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(54) **THERMOELECTRIC POWER SOURCE UTILIZING AMBIENT ENERGY HARVESTING FOR REMOTE SENSING AND TRANSMITTING**

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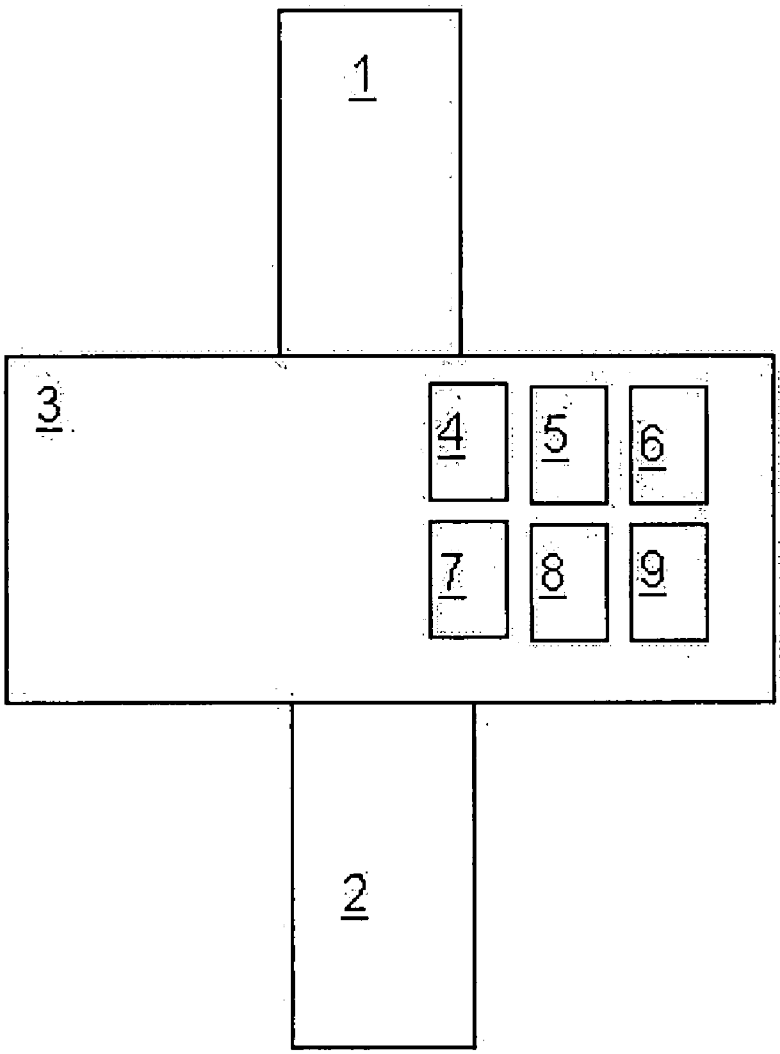
(57) **ABSTRACT**

A method and apparatus for providing electrical energy to an electrical device wherein the electrical energy is originally generated from temperature differences in an environment having a first and a second temperature region. A thermoelectric device having a first side and a second side wherein the first side is in communication with a means for transmitting ambient thermal energy collected or rejected in the first temperature region and the second side is in communication with the second temperature region thereby producing a temperature gradient across the thermoelectric device and in turn generating an electrical current.



