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**Xu et al.**

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(54) **TEMPERATURE AND PRESSURE SENSORS AND METHODS**


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***G01D 3/08*** (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ................. ***G01D 3/08*** (2013.01); ***G01K 7/32*** (2013.01); ***G01K 7/343*** (2013.01); ***G01L 9/007*** (2013.01);
(Continued)

(58) **Field of Classification Search**
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See application file for complete search history.


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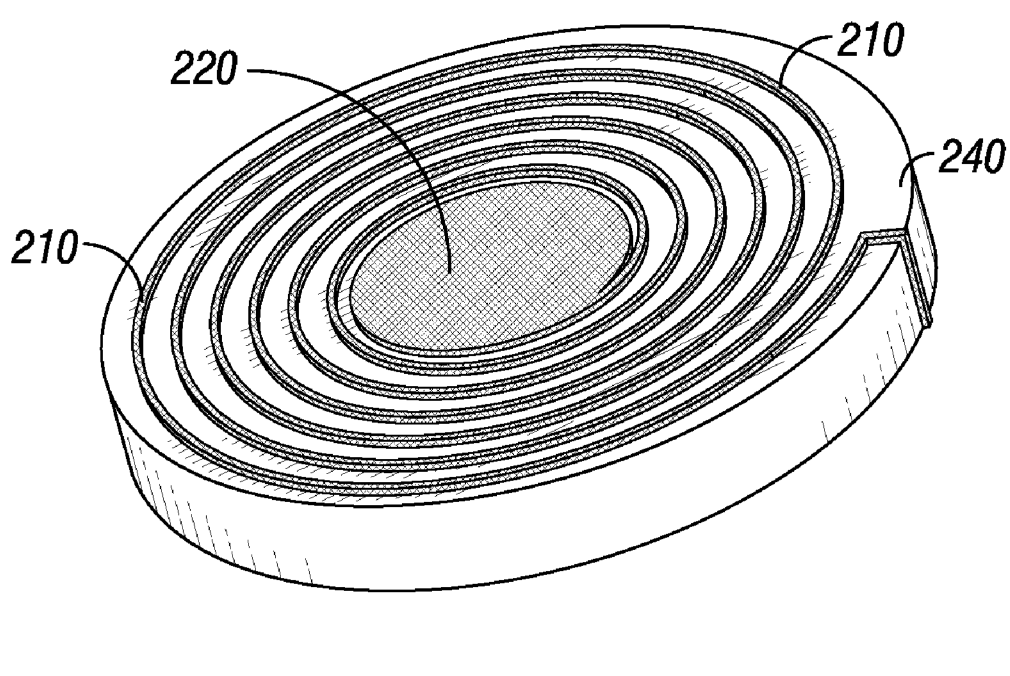
(74) *Attorney, Agent, or Firm* — Eversheds Sutherland (US) LLP


(57) **ABSTRACT**


Temperature sensors, pressure sensors, methods of making the same, and methods of detecting pressures and temperatures using the same are provided. In an embodiment, the temperature sensor includes a ceramic coil inductor having a first end plate and a second end plate, wherein the ceramic coil inductor is formed of a ceramic composite that comprises carbon nanotubes or, carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers thereof dispersed in a ceramic matrix; and a thin film polymer-derived ceramic (PDC) nanocomposite disposed between the first and the second end plates, wherein the thin film PDC nanocomposite has a dielectric constant that increases monotonically with temperature.


**8 Claims, 7 Drawing Sheets**



(51) **Int. Cl.**

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|---|---|
| ***G01L 9/10*** | (2006.01) |
| ***G01K 7/34*** | (2006.01) |
| ***G01L 9/00*** | (2006.01) |
| ***G01L 19/04*** | (2006.01) |
| ***G01K 7/32*** | (2006.01) |

(52) **U.S. Cl.**
CPC .............. ***G01L 9/105*** (2013.01); ***G01L 19/04*** (2013.01); *G01K 2211/00* (2013.01)

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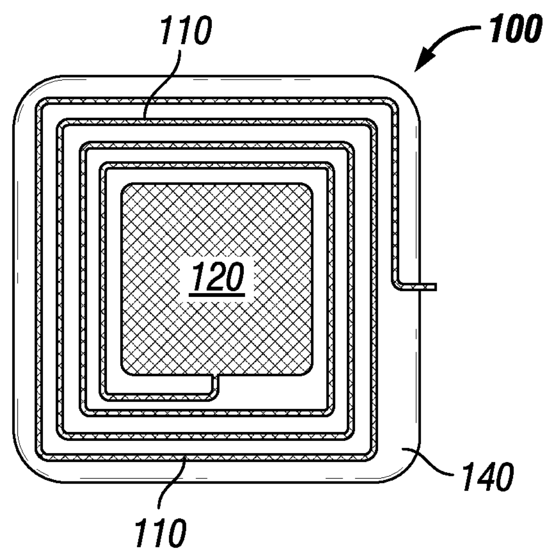



