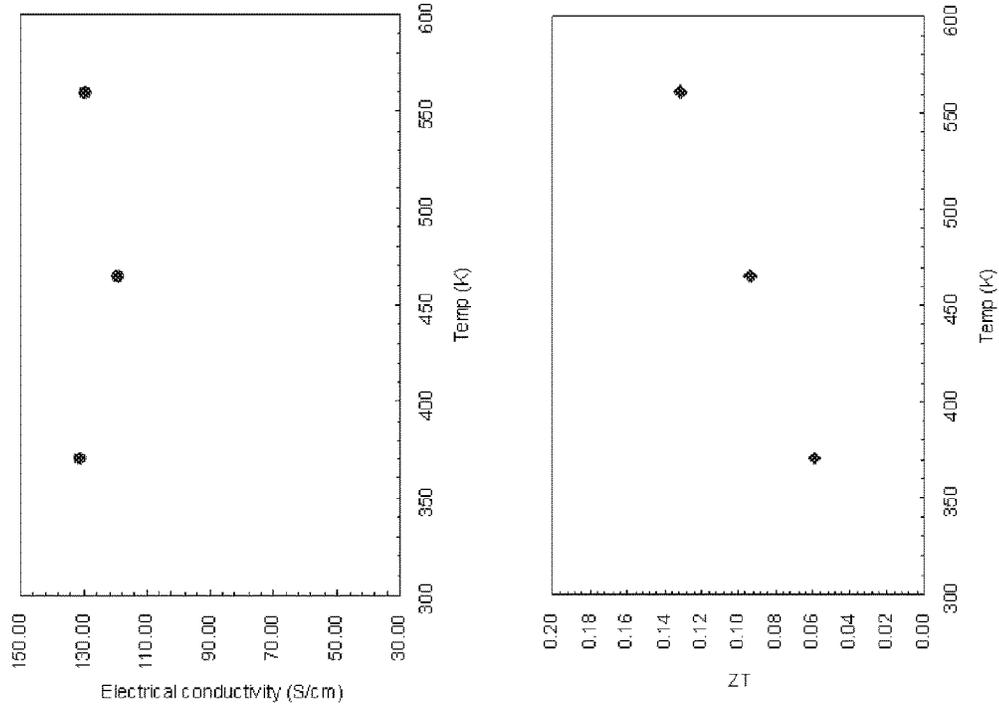
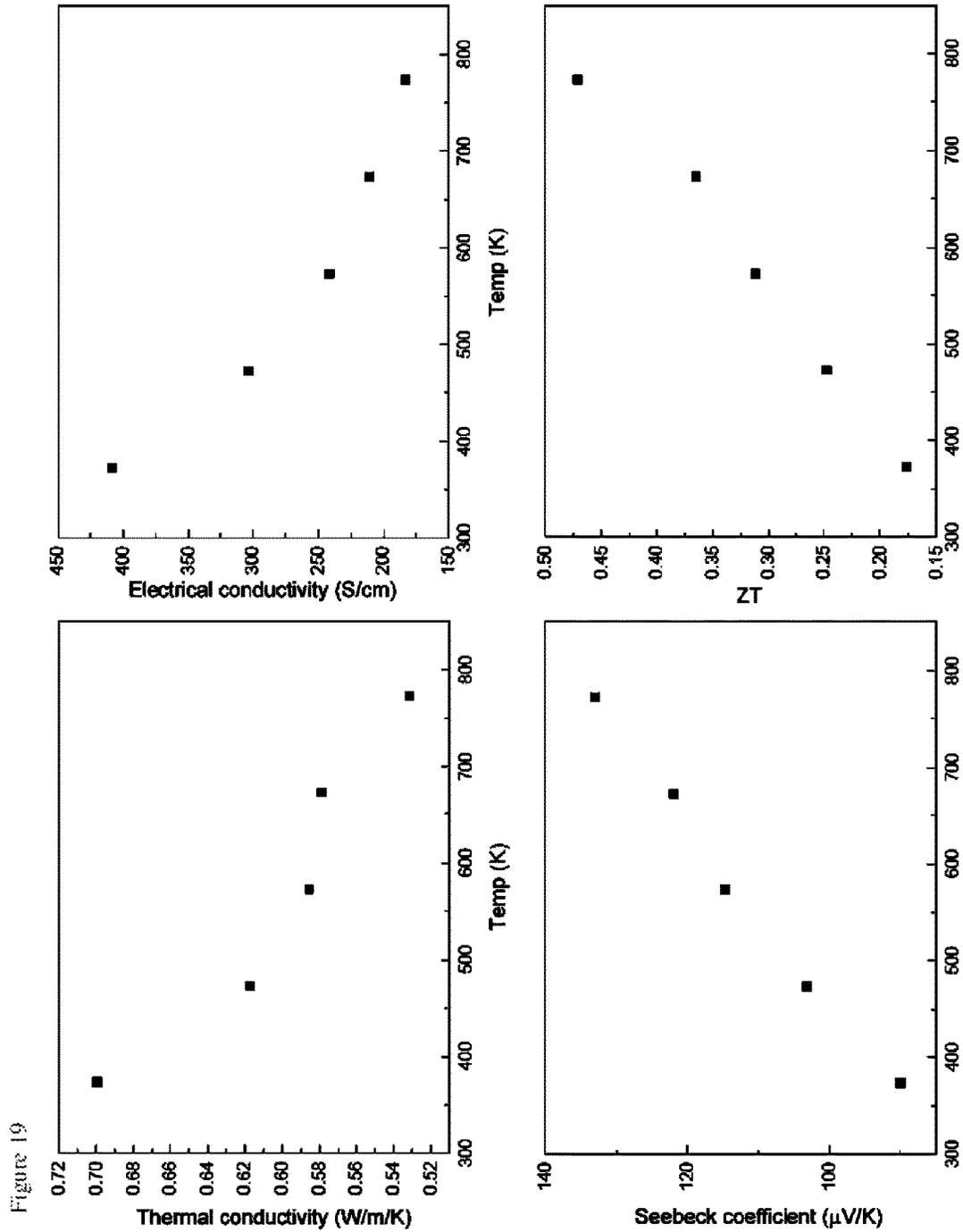


