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(54) **DOWNHOLE TOOL WITH THIN FILM THERMOELECTRIC COOLING**

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(57) **ABSTRACT**

Apparatus and method for cooling a die downhole are disclosed. The apparatus includes a semiconductor die. A thin film thermoelectric cooling layer is coupled to the semiconductor die, and a heat spreader is coupled to the thin film thermoelectric cooling layer. A method includes conveying a semiconductor die on a carrier to a downhole location and activating a thin film thermoelectric cooling layer coupled to the semiconductor die. The method further includes pumping heat from the thin film thermoelectric cooling layer using a heat spreader coupled to the thin film thermoelectric cooling layer.

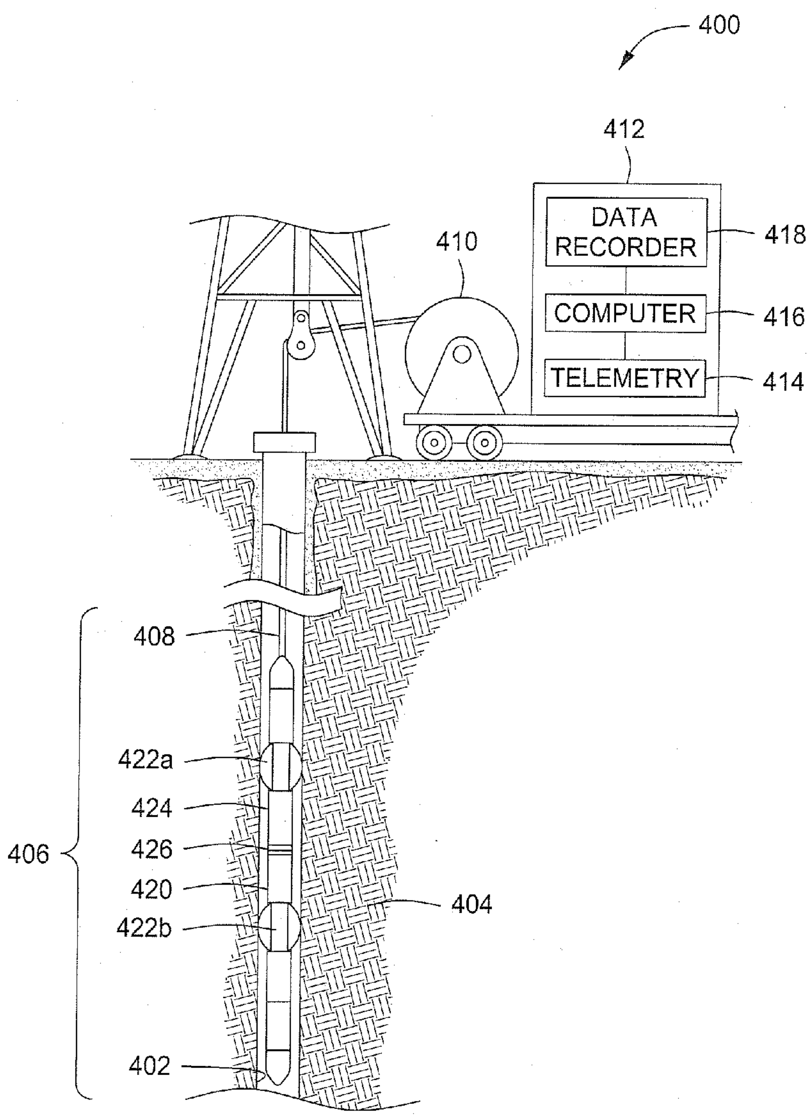


FIG. 1

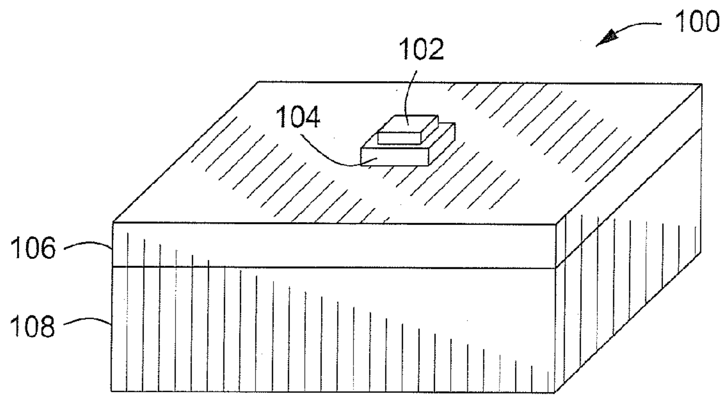


FIG. 2

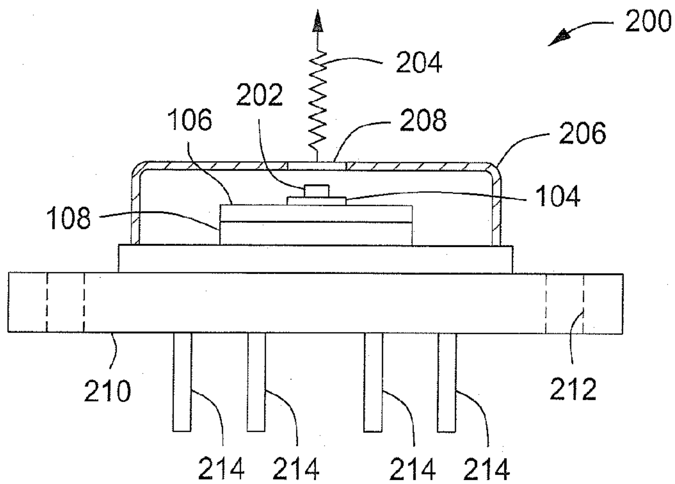
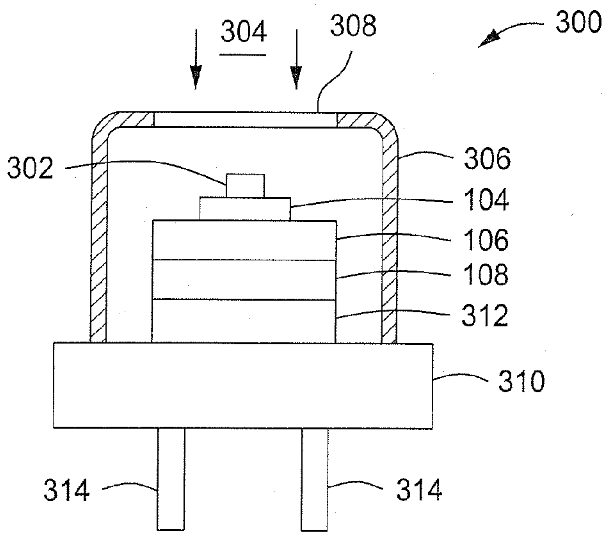


