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(10) **Pub. No.: US 2005/0161072 A1**(43) **Pub. Date: Jul. 28, 2005**(54) **THERMOELECTRIC DEVICE HAVING AN ENERGY STORAGE DEVICE LOCATED BETWEEN ITS HOT AND COLD SIDES****Publication Classification**(51) **Int. Cl.⁷** **H01L 37/00**; H01L 35/00;
H01L 35/30; H01L 35/28(52) **U.S. Cl.** **136/205**; 136/212; 136/211(76) Inventors: **Brian Esser**, Colchester, VT (US);
Dryver R. Huston, S. Burlington, VT (US); **James O. Plumpton**, Burlington, VT (US)(57) **ABSTRACT**

A thermoelectric device (100, 342) that includes at least one thermoelectric couple (118, 304) that contains a thermoelectric junction (156) between two dissimilar materials (P, N) that allow exploitation of either the Seebeck effect or Peltier effect of the junction. The thermoelectric couple includes two thermoelements (120, 124, 324, 326) that extend between the hot side (104) and cold side (108) of the device. Each thermoelement has a thermally insulating region (128, 132) that insulates the hot side from the cold side and an electrical energy storage device (136, 138, 308, 310) that stores electrical energy. When operating in a Seebeck mode, each storage device may be periodically discharged by harvesting circuitry (200, 300) so as to harvest the energy stored therein. When operating in a Peltier mode, each storage device may be periodically charged by charging circuitry (900, 1000) so as to induce a temperature change at the thermoelectric junction.

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Related U.S. Application Data

(60) Provisional application No. 60/460,067, filed on Apr. 3, 2003.

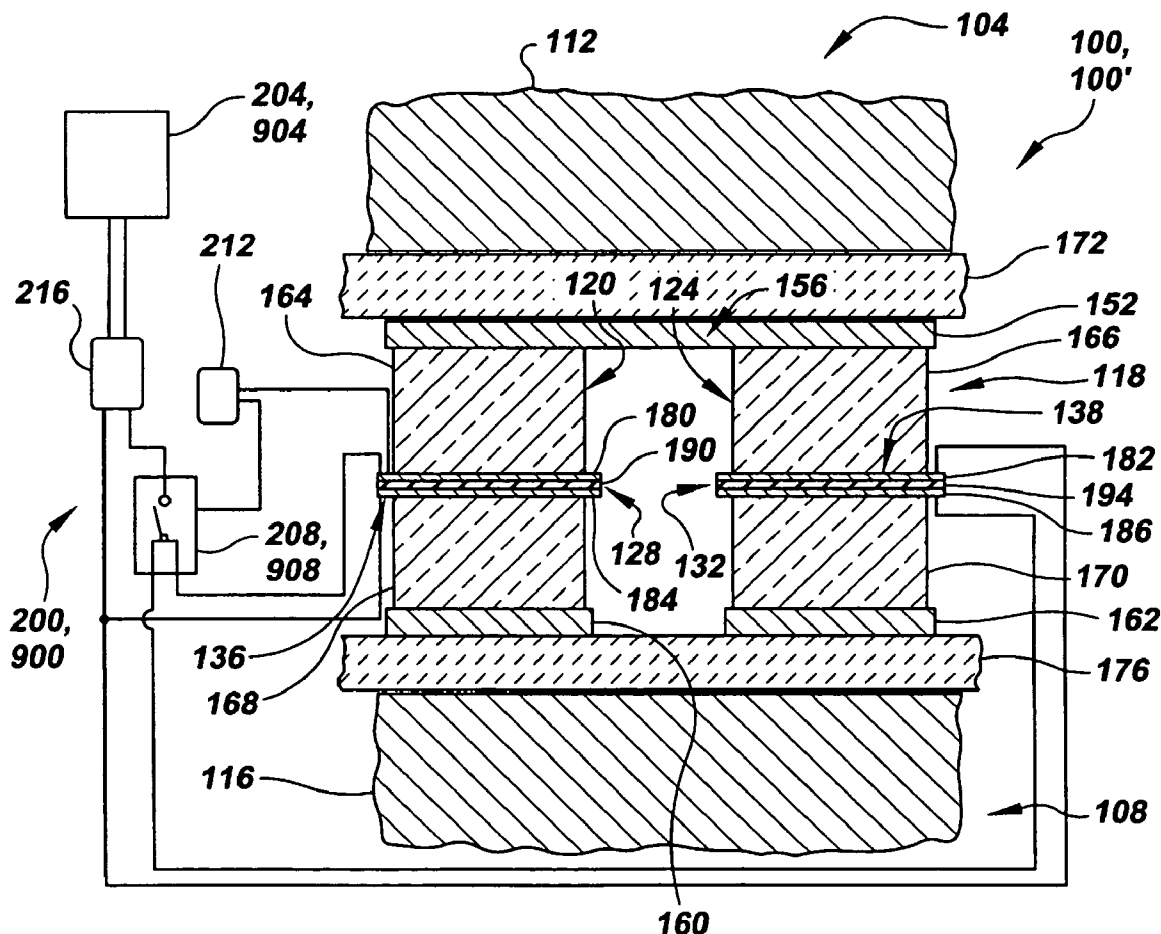


FIG. 1
(PRIOR ART)