Figure 18



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**THERMOELECTRIC CONVERSION
MATERIAL AND PRODUCING METHOD
THEREOF, AND THERMOELECTRIC
CONVERSION ELEMENT USING THE SAME**

CROSS REFERENCE TO RELATED
APPLICATIONS

This application is a continuation-in-part of U.S. Ser. No. 14/175,513, filed on Feb. 7, 2014, which is a divisional of U.S. Ser. No. 13/531,186, filed on Jun. 22, 2012, now issued as U.S. Pat. No. 8,715,538, which is a continuation of U.S. Ser. No. 12/906,917, filed on Oct. 18, 2010, now issued as U.S. Pat. No. 8,226,843, which is a continuation of International Application No. PCT/KR2008/007041 filed Nov. 28, 2008, which claims priorities to Korean Patent Applications Nos. 10-2008-0085240, 10-2008-0097779 and 10-2008-0111557 filed in Republic of Korea on Aug. 29, 2008, Oct. 6, 2008 and Nov. 11, 2008, respectively, the entire contents of which are incorporated herein by reference.

TECHNICAL FIELD

The present invention provides new thermoelectric conversion material, their method of preparation, and thermoelectric conversion elements by using the same.

BACKGROUND OF THE INVENTION

The thermoelectric conversion element is applied to thermoelectric conversion power generation or thermoelectric conversion cooling. For example, for the thermoelectric conversion power generation, a temperature difference is applied to the thermoelectric conversion element to generate thermoelectromotive force, and then the thermoelectromotive force is used to convert thermal energy into electric energy.

Energy conversion efficiency of the thermoelectric conversion element depends on ZT value that is a performance index of thermoelectric conversion material. ZT value is determined by Seebeck coefficient, electric conductivity and thermal conductivity. In more detail, ZT value is in proportion to electric conductivity and square of Seebeck coefficient and in reverse proportion to thermal conductivity. Thus, in order to enhance the energy conversion efficiency of a thermoelectric conversion element, it is required to develop thermoelectric conversion materials with high Seebeck coefficient, high electric conductivity or low thermal conductivity.

DISCLOSURE

Technical Problem

An object of the present invention is to provide new thermoelectric conversion material having excellent thermoelectric conversion performance.

Another object of the present invention is to provide a method for producing the above new thermoelectric conversion material.

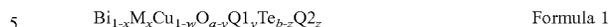
Furthermore, another object of the present invention is to provide a thermoelectric conversion element using the new thermoelectric conversion material.

Technical Solution

As a result of the research for thermoelectric conversion material, compositions of the formula 1 are proposed in the

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present invention. It was found that these new compounds may be used as thermoelectric conversion materials of thermoelectric conversion elements, and so on.



where M is at least one element selected from the group consisting of Ba, Sr, Ca, Mg, Cs, K, Na, Cd, Hg, Sn, Pb, Mn, Ga, In, Tl, As and Sb; Q1 and Q2 are at least one element selected from the group consisting of S, Se, As and Sb with $0 \leq x < 1$, $0 < w < 1$, $0.2 < a < 4$, $0 \leq y < 4$, $0.2 < b < 4$, $0 \leq z < 4$ and $x+y+z > 0$.

According to the present invention, a, y, b and z are preferably $a=1$, $0 \leq y < 1$, $b=1$ and $0 \leq z < 1$, respectively.