FIG. 1A

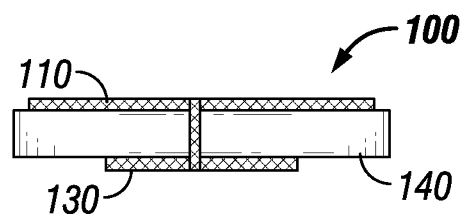



FIG. 1B

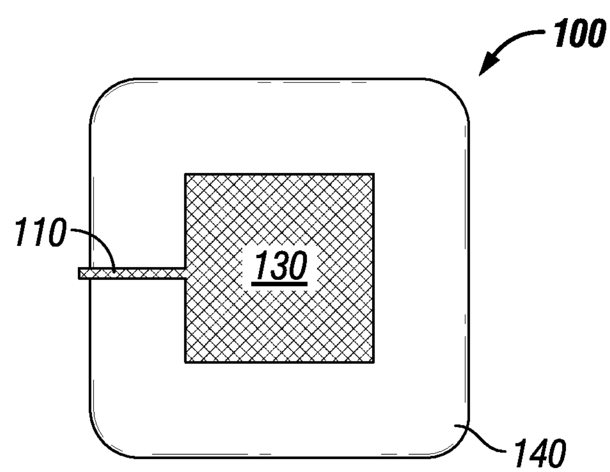



FIG. 1C

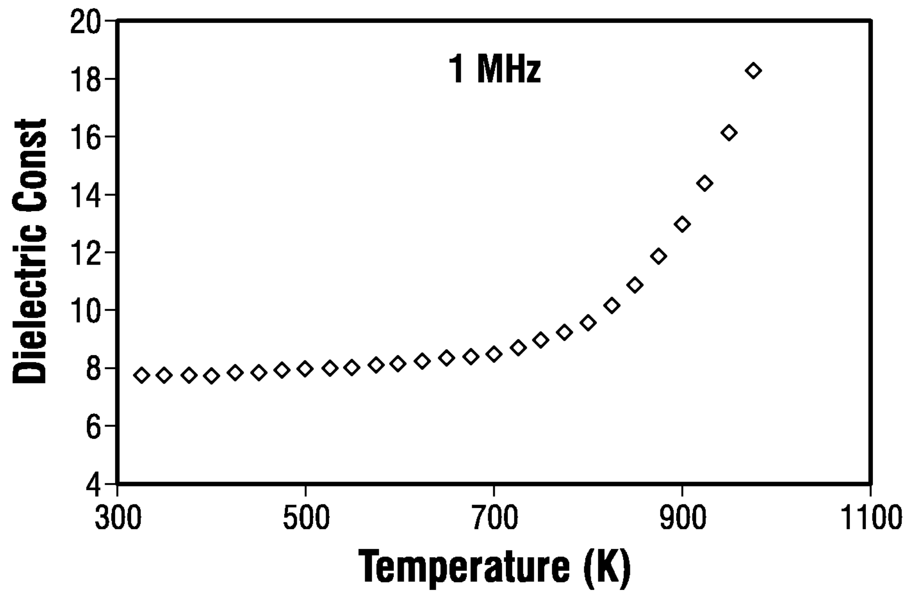

1 MHz
Dielectric Const
20
18
16
14
12
10
8
6
4
300
500
700
900
1100
Temperature (K)

FIG. 2

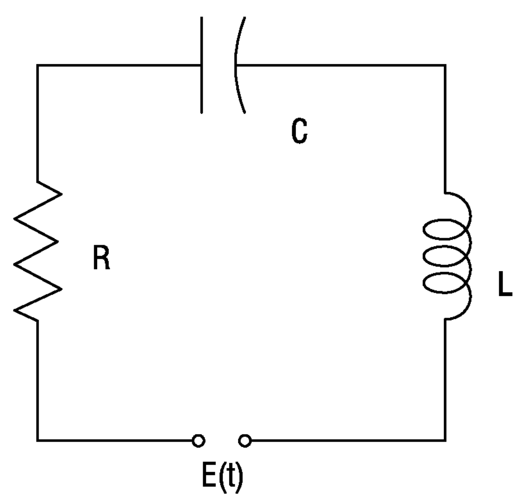
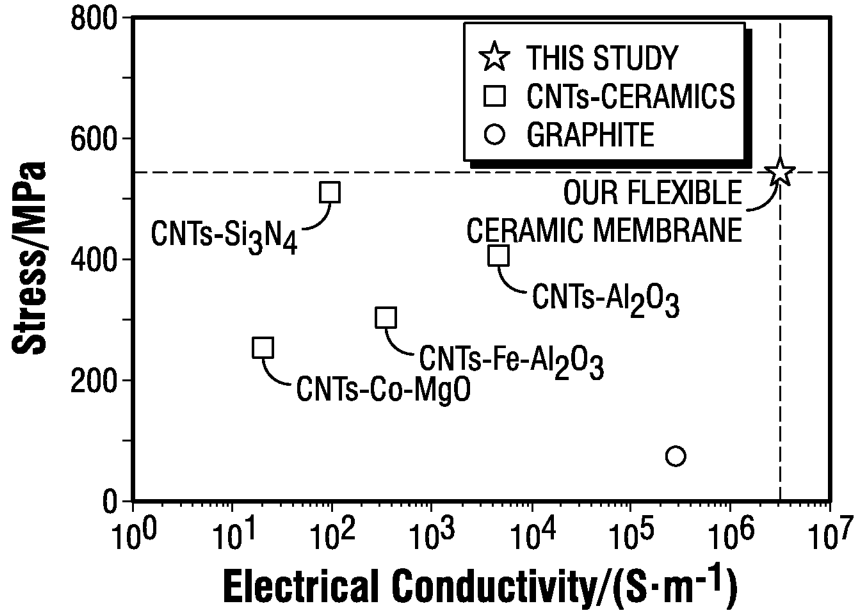
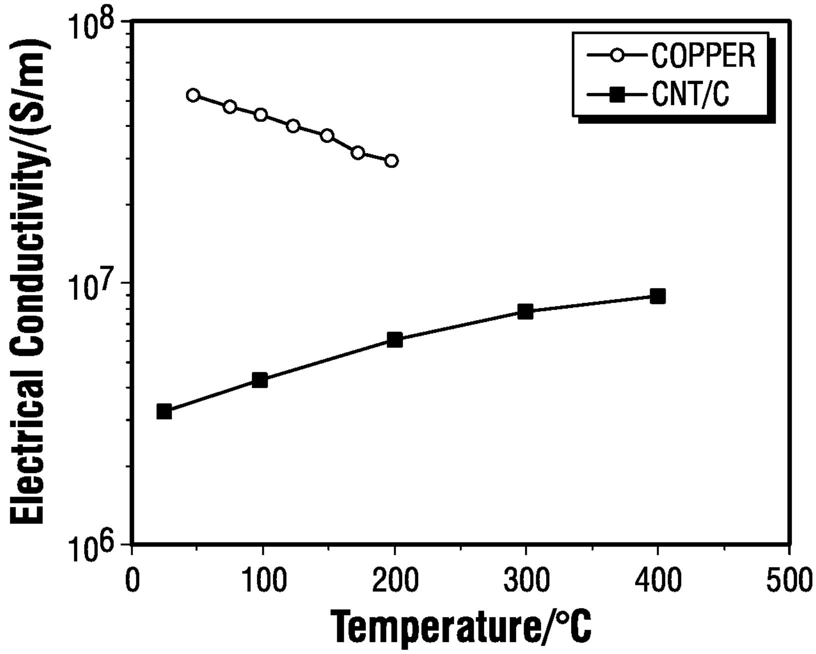

C
R
L
E(t)

FIG. 3



800
600
400
200
0
Stress/MPa
THIS STUDY
CNTs-CERAMICS
GRAPHITE
OUR FLEXIBLE CERAMIC MEMBRANE
CNTs-Si3N4
CNTs-Al2O3
CNTs-Fe-Al2O3
CNTs-Co-MgO
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
Electrical Conductivity/(S·m^-1)


*FIG. 4A*



10^8
10^7
10^6
Electrical Conductivity/(S/m)
COPPER
CNT/C
0 100 200 300 400 500
Temperature/°C