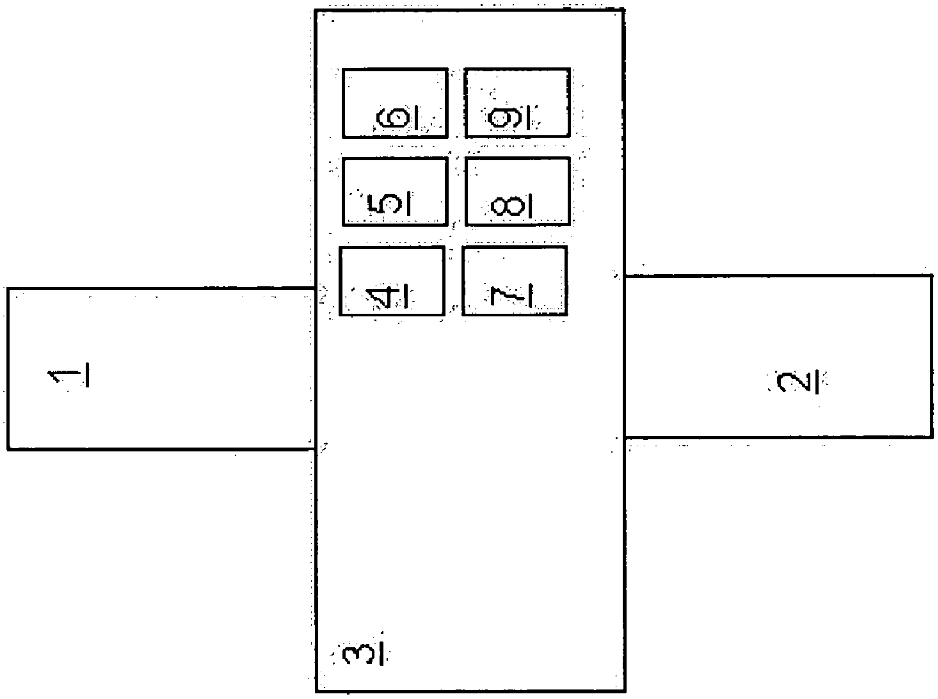


Figure 1

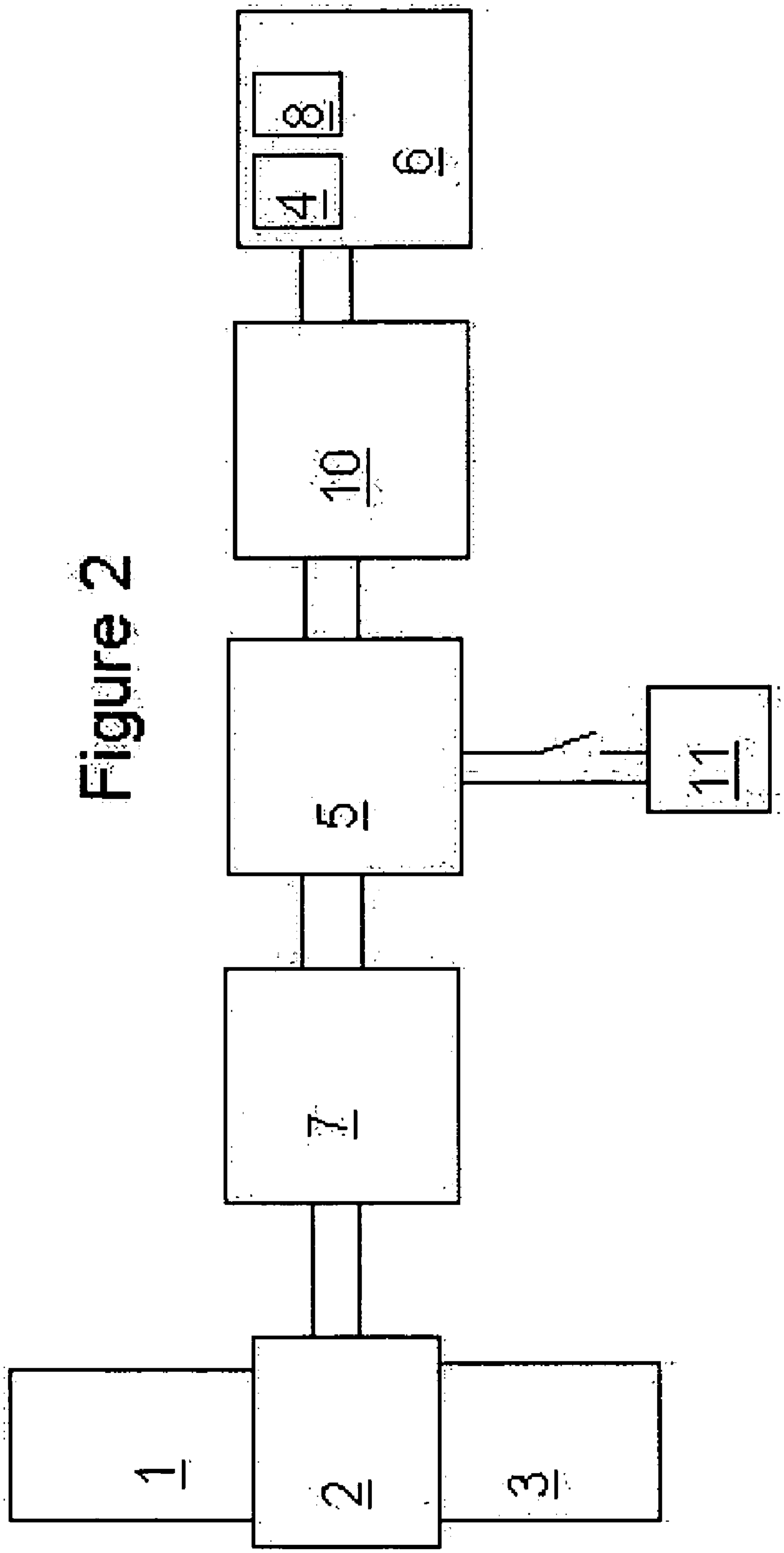


Figure 2

Figure 3