In other case, x, w, a, y, b and z are preferably $0 \leq x < 0.15$, $0 < w \leq 0.2$, $a=1$, $0 \leq y < 0.2$, $b=1$ and $0 < z < 0.5$, respectively. Here, M is preferably any one selected from the group consisting of Sr, Cd, Pb and Tl, and Q1 and Q2 are preferably Se or Sb, respectively.

In another aspect of the present invention, it provides methods for producing thermoelectric conversion materials expressed by the formula 1 by heating mixtures of Bi_2O_3 , Bi, Cu, Te, and at least one selected from the group consisting of elemental Ba, Sr, Ca, Mg, Cs, K, Na, Cd, Hg, Sn, Pb, Mn, Ga, In, Tl, As and Sb, or their oxides.

Alternatively, the present invention provides methods for producing thermoelectric conversion materials expressed by the formula 1 by heating mixtures of Bi_2O_3 , Bi, Cu, Te, at least one selected from the group consisting of elemental S, Se, As, and Sb, or their oxides, and optionally at least one selected from the group consisting of elemental Ba, Sr, Ca, Mg, Cs, K, Na, Cd, Hg, Sn, Pb, Mn, Ga, In, Tl, As, and Sb, or their oxides.

In the method according to the present invention, the sintering process is preferably executed at temperatures of 400 to 570° C.

Advantageous Effects

The new thermoelectric conversion materials of the present invention may replace thermoelectric conversion materials in common use, or be used along with thermoelectric conversion materials in common use. In particular, the thermoelectric conversion materials may be useful for thermoelectric conversion elements due to their excellent thermoelectric conversion performance.

DESCRIPTION OF DRAWINGS

Other objects and aspects of the present invention will become apparent from the following description of embodiments with reference to the accompanying drawing in which:

FIG. 1 shows Rietveld refinement profiles for BiCuOTe , comparing X-ray diffraction pattern with a calculated pattern from a structural model;

FIG. 2 shows the crystal structure of BiCuOTe ;

FIG. 3 shows X-ray diffraction pattern of $\text{BiCu}_{0.9}\text{OTe}$;

FIG. 4 shows Rietveld refinement profiles for $\text{Bi}_{0.98}\text{Pb}_{0.02}\text{CuOTe}$, comparing X-ray diffraction pattern with a calculated pattern from a structural model;

FIG. 5 shows the crystal structure of $\text{Bi}_{0.98}\text{Pb}_{0.02}\text{CuOTe}$;

FIG. 6 shows X-ray diffraction pattern of $\text{Bi}_{0.9}\text{Pb}_{0.1}\text{CuOTe}$;

FIG. 7 shows X-ray diffraction pattern of $\text{Bi}_{0.9}\text{Cd}_{0.1}\text{CuOTe}$;

FIG. 8 shows X-ray diffraction pattern of $\text{Bi}_{0.9}\text{Sr}_{0.1}\text{CuOTe}$;

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FIG. 9 shows Rietveld refinement profiles for BiCuOSe_{0.5}Te_{0.5}, comparing X-ray diffraction pattern with a calculated pattern from a structural model;

FIG. 10 shows the crystal structure of BiCuOSe_{0.5}Te_{0.5};

FIG. 11 shows X-ray diffraction pattern of Bi_{0.9}Tl_{0.1}CuOTe;

FIG. 12 shows X-ray diffraction pattern of BiCuOTe_{0.9}Sb_{0.1};

FIG. 13 shows electrical conductivities, Seebeck coefficients, thermal conductivities, and ZT values of BiCuOTe at different temperatures;

FIG. 14 shows electrical conductivities, Seebeck coefficients, thermal conductivities, and ZT values of Bi_{0.9}Sr_{0.1}CuOTe at different temperatures;

FIG. 15 shows electrical conductivities, Seebeck coefficients, thermal conductivities, and ZT values of Bi_{0.9}Cd_{0.1}CuOTe at different temperatures;

FIG. 16 shows electrical conductivities, Seebeck coefficients, thermal conductivities, and ZT values of Bi_{0.9}Pb_{0.1}CuOTe at different temperatures;

FIG. 17 shows electrical conductivities, Seebeck coefficients, thermal conductivities, and ZT values of Bi_{0.98}Pb_{0.02}CuOTe at different temperatures; and

FIG. 18 shows electrical conductivities, Seebeck coefficients, thermal conductivities, and ZT values of Bi_{0.9}Tl_{0.1}CuOTe at different temperatures.

FIG. 19 shows electrical conductivities, Seebeck coefficients, thermal conductivities, and ZT values of Bi_{0.95}Pb_{0.05}Cu_{0.96}Te_{0.95}Se_{0.05} at different temperatures.

BEST MODE

Compositions of the thermoelectric conversion materials of the present invention are expressed by the following formula 1.