FIG. 3



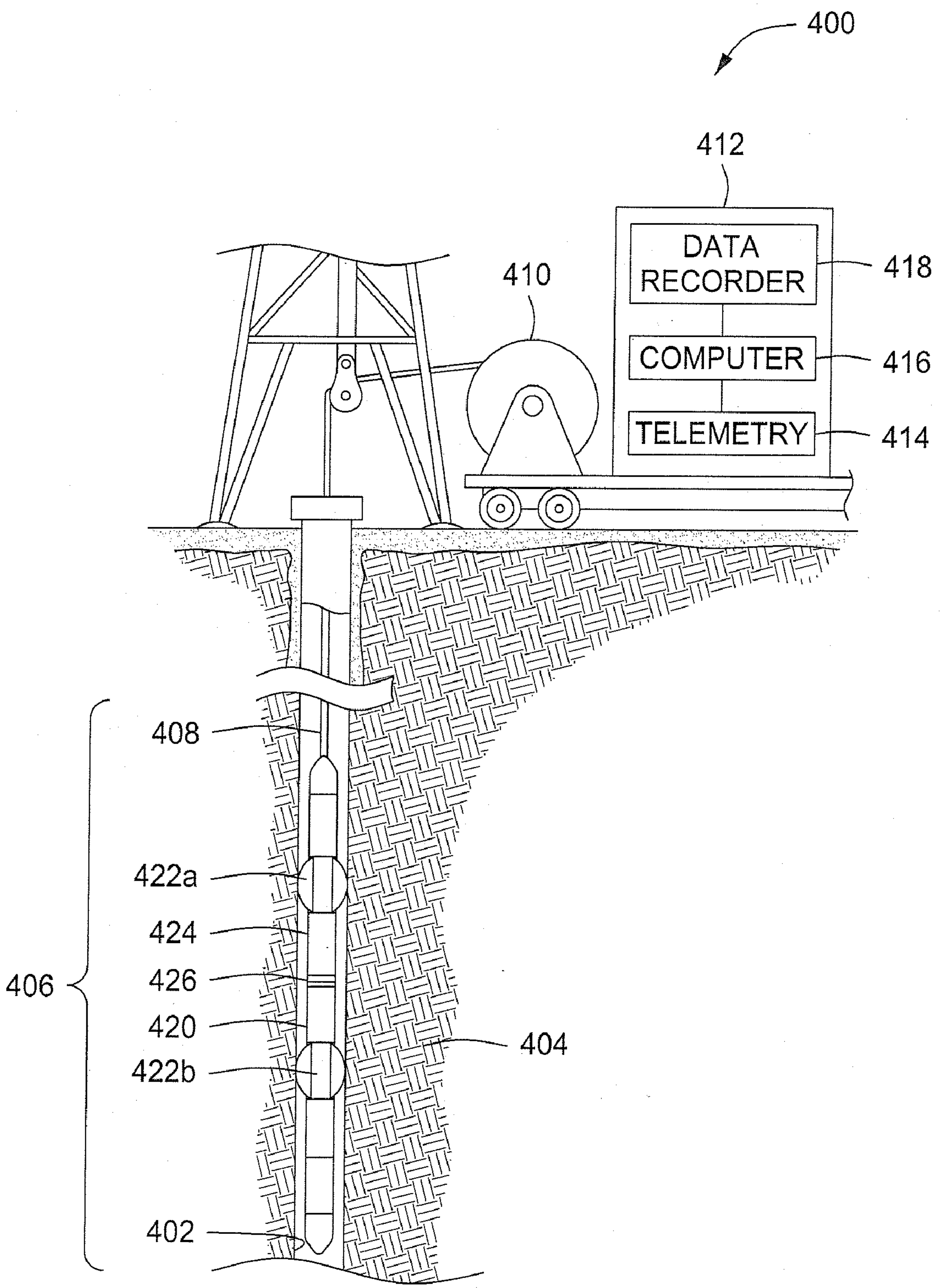

400
412
DATA
RECORDER
418
410
COMPUTER
416
TELEMETRY
414
408
422a
424
426
406
420
404
422b
402

FIG. 4

DOWNHOLE TOOL WITH THIN FILM THERMOELECTRIC COOLING

BACKGROUND

[0001] 1. Technical Field

[0002] The present disclosure generally relates to well bore tools and in particular to apparatus and methods for conducting downhole operations.

[0003] 2. Background Information

[0004] Oil and gas wells have been drilled at depths ranging from a few thousand feet to as deep as 5 miles. Wireline and drilling tools often incorporate various sensors, instruments and control devices in order to carry out any number of downhole operations. These operations may include formation testing, fluid analysis, and tool monitoring and control.

[0005] The environment in these wells present many challenges to maintain the tools used at depth due to vibration, harsh chemicals and temperature. Temperature in downhole tool applications presents a unique problem to these tools. High downhole temperatures may reach as high as 392° F. (200° C.) or more making it difficult to operate sensitive electronic components in the environment. Space in a downhole carrier is usually limited to a few inches in diameter. Cooling systems typically utilize large amounts of power and take up valuable space in the tool carrier and add an additional failure point in the system.

