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Fleurial et al.

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[54] HIGH PERFORMANCE THERMOELECTRIC MATERIALS AND METHODS OF PREPARATION

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[21] Appl. No.: **189,087**

[22] Filed: **Jan. 28, 1994**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 101,901, Aug. 3, 1993.

[51] **Int. Cl.**[6] **H01L 35/18**

[52] **U.S. Cl.** .... **136/202**; 204/200; 204/223; 252/62.3 T; 136/236.1; 136/240; 136/238; 136/205

[58] **Field of Search** .... 257/62.3 T; 117/200, 117/223; 136/203, 205, 224, 236.1, 240, 202, 238

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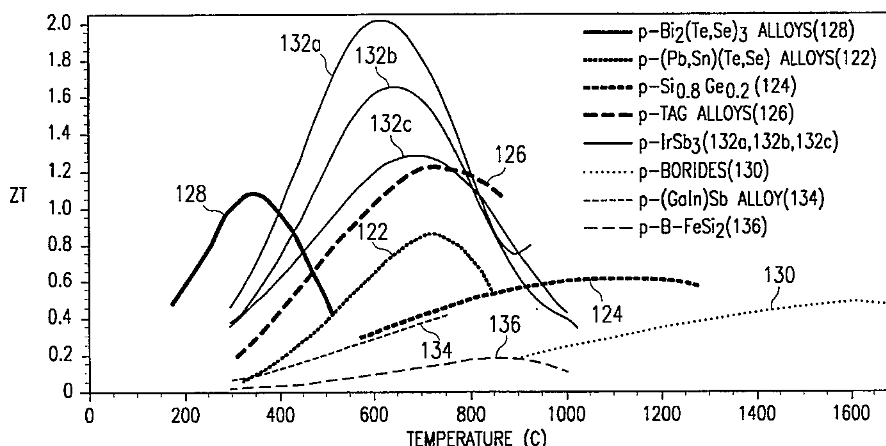
Primary Examiner—William D. Larkins
Attorney, Agent, or Firm—Baker & Botts, L.L.P.

[57] **ABSTRACT**

Transition metals (T) of Group VIII (Co, Rh and Ir) have been prepared as semiconductor alloys with Sb having the general formula TSb_3. The skutterudite-type crystal lattice structure of these semiconductor alloys and their enhanced thermoelectric properties results in semiconductor materials which may be used in the fabrication of thermoelectric elements to substantially improve the efficiency of the resulting thermoelectric device. Semiconductor alloys having the desired skutterudite-type crystal lattice structure may be prepared in accordance with the present invention by using vertical gradient freeze techniques, liquid-solid phase sintering techniques, low temperature powder sintering and/or hot-pressing. Measurements of electrical and thermal transport properties of selected semiconductor materials prepared in accordance with the present invention, demonstrated high Hall mobilities (up to 8000 $cm^2.V^{-1}.s^{-1}$), good Seebeck coefficients (up to 400 μVK^{-1} between 300° C. and 700° C.), and low thermal conductivities (as low as 15 mW/cmK). Optimizing the transport properties of semiconductor materials prepared from elemental mixtures Co, Rh, Ir and Sb resulted in a two fold increase in the thermoelectric figure of merit (ZT) at temperatures as high as 400° C. for thermoelectric elements fabricated from such semiconductor materials.

42 Claims, 6 Drawing Sheets



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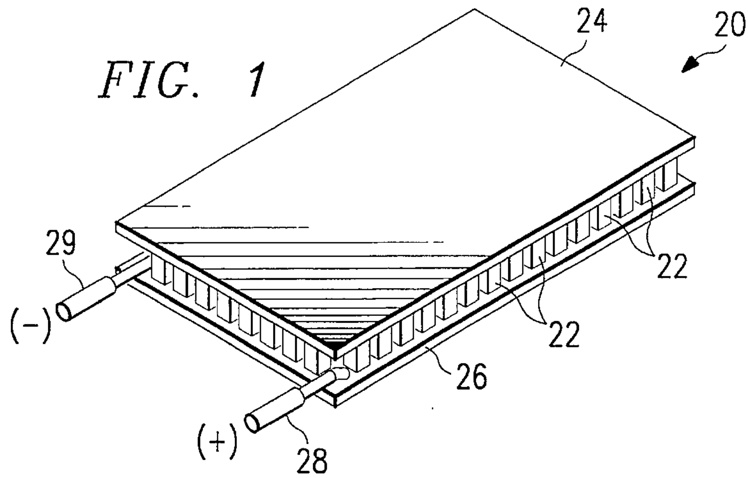