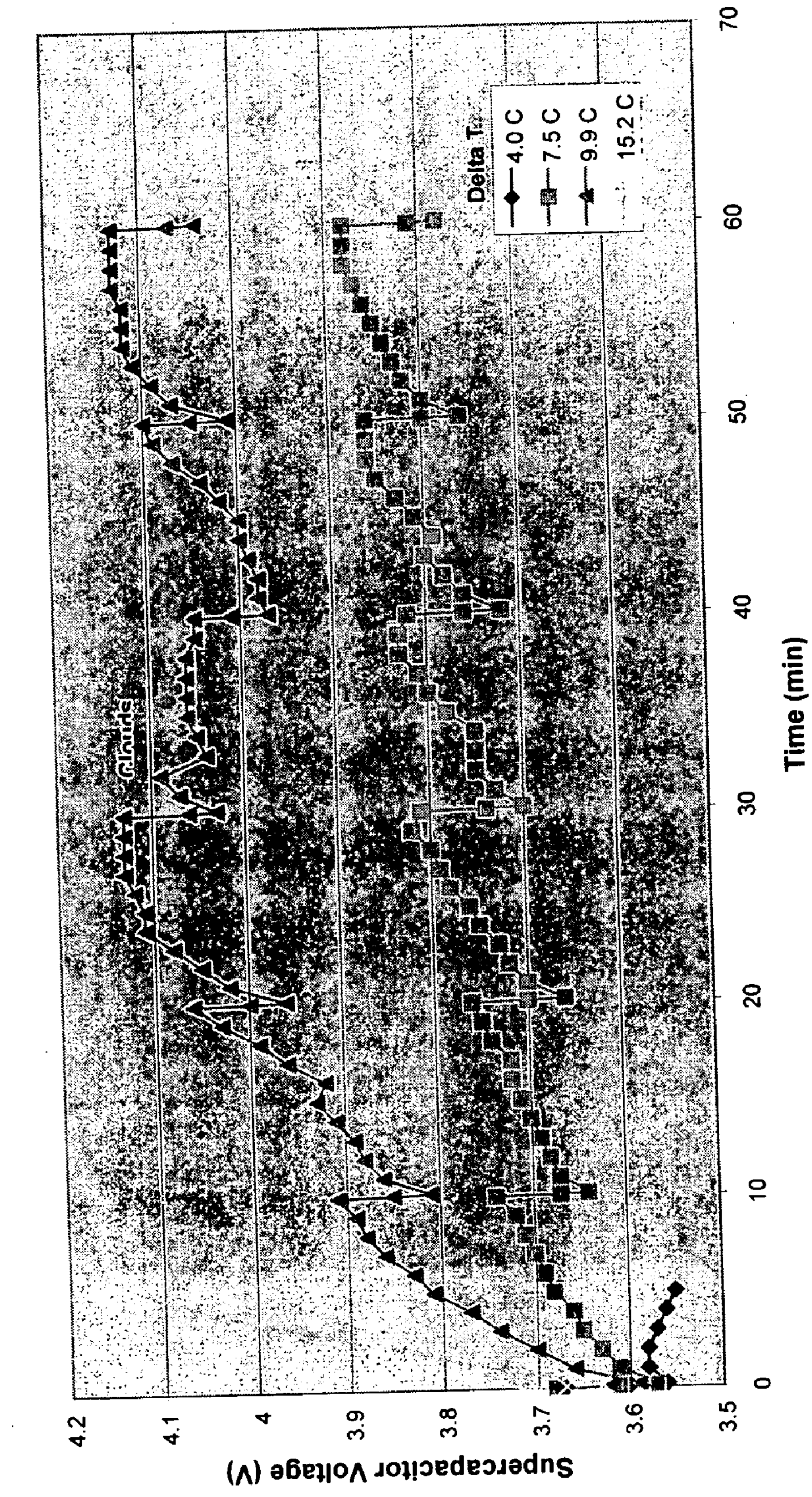
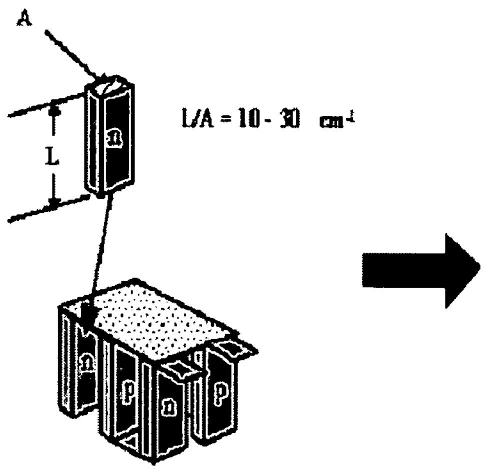
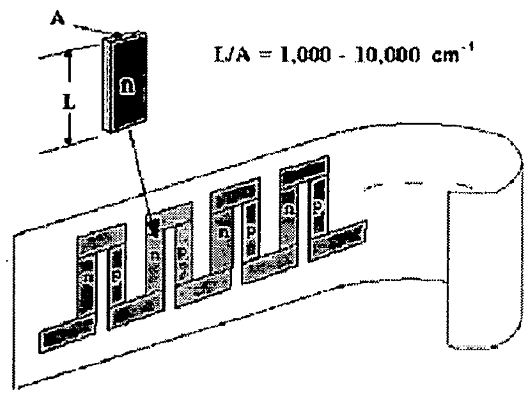