[0006] One of the most challenging aspects of building downhole tools is the deleterious effect that high temperatures have on the performance of semiconductor based electronics. Some examples of semiconductor electronics that may require cooling include, but are not limited to, central processing units (CPUs), amplifiers, digital-to-analog converters (DAC), analog-to-digital converters (ADC), field programmable gate arrays FPGA, and the like. Sensors such as photodiodes, charged coupled device (CCD) arrays, and other light detectors, metal oxide semiconductors (MOS), metal oxide semiconductor field effect transistors (MOSFET), and ion-sensitive field-effect transistors (IsFET) chemical sensors are just some examples of semiconductor sensors used downhole that may be adversely affected by high temperatures. Electromagnetic emitters, sometimes referred to as light sources, include laser diodes, light emitting diodes (LEDs), superluminescent LEDs, and others may also lose performance characteristics at high temperatures. High temperatures can cause drift, nonlinearity of response, reduced response, and even complete failure of such devices at elevated temperatures. Usually, the devices recover their original performance when returned to room temperature but sometimes they suffer permanent damage from having been exposed to such high temperatures.

[0007] The shunt resistance of a photodiode may start out at one gigaohm at room temperature but drop to only 100 ohms at 175 C. When attempting to perform quantitative optical measurements downhole, it is necessary to account for the significantly reduced response of semiconductor based photodetectors at elevated temperatures. Similarly, laser diodes and LEDs suffer significant losses of emitted light intensity at elevated temperatures. Most laser diodes completely stop lasing above 125 C. Conversely, some sensors such as metal oxide semiconductor gas sensors must operate at a fixed, but elevated, temperature such as 175 C or 200 C.

SUMMARY

[0008] The following presents a general summary of several aspects of the disclosure in order to provide a basic understanding of at least some aspects of the disclosure. This summary is not an extensive overview of the disclosure. It is not intended to identify key or critical elements of the disclosure or to delineate the scope of the claims. The following summary merely presents some concepts of the disclosure in a general form as a prelude to the more detailed description that follows.

[0009] Disclosed is an apparatus for cooling a die downhole. The apparatus includes a semiconductor die. A thin film thermoelectric cooling layer is coupled to the semiconductor die, and a heat spreader is coupled to the thin film thermoelectric cooling layer.

[0010] In another aspect, a method for cooling a semiconductor die downhole includes conveying a semiconductor die on a carrier to a downhole location and activating a thin film thermoelectric cooling layer coupled to the semiconductor die. The method further includes pumping heat from the thin film thermoelectric cooling layer using a heat spreader coupled to the thin film thermoelectric cooling layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] For a detailed understanding of the present disclosure, reference should be made to the following detailed description of the several non-limiting embodiments, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals and wherein:

[0012] FIG. **1** illustrates an unpackaged device with active die cooling according to several embodiments of the disclosure;

[0013] FIGS. **2** and **3** illustrate non-limiting examples of packaged devices having active die cooling within the package; and

[0014] FIG. **4** illustrates a downhole logging environment having downhole tool that includes a cooled die device according to several disclosed embodiments.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0015] The present disclosure uses terms, the meaning of which terms will aid in providing an understanding of the discussion herein. As used herein, high temperature refers to a range of temperatures typically experienced in oil production well boreholes. For the purposes of the present disclosure, high temperature and downhole temperature include a range of temperatures from about 100° C. to about 200° C. (about 212° F. to about 392° F.). In recent years, as wells have gotten deeper, a few wells now exceed 200° C. One or more embodiments disclosed herein may use the term carrier. The term "carrier" as used herein means any device, device component, combination of devices, media and/or member that may be used to convey, house, support or otherwise facilitate the use of another device, device component, combination of devices, media and/or member. Exemplary non-limiting carriers include drill strings of the coiled tube type, of the jointed pipe type and any combination or portion thereof. Other carrier examples include casing pipes, wirelines, wireline sondes, slickline sondes, drop shots, downhole subs, bottom hole assemblies (BHA's), drill string inserts, modules, internal housings and substrate portions thereof. The term "die" includes any semiconductor electrical circuit, semiconductor electrical circuit component or semiconductor device that may be used in a downhole tool. Non-limiting examples of a semiconductor die include semiconductor devices, circuits, detectors, emitters, memory devices, data communication devices, controllers and others as described herein without limiting the scope of the disclosure.