FIG. 1

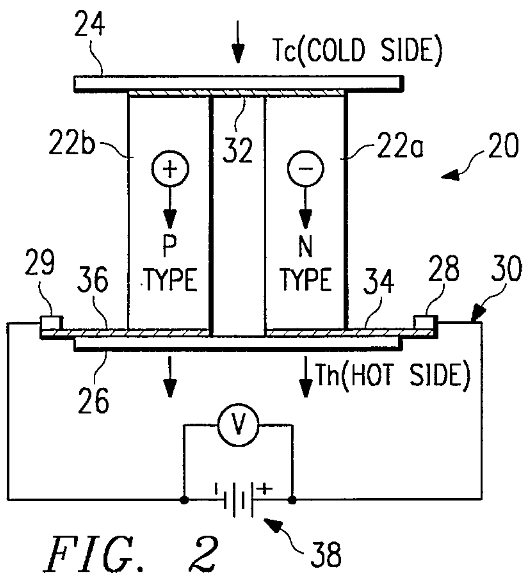


FIG. 2

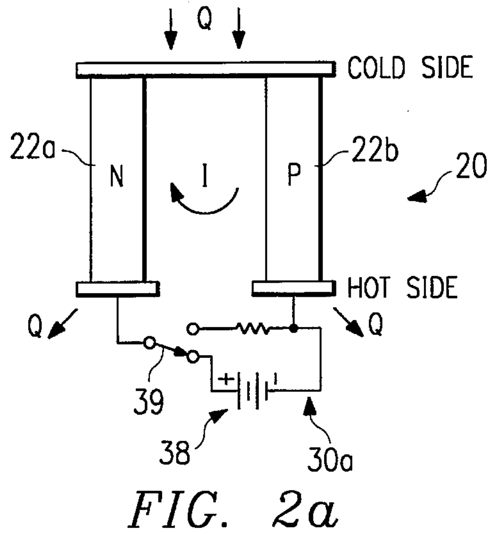


FIG. 2a

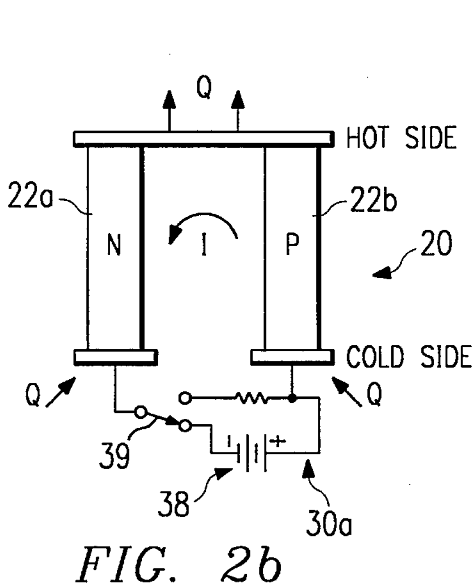


FIG. 2b

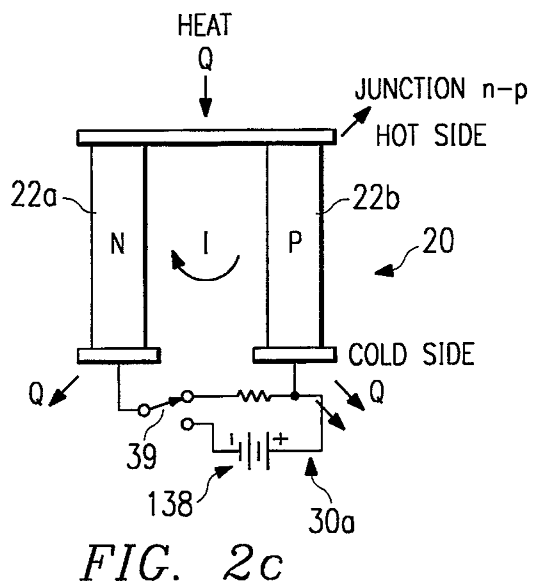


FIG. 2c

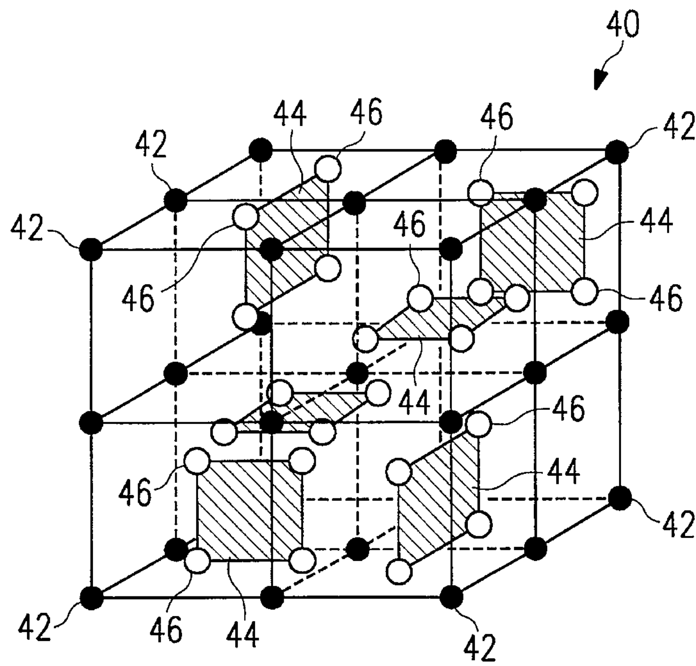


FIG. 3

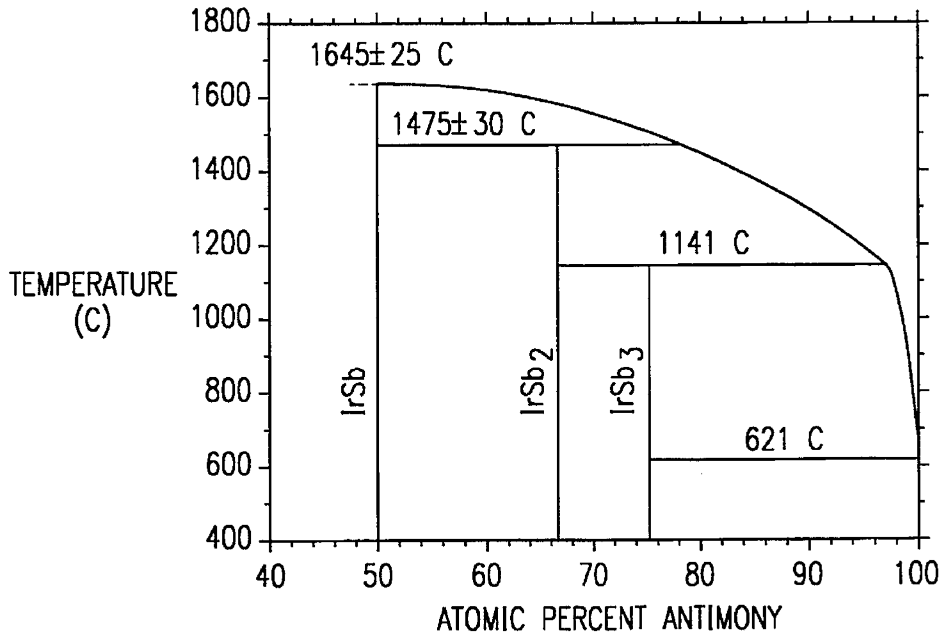


FIG. 4

FIG. 5b FIG. 5a FIG. 6

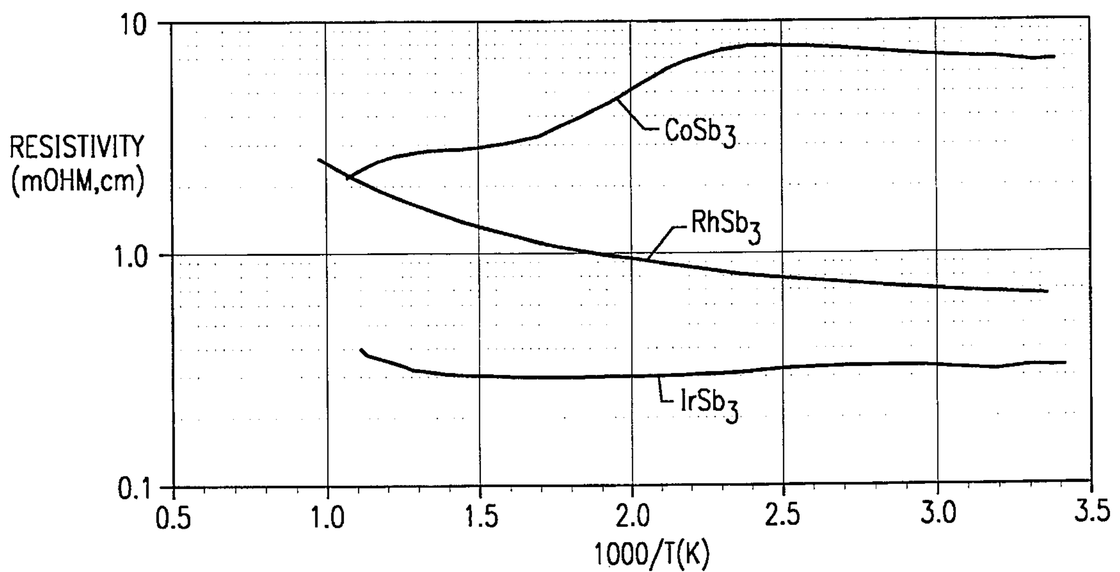


FIG. 7

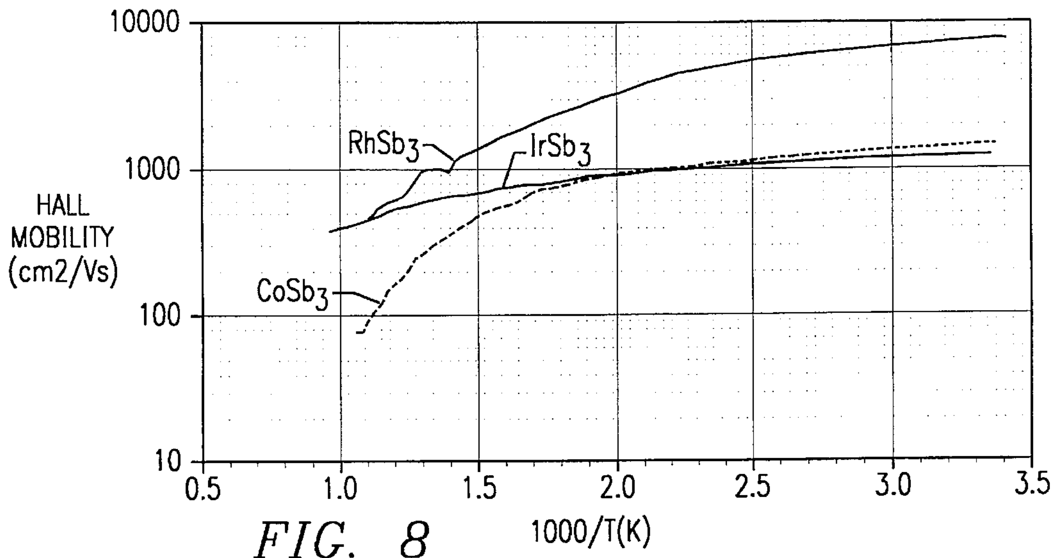


FIG. 8

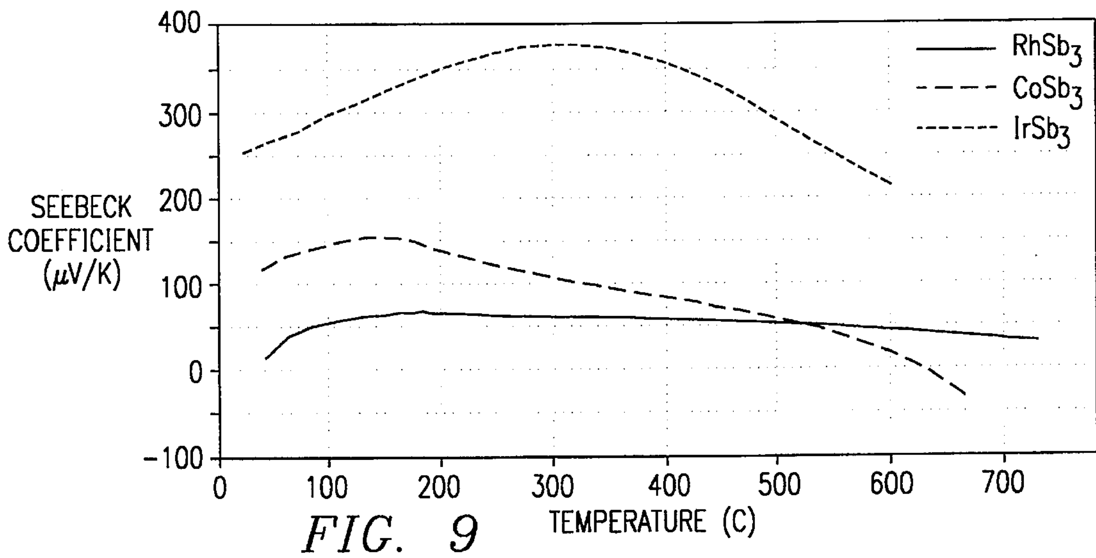