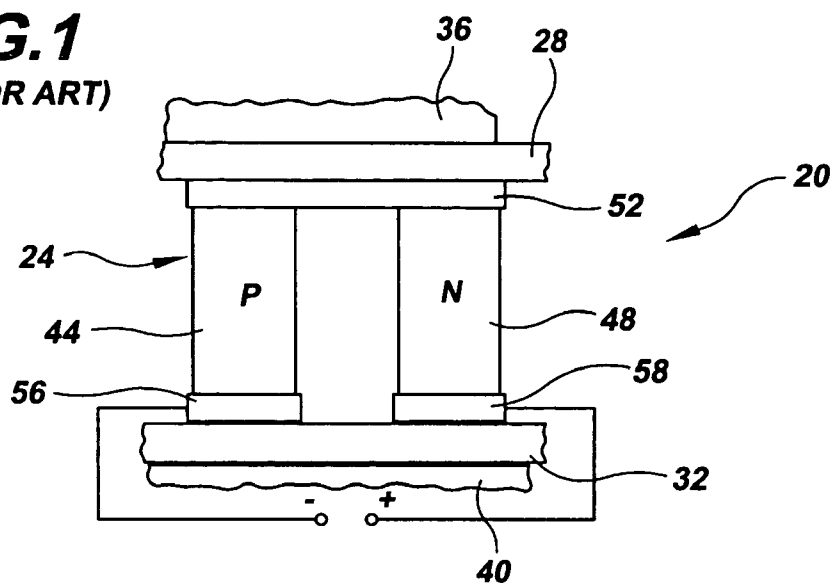


FIG.2A

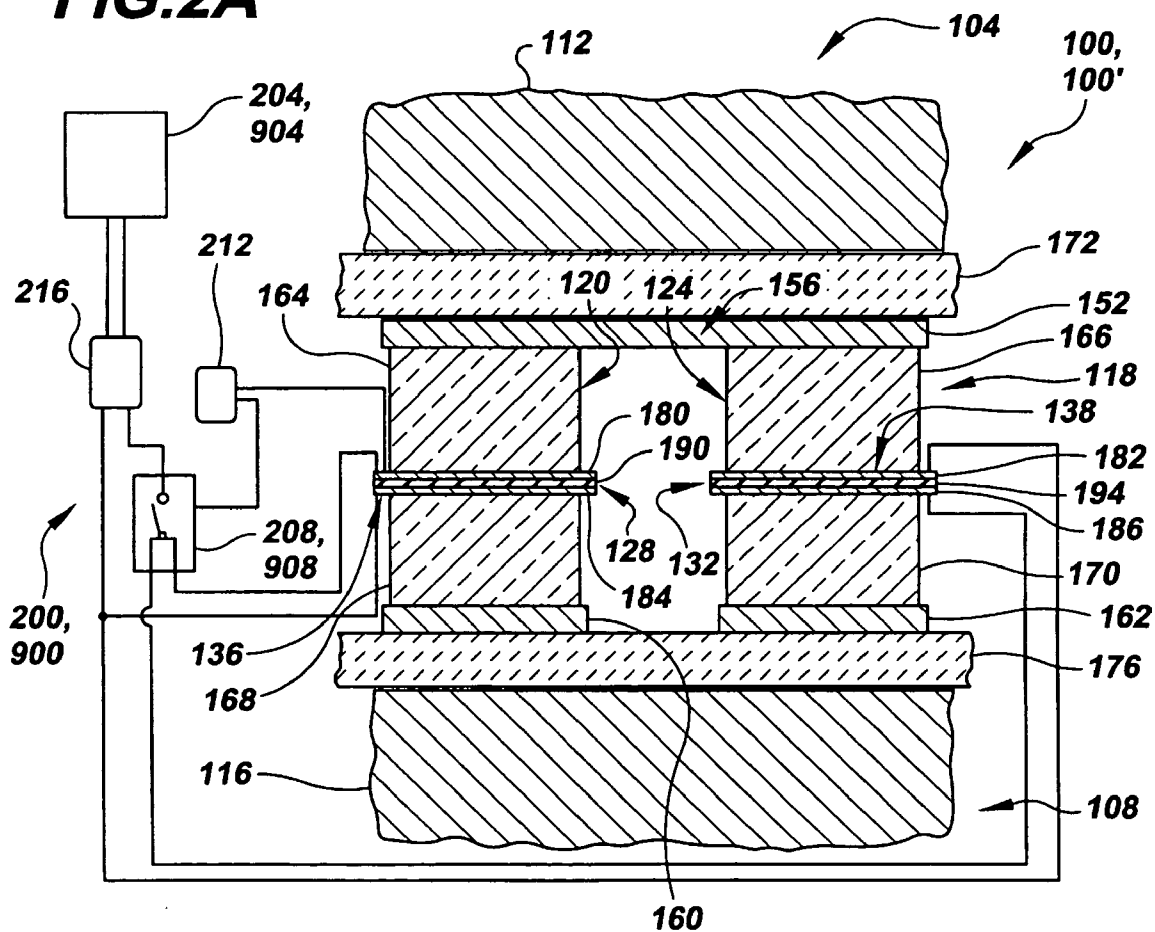


FIG. 2B

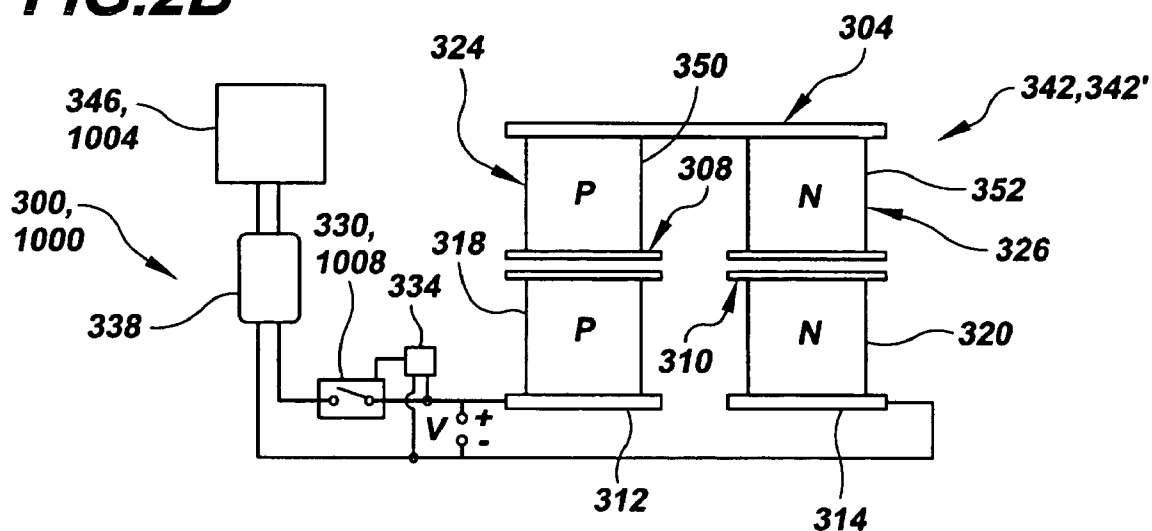


FIG. 3A

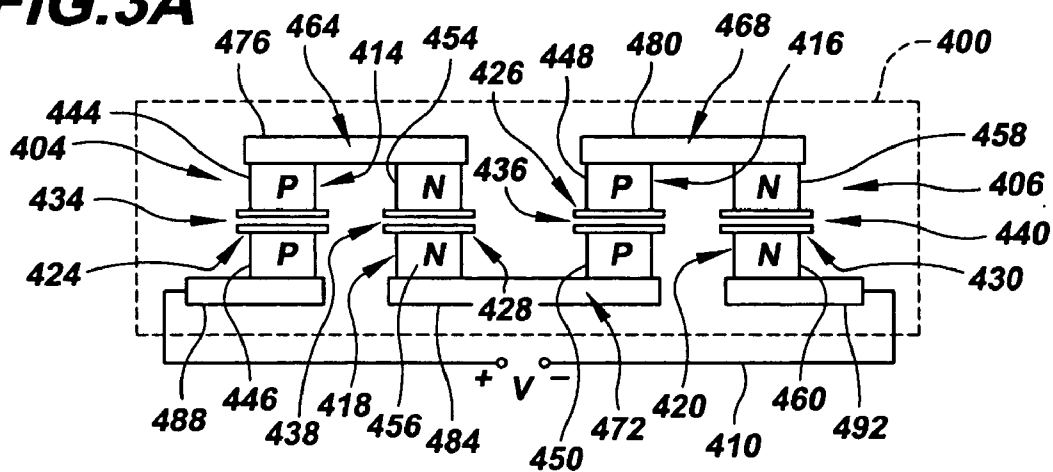


FIG. 3B

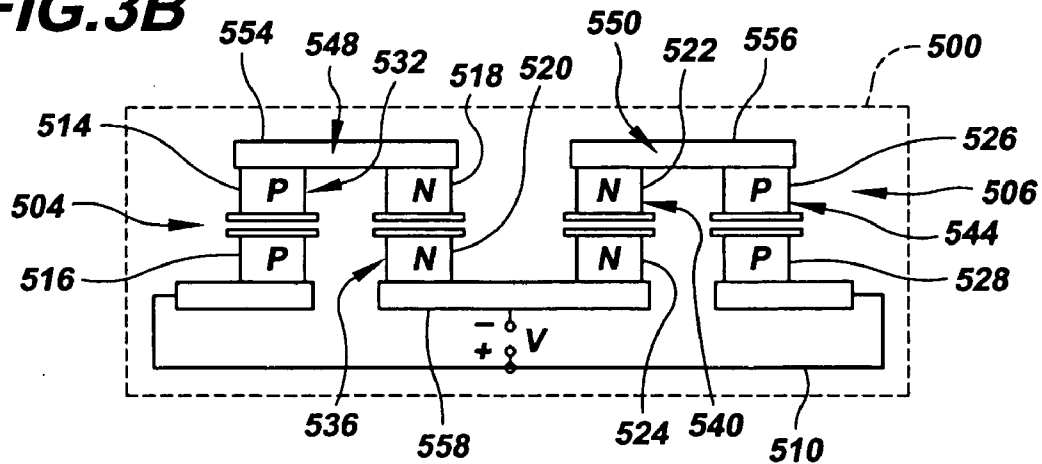


FIG. 4

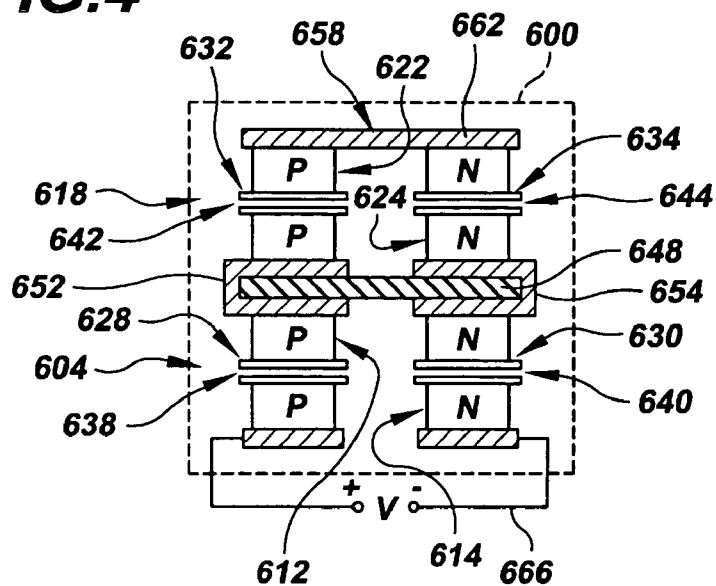


FIG. 5A

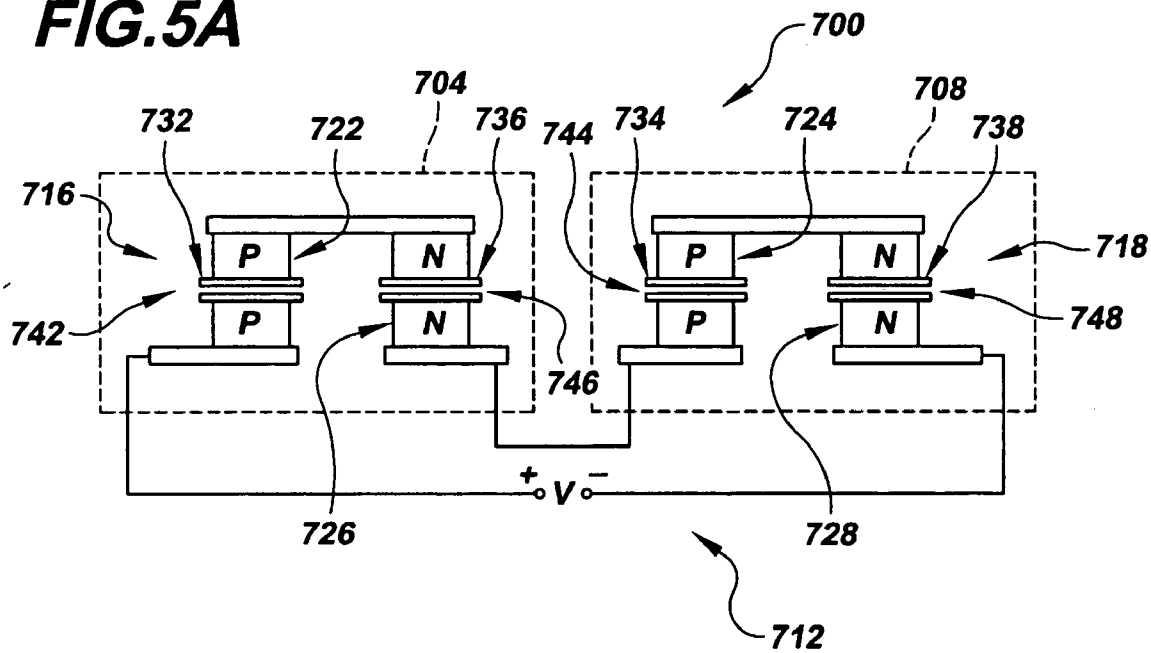
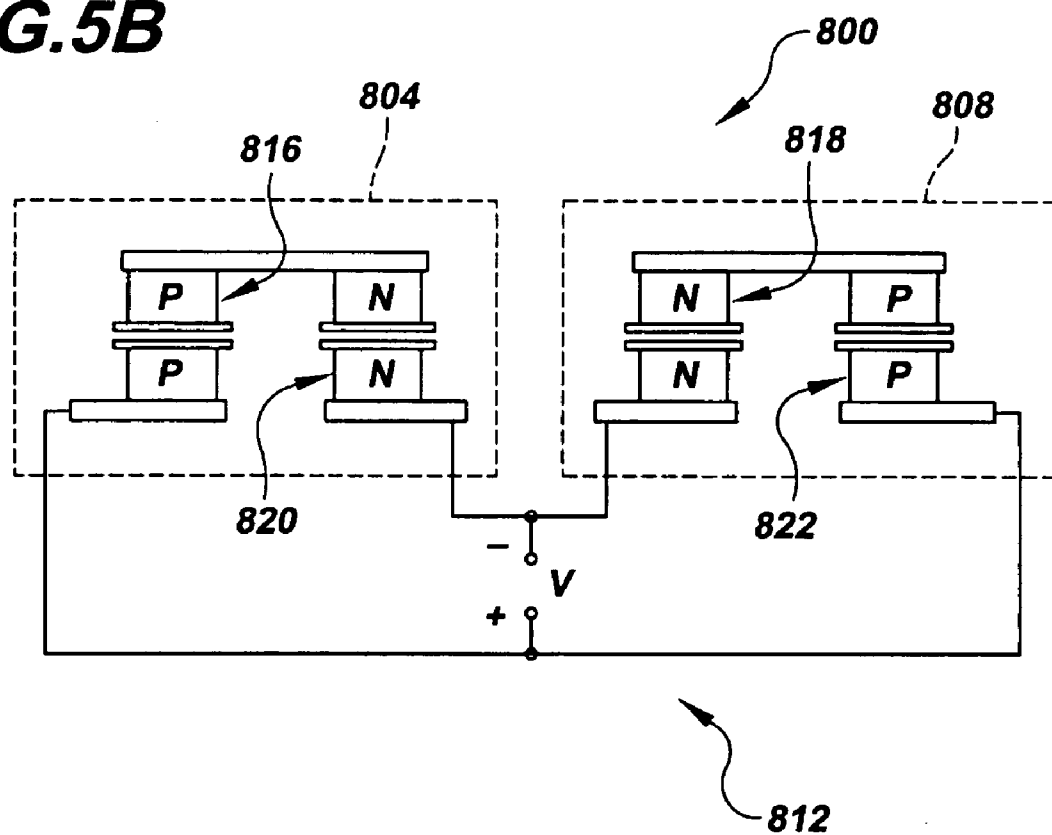


FIG. 5B



THERMOELECTRIC DEVICE HAVING AN ENERGY STORAGE DEVICE LOCATED BETWEEN ITS HOT AND COLD SIDES

RELATED APPLICATION DATA

[0001] This application claims the benefit of U.S. Provisional Patent Application Ser. No. 60/460,067, "Thermoelectric Device Having A Capacitor/Insulator Located Between Its Hot And Cold Sides," filed Apr. 4, 2003, which is incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates generally to the field of thermoelectric devices. More particularly, the present invention is directed to a thermoelectric device having an energy storage device located between its hot and cold sides.

BACKGROUND OF THE INVENTION

[0003] FIG. 1 illustrates a conventional thermoelectric device 20 that includes a thermoelectric couple 24 thermally coupled between a hot-side thermal interface member 28 and a cold-side thermal interface member 32. During use, hot-side thermal interface member 28 thermally communicates with a region or structure, e.g., a heat source 36, having a first temperature, and cold-side thermal interface member 32 thermally communicates with a region or structure, e.g., a heat sink 40, having a second temperature lower than the first temperature. Thermoelectric couple 24 includes a first thermoelement 44 and a second thermoelement 48. Often, but not necessarily, one of thermoelements 44, 48 is made of a p-type semiconductor material and the other is made of an n-type semiconductor material. Accordingly, first and second thermoelements 44, 48 are labeled, respectively, "P" and "N" as a matter of convenience for denoting that the two thermoelements are made of different materials. First and second thermoelements 44, 48 are typically electrically coupled to one another at one end by a tie contact 52 and include contacts 56, 58 at their respective other ends. Contacts 56, 58 are typically also tie contacts that electrically connect each of first and second thermoelements 44, 48 to corresponding adjacent thermoelements (not shown). Typical thermoelectric devices often comprise tens, hundreds or more thermoelectric couples.