[0016] FIG. **1** illustrates a non-limiting example of a device **100** that includes a cooled die **102** useful for operation in a downhole environment. In one or more embodiments, the die **102** may be disposed on an active cooling layer **104**, and the active cooling layer **104** may be disposed on a heat spreader **106**. In one or more embodiments, the heat spreader **106** may be disposed on a heat sink **108**. In one or more embodiments, the heat sink may be a high volumetric heat capacity heat sink whose heat capacity is sufficient to minimize its temperature rise as the die is being cooled and thereby to allow the die to reach its lowest possible temperature for that thermoelectric cooler's maximum AT rating. For devices that need to be cooled to improve their performance but which are not damaged by borehole temperatures, intermittent, but rapid, cooling to the desired temperature is possible because of the high heat pumping ability of thin film thermoelectric coolers. Such a low duty cycle can result in a many fold reduction in the total energy required for cooling, which is particularly useful for battery powered downhole tools or for any downhole tool which has limited available power

[0017] The die **100** may be any die selected for downhole operations. For example, the die may include a CPU, an amplifier, a DAC, an ADC, one or more FPGAs, sensors such as photodiodes, CCD arrays, and other light detectors. The die **100** may include MOS, MOSFET, IsFET and other devices and sensors. The die **100** may also include electromagnetic emitters such as laser diodes, LEDs, superluminescent LEDs, and other semiconductor light sources and electromagnetic energy emitters.

[0018] The active cooling layer **104** may be any suitable layer material providing active cooling for the die **100**. In one or more embodiments, the active cooling layer **104** may include thermoelectric cooling materials. Suitable thermoelectric materials may be based on very thin films, which can be placed in substantially direct contact with the die **102** to be cooled for maximum heat transfer and minimum excess mass heating or cooling. Thin film thermoelectric cooling layers described herein refers to active cooling layers formed using one or more micromachining and/or deposition processes for forming small-scale devices, such as semiconductor chips. Thin film thermoelectric materials can pump as much as 700 Watts/cm^2 (which is 6.06 horsepower per square inch) of heat, can have Coefficients of Performance (where COP is the Watts of heat pumped per Watt of electricity used) in excess of unity, and can become more efficient with increasing borehole temperature over the range of borehole temperatures. The thermoelectric materials may include a superlattice structure of about a thousand alternating 5-nm thick layers of thermoelectric materials, such as alternating bismuth telluride and antimony telluride. In one or more embodiments, the active cooling layer **104** may have a figure of merit (ZT) that improves moderately with increasing temperature over the range of oilfield borehole temperatures and may have a coefficient of performance of about 1 or more. A thermoelectric's figure of merit is positively correlated to its coefficient of performance. In one or more embodiments, the COP may be in a range of about 1 to 4. In one or more embodiments, the COP may be in a range of about 1 to 8.

[0019] As shown in FIG. **1**, the active cooling layer **104** may be placed in substantially direct contact with the die **102**. The active cooling layer **104** may further be in substantially direct contact with the heat spreader **106**. In one or more embodiments, the heat spreader **106** may be made of highly thermally conductive material such as diamond having a thermal conductivity of about 630 W/mK. In one or more embodiments, the heat spreader **106** may be made of highly thermally conductive material such as aluminum nitride having a thermal conductivity of about 180 W/mK. In one or more embodiments, the heat spreader **106** may have a surface that has a much larger area than either the die **102** or the active cooling layer surface areas.