FIG. 9

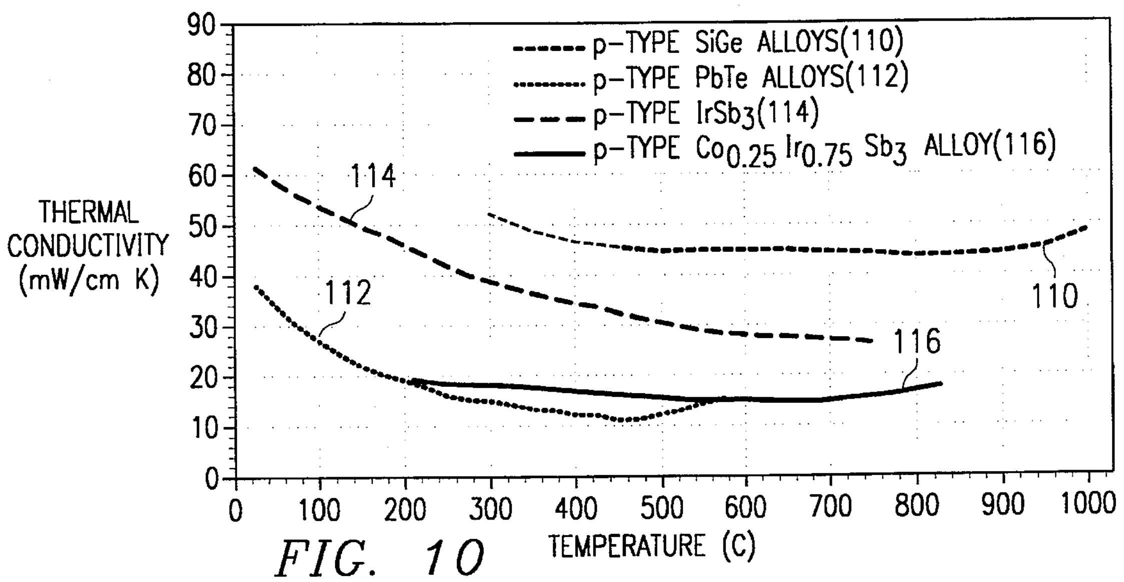


FIG. 10

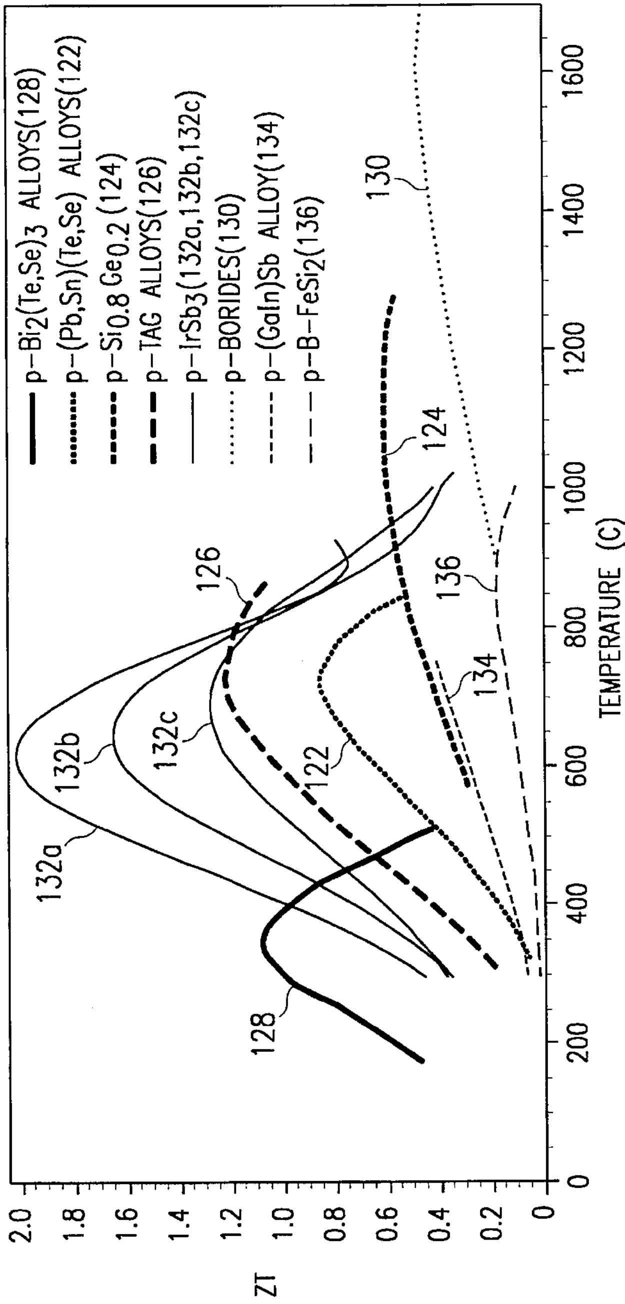


FIG. 11

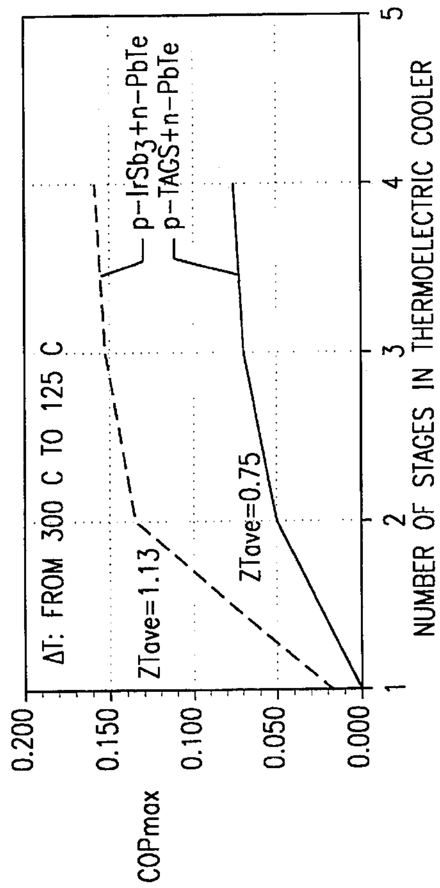


FIG. 12

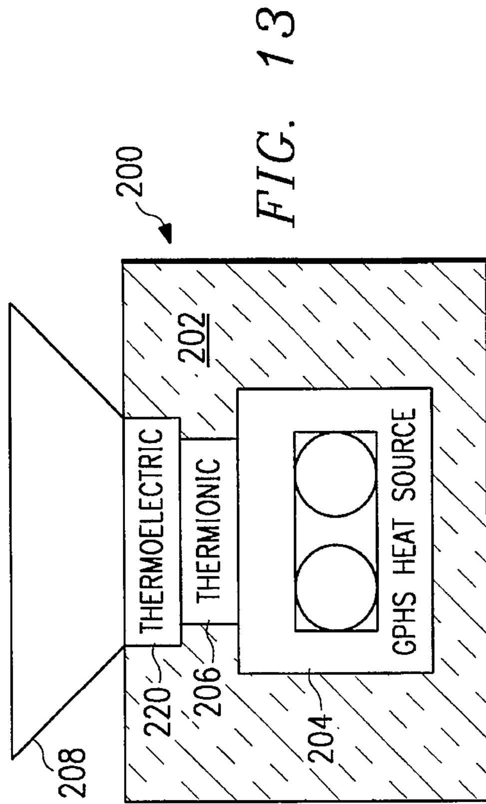


FIG. 13

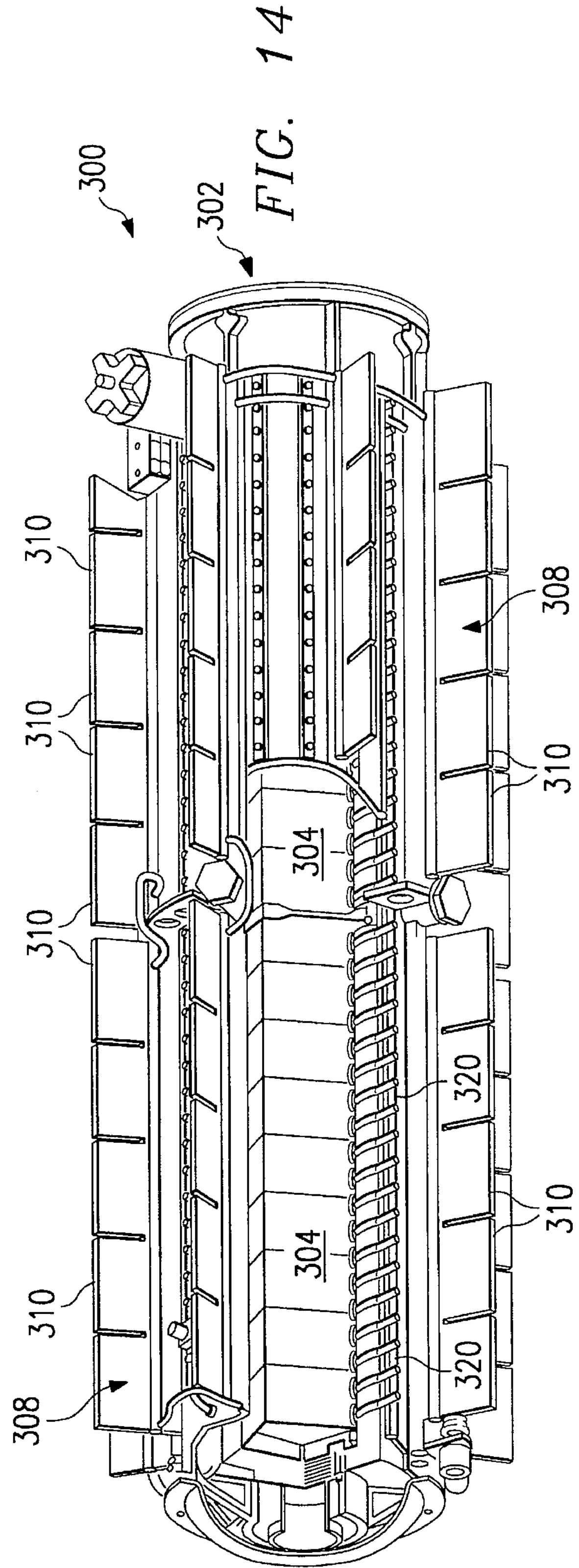


FIG. 14

HIGH PERFORMANCE THERMOELECTRIC MATERIALS AND METHODS OF PREPARATION

NOTICE

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. 202) in which the Contractor has elected to retain title.