[0004] Thermoelectric devices, such as thermoelectric device 20 of FIG. 1, operate via two general phenomena: the Seebeck effect and the Peltier effect. The Seebeck effect is where a voltage is observed when two dissimilar materials, e.g., the dissimilar materials (P and N) of first and second thermoelements 44, 48, are coupled electrically in series and thermally in parallel, and are subjected to a thermal gradient across the thermoelements. This voltage is proportional to the temperature gradient across device 20 and a property of each material known as the Seebeck coefficient.

[0005] The Peltier effect is a second, complementary effect in which a temperature difference is observed at the interface of two dissimilar thermoelectric materials, e.g., the two dissimilar materials (P and N) of second and first thermoelements 44, 48, when an electric current passes through a circuit comprising the thermoelements. Generally, the Seebeck effect is exploited to generate power from thermal gradients, and the complementary Peltier effect is exploited for cooling or heating applications, given a power source.

[0006] As a thermal engine, the performance of a thermoelectric device, such as thermoelectric device 20, is limited by the thermodynamic Carnot efficiency ($\eta_c = [T_{\text{Hot}} - T_{\text{Cold}}] / T_{\text{Hot}}$). Presently available solid-state thermoelectric devices operate at only a fraction of the potential Carnot efficiency, with overall efficiencies ranging from 3-15%. Efficiencies of this order make it exceedingly difficult for thermoelectric devices to compete with traditional methods of heating, refrigeration and power generation. The most significant contributor to such poor efficiencies is the conduction of heat through thermoelements 44, 48 from the hot to the cold side.

[0007] There are two modes by which heat conduction through thermoelements 44, 48 causes a reduction in the overall thermodynamic efficiency of thermoelectric device. The first mode concerns the distribution of heat throughout thermoelements 44, 48. In the case of power generation, heat is the energy source that thermoelectric couple 24 converts into electrical energy. Therefore, any heat conducted away from heat source 36 and distributed throughout thermoelements 44, 48 is energy that potentially could have been converted into electrical energy.

[0008] The second and more significant mode resulting in reduced efficiency due to heat conduction is the compromise of the temperature differential between hot side member 28 and cold side member 32 of thermoelectric device 20. According to the Seebeck effect, the voltage across a thermoelectric couple is directly proportional to the temperature gradient. Ideally, the temperatures of hot and cold side members 28, 32 would always remain constant, i.e., both temperatures would be unaffected by heat transfer through thermoelements 44, 48. Unfortunately, this is not realistic and heat transfer through thermoelements 44, 48 can greatly affect the temperature of either or both of hot and cold side members 28, 32. Thus, if the temperature of cold side member 32 increases due to heat conduction, the temperature gradient between hot side member 28 and the cold side member will decrease, resulting in a smaller voltage and less power generated. In one aspect, the present invention seeks to significantly increase thermoelectric device efficiencies by greatly reducing heat transfer through the thermoelements.

[0009] The present inventors are presently aware of only two known technologies in the context of thermoelectric devices that attempt to insulate against thermal conduction. The first technology utilizes thermionic emission using semiconductor thermal diodes and a complex microstructure. These materials are difficult and expensive to manufacture. There are several patents on this technology, including U.S. Pat. No. 6,396,191 to Hagelstein, et al. entitled "Thermal Diode for Energy Conversion." The second technology uses thermotunneling of electrons through a very thin (i.e., nanometer scale) barrier. There are several patents on this technology, including U.S. Pat. No. 6,495,843 to Tavkelidze entitled "Method for Increasing Emission through a Potential Barrier."

SUMMARY OF THE INVENTION

[0010] In one aspect, the present invention is directed to a thermoelectric device comprising a hot side when the thermoelectric device is operating. A cold side is spaced from the hot side when the thermoelectric device is operating. A first thermoelement has a first end in thermal communication

with the hot side and a second end in thermal communication with the cold side. The first thermoelement comprises at least one electrically conducting portion and an electrical energy storage device electrically connected in series with the at least one conducting portion between the hot side and the cold side.

[0011] In another aspect, the present invention is directed to a method of transferring heat from a hot side comprising the step of placing a thermoelectric couple so that a side of the thermoelectric couple is in thermal communication with the hot side, the thermoelectric couple comprising at least one electrical energy storage device. The at least one electrical energy storage device is then periodically charged so as to cause heat to flow from the hot side via the Peltier effect.

[0012] In a further aspect, the present invention is directed to a method of powering an electrical device comprising the step of placing a thermoelectric couple so that a first side of the thermoelectric couple is in thermal communication with a hot side and so that a second side of the thermoelectric couple is in thermal communication with a cold side, the thermoelectric couple comprising at least one electrical energy storage device. Electrical energy stored as a result of the Seebeck effect is then periodically harvested from the at least one electrical energy storage device so as to power the electrical device. The harvested electrical energy is provided to the electrical device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] For the purpose of illustrating the invention, the drawings show forms of the invention that are presently preferred. However, it should be understood that the present invention is not limited to the precise arrangements and instrumentalities shown in the drawings, wherein:

[0014] **FIG. 1** is a partial elevational view/partial schematic diagram of a prior art thermoelectric device;

[0015] **FIG. 2A** is a partial cross-sectional view/partial schematic diagram of a thermoelectric device of the present invention; **FIG. 2B** is a partial elevational view/partial schematic diagram of the thermoelectric couple of **FIG. 2A** and alternative harvesting circuitry;

[0016] **FIG. 3A** is partial elevational view/partial high-level schematic diagram of a thermoelectric module of the present invention that includes a plurality of thermoelements electrically connected in series with one another; **FIG. 3B** is a partial elevational view/partial high-level schematic diagram of a thermoelectric module of the present invention that includes a plurality of thermoelements electrically connected in parallel with one another;

[0017] **FIG. 4** is a partial cross-sectional view/partial high-level schematic diagram of a thermoelectric module of the present invention that includes a plurality of stages of thermoelements electrically connected in series with one another;

[0018] **FIG. 5A** is a partial cross-sectional view/partial high-level schematic diagram of a system of the present invention comprising a plurality of thermoelectric modules electrically connected in series with one another; and **FIG. 5B** is a partial cross-sectional view/partial high-level schematic diagram of a system of the present invention com-

prising a plurality of thermoelectric modules electrically connected in parallel with one another.

DETAILED DESCRIPTION OF THE DRAWINGS

[0019] Referring again to the drawings, **FIG. 2A** shows in accordance with the present invention a thermoelectric device, which is generally denoted by the numeral **100**. When operating, thermoelectric device **100** may be said to have a hot side **104** and a cold side **108**. It is noted that the terms “hot side” and “cold side” are conventional terms used to describe thermoelectric devices and components thereof. These terms simply indicate that two portions of the thermoelectric device under consideration, e.g., thermoelectric device **100**, are at temperatures different from one another.

[0020] It is noted that the use of the words “hot” and “cold,” which typically indicate temperature magnitudes, do not necessarily indicate or imply any temperature magnitude of corresponding hot or cold side **104**, **108**, only that the temperatures of the two sides are not equal, i.e., one side is at a higher temperature than the other. This convention is used throughout this disclosure, including the claims. Further, it is noted that the conditional language “when operating” used above acknowledges the fact that when a thermoelectric device is used for cooling (or heating), the cold side may actually be hotter than the hot side of the device and the hot side may be cooler than the cold side. However, once the thermoelectric device is operating to provide cooling (or heating), the Peltier effect will result in heat being removed from the “cold side” and heat being added to the “hot side.”