[0020] In operation, the heat spreader **106** moves any pumped heat away from the die **102** and the active cooling layer **104** and spreads it over the surface of the large area and volume heat sink **108**. In one or more embodiments, the heat sink may be an electrical insulating material, or the heat sink may be electrically conductive. In one or more embodiments, the heat sink may be made of a material that has high volumetric heat capacity, which is the product of mass density and specific heat for the material used. An electrically insulating heat sink, for example, may be made using alumina (Al2O3) whose volumetric heat capacity is about 3.37E+06 $Jm^{-3}K^{-1}$ or aluminum nitride (AlN) whose volumetric heat capacity is about 2.59E+06 $Jm^{-3}K^{-1}$. For an electrically conducting heat sink, one can use copper whose volumetric heat capacity is 3.45E+06 $Jm^{-3}K^{-1}$ or aluminum whose volumetric heat capacity is 2.42E+06 $Jm^{-3}K^{-1}$ or silicon whose volumetric heat capacity is 1.63E+06 $Jm^{-3}K^{-1}$. Alternatively, or in addition to the above-described heat sinks, the heat sink **108** may include a liquid-filled heat pipe in contact with the heat spreader to move the heat pumped by the thermoelectric cooler.

[0021] The device **100** described above and shown in FIG. **1** may be operated as an unpackaged device or as a packaged device as will be described in more detail with respect FIGS. **2** and **3**. An unpackaged device may be of the chip-on-board (COB) type, which may be used in many motherboard applications. Downhole tools may include a case or housing for encapsulating a circuit board as part of the downhole tool. A device **100** may then be an unpackaged device **100** that is mounted on the circuit board and mechanically protected using the tool casing, while the thermoelectric layer operates to cool the device **100**.

[0022] Referring now to FIGS. **2** and **3**, a device such as the device **100** described above and shown in FIG. **1** may be packaged. Some non-limiting examples of packaged devices include electromagnetic energy emitters and photodetectors. Packages may be custom designed or may be of standard type. FIG. **2** illustrates an electromagnetic energy source **200** that includes a die **202** that is disposed within a package **206**. The die **202** in this example is an electromagnetic energy emitter that emits electromagnetic energy **204**, and the package **206** includes a window **208** that allows the electromagnetic energy **204** to emit from the package **206**. The package **206** may include a base **210**, and the base **210** may include one or more holes **212** for receiving fasteners to secure the electromagnetic energy source **200** to a downhole tool carrier. One or more electrically conductive leads **214** may be connected to the die and active cooling layer **104**, and the leads **214** may extend externally to the package **206** to provide electrical connection for power and control of the electromagnetic energy source **200**.

[0023] The internal package components may be substantially as described above and shown in FIG. **1**. The emitter **202** may be disposed on an active cooling layer **104**, and the active cooling layer **104** may be disposed on a heat spreader **106**. In one or more embodiments, the heat spreader **106** may be disposed on a heat sink **108**. The heat sink **108** may then be coupled to the base **210** or to an intermediate substrate as desired. The materials of construction may be substantially as described above with respect to the unpackaged embodiments.

[0024] FIG. **3** is another non-limiting example of a cooled die in a package. In the example of FIG. **3** a detector **300** includes a die **302** that may be used as a sensing element. The die **302** is disposed on an active cooling layer **104** substantially as described above and shown in FIG. **1**. The active cooling layer **104** may be disposed on a heat spreader **106**, which may be disposed on a heat sink **108**. The die, cooler, spreader and heat sink, may then be disposed on one or more substrates **312** suitable for mounting the device within a detector package **306**.

[0025] The package **306** may further include a window **308** for allowing electromagnetic energy to enter the package **306** and to be detected by the detector **302**. The package may include a base **310** and one or more electrical leads **214** for mounting the package in a downhole tool or carrier.