RELATED PATENT APPLICATION

This patent application is a continuation-in-part of patent application U.S. Ser. No. 08/101,901 filed Aug. 3, 1993 (Attorney's Docket 17083-0118).

TECHNICAL FIELD OF THE INVENTION

This invention relates to semiconductor materials having enhanced thermoelectric properties and preparation of such materials.

BACKGROUND OF THE INVENTION

The basic theory and operation of thermoelectric devices has been developed for many years. Such devices may be used for heating, cooling, temperature stabilization, power generation and temperature sensing. Modern thermoelectric coolers typically include an array of thermocouples which operate by using the Peltier effect.

Thermoelectric devices are essentially heat pumps and power generators which follow the laws of thermodynamics in the same manner as mechanical heat pumps, refrigerators, or any other apparatus used to transfer heat energy. The principal difference is that thermoelectric devices function with solid state electrical components (thermocouples) as compared to more traditional mechanical/fluid heating and cooling components. The efficiency of a thermoelectric device is generally limited to its associated Carnot cycle efficiency reduced by a factor which is dependent upon the thermoelectric figure of merit (ZT) of the materials used in fabrication of the thermoelectric device.

The dimensionless figure of merit ZT represents the coupling between electrical and thermal effects in a material and is defined as:

$$ZT=S^2\sigma T/\kappa \qquad (1)$$

where S, σ, κ, and T are the Seebeck coefficient, electrical conductivity, thermal conductivity and absolute temperature, respectively. The basic thermoelectric effects are the Seebeck and Peltier effects. The Seebeck effect is the phenomenon underlying the conversion of heat energy into electrical power and is used in thermoelectric power generation. The complementary effect, the Peltier effect, is the phenomenon used in thermoelectric refrigeration and is related to heat absorption accompanying the passage of current through the junction of two dissimilar materials.

The ZT may also be stated by the equation:

$$ZT=\frac{S^2T}{\rho\kappa} \qquad (2)$$

ρ = electrical resistivity
σ = electrical conductivity

$$\text{electrical conductivity}=\frac{1}{\text{electrical resistivity}}$$

-continued

or

$$\sigma=\frac{1}{\rho}$$

Thermoelectric materials such as alloys of Bi_2Te_3, PbTe and BiSb were developed thirty to forty years ago. Semiconductor alloys such as SiGe have also been used in the fabrication of thermoelectric devices. Commercially available thermoelectric materials are generally limited to use in a temperature range between 200° K. and 1300° K. with a maximum ZT value of approximately one. The efficiency of such thermoelectric devices remains relatively low at approximately five to eight percent (5–8%) energy conversion efficiency. For the temperature range of −100° C. to +1000° C., maximum ZT of current state of the art thermoelectric materials remains limited to values of approximately 1, except for Te-Ag-Ge-Sb alloys (TAGS) which may achieve a ZT of 1.2 in a very narrow temperature range. Thermoelectric materials such as $Si_{80}Ge_{20}$ alloys used in thermoelectric generators to power spacecrafts for deep space missions have a ZT approximately equal to 0.7 from 300° C. to 1,000° C.

SUMMARY OF THE INVENTION

In accordance with the present invention disadvantages and problems associated with the previous design and preparation of materials used in the manufacture of thermoelectric devices have been substantially reduced or eliminated. The present invention provides the ability to obtain increased efficiency from a thermoelectric device by using materials with a skutterudite-type crystal lattice structure and desired thermoelectric properties in fabrication of the thermoelectric device. Examples of semiconductor materials and alloys which are satisfactory for use with the present invention include, but are not limited to, $IrSb_3$, $RhSb_3$, $CoSb_3$, $Co_{1-x-y}Rh_xIr_ySb_3$ wherein $0\leqq x\leqq 1$ and $0\leqq y\leqq 1$ and related alloys.

In accordance with one aspect of the present invention, P-type semiconductor materials are formed from alloys of $CoSb_3$, $RhSb_3$, $IrSb_3$ or $Co_{1-x-y}Rh_xIr_ySb_3$ for use in manufacturing thermoelectric devices with substantially enhanced operating characteristics and improved efficiency as compared to previous thermoelectric devices.

In accordance with another aspect of the present invention, N-type semiconductor materials are formed from alloys of $CoSb_3$, $RhSb_3$, $IrSb_3$ or $Co_{1-x-y}Rh_xIr_ySb_3$ for use in manufacturing thermoelectric devices with substantially enhanced operating characteristics and improved efficiency as compared to previous thermoelectric devices.

An important technical advantage of the present invention includes the use of gradient freeze techniques in the preparation of semiconductor materials such as $IrSb_3$, $RhSb_3$ and $CoSb_3$. The use of gradient freeze techniques in accordance with the present invention produces a large, single crystal of semiconductor alloys having a skutterudite lattice structure. A Bridgman Two-Zone furnace and a sealed container have been modified for use in preparation of semiconductor materials in accordance with the present invention.

Another important technical advantage of the present invention includes the use of liquid-solid phase sintering techniques in the preparation of semiconductor materials such as $IrSb_3$, $RhSb_3$, $CoSb_3$ and $Co_{1-x-y}Rh_xIr_ySb_3$. The use of liquid-solid phase sintering techniques in accordance with

the present invention produces large, polycrystalline ingots of semiconductor alloys having a skutterudite lattice structure. An isothermal furnace and a sealed container have been modified for use in preparation of semiconductor alloys in accordance with the present invention.

A further important technical advantage of the present invention includes the use of low temperature powder sintering and/or hot pressing in the preparation of semiconductor alloys such as $IrSb_3$, and $Co_{1-x-y}Rh_xIr_ySb_3$. The use of powder sintering and/or hot pressing in accordance with the present invention produces large polycrystalline pellets of semiconductor alloys having a skutterudite lattice structure.

Another aspect of the present invention includes manufacturing a thermoelectric device with P-type thermoelectric elements formed from materials such as $CoSb_3$, $RhSb_3$, $IrSb_3$ or $Co_{1-x-y}Rh_xIr_ySb_3$ and N-type thermoelectric elements formed from Bi-Sb alloys, Bi_2Te_3 based alloys, PbTe based alloys, β-$FeSi_2$ based alloys, $Ga_{1-x}In_xSb$ based alloys, or SiGe alloys.

The present invention allows the manufacture of thermoelectric energy conversion devices such as electrical power generators, heaters, coolers, thermocouples and temperature sensors with high ZT and associated increased efficiency. By using semiconductor alloys such as $IrSb_3$, $RhSb_3$, $CoSb_3$, $Co_{1-x-y}Rh_xIr_ySb_3$ and related alloys which have been prepared in accordance with the present invention, the overall efficiency of a thermoelectric device may be substantially enhanced. Thermoelectric elements fabricated from semiconductor materials such as $IrSb_3$, $RhSb_3$, $CoSb_3$, and $Co_{1-x-y}Rh_xIr_ySb_3$ with skutterudite-type crystal lattice structures have demonstrated a ZT of 2.

A further important technical advantage includes the use of semiconductor materials prepared in accordance with the present invention in the manufacture of a radioisotope thermoelectric generator (RTG) to double the associated system efficiency of the resulting RTG. Other thermoelectric devices manufactured from semiconductor materials fabricated in accordance with the present invention may be used in waste heat recovery systems, automobiles, remote power generators, temperature sensors and coolers for advanced electronic components such as field effect transistors.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and its advantages, reference is now made to the following description taken in conjunction with the accompanying drawings in which:

FIG. **1** is an isometric drawing of a thermoelectric device which may be manufactured from materials incorporating the present invention;

FIG. **2** is a schematic drawing of the electrical circuit associated with the thermoelectric device of FIG. **1**;

FIG. **2***a* is a schematic drawing of an electrical circuit associated with the thermoelectric device of FIG. **1** functioning as a cooler;

FIG. **2***b* is a schematic drawing of an electrical circuit associated with the thermoelectric device of FIG. **1** functioning as a heat pump;

FIG. **2***c* is a schematic drawing of an electrical circuit associated with the thermoelectric device of FIG. **1** functioning as a power generator;

FIG. **3** is an isometric representation of a skutterudite-type crystal lattice structure associated with semiconductor materials which have been fabricated in accordance with the present invention;

FIG. **4** is an iridium antimony phase diagram;

FIG. **5***a* is a schematic drawing in elevation and in section with portions broken away showing a Bridgman Two-Zone furnace which may be used to prepare semiconductor materials using gradient freeze techniques in accordance with the present invention;