*FIG. 4B*

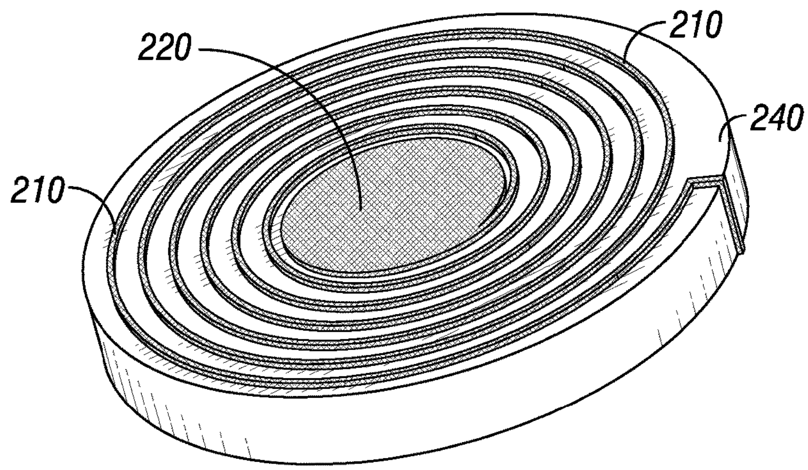
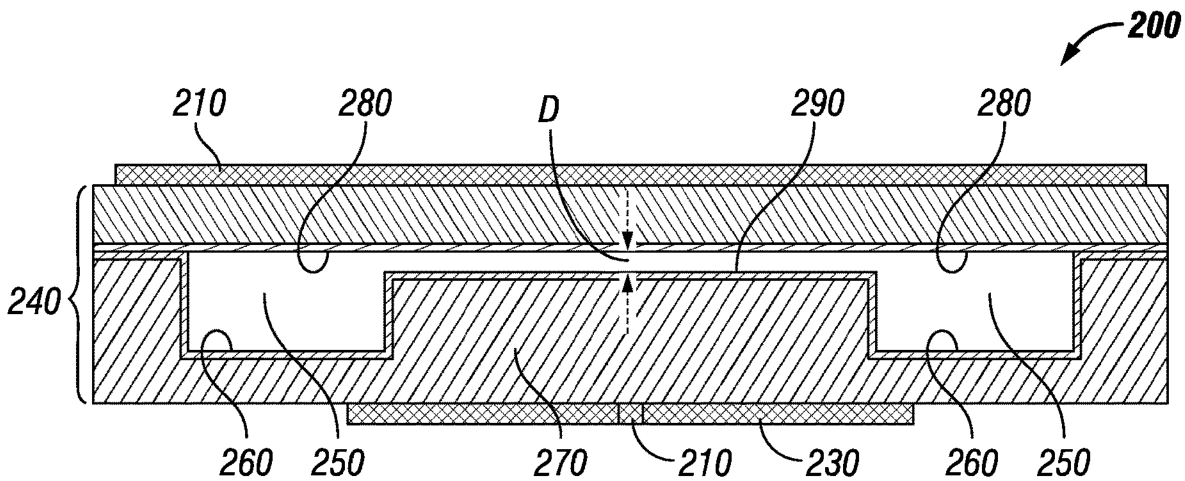

220
210
240
210

FIG. 5A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210
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D
290
280
240
260
250
270
210
230
260
250