In the formula 1, M is at least one element selected from the group consisting of Ba, Sr, Ca, Mg, Cs, K, Na, Cd, Hg, Sn, Pb, Mn, Ga, In, Tl, As and Sb, and Q1 and Q2 are at least one element selected from the group consisting of S, Se, As and Sb with $0 \leq x < 1$, $0 < w < 1$, $0.2 < a < 4$, $0 \leq y < 4$, $0.2 < b < 4$, $0 \leq z < 4$ and $x+y+z > 0$.

In the formula 1, x, y, and z are preferably $0 \leq x \leq 1/2$, $0 \leq y \leq a/2$ and $0 \leq z \leq b/2$, respectively.

In the formula 1, a, y, b and z of the formula 1 are preferably $a=1$, $0 \leq y < 1$, $b=1$ and $0 \leq z < 1$, respectively. In other cases, x, w, a, y, b and z may be respectively $0 \leq x < 0.15$, $0 < w \leq 0.2$, $a=1$, $0 \leq y < 0.2$, $b=1$ and $0 \leq z < 0.5$. Here, M is preferably any one selected from the group consisting of Sr, Cd, Pb and Tl, and Q1 and Q2 are preferably Se or Sb, respectively.

For the thermoelectric conversion materials of the formula 1, it is more preferred that x, a, y, b and z of the formula 1 are respectively $0 < x < 0.15$, $a=1$, $y=0$, $b=1$ and $z=0$, and M is any one selected from the group consisting of Sr, Cd, Pb and Tl. In addition, in the formula 1 where x, a, y, b and z of the formula 1 are respectively $x=0$, $a=1$, $y=0$, $b=1$ and $0 < z \leq 0.5$, and Q2 is Se or Sb.

Meanwhile, the thermoelectric conversion materials expressed by the formula 1 may be produced by mixing powders of Bi₂O₃, Bi, Cu and Te and then vacuum-sintering the mixture, but the present invention is not limited thereto.

Also, the thermoelectric conversion materials expressed by the formula 1 may be produced by heating mixtures of Bi₂O₃, Bi, Cu, Te, and at least one selected from the group consisting of Ba, Sr, Ca, Mg, Cs, K, Na, Cd, Hg, Sn, Pb, Mn,

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Ga, In, Tl, As and Sb, or their oxides in an evacuated silica tube, however the present invention is not limited thereto.

In addition, the thermoelectric conversion materials expressed by the formula 1 may be produced by heating mixtures of Bi₂O₃, Bi, Cu, Te, at least one element selected from the group consisting of S, Se, As and Sb, or their oxides, and optionally at least one selected from the group consisting of Ba, Sr, Ca, Mg, Cs, K, Na, Cd, Hg, Sn, Pb, Mn, Ga, In, Tl, As, and Sb, or their oxides in an evacuated silica tube, however the present invention is not limited thereto.

The thermoelectric conversion materials of the present invention may be produced by sintering mixtures in a flowing gas such as Ar, He or N₂, which partially includes hydrogen or does not include hydrogen. The sintering process is preferably executed at a temperature of 400 to 750° C., more preferably 400 to 570° C.

MODE FOR INVENTION

Hereinafter, the preferred embodiment of the present invention will be described in detail based on examples. However, the embodiments of the present invention may be modified in various ways, and the scope of the present invention should not be interpreted as being limited to the examples. The embodiments of the present invention are provided just for explaining the present invention more perfectly to those having ordinary skill in the art.

Example 1

BiCuOTe

In order to prepare BiCuOTe, 1.1198 g of Bi₂O₃ (Aldrich, 99.9%, 100 mesh), 0.5022 g of Bi (Aldrich, 99.99%, <10 μm), 0.4581 g of Cu (Aldrich, 99.7%, 3 μm), and 0.9199 g of Te (Aldrich, 99.99%, ~100 mesh) were well mixed by using agate mortar, and then heated in an evacuated silica tube at 510° C. for 15 hours, thereby obtaining BiCuOTe powder.

The powder X-ray diffraction (XRD) data were collected at room temperature on a Bragg-Brentano diffractometer (Bruker Advance D8 XRD) with a Cu X-ray tube ($\lambda=1.5406$ Å, 50 kV, 40 mA). The step size was 0.02 degree.

TOPAS program (R. W. Cheary, A. Coelho, J. Appl. Crystallogr. 25 (1992) 109-121; Bruker AXS, TOPAS 3, Karlsruhe, Germany (2000)) was used in order to determine the crystal structure of the obtained material. The analysis results are shown in Table 1 and FIG. 2.