Supercapacitor Voltage (V)
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
Time (min)
0
10
20
30
40
50
60
70
Clouds
Delta T
4.0 C
7.5 C
9.9 C
15.2 C

Figure 4



TE Module With Discreet Elements



Thin-Film TE Array

THERMOELECTRIC POWER SOURCE UTILIZING AMBIENT ENERGY HARVESTING FOR REMOTE SENSING AND TRANSMITTING

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0001] This invention was made with Government support under Contract DE-AC0676RLO1830 awarded by the U.S. Department of Energy. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

[0002] Advances in electronics have created a variety of devices having heretofore unanticipated capabilities and requirements. In many circumstances, these devices present capabilities and requirements that are particularly useful in remote or inaccessible locations where the electrical power necessary to operate the devices is not readily available. For example, remote sensors, such as might be used to measure temperature, pressure, humidity, the presence or movement of vehicles, humans and animals, or other environmental attributes, can easily be configured to acquire and transmit such data to a more accessible location. Several options are available for providing power to such devices, such as batteries and solar cells, however, each of these approaches has drawbacks.

[0003] While battery technology has advanced tremendously in recent years, any device that draws electrical energy resulting from a chemical reaction has a useful life limited by the duration of the chemical reaction. Thus, remote applications relying exclusively on batteries are inherently limited by the battery life and reliability. Environmental factors can hinder the useful life of solar energy sources used in remote locations as well. Excessive cloud cover and shifting weather patterns can make solar cells unreliable. Dust and debris deposited on the surface of solar devices by rain or other weather related effects together with normal aging can also degrade the regular operation of these devices. Due to the drawbacks associated with these and other power technologies, there remains a need for reliable power sources that can operate over long time periods in remote locations.

[0004] Different constraints apply in non-remote settings. For example, in large buildings, tens of thousands of sensors could be usefully employed to provide smart sensing and control of energy delivery and distribution, as well as sensing and reporting of environmental conditions. At present, this vision is impractical because conventional power solutions are either technically inadequate or too expensive. Fitting every sensor with a battery power supply involves the above noted performance limitations of batteries in addition to the high cost of initial installation and periodic replacement. The alternative of hard wiring a large number of sensors to a central supply would improve reliability, but would necessarily involve complex circuitry and cost that make this approach economically unviable. These deficiencies of conventional solutions are overcome by integral, long-lived power sources that produce electric power by harvesting and converting ambient energy in the manner provided by this invention.