[0021] In general, thermoelectric device **100** is similar to conventional thermoelectric devices, e.g., thermoelectric device **20** of **FIG. 1**, in the respect that it may be used in substantially the same manner as a conventional thermoelectric device, e.g., as a means for generating electrical energy via a temperature gradient between a heat source **112** and a heat sink **116**, as a means for cooling a hot region or heat source or as a means for heating a cold region or heat sink. However, thermoelectric device **100** of the present invention differs from conventional thermoelectric devices in several important respects. As discussed in the background section above, typical conventional thermoelectric devices have thermoelements, e.g., thermoelements **44**, **48** of **FIG. 1**, that conduct electrical current uninterrupted from the hot side to the cold side of the device, or vice versa. Consequently, conventional thermoelements also conduct heat uninterrupted from the hot side to the cold side. As discussed above, this conducted heat can reduce the efficiency of the thermoelectric device.

[0022] In contrast to typical conventional thermoelectric devices, thermoelectric device **100** of the present invention generally comprises at least one thermoelectric couple **118** having first and second thermoelements **120**, **124** that each include a thermally insulating region **128**, **132** that substantially impedes the flow of heat through the thermoelements from hot side **104** to cold side **108**. Since conventional good thermal insulators are typically good electrical insulators, placing a good thermal insulator in each thermally insulating region **128**, **132** would typically severely impede the flow of electrons through thermoelements **120**, **124** effectively rendering thermoelectric device **100** unusable for its intended application. This is so because a current must flow within

thermoelectric couple **118** in order for thermoelectric device **100** to display the Seebeck or Peltier effect.

[0023] To alleviate the detrimental effects of placing a good thermal insulator in thermally insulating region **128, 132** of each thermoelement **120, 124**, the present inventors have found it highly effective to provide at least one of the thermoelements, and preferably both, with an electrical energy storage device **136, 138**, such as a capacitor or battery. It is noted that the term “capacitor” as used herein and in the claims includes so-called “pseudo-capacitors,” such as ultracapacitors (a/k/a supercapacitors). Certain types of capacitors are particularly suitable for use in thermoelectric device **100** due to their designs that may include dielectrics that are good thermal insulators. Such dielectrics can thus function as thermally insulating region **128, 132** of each thermoelement **120, 124**. With the generalities of thermoelectric device **100** of the present invention having been described above, further details and features of the device are provided below.

[0024] Referring still to **FIG. 2A**, first thermoelement **120** and a second thermoelement **124**, when electrically coupled with one another in series as shown, form thermoelectric couple **118** in a manner similar to the manner described in the background section relative to conventional thermoelectric device **20** of **FIG. 1**. Thermoelectric couple **118** may include a tie contact **152** that electrically connects first thermoelement **120** in series to second thermoelement **124** at one end of the couple. Tie contact **152** may comprise any suitable electrically and thermally conductive material, such as high temperature solder, among others. When tie contact **152** is provided, a thermoelectric junction **156** between first and second thermoelements **120, 124** necessary for the Seebeck or Peltier effects to occur is essentially present across the tie contact. However, in alternative embodiments, thermoelectric junction **156** between first and second thermoelements **120, 124** may be created by the direct interfacing, e.g., direct contact, of the two thermoelements with one another. At the opposite end of thermocouple **118**, one or more additional contacts **160, 162** may be provided, e.g., to electrically tie each of thermoelements **120, 124** to an adjacent thermoelement (not shown) other than the other one of thermoelements and/or to provide contacts for various circuitry as discussed below.

[0025] In addition to an energy storage device (**136, 138**) and a thermally insulating region (**128, 132**) as discussed above, each thermoelement **120, 124** may also include one or more conducting portions. For example, each thermoelement **120, 124** may have a first conducting portion **164, 166** in thermal and electrical communication with hot side **104** of thermoelectric device **100** and a second conducting portion **168, 170** in thermal and electrical communication with cold side **108**. In the embodiment shown, first conducting portions **164, 166** of first and second thermoelements **120, 124** are made of materials having Seebeck coefficients different from one another. Generally, with all other variables being equal, the larger the difference between the Seebeck coefficients of the two materials, the greater the electrical energy that can be obtained from thermoelectric device **100**. Materials suitable for first regions **164, 166** include all materials used for conventional thermoelements, including p-type and n-type semiconductor materials. A popular example of a base semiconductor material that may be used for the p- and

n-type materials is bismuth telluride. As those skilled in the art will appreciate, however, other materials may certainly be used.

[0026] Second conducting portion **168, 170** of each first and second thermoelements **120, 124** may be made of the same material as the material of first conducting portion **164, 166** of that thermoelement. That is, second conducting portion **168** of first thermoelement **120** may be made of the same material as first conducting portion **164** and second conducting portion **170** of second thermoelement **124** may be made of the same material as first conducting portion **166**. In alternative embodiments, the materials of second conducting portions **168, 170** of first and second thermoelements **120, 124** may be different from the materials in corresponding first conducting portions **164, 166**. For example, if first conducting portion **164** is made of an n-type semiconductor material and first conducting portion **166** is made of a p-type semiconductor material, second conducting portions **168, 170** may be made of, respectively, the p-type and n-type semiconductor materials used in first semiconducting portions **166, 164**, respectively, or, alternatively, other materials having suitable Seebeck coefficients.

[0027] Although not shown, if an additional thermoelement were provided immediately adjacent each thermoelement **120, 124**, each of these additional thermoelements would typically be connected in series to the corresponding thermoelement via the corresponding one of contact **160, 162**. In this case, the conducting portion **168** of the additional thermoelement **120** in electrical and thermal communication with second conducting portion **168** of first thermoelement **120** would typically be made of a material different from the material of the second conducting portion so that the difference between the Seebeck coefficients of the two materials would be suitable for the intended application. Likewise, the conducting portion of the additional thermoelement in electrical and thermal communication with second conducting portion **170** of second thermoelement **124** would typically be made of a material different from the material of second conducting portion **170** so that the difference between the Seebeck coefficients of these two materials would also be suitable for the intended application.

[0028] Still referring to **FIG. 2A**, thermoelectric device **100** may include a hot-side thermal interface member **172** in thermal communication with thermoelectric couple **118**, e.g., via tie contact **152**, if this tie contact is provided. Hot-side thermal interface member **172** may be made of a material having good or high thermal conductivity and may be adapted for engaging heat source **112**, a heat sink or a region having a temperature suitable for thermoelectric device **100** to operate as desired. Similarly, thermoelectric device **100** may also include a cold-side thermal interface member **176** in thermal communication with thermocouple **118**, e.g., via contacts **160, 162**, if these contacts are provided. Like hot-side thermal interface member **172**, cold-side thermal interface member **176** may be made of a material having good or high thermal conductivity and may be adapted for engaging heat sink **116**, a heat source or a region having a temperature suitable for thermoelectric device **100** to operate as desired. In alternative embodiments, thermal interface members **172, 176** may not be part of thermoelectric device **100**, but rather may be part of a device or structure, e.g., heat source **112** or heat sink **116**, with which the thermoelectric device is used. In yet other

alternative embodiments, one, the other or both of monolithic thermal interface members **172**, **176** may be replaced by multi-member structures, as desired. Hot- and cold-side thermal interface members **172**, **176** are typically, but not necessarily, dielectric and may be made of any suitable material, such as various ceramics or composite materials, among others.