[0026] FIG. **4** shows a non-limiting example of a well logging apparatus **400** according to several embodiments of the disclosure. The well logging apparatus **400** is shown disposed in a well borehole **402** penetrating earth formations **404** for making measurements of properties of the earth formations **404**. The borehole **402** is typically filled with drilling fluid to prevent formation fluid influx.

[0027] A string of logging tools **406** is lowered into the well borehole **402** by an armored electrical cable **408**. The cable **408** can be spooled and unspooled from a winch or drum **410**. The tool string **406** can be electrically connected to surface equipment **412** by an optical fiber (not shown separately) forming part of the cable **408**. The surface equipment **412** can include one part of a telemetry system **414** for communicating control signals and data to the tool string **406** and computer **416**. The computer can also include a data recorder **418** for recording measurements made by the apparatus and transmitted to the surface equipment **412**.

[0028] One or more logging devices **420** form part of the tool string **406**. The tool string **406** is preferably centered within the well borehole **402** by a top centralizer **422*a*** and a bottom centralizer **422*b*** attached to the tool string **406** at axially spaced apart locations. The centralizers **422*a***, **422*b*** can be of types known in the art such as bowsprings.

[0029] Circuitry for operating the logging tool **420** may be located within the string **406** and within the electronics cartridge **424**. The circuitry may further be connected to the tool **420** through a connector **426**. In several embodiments, the logging tool **420** may incorporate a semiconductor-based device such as any of the devices described herein and shown in FIGS. **1** through **3**.

[0030] Several operational examples may now be described in view of the above discussion. In a borehole tool, it is often desirable to keep a semiconductor-based device below a certain temperature or within a selected range of temperatures. However, the higher the borehole temperature, the harder that it is to cool the device to the desired temperature. Eventually, one exceeds the maximum possible ΔT that typical external thermoelectric cooler or stack of coolers may provide. Also, the power required to continuously maintain a large ΔT may exceed the allowed electrical power in a downhole tool.

[0031] An active cooling layer **104** as described above may be used for a selected die **102**, **202**, **302** to cool the device when the borehole temperature exceeds the ideal operating temperature or, by simply reversing the polarity of an applied DC voltage, it can be used to heat the device when the borehole temperature is below its ideal operating temperature.

[0032] In several non-limiting examples, the very fast cooling rate of the active cooling layer **104** permits intermittent, low-duty-cycle operation, which will not continuously draw large amounts of electrical power from the downhole tool. A large ΔT may be maintained during such a fast cool down by using a heat sink **108** to which the heat is being pumped, where the heat sink **108** has a sufficiently high heat capacity that it only undergoes a small temperature rise during operation of the active cooling layer **104**. Because the die **102** is relatively small (perhaps 1 mm×1 mm and a less than a mm thick), a passive method may be used for keeping the heat sink temperature from rising significantly above the normal ambient borehole temperature. In one or more embodiments, passive heat sinking includes the use of a heat sink structure as described above and shown in FIGS. **1**-**3**. In one or more embodiments, a passive heat sink method may include the use of a liquid-filled heat pipe in contact with the heat spreader to move the heat pumped by the thermoelectric cooler **104**.

[0033] In another operational example, a die may include a semiconductor detector used for downhole fluid spectroscopy. A downhole fluid spectrometer may be used to collect a visible and infrared optical spectrum every three seconds while pumping formation fluid from the wellbore during fluid sample cleanup; a process that could take 1 to 3 hours. It is desirable to cool the photodiodes used as detectors for the spectrometer when used in a high temperature environment such as in a borehole. In one or more embodiments, the photodiodes may be cooled for 100 to 300 milliseconds out of each 3 second cycle. In this manner, the cooling cycle is long enough to reach a stable and sufficiently-low temperature to collect a spectrum yet the total Watt-Hours of electrical energy needed for cooling is greatly reduced. It is desirable to know the temperature of the photodiode very accurately to properly correct its photo response for temperature. In one or more embodiments, the photodiode shunt resistance, which has a one to one correspondence to its temperature, may be measured. In one or more embodiments, a photocurrent may be measured.