[0005] One potential source of energy for such devices theoretically may be found in the differing temperatures that occur naturally in these remote, non-remote and less accessible locations, since it is known that thermoelectric devices can generate electric power in response to the existence of a temperature differential across the thermoelectric device. However, the distances across typical thermo electric devices are typically small, that heretofore none have been successfully configured to take advantage of the temperature variation between, for example, the ground below and the air above it.

BRIEF SUMMARY OF THE INVENTION

[0006] Accordingly, it is an object of the present invention to provide methods and apparatus for providing reliable power for long periods of time. These and other objects of the present invention are accomplished by taking advantage of temperature differences existing in the environment, and providing devices and techniques to convert these differences in temperature into electrical energy. The present invention in particular relies on the use of techniques and devices to harvest ambient energy in the environment, thereby focusing and concentrating temperature differences that exist in natural and man made environments. Thus, while the present invention is most advantageous in remote and less accessible locations, the concept and operation of the present invention is equally applicable in any environment having at least two regions of different temperature.

[0007] Accordingly, the present invention is a method and apparatus for providing electrical energy to an electrical device wherein the electrical energy is originally generated from temperature differences in an environment having a first and a second temperature region. The first and second temperature regions may, for example, be adjacent features of the natural environment that exhibit a pervasive difference of temperature, such as the ground and the air above the ground or the air inside and outside of heating, air-conditioning or ventilation ducts in buildings. While large temperature differences assist in the generation of electrical energy in a thermoelectric device, one of the several advantages of the present invention is that it allows for the generation of electrical energy in environments having very slight temperature differences. Accordingly, while not meant to be limiting, it is preferred that the temperature difference between said first temperature region and said second temperature region be between 0.5° F. and 100° F., and it is more preferred that the temperature differential between said first temperature region and said second temperature region be between 0.5° F. and 50° F. It should be noted that the present invention is useful beyond the preferred temperature ranges and at all intermediate temperature ranges. It should further be noted that the present invention is operable in applications wherein the relative temperatures of the first and second regions are reversed on occasion, as is the case, for example when soil is the first temperature region and air is the second temperature region, and the two are in a climate wherein the soil tends to be cooler than the air in the summer time, and hotter than the air in the winter time, or vise versa.

[0008] As shown in **FIG. 1**, the present invention in one embodiment is thus an apparatus for generating electrical energy from an environment having a first temperature region and a second temperature region comprising a thermoelectric device **1** having a first side and a second side wherein the first side is in communication with a means **2** for transmitting ambient thermal energy collected or rejected in the first temperature region and the second side is in communication with the second temperature region thereby producing a temperature gradient across the thermoelectric device and in turn generating an electrical current. Preferably, in addition to the first means **2** for transmitting ambient thermal energy on the first side of the apparatus, the apparatus further utilizes a second means **3** for transmitting ambient energy collected or rejected in said second temperature region and in communication with the second side of the thermoelectric device. While not meant to be limiting, an example of a means for transmitting ambient energy would include a heat pipe. However, as used herein, the terms "transmitting energy" and/or "transmitting ambient energy" should be understood to include, either alone or in combination, collecting ambient energy, focusing ambient energy, or transferring ambient energy, (wherein transferring ambient energy could be performed by convection, conduction, radiation, and combinations thereof), and the means for "transmitting energy" or "transmitting ambient energy" should be understood to included any of the wide variety of devices known to those having skill in the art that are capable of collecting ambient energy, focusing ambient energy, or transferring ambient energy, either alone or in combination, and wherein transferring ambient energy is performed by convection, conduction, radiation, and combinations thereof. As examples of these heat delivery options, heat can be delivered or rejected at the thermally active surfaces of the TE element by natural convection in air or any other fluid existing on either side of a barrier, such as ductwork, in which the invention is mounted. Heat can be delivered to or removed from the TE device by the conduction and convection that occurs in a heat pipe. In this case, conduction occurs in the walls of the pipe and convection occurs in the interior working fluid contained in the heat pipe. The invention may be operated outdoors, where the primary heat input is photon radiation from the sun, and has also been demonstrated to operate in the laboratory, where the hot shoe was heated by radiation from a lamp. As is also used herein, "ambient" energy means energy available in or transmitted by media forming the environment surrounding the device and used by the present invention to generate electricity.