FIG. **5***b* is a graph showing the temperature gradient associated with growing large, single crystals of semiconductor materials having a skutterudite lattice structure in accordance with the present invention;

FIG. **6** is a schematic drawing in elevation and in section with portions broken away showing an isothermal furnace which may be used during liquid solid phase sintering to prepare large polycrystalline ingots of semiconductor materials having a skutterudite lattice structure in accordance with the present invention;

FIG. **7** is a graph showing typical electrical resistivity values as an inverse function of temperature associated with semiconductor materials prepared in accordance with the present invention;

FIG. **8** is a graph showing typical Hall mobility values as an inverse function of temperature associated with semiconductor materials prepared in accordance with the present invention;

FIG. **9** is a graph showing typical Seebeck coefficients as a function of temperature for semiconductor materials prepared in accordance with the present invention;

FIG. **10** is a graph showing thermal conductivity as a function of temperature for semiconductor materials prepared in accordance with the present invention as compared with presently available thermoelectric materials;

FIG. **11** is a graph showing the ZT as a function of temperature for P-type semiconductor materials prepared in accordance with the present invention as compared with the ZT of previously available P-type semiconductor materials; and

FIG. **12** is a graph showing the calculated performance of a multiple stage thermoelectric cooler fabricated in part from semiconductor materials incorporating the present invention as compared to a multiple stage thermoelectric cooler fabricated from previously available semiconductor materials;

FIG. **13** is a schematic representation of a hybrid thermionic-thermoelectric power generator which may be manufactured with thermoelectric materials incorporating the present invention; and

FIG. **14** is a schematic representation of an actual radioisotope thermoelectric power generator which may be manufactured with thermoelectric materials incorporating the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The preferred embodiments of the present invention and its advantages are best understood by reference to FIGS. **1** through **14** of the drawings, like numerals being used for like and corresponding parts of the various drawings.

Thermoelectric device **20**, as shown in FIGS. **1** and **2**, may be manufactured from semiconductor materials and alloys which have been prepared in accordance with the present invention. The use of such semiconductor materials will substantially increase the energy conversion efficiency of thermoelectric device **20**. Thermoelectric device **20** may be used as a heater and/or a cooler.

Thermoelectric device **20** is preferably manufactured with a plurality of thermoelectric elements (sometimes referred to as "thermocouples") **22** disposed between cold plate **24** and hot plate **26**. Ceramic materials are frequently used in the manufacture of plates **24** and **26** which define in part the cold side and hot side, respectively, of thermoelectric device **20**.

Electrical power connections **28** and **29** are provided to allow attaching thermoelectric device **20** to an appropriate source of DC electrical power. If thermoelectric device **20** was redesigned to function as an electrical power generator, electrical connections **28** and **29** would represent the output terminals from such a power generator operating between hot and cold temperature sources (not shown). Such electrical power generators may be used for various applications such as waste heat recovery systems (not shown), space power system **200** and radioisotope thermoelectric power generator **300**.

FIG. **2** is a schematic representation of electrical circuit **30** associated with thermoelectric device **20**. Electrical circuit **30** is typical of electrical circuits associated with using thermoelectric elements or thermocouples **22** for heating and/or cooling. Electrical circuit **30**, which is typical for a single stage thermoelectric device such as thermoelectric device **20**, generally includes two dissimilar materials such as N-type thermoelectric elements **22*a*** and P-type thermoelectric elements **22*b***. Thermoelectric elements **22** are typically arranged in an alternating N-type element to P-type element configuration. In many thermoelectric devices, semiconductor materials with dissimilar characteristics are connected electrically in series and thermally in parallel.

A common property of semiconductor materials is that electricity can be conducted by two type of carriers: electrons in N-type materials and holes in P-type materials. In a crystal, when one atom is replaced by another atom with more valence electrons, the extra electrons are not needed for bonding and are free to move throughout the crystal. This type of electrical conduction is called n-type. However, when an atom is replaced by another atom with fewer electrons, a bond is left vacant and this shortage is referred to as a hole. This type of electrical conduction is called P-type. The extra electrons in the N-type semiconductor materials and the extra holes in the P-type semiconductor materials are frequently referred to as "charge carriers." Heat may be conducted between cold side (or cold plate **24**) and hot side (or hot plate **26**) of thermoelectric elements **22** by charge carriers (electron or holes) and vibrations of the crystal lattice structure. Such lattice vibrations are referred to as "phonons".

In thermoelectric device **20**, alternating thermoelectric elements **22** of N-type and P-type semiconductor materials have their ends connected in a serpentine fashion by electrical conductors such as **32**, **34** and **36**. Conductors **32**, **34** and **36** are typically metallizations formed on the interior surfaces of plates **24** and **26**. Commercially available thermoelectric coolers frequently include two metallized ceramic plates with P-type and N-type elements of bismuth telluride alloys soldered between the ceramic plates.

When DC electrical power from power supply **38** is applied to thermoelectric device **20** having an array of thermoelectric elements **22**, heat energy is absorbed on cold side **24** of thermoelectric elements **22**. The heat energy passes through thermoelectric elements **22** and is dissipated on hot side **26**. A heat sink (sometimes referred to as the "hot sink", not shown) may be attached to hot plate **26** of thermoelectric device **20** to aid in dissipating heat from thermoelectric elements **22** to the adjacent environment. In a similar manner a heat sink (sometimes referred to as a "cold sink", not shown) may be attached to cold side **24** of thermoelectric device **20** to aid in removing heat from the adjacent environment.

Thermoelectric device **20** may sometimes be referred to as a thermoelectric cooler. However, since thermoelectric devices are a type of heat pump, thermoelectric device **20** may be designed to function as either a cooler, heater, or power generator. FIGS. **2*a*** **2*b*** and **2*c*** are schematic representations showing these alternative uses for thermoelectric device **20**. In FIG. **2*a*** thermoelectric elements **22** and the electrical circuit **30*a*** have been configured to allow thermoelectric device **20** to function as a cooler similar to circuit **30** shown in FIG. **2**. FIG. **2*b*** demonstrates that changing the position of switch **39** allows essentially the same electrical circuit **30*a*** to convert thermoelectric device **20** from a cooler to a heater. In FIG. **2*c*** thermoelectric device **20** and electric circuit **20*a*** are configured to produce electricity by placing thermoelectric device **20** between a source of high temperature (not shown) and a source of low temperature (not shown).

Semiconductor materials (sometimes referred to as "semiconductor alloys") $CoSb_3$, $RhSb_3$, $IrSb_3$ and $Co_{1-x-y}Rh_xIr_ySb_3$ have been prepared in accordance with the present invention in the form of large, single crystals and polycrystalline ingots with skutterudite crystal lattice structure **40** as shown in FIG. **3**. A typical skutterudite crystal lattice structure is defined in part by a unit cell with eight members having the formula AB_3. A may be selected from the group consisting of Co, Rh and Ir. B may be Sb. Alloys of these elements having the formula $Co_{1-x-y}Rh_xIr_ySb_3$, where $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$, have also been prepared using the present invention.

Skutterudite-type crystal lattice structure **40** includes a cubic lattice of metal atoms **42**. Metal atoms **42** are preferably selected from the group consisting of cobalt, iridium, and/or rhodium. A four-member plenary ring **44** of non-metal atoms **46** is disposed within the cubic lattice structure. Each plenary ring **44** preferably includes four atoms of antimony. Each metal atom **42** has six neighbor atoms **42**. Non-metal atoms **46** have two adjacent non-metal atoms **46** and two metal atoms **42**. The covalent bonding associated with skutterudite-type crystal lattice structure **40** provides high hole mobility. The complex structure and heavy atoms associated with skutterudite-type crystals also result in low thermal conductivity.

Semiconductor materials having skutterudite-type crystal lattice structure **40** may be doped with selected impurities to produce N-type thermoelectric elements **22*a*** and P-type thermoelectric elements **22*b***. By optimizing the doping level, $IrSb_3$ semiconductor alloys may be used to produce P-type thermoelectric elements having a ZT of approximately two at a temperature of 400° C. If desired, thermoelectric device **20** may be manufactured with P-type thermoelectric elements **22*b*** fabricated from $IrSb_3$ and N-type thermoelectric elements **22*a*** fabricated from previously available semiconductor materials such as Bi-Sb alloys, Bi_2Te_3 based alloys, PbTe based alloys, β-$FeSi_2$ based alloys, $Ga_{1-x}In_xSb$ based alloys, and SiGe alloys

Large, single crystals of semiconductor alloys have been prepared in accordance with the present invention using gradient freeze techniques. Liquid-solid phase sintering techniques have been used to prepare large, polycrystalline ingots of semiconductor alloys in accordance with the present invention. The phase diagram for iridium-antimony, as shown in FIG. **4**, demonstrates that $IrSb_3$ with the desired

skutterudite-type crystal lattice structure is very difficult to obtain. Crystal growth is preferably initiated from a narrow range of compositions. In addition, the liquidus curve in antimony rich region forming $IrSb_3$ is relatively sharp which further increases the difficulty of separating liquid and solid phases during crystallization.