TABLE 1

Atom	site	x	y	z	Occup.	Beq
Bi	2c	0.25	0.25	0.37257(5)	1	0.56(1)
Cu	2a	0.75	0.25	0	1	0.98(3)
O	2b	0.75	0.25	0.5	1	0.26(12)
Te	2c	0.25	0.25	0.81945(7)	1	0.35(1)

Crystallographic data obtained from Rietveld refinement of BiCuOTe [Space group I4/mmm (No. 129), $a=4.04138(6)$ Å, $c=9.5257(2)$ Å]

FIG. 1 shows a Rietveld refinement profile that compares observed X-ray diffraction pattern of BiCuOTe with a calculated X-ray diffraction pattern from a structural model. FIG. 1 shows that the measured pattern well agrees with the calculated pattern according to Table 1, which implies that the material obtained in this example is BiCuOTe.

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As shown in FIG. 2, the BiCuOTe exhibits a natural super-lattice structure in which Cu_2Te_2 layers and Bi_2O_2 layers are repeated along a c-crystalline axis. Also, it can be said that BiTeCu layers and O layers are repeated along the c-crystalline axis in the natural super-lattice structure.

Example 2

 $\text{BiCu}_{0.9}\text{OTe}$

In order to prepare $\text{BiCu}_{0.9}\text{OTe}$, 1.1371 g of Bi_2O_3 (Aldrich, 99.9%, 100 mesh), 0.51 g of Bi (Aldrich, 99.99%, <10 μm), 0.4187 g of Cu (Aldrich, 99.7%, 3 μm), and 0.9342 g of Te (Aldrich, 99.99%, ~100 mesh) were well mixed by using agate mortar, and then heated in an evacuated silica tube at 510° C. for 15 hours, thereby obtaining $\text{BiCu}_{0.9}\text{TeO}$ powder.

X-ray diffraction analysis was conducted for the sample in the same way as the example 1. As shown in FIG. 3, the material obtained in the example 2 was identified as $\text{BiCu}_{0.9}\text{TeO}$.

Example 3

 $\text{Bi}_{0.98}\text{Pb}_{0.02}\text{CuOTe}$

In order to prepare $\text{Bi}_{0.98}\text{Pb}_{0.02}\text{CuOTe}$, 2.5356 g of Bi_2O_3 (Aldrich, 99.9%, 100 mesh), 1.1724 g of Bi (Aldrich, 99.99%, <10 μm), 1.0695 g of Cu (Aldrich, 99.7%, 3 μm), 0.0751 g of PbO (Canto, 99.5%), and 2.1475 g of Te (Aldrich, 99.99%, ~100 mesh) were well mixed by using agate mortar, and then heated in an evacuated silica tube at 510° C. for 15 hours, thereby obtaining $\text{Bi}_{0.98}\text{Pb}_{0.02}\text{CuOTe}$ powder.

The powder X-ray diffraction (XRD) data were collected at room temperature on a Bragg-Brentano diffractometer (Bruker D4-Endeavor XRD) with a Cu X-ray tube ($\lambda=1.5406 \text{ \AA}$, 50 kV, 40 mA). The step size was 0.02 degree.

TOPAS program (R. W. Cheary, A. Coelho, J. Appl. Crystallogr. 25 (1992) 109-121; Bruker AXS, TOPAS 3, Karlsruhe, Germany (2000)) was used in order to determine the crystal structure of the obtained material. The analysis results are shown in Table 2 and FIG. 5.

TABLE 2

Atom	site	x	y	z	Occup.	Beq.
Bi	2c	0.25	0.25	0.37225(12)	0.98	0.59(4)
Pb	2c	0.25	0.25	0.37225(12)	0.02	0.59(4)
Cu	2a	0.75	0.25	0	1	1.29(10)
O	2b	0.75	0.25	0.5	1	0.9(4)
Te	2c	0.25	0.25	0.81955(17)	1	0.55(5)

Crystallographic data obtained from Rietveld refinement of $\text{Bi}_{0.98}\text{Pb}_{0.02}\text{CuOTe}$ [Space group P4/nmm (No. 129), $a=4.04150(4) \text{ \AA}$, $c=9.53962(13) \text{ \AA}$]

FIG. 4 shows a Rietveld refinement profile that compares observed X-ray diffraction pattern of $\text{Bi}_{0.98}\text{Pb}_{0.02}\text{CuOTe}$ with calculated pattern of a structural model. FIG. 4 shows that the measured pattern well agrees with the calculated pattern according to Table 2, which implies that the material obtained in this example is $\text{Bi}_{0.98}\text{Pb}_{0.02}\text{CuOTe}$.

As shown in FIG. 5, the $\text{Bi}_{0.98}\text{Pb}_{0.02}\text{CuOTe}$ exhibits a natural super-lattice structure in which Cu_2Te_2 layers and $(\text{Bi,Pb})_2\text{O}_2$ layers where Pb is partially substituted in place of Bi are repeated along a c-crystalline axis. Also, it can be

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said that $(\text{Bi,Pb})\text{TeCu}$ layers and O layers are repeated along the c-crystalline axis in the natural super-lattice structure.