[0009] Whatever particular means or combination of means are selected for transmitting ambient energy, the goal remains the same; to gather enough of the energy in the surrounding environment to generate a useful amount of power in the thermoelectric device. Conceptually, a preferred embodiment of the present invention can be envisioned as a thermoelectric device that is placed at the boundary between two regions in the environment that exhibit pervasive differences in temperature. Means for transmitting the ambient energy in either of these regions to opposite sides or ends of the thermoelectric device extend into each of the respective energy regions, thereby amplifying the actual temperature difference experienced by the thermoelectric device, and exaggerating the boundary between the two energy regions.

[0010] Suitable thermoelectric devices may be constructed from: 1) metallic wire thermocouples including, but not limited to iron-constantan; copper-constantan; chromel-alumel; chromel-constantan; platinum-rhodium alloys and tungsten-rhenium alloys, 2) discrete element semiconductors assembled in alternating p- and n-type arrays connected electrically in series, parallel or series/parallel. All combinations that can be prepared as p-type semiconductors are suitable. Examples of such p-type materials that may be employed include, but are not limited to, bismuth telluride, lead telluride, tin telluride; zinc antimonide; cerium-iron antimonide; silicon-germanium. All combinations that can be prepared as n-type semiconductors are also suitable. Examples of such n-type materials that may be employed include, but are not limited to, bismuth telluride, lead telluride, cobalt antimonide; silicon-germanium.

[0011] While not meant to be limiting, preferred thermoelectric devices are composed of thin film semiconductors such as bismuth telluride sputter deposited as thin films on a substrate, as described in U.S. patent application Ser. No. ______ entitled "THERMOELECTRIC DEVICES AND APPLICATIONS FOR THE SAME" the entire contents of which are hereby incorporated herein by this reference. Other suitable thin-film devices include superlattice and quantum well structures. As shown in **FIG. 1**, the present invention is advantageously used to provide power to sensors **4**, such as but not limited to those used for remote region monitoring and surveillance, measurement of ambient conditions such as environmental temperature, pressure, humidity and intrusion in remote areas and measurement and control of building environments and energy. The present invention may further be combined with a battery, capacitor, supercapacitor and any suitable device **5** that stores energy electrically for alternately storing and discharging electrical energy produced by the thermoelectric device. The combination of the present invention with any other combination of one or more sensors **4**, transmitters **6**, voltage amplifiers **7**, micoprossessors **8**, data storage means **9**, batteries or electrical storage devices **5** and voltage regulators **10** wherein the sensor(s) **4**, batteries or storage devices **5**, voltage amplifiers **7**, micoprossessors **8**, data storage means **9**, voltage regulators **10** and transmitters **6** are all ultimately powered by the electrical energy from the thermoelectric device **2**, represents a preferred embodiment of the present invention. Once set in place, such a device is capable of gathering and transmitting data gathered by the sensor to a remote location for an essentially indefinite period of time and potentially for the lifetime of the application with no further human intervention required. The operation and advantages of the present invention are illustrated in the detailed description of a preferred embodiment that follows. However, this preferred embodiment is merely provided for such illustrative purposes, and the present invention should in no way be limited to the specific configuration described therein.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

[0012] **FIG. 1** is a schematic drawing of a preferred embodiment of the present invention.

[0013] **FIG. 2** is a block diagram of the components and circuit connections used to demonstrate the functionality and reduction of practice of this invention.

[0014] **FIG. 3** is a graph showing the electrical charging and discharging of the device used in experiments that reduced a preferred embodiment of the present invention to practice.