Depending upon the desired composition of the semiconductor materials either gradient freeze techniques, liquid-solid phase sintering techniques, and low temperature powder sintering with or without hot pressing may be used to produce semiconductor alloys with the desired skutterudite-type crystal lattice structure. For some semiconductor materials such as $CoSb_3$, $RhSb_3$, and $Co_{1-x-y}Rh_xIr_ySb_3$ gradient freeze techniques have produced the desired large, single crystal. Crystal growth by gradient freeze techniques is preferably initiated from non-stoichiometric (antimony rich) melts based on the liquid-solid phase diagram associated with the elements which will comprise the resulting semiconductor materials.

For other semiconductor materials such as single phase $IrSb_3$ and $Co_{1-x-y}Rh_xIr_ySb_3$, liquid-solid phase sintering techniques have produced the desired large, polycrystalline ingots. Semiconductor alloys such as $IrSb_3$ and $Co_{1-x-y}Rh_xIr_ySb_3$ have been produced using low temperature powder sintering and/or hot pressing. Liquid-solid phase sintering, low temperature powder sintering, and hot pressing are preferably conducted in an isothermal furnace starting from an elemental mixture (TSb_3) of the desired elements close to stoichiometry (±2 atomic %).

Liquid-solid phase sintering may be satisfactorily performed with powders of Co, Rh, Ir, and shots of Sb. Low temperature powder sintering process is preferably initiated with powders of Co, Ir, and Sb. For some application powders of $IrSb_3$ and $Co_{1-x-y}Rh_xIr_ySb_3$ may also be synthesized into large polycrystalline pellets. Hot pressing may be included as part of the low temperature provider entering process.

Large, single crystals of semiconductor alloys with the desired skutterudite lattice structure **40** may be grown by using gradient freeze techniques and furnace **50** as shown in FIG. *5a*. Furnace **50**, frequently referred to as a Bridgman Two-Zone furnace, includes housing **52** with a first or upper heater assembly **54** and a second or lower heater assembly **56**. Housing **52** defines in part chamber **60**. Thermal baffle **58** is preferably disposed between first heater assembly **54** and second heater assembly **56** intermediate chamber **60**. Various components which comprise furnace **50** are preferably disposed vertically within chamber **60** of housing **52**.

As shown in FIG. *5a*, housing **52** includes end closure **62** which seals the upper portion of chamber **60** and end closure **64** which seals the lower portion of chamber **60**. Quartz rod **66** may be vertically disposed within chamber **60**. Container **68** is preferably secured to one end of rod **66** adjacent to thermal baffle **58**.

The lower portion **70** of container **68** is preferably pointed or tapered with respect to rod **66**. Various types of containers **68** may be satisfactorily used with the present invention. A sealed quartz ampoule has been found satisfactory for use with furnace **50**. If desired, housing **52** and end closure **64** may be modified to allow a conveyor (not shown) with a plurality of rods **66** and containers **68** to pass sequentially through furnace **50**.

Elements such as Co, Rh and Sb powders which will form the desired semiconductor alloy using furnace **50** are preferably sealed within container **68** under a vacuum. Pointed or tapered end **70** of container **68** is attached to quartz rod **66** and disposed vertically within chamber **60**. Tapered end **70** and its attachment to rod **66** cooperate to maintain the desired temperature gradients in container **68**. Furnace **50** is then heated to establish the desired temperature gradient **69** and controlled cooling **67** as shown in FIG. *5b*. Various temperature gradients may be used depending upon the elements placed within container **68** to produce the desired semiconductor alloy.

For one embodiment of the present invention samples of $CoSb_3$ and $RhSb_3$ were directionally crystallized from non-stoichiometric melt **72** rich in antimony. Crystals of $CoSb_3$ and $RhSb_3$ were grown with an axial temperature gradient of about 50° C./cm and a growth rate about 1 mm/day. The crystals of $CoSb_3$ and $RhSb_3$ were approximately 10 mm long and 6 mm in diameter. The average density of the $CoSb_3$ crystals was measured and found to be 99.7% of the theoretical density (7.69 g/cm^3). The average density of the $RhSb_3$ crystals was measured and found to be 99.5% of the theoretical density (7.96 g/cm^3). Crystals of the $Ir_xCo_{1-x}Sb_3$ solid solutions were also successfully grown by gradient freeze techniques from antimony-rich melts in furnace **50**. The samples produced had good semiconducting properties including exceptional P-type Hall mobilities as high as 8000 $cm^2.V^{-1}.s^{-1}$ at room temperature.

Large polycrystalline ingots of semiconductor materials with a skutterudite lattice structure may also be prepared by using liquid-solid phase sintering techniques and furnace **80** as shown in FIG. **6**. Furnace **80** may be referred to as an isothermal furnace as compared to furnace **50** which has two different temperature zones. Furnace **80** includes housing **82** with heater assembly **84** disposed therein. Housing **82** defines in part chamber **90**. Various components which comprise furnace **80** are preferably vertically disposed within chamber **90** of housing **82**.

As shown in FIG. **6**, housing **82** includes end closure **92** which seals the upper portion of chamber **90** and end closure **94** which seals the lower portion of chamber **90**. Quartz rod **66** is preferably disposed vertically within chamber **90**. Container **68** is preferably secured within chamber **90** intermediate end closures **94** and **92** at approximately the mid point of chamber **90**. For one embodiment of the present invention vibrating rod **66** improved the yield of the sintering technique.

The elements such as Ir, Rh, Co and Sb which will be used to form the desired semiconductor material may be sealed within container **68**. The lower portion **70** of container **68** may be pointed or tapered with respect to quartz rod **66**. For some applications container **68** may have a relatively flat lower portion **70**. The relationship of lower portion **70** with quartz rod **66** cooperate to maintain the desired temperature in container **68** during preparation of the skutterudite-type crystal structure **40**. Various types of containers **68** may be satisfactorily used with the present invention. A sealed quartz crystal or crystal ampoule has been found satisfactory for use with the present invention. As previously noted for furnace **50**, housing **82** and end closure **94** may be modified to allow a conveyor (not shown) to pass a plurality of rods **66** and containers **68** sequentially through furnace **80**.

Liquid-solid phase sintering techniques have been used to prepare large, polycrystalline ingots of semiconductor material $IrSb_3$ and also some alloys of $(Ir_{1-x-y}Rh_xCO_y)Sb_3$ solid solutions using furnace **80** and container **68**. The ingots were approximately 10 mm long and 6 mm in diameter.

The liquid-solid phase sintering technique used to produce $IrSb_3$ and $(Ir_{1-x-y}Rh_xCO_y)Sb_3$ solid solutions included placing a first layer **98** of elemental iridium, cobalt and/or

rhodium powders together with a second layer **100** of antimony shots in container **68** sealed under vacuum. In the case of the preparation of a solid solution $(Ir_{1-x-y}Rh_xCO_y)Sb_3$, the powders of iridium, cobalt and rhodium in the desired ratio were loaded in plastic vials, mixed and shaken in a mixer mill (not shown) for about thirty minutes. Container **68** with material layers **98** and **100** was then positioned vertically and heated in furnace **80** as illustrated in FIG. **6**. Several different reaction times and temperatures were tried. For some mixtures, the best results were obtained with a reaction time of 24 hours at a temperature of 1000° C. Under these conditions, the resulting ingots were the most dense.

Transport properties measurements performed on samples of $CoSb_3$, $RhSb_3$ and $(Ir_{1-x-y}Rh_xCO_y)Sb_3$ prepared using the previously described procedures and apparatus demonstrated excellent semiconducting and thermoelectric properties. For example, the alloys with skutterudite-type crystal lattice structure **40** had exceptional high P-type Hall mobilities. Room temperature values as high as 7725 $cm^2.V^{-1}.s^{-1}$ were measured on a $RhSb_3$ sample at a doping level of 2.4 10^{18} cm^{-3}. Although linked to the particular crystal structure of this alloy, this high value is also a result of the good quality of the sample. For example, lower mobilities were measured on hot-pressed $RhSb_3$ samples such as a maximum value of 1500 $cm^2.V^{-1}.s^{-1}$. Mobility as high as 1732 $cm^2.V^{-1}.s^{-1}$ were measured on P-type $CoSb_3$ single crystals compared to a maximum value of 290 $cm^2.V^{-1}.s^{-1}$ for samples prepared by other procedures. $IrSb_3$ samples also possessed high P-type Hall mobilities as high as 1241 $cm^2.V^{-1}.s^{-1}$ at a doping level of 7.2 10^{18} cm^{-3}.

Semiconductor alloys and related solid solutions have also been prepared by low temperature powder sintering of iridium, cobalt, rhodium and antimony in ratios close to stoichiometry (±2 atomic %). Completion of the reaction was achieved in times as short as six hours at a temperature of 600° C. The resulting powders of $IrSb_3$ alloy and several compositions of the $(Ir_{1-x-y}Rh_xCO_y)Sb_3$ solid solutions were placed in a graphite die container and subjected to hot pressing of the alloy powders to form the desired polycrystalline pellets. The hot pressing was typically conducted for at least 30 minutes at a temperature of at least 650° C.

These same elemental powders of iridium, cobalt, antimony and rhodium have also been successfully hot-pressed under specific conditions into large pellets (not shown). Several different mixtures of elemental powders were successfully hot-pressed in a graphite die (not shown) into dense polycrystalline pellets about 15 mm long and 6 mm in diameter. The resulting alloys demonstrated exceptional thermoelectric properties. Hot pressing was typically performed for six hours at 800° C.