[0029] As mentioned above, each electrical energy storage device **136**, **138** may be a capacitor, battery or other device. Such a capacitor, battery or other device may be of any conventional design. For convenience, **FIG. 2A** shows each storage device **136**, **138** as being a simple flat-plate capacitor comprising a first flat-plate charge condenser **180**, **182** (or collector) and a second flat-plate charge condenser **184**, **186** spaced apart by a dielectric layer **190**, **194**. First charge condensers **180**, **182** are electrically coupled, respectively, to first conductive portions **164**, **166** of first and second thermoelements **120**, **124**, and second charge condensers **184**, **186** are electrically coupled, respectively, to second conductive portions **168**, **170** of the thermoelements. Each dielectric layer **190**, **194** may comprise any suitable dielectric that provides the necessary electrical insulation that allows the capacitor to function. Examples of suitable dielectrics include air, vacuum and various polymers, among a host of other materials. Since dielectric layers **190**, **194** will typically also function as thermally insulating regions **128**, **132**, it is desirable to select a dielectric having a good or high thermal insulating value. Of course, other capacitor arrangements can be used, such as thin film arrangements, wherein each of first and second charge condensing plates **180**, **182**, **184**, **186** and dielectric layers **190**, **194** would essentially be replaced by multiple thin metal layers interleaved with thin dielectric layers. As those skilled in the art will appreciate, capacitors and other storage devices suitable for use as electrical energy storage devices are well known in the art and, thus, do not need to be exhaustively listed nor explained in any great detail in order to understand how to make and use thermoelectric device **100** of the present invention.

[0030] In addition, when energy storage devices **136**, **138** are capacitors, those skilled in the art will readily understand how to select the proper capacitance of these devices. Since the required capacitance is generally a function of the number, electrical arrangement and materials of thermoelements **120**, **124**, as well as operating temperatures and nature of the use of thermoelectric device **100**, it is impractical to provide exact specifications for designing the capacitors. However, once a designer has determined these and other parameters, the designer can determine the required capacitance based on elementary circuit design principles, certainly without undue experimentation. Those skilled in the art would likewise be able to design storage devices other than capacitors without undue experimentation using ordinary, well-known design principles.

[0031] When capacitors are provided for electrical energy storage devices **136**, **138** and a temperature gradient exists between hot and cold sides **104**, **108**, dielectric layers **190**, **194** between charge condensing plates **180**, **184**, **182**, **186** of each capacitor will, of course, also substantially impede the transport of electrons through thermoelements **120**, **124** from hot side **104** to cold side **108**, or vice versa. However, the migration of electrons through the thermoelements **120**, **124** that cause the Seebeck voltage will produce an electric potential across the capacitors. Thus, by discharging storage

devices **136**, **138**, e.g., periodically, electrical energy stored in these devices may be harvested by harvesting circuitry **200** for use in powering an electrical device **204**, such as a spacecraft, remote sensor modules or weather stations, to name just a few of many. As those skilled in the art will readily appreciate, the variety of electrical devices **204** that may be powered using thermoelectric device **100** of the present invention is large. Accordingly, it is not practical, nor necessary, to include an exhaustive list of all such devices for those skilled in the art to appreciate the broad applicability of the present invention.

[0032] That said, for the sake of providing at least one example, thermoelectric device **100** may be used to power instrumentation, i.e., device **204**, or charge one or more batteries aboard a space satellite or space craft (not shown). In this example, heat source **112** may be a radiant heat collector that collects heat from the sun and heat sink **116** may be a radiator located, e.g., in the shadow of thermoelectric device **100** or other structure. This arrangement would cause a thermal gradient across thermoelectric device **100** that would charge electrical energy storage devices **136**, **138**. Harvesting circuitry **200** would then transfer this energy to electrical device **204** so as to provide electrical power to the device.

[0033] In one embodiment, harvesting circuitry **200** may be electrically coupled directly to electrical energy storage devices **136**, **138** and include one or more switches **208** that alternately open and close to permit the storage devices to become charged by the Seebeck effect and then discharge to the harvesting circuitry. Each switch **208** may be any conventional switching device, including a transistor-based device. Each switch may be controlled by one or more switch controllers **212** that, e.g., sense the charge state of one or more electrical energy storage devices **136**, **138** and actuate each switch when the controller(s) determine(s) that the storage devices are suitably charged. Such determination may be accomplished using a high-impedance comparator (not shown), among other devices.

[0034] Harvesting circuitry **200** may optionally include signal conditioning circuitry **216** for adjusting the magnitudes of the voltage and current flowing through switch **208** and/or smoothing the periodic waveform that results from the periodic operation of the switch. It is noted that many arrangements of harvesting circuitry **200** are possible, some due to the electrical arrangement of the one or more thermoelectric couples **118** within thermoelectric device **100**. For example, thermoelectric device **100** may include a plurality of groupings of thermoelectric couples **118** electrically isolated from one another so that electrical energy storage devices **136**, **138** within each group may be discharged at different times from one another to produce a smoother waveform. Harvesting circuitry **200** could readily be configured for implementing this scheme. With an understanding of the underlying principles of thermoelements **120**, **124** of the present invention discussed above, those skilled in the art will readily appreciate that the variety of configurations of harvesting circuitry **200** is large and that it is not practical, nor necessary, to include an exhaustive list of all possible configurations for those skilled in the art to appreciate the broad applicability of the present invention. Moreover, those skilled in the art can design functional energy harvesting circuitry **200** using elementary circuit design principles.

[0035] Alternative electrical energy harvesting circuitry **300** is shown in **FIG. 2B** relative to a thermoelectric couple **304** that is essentially the same as thermoelectric couple **118** of **FIG. 2A**. Rather than harvesting electrical energy directly from electrical energy storage devices **308, 310**, harvesting circuitry **300** of **FIG. 2B** harvests energy via contacts **312, 314** through second portions **318, 320** of thermoelements **324, 326**. Like harvesting circuitry **200** of **FIG. 2A**, harvesting circuitry **300** of **FIG. 2B** may include various components for facilitating the harvesting, including, but not limited to, one or more switches **330**, switch controllers **334** and signal conditioning circuitry **338**. Also similar to harvesting circuitry **200** of **FIG. 2A**, depending upon the desired level of integration, none, some or all of energy harvesting circuitry **300** may be packaged aboard thermoelectric device **342**. If all of harvesting circuitry **300** is not placed aboard thermoelectric device **342**, the components not aboard the thermoelectric device may be integrated into an electrical device **346** and/or an interface device electrically coupled between the thermoelectric device and the electrical device.

[0036] As mentioned above, although non-semiconductor materials may be used for first and second conducting portions **350, 352, 318, 320** of first and second thermoelements **324, 326**, p- and n-type semiconductor materials are often used. Accordingly, first and second portions **350, 352, 318, 320** of first and second thermoelements **324, 326** are as a matter of convenience labeled with either a "P" or an "N" that corresponds to the type of material of which that portion may be made. However, since the materials for first and second portions **350, 352, 318, 320** of first and second thermoelements **324, 326** may be materials other than p- and n-type semiconductor materials, the designations "P" and "N" may also be interpreted as simply representing two different materials. In addition, although first and second portions **350, 318** of first thermoelement **324** are labeled "P" so as to indicate a first material, e.g., a p-type semiconductor material, and first and second portions **352, 320** of second thermoelement **326** are labeled "N" so as to indicate a second, different material, e.g., an n-type semiconductor material, the materials may be reversed, i.e., the "P" and "N" materials swapped for one another. This would cause the polarities across the two sides of harvesting circuitry **300** to reverse.

[0037] Thermoelectric couples, such as thermoelectric couples **118, 304** are typically, but not necessarily, used in various numbers to construct thermoelectric modules. **FIGS. 3A, 3B**, and **4** illustrate some exemplary arrangements of thermoelectric couples that may be used in thermoelectric modules of the present invention, and **FIGS. 5A and 5B** illustrate some exemplary arrangements of thermoelectric modules with one another.