[0015] **FIG. 4** is a schematic drawing showing the contrast between the configuration of conventional discrete element thermoelectric elements and a thermoelectric element composed of a plethora of miniature thin-film thermocouples with high length to cross-section ratios supported by a substrate that would be used in a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[**0016**] A series of experiments were conducted to demonstrate the operation of a preferred embodiment of the present invention. The basic circuit configuration in these experiments is shown in **FIG. 2**. In this circuit, a commercial 40 mm×40 mm bismuth telluride thermoelectric element **2** supplied by MELCOR of Trenton, N.J. was attached to heat pipes **1**, **3** supplied by Beckwith Electronics of Fenton, Mo. One of the heat pipes supplied thermal energy from the warmer ambient region to the 40 mm×40 mm hot shoe side of the device. The second heat pipe **3** conducted heat from the corresponding 40 mm×40 mm cold shoe located on the opposite side of the thermoelectric element and dissipated this heat in the colder ambient region. The balance of the circuit consisted of a voltage amplifier **7**, a supercapacitor **5**, a temperature sensor **4**, a microprocessor **8** that managed data acquisition and storage, a voltage regulator **10** and a radio frequency transmitter **6**. The voltage amplifier **7** transformed the typically few tenths of a volt raw output of the thermoelectric device into as much as a 4.3 V for input into the supercapacitor **5**. The balance of the system consisting of the temperature sensor **4**, microprocessor **8**, and transmitter **6** subsystem functioned properly when a charge of more than 3.6 V was maintained on the supercapacitor **5**. This system transmitted temperature data periodically when operated in the laboratory with an electrical heat source and ambient cooling. The assembly was also operated outdoors in a natural environment. The cold side heat pipe **3** was buried in soil to provide the heat sink. The exposed hot side heat pipe **1** received ambient heat from the air above ground and also sunshine. Operating characteristics of this configuration are shown in **FIG. 3**. The figure shows that natural ambient energy successfully activated the thermoelectric element that was able to maintain a satisfactory charge on the supercapacitor when the temperature differential across the thermoelement was above 5° C. (9° F.). In this experiment, transmitter function was simulated by discharging from the supercapacitor, every 10 minutes, the same amount of energy the sensor/microprocessor/transmitter subsystem would have demanded when transmitting sensor data at 10 minute-intervals. This simulation of a transmission sequence was achieved by periodically closing the switch attached to the 10-kΩ resistive load **11** shown in **FIG. 2**. The vertical steps in the charging characteristics in **FIG. 3** show the voltage drop that results from each simulated transmission sequence. The demonstrated ability of the thermoelectric element to recharge the supercapacitor after each simulated data transmission step is evidence that the invention functions usefully when powered solely by thermal energy in the natural ambient environment of the device.

[**0017**] Commercial discrete element thermoelectric elements assembled in the conventional configuration shown in the left hand side illustration of **FIG. 4** while useful in demonstrating the principles in this invention, typically have low-voltage outputs resulting from relatively low length to cross sectional area (L/A) ratios that require a separate voltage amplifier, as described above. The preferred solution is to use thermoelectric element composed of a plethora of miniature thin-film thermocouples with high length to cross-section ratios supported by a substrate shown in the right hand side illustration in **FIG. 4** and described in greater detail in the companion U.S. patent application Ser. No. ______ entitled "THERMOELECTRIC DEVICES AND APPLICATIONS FOR THE SAME." Themocouple assemblies of the latter type may be designed with output voltages higher than those typical of the discrete element type and are inherently more compact. The advances embodied in the preferred thin-film thermocouple concept enable this invention to be more efficient and compact and to be functional in simpler and cheaper assemblies.

Closure

[**0018**] While a preferred embodiment of the present invention has been shown and described, it will be apparent to those skilled in the art that many changes and modifications may be made without departing from the invention in its broader aspects. The appended claims are therefore intended to cover all such changes and modifications as fall within the true spirit and scope of the invention.

1) A method for providing electrical energy to an electrical device in an environment having a first and a second temperature region comprising the steps of:

a. providing a means for transmitting ambient energy collected in said first temperature region,

b. providing a thermoelectric device having a first side and a second side,

c. providing said means for transmitting said ambient energy collected in said first temperature region in communication with said first side of said thermoelectric device, and

d. providing said second side of said thermoelectric device in communication with said second temperature region.

2) The method of claim 1 wherein said thermoelectric device is selected from the group consisting of metallic wire thermocouples, discrete element semiconductors, and thin film semiconductors assembled in alternating p- and n-type arrays, and combinations thereof.

3) The method of claim 2 wherein said metallic wire thermocouples are selected from the group consisting of iron-constantan; copper-constantan; chromel-alumel; chromel-constantan; platinum-rhodium alloys and tungsten-rhenium alloys, and combinations thereof.

4) The method of claim 2 wherein said discrete element semiconductors assembled in alternating p- and n-type arrays are connected electrically in series, parallel, and in combinations thereof.

5) The method of claim 4 wherein said p-type arrays are selected from the group consisting of bismuth telluride, lead telluride, tin telluride, zinc antimonide, cerium-iron antimonide, silicon-germanium, and combinations thereof.