Doping of elemental and alloyed powders can be achieved by introducing the desired amount of dopant in the initial powder load. By using commercially available hot presses and graphite die containers, this process is quick, cost effective and may be easily adapted to industrial manufacturing of large quantities of $(Ir_{1-x-y}Rh_xCO_y)$ Sb_3 samples of different compositions and doping level.

Semiconductor alloys of $CoSb_3$, $RhSb_3$ and $IrSb_3$ with skutterudite-type crystal lattice structure **40** prepared in accordance with the present invention have demonstrated the characteristics shown in the following Table I.

TABLE I

Material	$CoSb_3$	$RhSb_4$	$IrSb_3$
Melting Point (C.)	850	900	1140
Type of formation from the melt	peritectic	peritectic	peritectic
Structure type	cubic	cubic	cubic
Prototype	$CoAs_3$	$CoAs_3$	$CoAs_3$
Number of atoms/unit cell	32	32	32
Lattice parameter (Å)	9.0347	9.2322	9.2533
Density ($g \cdot cm^{-3}$)	7.69	7.96	9.32
Thermal expansion coefficient ($C.^{-1}$)	13.46×10^{-6}	12.7×10^{-6}	7.96×10^{-6}
Energy bandgap (eV)	0.5	~0.9	1.17
Conductivity type	p	p	p
Electrical resistivity (mΩ · cm) at 25 C.	0.55	0.34	0.70
Hall mobility ($cm2 \cdot V^{-1} \cdot s^{-1}$) at 25 C.	1732	7725	1241
Hall carrier concentration (cm^{-3}) at 25 C.	6.5×10^{18}	2.4×10^{18}	7.2×10^{18}
Seebeck coefficient ($\mu V \cdot K.^{-1}$ at 25 C.	150	~80	250

FIG. **7** is a graphical representation of typical electrical resistivity values as a function of inverse temperature for semiconductor alloys $CoSb_3$, $RhSb_3$ and $IrSb_3$ having skutterudite-type crystal lattice structure **40**. FIG. **8** is a graphical representation of typical Hall mobility values as a function of inverse temperatures for semiconductor alloys $CoSb_3$, $RhSb_3$ and $IrSb_3$ having skutterudite-type crystal lattice structure **40**. FIG. **9** is a graphic representation of typical Seebeck coefficient values as a function of temperature for semiconductor alloys $CoSb_3$ and $IrSb_3$ having skutterudite-type crystal lattice structure **40**.

FIG. **10** shows comparisons of thermal conductivity as a function of temperature for semiconductor materials $IrSb_3$ and $Ir_{0.75}Co_{0.25}Sb_3$ prepared in accordance with the present invention as compared with previously available thermoelectric materials SiGe alloys and PbTe alloys. Curves **110** and **112** show thermal conductivity measured for SiGe alloys and PbTe based alloys respectively. Curves **114** and **116** are based on thermal conductivity measurements for semiconductor materials $IrSb_3$ and $Ir_{0.75}Co_{0.25}Sb_3$ respectively prepared in accordance with the present invention.

FIG. **11** is a graph showing various values of ZT as a function of temperature for three samples (**132*a*, 132*b*** and **132*c***) of semiconductor material $IrSb_3$ with different P-type doping levels. FIG. **11** also contains a graphical representation of ZT for previously available P-type thermoelectric materials. Ni, Pd, Pt, Te, Se. Cu, Ag and Au have been found to be satisfactory doping impurities for use with semiconductor alloys prepared in accordance with the present invention. Excess amounts of Sb and/or Ir have also been found to result in substantial changes in carrier concentration for use with the present invention.

Multiple stage thermoelectric coolers (not shown) are typically fabricated by vertically stacking two or more single stage thermoelectric devices. Each ascending thermoelectric device will have fewer thermoelectric elements or thermocouples. A multiple stage thermoelectric cooler is therefore typically pyramid shaped because the lower stage requires more thermoelectric elements to transfer the heat dissipated from the upper stage in addition to the heat pumped from the

object being cooled by the multiple stage thermoelectric cooler. Field effect transistors operating at high temperature are desirable and may be cooled from 300° C. to 125° C. by using such multiple stage thermoelectric coolers having thermoelectric elements fabricated in accordance with the present invention.

P-type semiconductor material $IrSb_3$ prepared in accordance with the present invention may be used to provide a portion of the thermoelectric elements in a multiple stage thermoelectric cooler. Currently available N-type semiconductor materials such as Bi_2Te_3 or any other suitable N-type semiconductor material may be used to provide another portion of the thermoelectric elements. The resulting combination substantially enhances the performance of the thermoelectric device. This combination of P-type and N-type semiconductor materials is particularly useful in the 100° C. to 400° C. temperature range. FIG. **12** is a graphical representation showing the increase in multiple stage thermoelectric cooler performance resulting from the use of P-type semiconductor materials $IrSb_3$. FIG. **12** shows the coefficient of performance (COP_{MAX}) as a function of the number of stages in each thermoelectric cooler.

A two stage hybrid thermionic-thermoelectric generator **200** is shown in FIG. **13**. Generator **200** preferably includes protective housing **202** with a general purpose heat source **204** disposed therein. Thermionic device **206** is disposed adjacent to heat source **204**. Thermoelectric device **220** may be placed adjacent to thermionic device **206**. Thermoelectric device **220** will preferably include one or more thermoelectric elements (not shown) which have been fabricated from thermoelectric alloys in accordance with the present invention. One or more fin type radiators **208** are disposed on the exterior of housing **202**. Radiator **208** cooperates with heat source **204** to establish a temperature gradient across thermionic device **206** and thermoelectric device **220**. By using thermoelectric elements fabricated in accordance with the present invention, the energy conversion efficiency of thermoelectric device **220** is substantially enhanced. Also, single stage thermoelectric devices can be manufactured from thermoelectric elements fabricated in accordance with the present invention to improve the overall design feasibility of hybrid thermionic/thermoelectric generators.

Radioisotope thermoelectric generator **300** is shown in FIG. **14**. Radioisotope thermoelectric generator **300** is used to convert nuclear energy to electrical energy. The principle components of radioisotope thermoelectric generator **300** include supporting structure **302**, a plurality of general purpose heat sources (radioactive material) **304**, a plurality of thermoelectric devices **320** and cooling assembly **308**. Thermoelectric devices **320** are preferably manufactured from thermoelectric alloys which have been fabricated in accordance with the present invention. Cooling assembly **308** cooperates with heat sources **304** to establish the desired temperature gradient across thermoelectric device **320** and to produce electrical power as a result of the temperature difference between heat source **304** and cooling assembly **308**. A plurality of fins **310** are used to dissipate heat energy to the surrounding environment. Generators **200** and **300** are particularly beneficial for use in space exploration activities.

Although the present invention has been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and the scope of the invention as defined in the following claims.

What is claimed is:

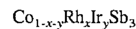
1. A thermoelectric device having a plurality of thermoelectric elements with at least one of the thermoelectric elements comprising a first material having a skutterudite-type crystal lattice structure with a unit cell of eight groups of AB_3 wherein A comprises a metal atom and B comprises a non-metal atom.

2. The thermoelectric device as defined in claim **1** wherein the first material further comprises $IrSb_3$.

3. The thermoelectric device as defined in claim **1** wherein the first material further comprises $CoSb_3$.

4. The thermoelectric device as defined in claim **1** wherein the first material further comprises $RhSb_3$.

5. The thermoelectric device as defined in claim **1** wherein the first material further comprises a semiconductor alloy having the formula:



$$Co_{1-x-y}Rh_xIr_ySb_3$$

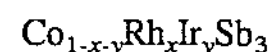
wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$.

6. A thermoelectric device comprising:

a first material having a skutterudite-type crystal lattice structure with a unit cell of eight groups of AB_3 wherein A comprises a metal atom and B comprises a non-metal atom; and

a second material selected from the group consisting of Bi-Sb alloys, Bi_2Te_3 based alloys, PbTe based alloys, β-$FeSi_2$ based alloys, $Ga_{1-x}In_xSb$ based alloys, and SiGe alloys.

7. A thermoelectric device having a plurality of thermoelectric elements with at least one of the thermoelectric elements comprising a first material having the formula:



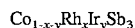
$$Co_{1-x-y}Rh_xIr_ySb_3$$

wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$.

8. The thermoelectric device as defined in claim **7** wherein the first material further comprises a skutterudite-type crystal lattice structure.

9. A thermoelectric device comprising:

a first material having the formula:



$$Co_{1-x-y}Rh_xIr_ySb_3$$

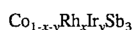
wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$; and

a second material selected from the group consisting of Bi-Sb alloys, Bi_2Te_3 based alloys, PbTe based alloys, β-$FeSi_2$ based alloys, $Ga_{1-x}In_xSb$ based alloys, and SiGe alloys.

10. A thermoelectric device having a plurality of thermoelectric elements formed from at least two different types of semiconductor materials comprising:

a portion of the thermoelectric elements formed from P-type semiconductor material having a skutterudite-type crystal lattice structure; and

the P-type semiconductor material having the formula:



$$Co_{1-x-y}Rh_xIr_ySb_3$$

wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$.