Example 4

 $\text{Bi}_{0.9}\text{Pb}_{0.1}\text{CuOTe}$

In order to prepare $\text{Bi}_{0.9}\text{Pb}_{0.1}\text{CuOTe}$, 1.2721 g of Bi_2O_3 (Aldrich, 99.9%, 100 mesh), 0.6712 g of Bi (Aldrich, 99.99%, <10 μm), 0.6133 g of Cu (Aldrich, 99.7%, 3 μm), 0.215 g of PbO (Canto, 99.5%), and 1.2294 g of Te (Aldrich, 99.99%, ~100 mesh) were well mixed by using agate mortar, and then heated in an evacuated silica tube at 510 r for 15 hours, thereby obtaining $\text{Bi}_{0.9}\text{Pb}_{0.1}\text{CuOTe}$ powder.

X-ray diffraction analysis was conducted for the sample in the same way as the example 3. As shown in FIG. 6, the material obtained in the example 4 was identified as $\text{Bi}_{0.9}\text{Pb}_{0.1}\text{CuOTe}$.

Example 5

 $\text{Bi}_{0.9}\text{Cd}_{0.1}\text{CuOTe}$

In order to prepare $\text{Bi}_{0.9}\text{Cd}_{0.1}\text{CuOTe}$, 1.3018 g of Bi_2O_3 (Aldrich, 99.9%, 100 mesh), 0.6869 g of Bi (Aldrich, 99.99%, <10 μm), 0.6266 g of Cu (Aldrich, 99.7%, 3 μm), 0.1266 g of CdO (Strem, 99.999%), and 1.2582 g of Te (Aldrich, 99.99%, ~100 mesh) were well mixed by using agate mortar, and then heated in an evacuated silica tube at 510° C. for 15 hours, thereby obtaining $\text{Bi}_{0.9}\text{Cd}_{0.1}\text{CuOTe}$ powder.

X-ray diffraction analysis was conducted for the sample in the same way as the example 3. As shown in FIG. 7, the material obtained in the example 5 was identified as $\text{Bi}_{0.9}\text{Cd}_{0.1}\text{CuOTe}$.

Example 6

 $\text{Bi}_{0.9}\text{Sr}_{0.1}\text{CuOTe}$

In order to prepare $\text{Bi}_{0.9}\text{Sr}_{0.1}\text{CuOTe}$, 1.0731 g of Bi_2O_3 (Aldrich, 99.9%, 100 mesh), 0.5662 g of Bi (Aldrich, 99.99%, <10 μm), 0.5165 g of Cu (Aldrich, 99.7%, 3 μm), 1.0372 g of Te (Aldrich, 99.99%, ~100 mesh), and 0.0842 g of SrO were well mixed by using agate mortar. Here, SrO was obtained by thermally treating SrCO_3 (Alfa, 99.994%) at 1125° C. for 12 hours in the air. The material obtained by thermal treatment was confirmed as SrO by X-ray diffraction analysis.

The mixture was then heated in an evacuated silica tube at 510° C. for 15 hours, thereby obtaining $\text{Bi}_{0.9}\text{Sr}_{0.1}\text{CuOTe}$ powder.

The powder X-ray diffraction (XRD) data were collected at room temperature on a Bragg-Brentano diffractometer (Bruker D8 Advance XRD) with a Cu X-ray tube ($\lambda=1.5406 \text{ \AA}$, 50 kV, 40 mA). The step size was 0.02 degree. FIG. 8 shows that the material obtained in the example 6 is $\text{Bi}_{0.9}\text{Sr}_{0.1}\text{CuOTe}$.

Example 7

 $\text{BiCuOSe}_{0.5}\text{Te}_{0.5}$

In order to prepare $\text{BiCuOSe}_{0.5}\text{Te}_{0.5}$, 1.9822 g of Bi_2O_3 (Aldrich, 99.9%, 100 mesh), 0.889 g of Bi (Aldrich, 99.99%, <10 μm), 0.811 g of Cu (Aldrich, 99.7%, 3 μm), 0.5036 g of Se (Aldrich, 99.99%), and 0.8142 g of Te (Aldrich, 99.99%,

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~100 mesh) were well mixed by using agate mortar, and then heated in an evacuated silica tube at 510° C. for 15 hours, thereby obtaining BiCuOSe_{0.5}Te_{0.5} powder.

The powder X-ray diffraction (XRD) data were collected at room temperature on a Bragg-Brentano diffractometer (Bruker D4-Endeavor XRD) with a Cu X-ray tube (40 kV, 40 mA). The step size was 0.02 degree. At this time, variable 6 mm slit was used as a divergence slit. The results are shown in FIG. 9. Crystal structure analysis was executed in the same way as the example 3. The analysis results are shown in Table 3 and FIG. 10.