6) The method of claim 4 wherein said n-type arrays are selected from the group consisting of bismuth telluride, lead telluride, cobalt antimonide; silicon-germanium, and combinations thereof.

7) The method of claim 2 wherein said thin film semiconductors are selected as having p-type materials fabricated of bismuth telluride, lead telluride, tin telluride, zinc antimonide, cerium-iron antimonide, silicon-germanium, and combinations thereof sputter deposited as thin films on a substrate; and n-type semiconductors fabricated of bismuth telluride, lead telluride, cobalt antimonide, silicon-germanium and combinations thereof sputter deposited as thin films on a substrate.

8) The method of claim 7 wherein said thin film semiconductors are selected as bismuth telluride sputter deposited as thin films on a substrate.

9) The method of claim 1 further comprising the steps of providing a second means for transmitting ambient energy collected in said second temperature region in communication with said second side of said thermoelectric device and in communication with said second temperature region.

10) The method of claim 1 wherein the step of transmitting ambient energy is performed by means selected from collecting ambient energy, focusing ambient energy, transferring ambient energy, and combinations thereof.

11) The method of claim 10 wherein the step of transferring ambient energy is performed by means selected from convection, conduction, radiation, and combinations thereof.

12) The method of claim 1 wherein the temperature difference between said first temperature region and said second temperature region is between 0.5° F. and 100° F.

13) The method of claim 1 wherein the temperature difference between said first temperature region and said second temperature region is between 0.5° F. and 50° F.

14) An apparatus for generating electrical energy from an environment having a first temperature region and a second temperature region comprising a thermoelectric device having a first side and a second side wherein said first side is in communication with a means for transmitting ambient thermal energy collected in said first temperature region.

15) The apparatus of claim 14 wherein said thermoelectric device is selected from the group consisting of metallic wire thermocouples and discrete element semiconductors assembled in alternating p- and n-type arrays, and combinations thereof.

16) The apparatus of claim 15 wherein said metallic wire thermocouples are selected from the group consisting of iron-constantan; copper-constantan; chromel-alumel; chromel-constantan; platinum-rhodium alloys and tungsten-rhenium alloys, and combinations thereof.

17) The apparatus of claim 15 wherein said discrete element semiconductors assembled in alternating p- and n-type arrays are connected electrically in series, parallel, and in combinations thereof.

18) The apparatus of claim 17 wherein said p-type arrays are selected from the group consisting of bismuth telluride, lead telluride, tin telluride, zinc antimonide, cerium-iron antimonide, silicon-germanium, and combinations thereof.

19) The apparatus of claim 18 wherein said n-type arrays are selected from the group consisting of bismuth telluride, lead telluride, cobalt antimonide; silicon-germanium, and combinations thereof.

20) The apparatus of claim 15 wherein said discrete element semiconductors are selected as thin film semiconductors of bismuth telluride sputter deposited as thin films on a substrate.

21) The apparatus of claim 14 further comprising a second means for transmitting ambient energy collected in said second temperature region in communication with said second side of said thermoelectric device.

22) The apparatus of claim 14 wherein the means for transmitting ambient energy is selected from an ambient energy collection means, an ambient energy focusing means, an ambient energy transmission means, and combinations thereof.

23) The apparatus of claim 22 wherein the ambient energy transferring means is selected from a convection means, a conduction means, a radiation means, and combinations thereof.

24) The apparatus of claim 14 further comprising a means for alternately storing and discharging electrical energy produced by said thermoelectric device.

25) The apparatus of claim 14 wherein said a means for alternately storing and discharging electrical energy produced by said thermoelectric device is selected from the group consisting of a battery, a capacitor, a supercapacitor, and combinations thereof.

26) The apparatus of claim 24 further comprising at least one sensor powered by electrical energy discharged from said means for alternately storing and discharging electrical energy produced by said thermoelectric device.

27) The apparatus of claim 26 further comprising at least one transmitter powered by electrical energy discharged from said means for alternately storing and discharging electrical energy produced by said thermoelectric device and capable of transmitting data gathered by said sensor.

28) The apparatus of claim 14 further comprising at least one voltage amplifiers for amplifying the voltage of electrical energy generated by said thermoelectric device.

29) The apparatus of claim 26 further comprising at least one micoprossessor capable of processing the data gathered by at least one of said sensors.

30) The apparatus of claim 26 further comprising at least one data storage means capable of storing the data gathered by at least one of said sensors.

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