[0038] **FIG. 3A** shows a thermoelectric module **400** having a plurality of thermoelectric couples **404, 406** configured for being electrically connected in series with one another, as shown. This series connection is primarily represented in harvesting circuitry **410**. It is noted that two thermoelectric couples **404, 406** are shown for convenience, however, there could be one or many more thermocouples as desired to suit a particular design. Similar to harvesting circuitries **200, 300** discussed in connection with **FIGS. 2A and 2B**, harvesting circuitry **410** may be fully or partially located outside module **400** or fully contained within the module. As shown,

at least a portion of harvesting circuitry **410** is outside of module **400**. Although not shown, harvesting circuitry **410** may include other components, such as one or more switches, switch controllers and signal conditioning circuitry, among others, also as discussed above in connection with **FIGS. 2A and 2B**. Module **400** may also include other elements, such as hot and cold side thermally conducting members (not shown), similar to thermoelectric device **100** of **FIG. 2A**.

[0039] Each thermoelectric couple **404, 406** may include first and second thermoelements **414, 416, 418, 420**, each containing an electrical energy storage device **424, 426, 428, 430** and a thermally insulating region **434, 436, 438, 440**, both in manners similar to or the same as discussed above relative to **FIG. 2A**. To create the series circuit through thermoelectric couples **404, 406**, each conductive portion **444, 446, 448, 450** of first thermoelements **414, 416** may be of one material type, denoted "P," and each conductive portion **454, 456, 458, 460** of second thermoelements **418, 420** may be of a different materials type, denoted "N." This series configuration forms three thermoelectric junctions **464, 468, 472** across the corresponding tie contacts **476, 480, 484** that electrically connect a "P" designated conducting portion **444, 446, 448, 450** to an "N" designated conducting portion **454, 456, 458, 460**. Tie contacts **476, 480, 484** and circuitry contacts **488, 492** may be made of any suitable conducting material.

[0040] **FIG. 3B** shows a thermoelectric module **500** similar to thermoelectric module **400** of **FIG. 3A**, but has the following differences. (Again, only two thermoelectric couples are shown for convenience.) First, thermoelectric couples **504, 506** are electrically connected in parallel with one another, as indicated primarily by harvesting circuitry **510**. This parallel nature of thermoelectric couples **504, 506** results in a different arrangement of materials for first and second conducting portions **514, 516, 518, 520, 522, 524, 526, 528** of the thermoelements **532, 536, 540, 544**. In this case, thermoelectric junctions **548, 550** are present across each of tie contacts **554, 556**, while tie contact **558** provides a contact between the like (N) materials of second conducting portions **520, 524** of adjacent thermoelements **536, 540**. The second difference is that harvesting circuitry **510** is contained entirely within thermoelectric module **500**. Like thermoelectric module **400** of **FIG. 3A**, harvesting circuitry **510** and other components of module **500** may be as described above in connection with **FIGS. 2A and 2B**.

[0041] **FIG. 4** shows a two-stage thermoelectric module **600** of the present invention that includes a first level, or stage **604**, of thermoelements **612, 614** and a second stage **618** of thermoelements **622, 624** electrically connected in series with the thermoelements of the first stage. Each thermoelement **612, 614, 622, 624** may include an electrical energy storage device **628, 630, 632, 634** and a thermally insulating region **638, 640, 642, 644** in manners described above relative to **FIG. 2A**. An electrically non-conductive, but thermally conductive layer **648** may be placed between first and second stages **604, 618**. If thermally conductive layer **648** is provided, it may be in thermal communication with a heat source or heat sink (not shown) in a manner similar to the hot or cold side thermal interface members (not shown, but similar to thermal interface members **172, 176** of **FIG. 2A**), as desired to suit a particular design. In addition, if electrically non-conductive layer **648** is pro-

vided, first thermoelements **612, 622** of first and second stages **604, 618** and second thermoelements **614, 624** of the first and second stages may be electrically connected to one another via tie contacts **652, 654**. A thermoelectric junction **658** is formed across tie contact **662**. Of course each of first and second stages **604, 618** may be made up of many more thermoelements, if desired. In addition, more than two stages **604, 618** may be provided. At least a portion of harvesting circuitry **666** may be provided outside module **600**, if desired. Harvesting circuitry **666** and other components (not shown) of thermoelectric module **600** may be similar to such components of thermoelectric device **100** of FIG. 2A.

[0042] FIG. 5A illustrates a system **700** containing an electrical coupling of two thermoelectric modules **704, 708** of the present invention in series with one another via harvesting circuitry **712**. Although FIG. 5A shows each module **704, 708** as comprising one thermoelectric couple **716, 718** for convenience, those skilled in the art will readily appreciate that each module may include any number of thermoelectric couples desired. Each thermoelectric couple **716, 718** include respective first and second thermoelements **722, 724, 726, 728**, each of which may include an energy storage device **732, 734, 736, 738** and a thermally insulating region **742, 744, 746, 748** as discussed above relative to FIG. 2A. Of course, each module **704, 708** may include other components (not shown), e.g., hot and cold side thermally conductive members, in a manner similar to thermoelectric device **100** of FIG. 2A. Likewise, harvesting circuitry **712** of FIG. 5A may include other components (not shown), e.g., one or more switches, switch controllers and signal conditioning circuitry, similar to harvesting circuitry **200** of FIG. 2A.

[0043] FIG. 5B shows a system **800** similar to system **700** of FIG. 5A, except that modules **804, 808** of FIG. 5B are electrically connected in parallel with one another via harvesting circuitry **812**. Note the differences in materials between thermoelements **816, 818, 820, 822** of FIG. 5B and corresponding (by location) thermoelements **722, 724, 726, 728** of FIG. 5A necessary to implement parallel electrical connectivity rather than series electrical connectivity.

[0044] Although the present invention has largely been described above with respect to the Seebeck effect, those skilled in the art will readily appreciate that the complementary Peltier effect may also be exploited. Relative to FIGS. 2A and 2B, harvesting circuitries **200, 300** and electrical devices **204, 346** would be replaced, respectively, by charging circuitries **900, 1000** and electrical energy sources **904, 1004**, such as batteries or other electrical power supplies. Like harvesting circuitries **200, 300**, each set of charging circuitry **900, 1000** may include one or more switches **908, 1008** that alternately open and close to periodically allow corresponding electrical energy storage devices **136, 138, 308, 310** to periodically discharge and charge. When the respective storage devices **136, 138, 308, 310** discharge, depending upon the direction of current through the thermoelectric junctions of thermocouples **118, 304**, the Peltier effect will cause heat to be adsorbed on the cold side (**104**) and heat to be generated on the hot side (**108**). Like energy harvesting circuitries **200, 300**, those skilled in the art will understand how to design charging circuitries **900, 1000** for virtually any configuration of thermoelectric devices using well-known circuit design

principles. Also similar to energy harvesting circuitries **200, 300**, none, some or all of charging circuitries **900, 1000** may be packaged aboard thermoelectric devices **100', 342'**, with any components not provided aboard the thermoelectric devices integrated into electrical energy sources **904, 1004** and/or an interface device (not shown), as desired. Harvesting circuitries **410, 510, 666, 712, 812** of FIGS. 3A, 3B, 4, 5A and 5B, respectively, may similarly be replaced with suitable charging circuitry in order to exploit the Peltier effect of device **342** and modules **400, 500, 600, 704, 708, 804, 808** rather than the Seebeck effect.

[0045] The present invention appears to be the first application of reducing heat transfer from source to sink using energy storage devices in series with the thermoelements of various thermoelectric devices. The expected reduction in heat transfer between the hot and cold sides of a thermoelectric device of the present invention has the potential to drastically increase the efficiencies of these devices, potentially leading to more widespread use of thermoelectric devices.

[0046] Although the invention has been described and illustrated with respect to exemplary embodiments thereof, it should be understood by those skilled in the art that the foregoing and various other changes, omissions and additions may be made therein and thereto, without parting from the spirit and scope of the present invention.

What is claimed is:

1. A thermoelectric device, comprising:

- a) a hot side when the thermoelectric device is operating;
- b) a cold side spaced from said hot side when the thermoelectric device is operating; and
- c) a first thermoelement having a first end in thermal communication with said hot side and a second end in thermal communication with said cold side, said first thermoelement comprising:
 - i) at least one electrically conducting portion; and
 - ii) an electrical energy storage device electrically connected in series with said at least one conducting portion between said hot side and said cold side.