TABLE 3

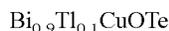
Atom	site	x	y	z	Occup.	Beq.
Bi	2c	0.25	0.25	0.36504(9)	1	0.86(2)
Cu	2a	0.75	0.25	0	1	2.00(9)
O	2b	0.75	0.25	0.5	1	1.9(3)
Te	2c	0.25	0.25	0.82272(14)	0.5	0.61(4)
Se	2c	0.25	0.25	0.82252(14)	0.5	0.55(5)

Crystallographic data obtained from Rietveld refinement of BiCuOSe_{0.5}Te_{0.5} [Space group P4/nmm (No. 129), a=3.99045(11) Å, c=9.2357(4) Å]

FIG. 9 shows that the measured pattern well agrees with the calculated pattern from the results in Table 3, and as a result the material obtained in this example is identified as BiCuOSe_{0.5}Te_{0.5}.

As shown in FIG. 10, the BiCuOSe_{0.5}Te_{0.5} exhibits a natural super-lattice structure in which Cu₂(Te,Se)₂ layers and Bi₂O₂ layers are repeated along a c-crystalline axis. Also, it can be said that Bi(Te,Se)Cu layers and O layers are repeated along the c-crystalline axis in the natural super-lattice structure.

Example 8



In order to prepare Bi_{0.9}Ti_{0.1}CuOTe, 1.227 g of Bi₂O₃ (Aldrich, 99.9%, 100 mesh), 0.7114 g of Bi (Aldrich, 99.99%, <10 μm), 0.6122 g of Cu (Aldrich, 99.7%, 3 μm), 1.2293 g of Te (Aldrich, 99.99%, ~100 mesh), and 0.22 g of Ti₂O₃ (Aldrich) were well mixed by using agate mortar.

The mixture was then heated in an evacuated silica tube at 510° C. for 15 hours, thereby obtaining Bi_{0.9}Ti_{0.1}CuOTe powder.

X-ray diffraction analysis was conducted for the sample in the same way as the example 3. As shown in FIG. 11, the material obtained in the example 8 was identified as Bi_{0.9}Ti_{0.1}CuOTe.

Example 9



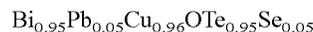
In order to prepare BiCuOTe_{0.9}Sb_{0.1}, 1.4951 g of Bi₂O₃ (Aldrich, 99.9%, 100 mesh), 0.6705 g of Bi (Aldrich, 99.99%, <10 μm), 0.6117 g of Cu (Aldrich, 99.7%, 3 μm), 1.1054 g of Te (Aldrich, 99.99%, ~100 mesh), and 0.1172 g of Sb (Kanto chemical, Cat. No. 01420-02) were well mixed by using agate mortar.

The mixture was then heated in an evacuated silica tube at 510° C. for 15 hours, thereby obtaining BiCuOTe_{0.9}Sb_{0.1} powder.

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X-ray diffraction analysis was conducted for the sample in the same way as the example 3. As shown in FIG. 12, the material obtained in the example 9 was identified as BiCuOTe_{0.9}Sb_{0.1}.

Example 10



In order to prepare Bi_{0.95}Pb_{0.05}Cu_{0.96}OTe_{0.95}Se_{0.05}, 3.7785 g of Bi₂O₃ (Aldrich, 99.9%, 100 mesh), 1.4404 g of Bi (Aldrich, 99.99%, <10 μm), 1.4840 g of Cu (Aldrich, 99.7%, 3 μm), 0.2520 g of Pb (Alfa aesar, 99.9%, 200 mesh), 2.9489 g of Te (Aldrich, 99.99%, 100 mesh), and 0.0960 g of Se (Alfa aesar, 99.999%, 200 mesh) were well mixed by using agate mortar.

The mixture was then heated in an evacuated silica tube at 500° C. for 12 hours, thereby obtaining Bi_{0.95}Pb_{0.05}Cu_{0.96}OTe_{0.95}Se_{0.05} powder.

X-ray diffraction analysis was conducted for the sample in the same way as the example 3, and the material obtained in the example 10 was identified as Bi_{0.95}Pb_{0.05}Cu_{0.96}OTe_{0.95}Se_{0.05}.

Evaluation of Thermoelectric Conversion Performance

Powder samples obtained in Examples 1, 3 to 6, 8 and 10 were shaped into cylinders with a diameter of 4 mm and a length of 15 mm (for electrical conductivity and Seebeck coefficient measurements), and disks having a diameter of 10 mm and a thickness of 1 mm (for thermal conductivity measurements) by using CIP at the pressure of 200 MPa. Subsequently, the resultant disks and cylinders were heated in an evacuated silica tube at 510° C. for 10 hours (for 12 hours for Example 10).