[0034] The present disclosure is to be taken as illustrative rather than as limiting the scope or nature of the claims below. Numerous modifications and variations will become apparent to those skilled in the art after studying the disclosure, including use of equivalent functional and/or structural substitutes for elements described herein, use of equivalent functional couplings for couplings described herein, and/or use of equivalent functional actions for actions described herein. Such insubstantial variations are to be considered within the scope of the claims below.

[0035] Given the above disclosure of general concepts and specific embodiments, the scope of protection is defined by the claims appended hereto. The issued claims are not to be taken as limiting Applicant's right to claim disclosed, but not yet literally claimed subject matter by way of one or more further applications including those filed pursuant to the laws of the United States and/or international treaty.

What is claimed is:

1. An apparatus for cooling a die downhole comprising:

a semiconductor die conveyable on a carrier to a downhole location;

a thin film thermoelectric cooling layer coupled to the semiconductor die; and

a heat spreader coupled to the thin film thermoelectric cooling layer.

2. An apparatus according to claim **1**, wherein the thin film thermoelectric cooling layer includes a superlattice structure of a plurality of alternating layers of thermoelectric materials.

3. An apparatus according to claim **2**, wherein the alternating layers comprise alternating bismuth telluride and antimony telluride materials.

4. An apparatus according to claim **1**, wherein the heat spreader includes a highly thermally conductive material.

5. An apparatus according to claim **1**, wherein the heat spreader comprises diamond as at least one material of construction.

6. An apparatus according to claim **1**, wherein the heat spreader comprises aluminum nitride as at least one material of construction.

7. An apparatus according to claim **1**, wherein the heat spreader includes a surface area larger than a surface area of the thin film thermoelectric cooling layer.

8. An apparatus according to claim **1**, further comprising a heat sink coupled to the heat spreader.

9. An apparatus according to claim **8**, wherein the heat sink includes an electrically insulating material selected from alumina, aluminum nitride or a combination thereof.

10. An apparatus according to claim **8**, wherein the heat sink includes an electrically conductive material selected from copper, aluminum, silicon or any combination thereof.

11. An apparatus according to claim **8**, wherein the heat sink includes a liquid-filled heat pipe in contact with the heat spreader to move the heat from the heat spreader.

12. An apparatus according to claim **1** further comprising a package, the semiconductor die, the thin film thermoelectric cooling layer and the heat spreader being disposed within the package.

13. A method for cooling a die downhole comprising:

conveying a semiconductor die on a carrier to a downhole location;

removing heat from the semiconductor die using a thin film thermoelectric cooling layer coupled to the semiconductor die; and

pumping heat from the thin film thermoelectric cooling layer using a heat spreader coupled to the thin film thermoelectric cooling layer.

14. A method according to claim **13**, wherein pumping heat from the thin film thermoelectric cooling layer includes using a highly thermally conductive material.

15. A method according to claim **13**, wherein the heat spreader comprises at least one material of construction selected from diamond and aluminum nitride.

16. A method according to claim **13**, wherein pumping heat from the thin film thermoelectric cooling layer includes pumping heat to a heat spreader surface area that is larger than a surface area of the thin film thermoelectric cooling layer.

17. A method according to claim **13**, further comprising conveying heat from the heat spreader to a heat sink coupled to the heat spreader.

18. A method according to claim **17**, wherein the heat sink includes a material selected from one or more of alumina, aluminum nitride, copper, aluminum, silicon or any combination thereof.

19. A method according to claim **17**, wherein the heat sink includes a liquid-filled heat pipe in contact with the heat spreader to move the heat from the heat spreader.

20. A method according to claim **13**, wherein the semiconductor die, the thin film thermoelectric cooling layer and the heat spreader are disposed within a package.

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