2. A thermoelectric device according to claim 1, wherein said thermoelement further comprises a thermally insulating region configured to impede a flow of heat from said hot side to said cold side via said thermoelement.

3. A thermoelectric device according to claim 2, wherein said electrical energy storage device comprises a capacitor and said thermally insulating region is contained in said capacitor.

4. A thermoelectric device according to claim 3, wherein said capacitor comprises a first charge condenser and a second charge condenser spaced from said first charge condenser by a dielectric contained in said thermally insulating region.

5. A thermoelectric device according to claim 4, wherein said capacitor is a parallel plate capacitor.

6. A thermoelectric device according to claim 1, wherein said thermoelement comprises a first electrically conducting portion in thermal communication with said hot side and a second electrically conducting portion in thermal communication with said cold side, said electrical energy storage

device electrically connected in series between said first and second electrically conducting portions.

7. A thermoelectric device according to claim 6, wherein said electrical energy storage device comprises a capacitor and said thermally insulating region is contained in said capacitor.

8. A thermoelectric device according to claim 7, wherein said capacitor comprises a first charge condenser spaced from a second charged condenser by a dielectric contained in said thermally insulating portion.

9. A thermoelectric device according to claim 8, wherein said capacitor is a parallel plate capacitor.

10. A thermoelectric device according to claim 1, further comprising a second thermal element that includes at least one electrically conducting portion and an electrical energy storage device electrically connected in series with said at least one conducting portion between said hot side and said cold side, wherein said at least one electrically conducting portion of said first thermoelement comprises a first material and said at least one electrically conducting portion of said second thermoelement comprises a second material different from said first material.

11. A thermoelectric device according to claim 10, wherein said first material comprises an n-type semiconductor and said second material comprises a p-type semiconductor.

12. A thermoelectric device according to claim 10, further comprising harvesting circuitry operatively configured to periodically harvest electrical energy stored in said electrical energy storage device of each of said first and second thermoelements.

13. A thermoelectric device according to claim 10, further comprising charging circuitry operatively configured to periodically charge said electrical storage device of each of said first and second thermoelements.

14. A thermoelectric device according to claim 1, further comprising harvesting circuitry operatively configured to periodically harvest electrical energy stored in said electrical energy storage device of said first thermoelement.

15. A thermoelectric device according to claim 1, further comprising charging circuitry operatively configured to periodically charge said electrical storage device of said first thermoelement.

16. A thermoelectric module, comprising:

- a) a hot side when the thermoelectric module is operating;
- b) a cold side spaced from said hot side when the thermoelectric module is operating;
- c) a first thermal interface member located on said hot side;
- d) a second thermal interface member located on said cold side;
- e) a plurality of thermoelectric couples extending between said first thermal interface member and said second thermal interface member, each of said thermoelectric couples comprising:
 - i) a first thermoelement comprising:
 - A) at least one electrically conducting portion made of a first material; and
 - B) a first electrical energy storage device electrically connected in series with said at least one conduct-

ing portion of said first thermoelement between said hot side and said cold side; and

ii) a second thermoelement comprising:

- A) at least one electrically conducting portion made of a second material; and
- B) a second electrical energy storage device electrically connected in series with said at least one conducting portion of said second thermoelement between said hot side and said cold side.

17. A thermoelectric module according to claim 16, wherein said plurality of thermoelectric couples are electrically connected in series with one another.

18. A thermoelectric module according to claim 16, wherein said plurality of thermoelectric couples are electrically connected in parallel to one another.

19. A thermoelectric module according to claim 16, wherein said first material comprises a p-type semiconductor and said second material comprises an n-type semiconductor.

20. A thermoelectric module according to claim 16, wherein each of said first thermoelements further includes a first thermally insulating region configured to impede flow of heat from said hot side to said cold side via said first thermoelement and each of said second thermoelements includes a second thermally insulating region configured to impede flow of heat from said hot side to said cold side via said second thermoelement.

21. A thermoelectric module according to claim 20, wherein each of said first electrical energy storage devices comprises a first capacitor and said first thermally insulating region is contained in said first capacitor and each of said second electrical energy storage devices comprises a second capacitor and said second thermally insulating region is contained in said second capacitor.

22. A thermoelectric module according to claim 21, wherein each of said first and second capacitors includes a first charge condenser and a second charge condenser spaced from said first charge condenser by a dielectric layer contained in the respective ones of said first and second thermally insulating regions.

23. A thermoelectric module according to claim 22, wherein each of said first and second capacitors is a parallel plate capacitor.

24. A thermoelectric module according to claim 16, further comprising harvesting circuitry operatively configured to periodically harvest electrical energy stored in said first and second electrical energy storage devices of said plurality of thermoelement couples.

25. A thermoelectric module according to claim 16, further comprising charging circuitry operatively configured to periodically charge said first and second electrical storage devices of said plurality of thermoelement couples.

26. A thermoelectric module according to claim 16, wherein each of said first thermoelements comprises a first hot-side electrically conducting portion in thermal communication with said first thermal interface member and a first cold-side electrically conducting portion in thermal communication with said second thermal interface member and each of said second thermoelements comprises a second hot-side electrically conducting portion in thermal communication with said first thermal interface member and a second cold-side electrically conducting portion in thermal communication with said second thermal interface member,

each of said first electrical energy storage devices electrically connected in series between corresponding ones of said first hot-side and cold-side electrically conducting portions and each of said second electrical energy storage devices electrically connected in series between corresponding ones of said second hot-side and cold-side electrically conducting portions.

27. A thermoelectric device, comprising:

- a) a hot side when the thermoelectric device is operating;
- b) a cold side spaced from said hot side when the thermoelectric device is operating; and
- c) a first thermoelement having a first end in thermal communication with said hot side and a second end in thermal communication with said cold side, said first thermoelement comprising:
 - i) a first means for storing electrical energy; and
 - ii) a second means for thermally insulating said hot side from said cold side.

28. A thermoelectric device according to claim 27, wherein said first means comprises a capacitor and said second means comprises a dielectric layer within said capacitor.

29. A method of transferring heat from a hot side, comprising the steps of:

- a) placing a thermoelectric couple so that a side of said thermoelectric couple is in thermal communication with the hot side; said thermoelectric couple comprising at least one electrical energy storage device; and
- b) periodically charging said at least one electrical energy storage device so as to cause heat to flow from the hot side via the Peltier effect.

30. A method according to claim 29, wherein said thermoelectric couple comprises at least two electrical energy storage devices and step b) includes periodically charging said at least two electrical energy storage devices so as to cause heat to flow from the hot region via the Peltier effect.

31. A method of powering an electrical device, comprising the steps of:

- a) placing a thermoelectric couple so that a first side of said thermoelectric couple is in thermal communication with a hot side and so that a second side of said thermoelectric couple is in thermal communication with a cold side; said thermoelectric couple comprising at least one electrical energy storage device;
- b) periodically harvesting electrical energy from said at least one electrical energy storage device stored as a result of at least one thermal energy conversion effect so as to power the electrical device; and
- c) providing said harvested electrical energy to the electrical device.

32. A method according to claim 31, wherein the thermoelectric couple comprises at least two electrical energy storage devices and step b) includes periodically harvesting electrical energy from said at least two electrical energy storage devices stored as a result of the at least one thermal energy conversion effect so as to power the electrical device.

33. A thermoelectric device, comprising:

at least one thermoelectric couple that includes:

- a) a hot side when the thermoelectric device is operating;
- b) a cold side spaced from said hot side when the thermoelectric device is operating; and
- c) a first thermoelement having a first end in thermal communication with said hot side and a second end in thermal communication with said cold side, said first thermoelement comprising:
 - i) at least one electrically conducting portion; and
 - ii) a thermally insulating region connected in series with said at least one conducting portion between said hot side and said cold side.

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