For the sintered cylinders, electric conductivity and Seebeck coefficient were measured by using a ZEM-2 (Ulvac-Rico, Inc.) The measurement results are shown in FIGS. 13 to 19. For example, at 346 K thermal conductivities of BiCuOTe and Bi_{0.98}Pb_{0.02}CuOTe were measured as 0.25 W/m/K and 0.35 W/m/K, respectively, which are significantly lower than those of Bi₂Te₃ (1.9 W/m/K, T. M. Tritt, M. A. Subramanian, MRS Bulletin 31 (2006) 188-194) and Co₄Sb₁₂:In_{0.2} (2 W/m/K, T. He, J. Chen, D. Rosenfeld, M. A. Subramanian, Chem. Mater. 18 (2006) 759-762) which are representative thermoelectric conversion materials.

Meanwhile, for the sintered disks, thermal conductivity was measured by using TC-9000 (Ulvac-Rico, Inc) (using a LEA457 (Netzsch) for Example 10). The measurement results are shown in FIGS. 13 to 19.

ZT value of each sample was calculated using the measured values. The calculated results are shown in FIGS. 13 to 19.

The invention claimed is:

1. Thermoelectric conversion materials, expressed by the following formula 1:



where M is at least one element selected from the group consisting of Ba, Sr, Ca, Mg, Cs, K, Na, Cd, Hg, Sn, Pb, Mn, Ga, In, Tl, As and Sb; Q1 and Q2 are at least one element selected from the group consisting of S, Se, As and Sb; x, y, z, w, a, and b are 0≤x<1, 0<w<1, 0.2<a<4, 0≤y<4, 0.2<b<4, 0≤z<4, b>z and x+y+z>0.

2. The thermoelectric conversion materials according to claim 1,

wherein x, y and z of the formula 1 are respectively 0≤x≤1/2, 0≤y≤a/2 and 0≤z≤b/2.

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3. The thermoelectric conversion materials according to claim 1,

wherein a, y, b and z of the formula 1 are respectively $a=1$, $0 \leq y < 1$, $b=1$ and $0 \leq z < 1$.

4. The thermoelectric conversion materials according to claim 3,

wherein x, w, a, y, b and z of the formula 1 are respectively $0 \leq x < 0.15$, $0 \leq w < 0.2$, $a=1$, $0 \leq y < 0.2$, $b=1$ and $0 \leq z < 0.5$.

5. The thermoelectric conversion materials according to claim 3,

wherein M of the formula 1 is any one selected from the group consisting of Sr, Cd, Pb and Tl.

6. The thermoelectric conversion materials according to claim 3,

wherein Q1 and Q2 of the formula 1 are respectively Se or Sb.

7. The thermoelectric conversion materials according to claim 3,

wherein x, w, a, y, b and z of the formula 1 are respectively $0 \leq x < 0.15$, $0 < w \leq 0.2$, $a=1$, $0 \leq y < 0.2$, $b=1$ and $0 \leq z < 0.5$; M is any one selected from the group consisting of Sr, Cd, Pb and Tl; Q1 and Q2 are respectively Se or Sb.

8. The thermoelectric conversion materials according to claim 7,

wherein x, a, y, b and z of the formula 1 are respectively $0 < x < 0.15$, $a=1$, $y=0$, $b=1$ and $z=0$.

9. The thermoelectric conversion materials according to claim 7,

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wherein x, y and z of the formula 1 are respectively $x=0$, $a=1$, $y=0$, $b=1$ and $0 < z \leq 0.5$.

10. A method for producing thermoelectric conversion materials,

wherein Bi_2O_3 , Bi, Cu, Te, and at least one selected from the group consisting of Ba, Sr, Ca, Mg, Cs, K, Na, Cd, Hg, Sn, Pb, Mn, Ga, In, Tl, As and Sb, or their oxides, are mixed and then sintered to produce the thermoelectric conversion materials expressed by the formula 1 in the claim 1.

11. The method for producing thermoelectric conversion materials according to claim 10,

wherein the sintering process is executed at a temperature of 400 to 570° C.

12. A method for producing thermoelectric conversion materials,

wherein Bi_2O_3 , Bi, Cu, and Te are mixed with at least one selected from the group consisting of S, Se, As and Sb, or their oxides, and then at least one selected from the group consisting of Ba, Sr, Ca, Mg, Cs, K, Na, Cd, Hg, Sn, Pb, Mn, Ga, In, Tl, As and Sb, or their oxides, are selectively further mixed thereto and then sintered to produce the thermoelectric conversion materials expressed by the formula 1 in the claim 1.

13. The method for producing thermoelectric conversion materials according to claim 12,

wherein the sintering process is executed at a temperature of 400 to 570° C.

14. A thermoelectric conversion element, which includes the thermoelectric conversion materials defined in claim 1.

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