11. The thermoelectric device as defined in claim **10** further comprising another portion of the thermoelectric elements formed from N-type semiconductor material selected from the group consisting of Bi-Sb alloys, Bi_2Te_3 based alloys, PbTe based alloys, β-$FeSi_2$ based alloys, $Ga_{1-x}In_xSb$ based alloys, and SiGe alloys.

12. Apparatus using gradient freeze techniques to prepare a semiconductor alloy for use in fabricating thermoelectric elements comprising:

a furnace defined in part by a housing having a chamber with a first heater and a second heater disposed therein;

the first heater disposed within the chamber above the second heater;

a thermal baffle disposed within the chamber between the first heater and the second heater;

a container disposed within the chamber with the container adjacent to the thermal baffle;

a plurality of elemental materials disposed within the container for melting within the furnace to form the desired semiconductor alloys;

a sealed vessel with a first elemental material and a second elemental material; and

the first elemental material selected from the group consisting of iridium, rhodium and cobalt, and the second elemental material comprising antimony.

13. The apparatus as defined in claim **12**, further comprising an antimony rich melt with a composition between 90% and 99.5% antimony as compared to the first elemental material.

14. The apparatus as defined in claim **12** further comprising the first heater, the second heater, and the thermal baffle cooperating to form a sharp temperature gradient within the container for forming a single crystal of semiconductor alloy selected from the group consisting of $CoSb_3$, $RhSb_3$ and $Co_{1-x-y}Rh_xIr_ySb_3$ wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$.

15. Apparatus using liquid-solid phase sintering techniques to prepare a semiconductor alloy for use in fabricating thermoelectric elements comprising:

an isothermal furnace defined in part by a housing having a chamber with a heater disposed therein;

a container disposed within the chamber, with the container spaced intermediate from the interior surfaces of the chamber; and

a stoichiometric mixture of elemental materials selected from the group consisting of Co, Rh, Ir and Sb disposed within the container for forming polycrystalline ingots.

16. The apparatus as defined in claim **15** further comprising:

the container sealed with a vacuum formed therein;

a rod vertically disposed within the chamber and the container secured to one end of the rod; and

the lower portion of the container tapered towards the one end of the rod.

17. The apparatus as defined in claim **15** further comprising:

a layer of iridium powder disposed within the lower portion of the container adjacent to the rod; and

a layer of antimony disposed within the container above the iridium powder.

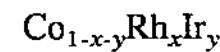
18. The apparatus as defined in claim **15** wherein the container further comprises:

a sealed vessel with a first elemental material layer and a second elemental material layer;

the first elemental material layer disposed within the lower portion of the sealed vessel, and the second elemental material layer disposed above the first material layer; and

the first elemental material layer selected from the group consisting of iridium, rhodium and cobalt, and the second elemental material layer comprising antimony.

19. The apparatus as defined in claim **15** wherein the stoichiometric mixture further comprises one layer of material having the formula:



$$Co_{1-x-y}Rh_xIr_y$$

wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$.

20. A method of preparing a semiconductor alloy having a skutterudite-type crystal lattice structure for use in fabricating thermoelectric elements comprising the steps of:

placing a first material selected from the group consisting of Ir, Rh and Co, and a second material comprising antimony in a container;

placing the container within a furnace with the second material vertically disposed above the first material;

heating the furnace to a preselected temperature to allow liquid-solid phase sintering of the first material and the second material; and

retaining the container within the furnace for a preselected length of time to allow formation of polycrystalline ingots of the semiconductor alloy having the desired skutterudite-type crystal lattice structure.

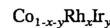
21. The method of preparing a semiconductor alloy as defined in claim **20**, further comprising the steps of forming an elemental mixture having the general formula (TSb_3) wherein T is provided by the first material and the elemental mixture is within ±2 atomic % of stoichiometry.

22. The method of preparing a semiconductor alloy as defined in claim **20**, further comprising the steps of:

forming a vacuum in the container after the first and second layers of material have been placed therein; and

sealing the container to trap the vacuum with the first and second material disposed therein.

23. The method of preparing a semiconductor alloy as defined in claim **22** further comprising the step of forming the first material from a mixture of Ir, Co and Rh with the formula:



$$Co_{1-x-y}Rh_xIr_y$$

wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$.

24. The method of preparing a semiconductor alloy as defined in claim **20** further comprising the steps of:

heating the furnace to a temperature of at least 650° C.; and

retaining the container in the furnace for at least fifteen minutes.

25. The method of preparing a semiconductor alloy as defined in claim **20** further comprising the step of vibrating a rod attached to the container for stirring the materials disposed within the container during growth of the skutterudite-type crystal lattice structure.

26. A method of preparing a semiconductor alloy having a skutterudite-type crystal lattice structure for use in fabricating thermoelectric elements comprising the steps of:

placing a first material selected from the group consisting of Ir, Rh and Co, and a second material comprising antimony in a container;

placing the container with the first material and second material vertically disposed within a furnace having two heaters;

heating the furnace to establish a preselected temperature gradient to melt the first and second materials to form a liquid and to grow a semiconductor crystal from the liquid by gradient freeze techniques; and

retaining the container within the furnace for a preselected length of time to allow growing the crystal of the semiconductor alloy having the desired skutterudite-type crystal lattice structure.

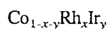
27. The method of preparing a semiconductor alloy as defined in claim **26**, further comprising the steps of forming the first material from cobalt powder and the second material from antimony powder with an atomic ratio rich in antimony.

28. The method of preparing a semiconductor alloy as defined in claim **27**, further comprising the steps of:

forming a vacuum in the container after the first and second materials have been placed therein; and

sealing the container to trap the vacuum with the first and second material disposed therein.

29. The method of preparing a semiconductor alloy as defined in claim **26** further comprising the step of forming the first material from a mixture of Ir, Co and Rh with the formula:



$Co_{1-x-y}Rh_xIr_y$

wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$.

30. The method of preparing a semiconductor alloy as defined in claim **26** further comprising the step of attaching one end of the container with a rod vertically disposed in the furnace.

31. A method of preparing a semiconductor alloy for use in fabricating thermoelectric elements from an approximately stoichiometric mixture comprising the steps of:

placing elemental powders selected from the group consisting of Ir, Rh, Co and Sb in a container to form the mixture;

placing the container with the mixture within an isothermal furnace; and

retaining the container and the mixture within the isothermal furnace for a preselected length of time to allow formation of the semiconductor alloyed powders having a skutterudite-type crystal lattice structure.

32. The method of preparing a semiconductor alloy as defined in claim **31**, further comprising the steps of placing the alloyed powders in a graphite die container.

33. The method of preparing a semiconductor alloy as defined in claim **31**, further comprising the step of retaining the container in the isothermal furnace for at least 30 minutes at a temperature not higher than 630° C. to form the alloyed powders.

34. The method of preparing a semiconductor alloy as defined in claim **33** further comprising to steps of:

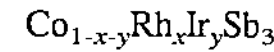
placing the alloyed powders in an isothermal furnace having a press;

applying pressure to the powders with the press for at least 30 minutes to form polycrystalline pellets; and

maintaining the isothermal furnace at a temperature of at least 650° C.

35. The method of preparing a semiconductor alloy as defined in claim **31**, further comprising the step of forming the mixture with the formula $IrSb_3$.

36. The method of preparing a semiconductor alloy as defined in claim **31** further comprising the step of forming the mixture with the formula:



$Co_{1-x-y}Rh_xIr_ySb_3$

wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$.

37. A method of preparing a semiconductor alloy for use in fabricating thermoelectric elements from an approximately stoichiometric mixture comprising the steps of:

placing elemental powders selected from the group consisting of Ir, Rh, Co, and Sb in a container to form the mixture;

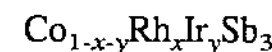
placing the container with the mixture into an isothermal furnace having a press; and

applying pressure to the mixture with the press for at least 30 minutes while maintaining the temperature of the isothermal furnace at a temperature of at least 600° C. to form polycrystalline pellets having a skutterudite-type crystal lattice structure from the mixture.

38. The method of preparing a semiconductor alloy as defined in claim **37** further comprising the steps of placing the mixture in a graphite die container.

39. The method of preparing a semiconductor alloy as defined in claim **37**, further comprising the step of forming the mixture with the formula $IrSb_3$.

40. The method of preparing a semiconductor alloy as defined in claim **39** further comprising the step of forming the mixture with the formula:



$Co_{1-x-y}Rh_xIr_ySb_3$

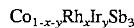
wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$.

41. A radioisotope thermoelectric generator having a general purpose heat source and a cooling assembly with a thermoelectric device disposed therebetween comprising:

a plurality of thermoelectric elements formed from at least two different types of semiconductor materials comprising:

a portion of the thermoelectric elements formed from a P-type semiconductor material having a skutterudite-type crystal lattice structure; and

the P-type semiconductor material having the formula:



$Co_{1-x-y}Rh_xIr_ySb_3$

wherein $0 \leqq x \leqq 1$ and $0 \leqq y \leqq 1$.

42. The radioisotope thermoelectric generator as defined in claim **41** further comprising another portion of the thermoelectric elements formed from an N-type semiconductor material selected from the group consisting of alloys of Bi-Sb alloys, Bi_2Te_3 based alloys, PbTe based alloys, β-$FeSi_2$ based alloys, $Ga_{1-x}In_xSb$ based alloys, and SiGe alloys.

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