FIG. 5B

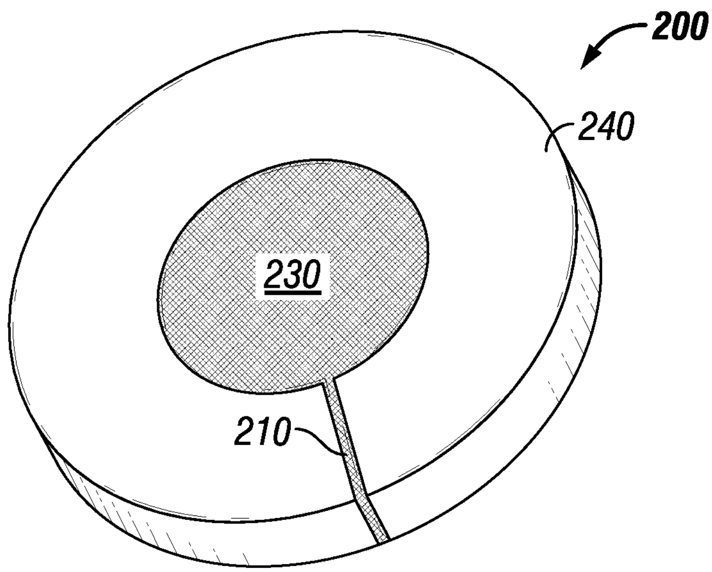


FIG. 5C

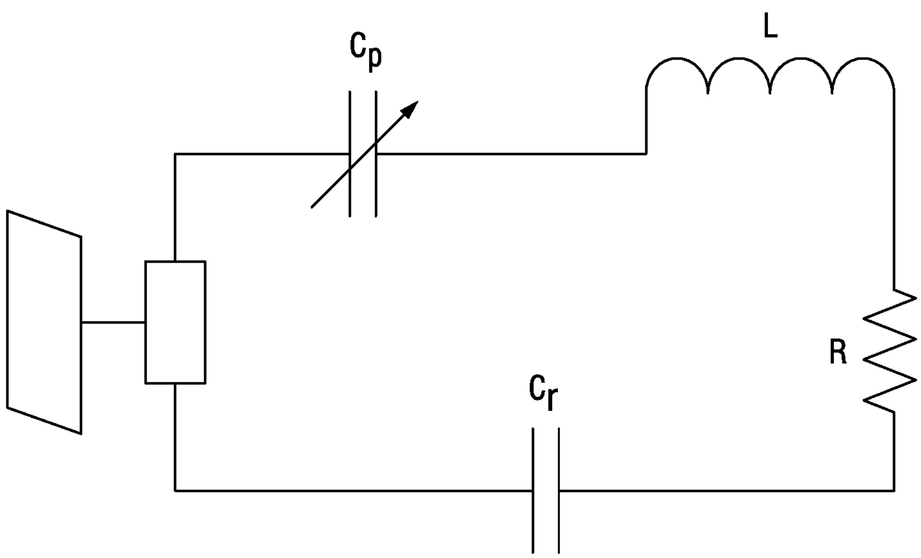


FIG. 6

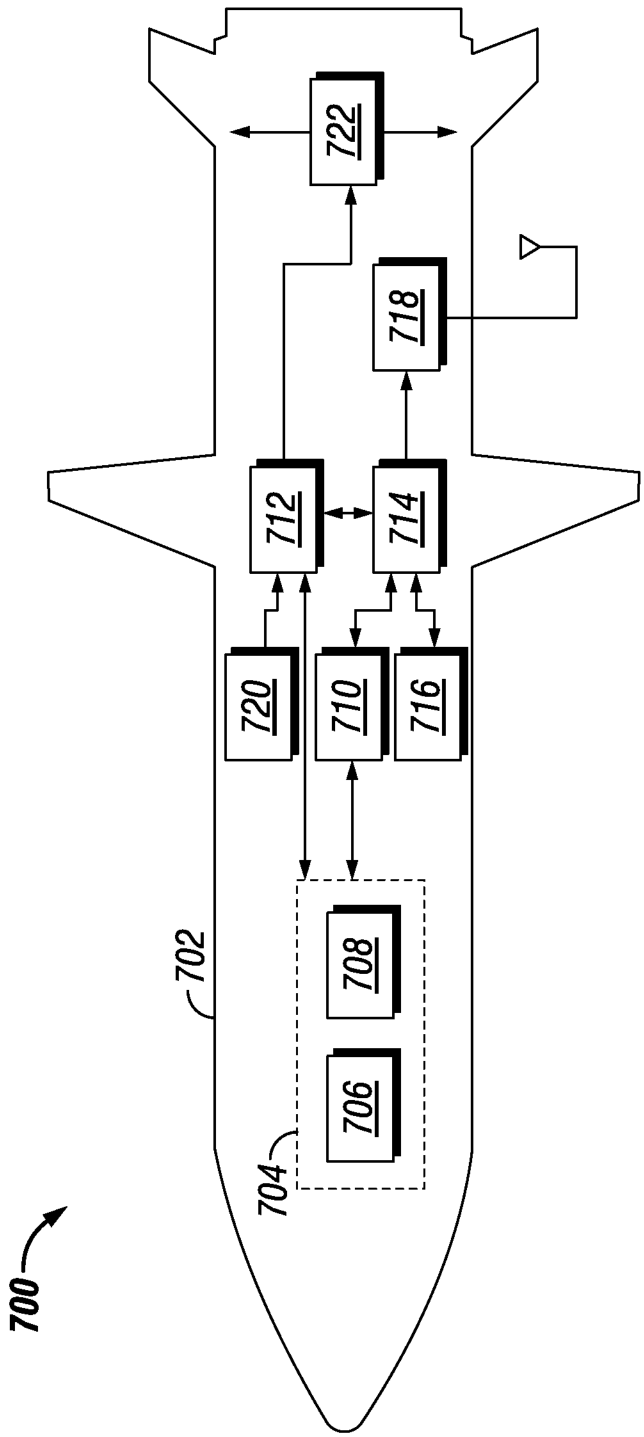


FIG. 7

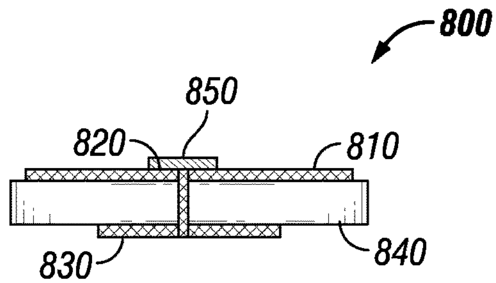
800
850
820
810
830
840

FIG. 8

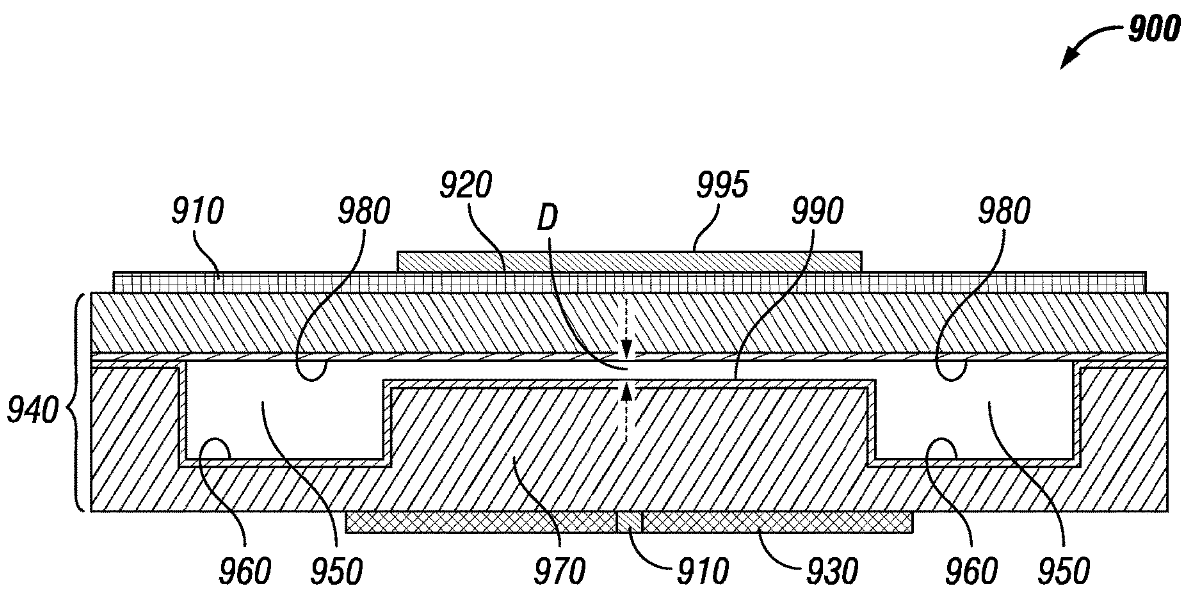
900
910
980
920
D
995
990
980
940
960
950
970
910
930
960
950

FIG. 9

# TEMPERATURE AND PRESSURE SENSORS AND METHODS

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 62/443,103, filed on Jan. 6, 2017, which is incorporated herein by reference in its entirety.

## STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under contract number N00014-11-1-0706 awarded by the Office of Naval Research. The government has certain rights in the invention. This invention was made with Government support from the U.S. Air Force under Grant No. FA8651-17-1-0005. The Government of the United States has the right to practice or have practiced on behalf of the United States this subject invention throughout the world.

## BACKGROUND

Maintaining situational awareness of the weapon environment is desirable for developing the next generation of robust missile and munition (M&M) systems that can withstand the extreme acceleration, temperature, and pressure conditions that are presented by traditional fighter and hypersonic aircraft. Conventional techniques for remotely monitoring munition assets are primarily performed by proximate environmental monitoring by fuel sensors, accelerometers, surface acoustic wave sensors, chemical resistors, and temperature sensors, which unfortunately are limited to storage and transportation purposes. In addition, conventional temperature testing for M&M surveillance is performed over a limited temperature range, e.g., −55° C. to 125° C.

Typical conventional temperature sensors used in the evaluation of M&M systems include thermocouples, thermistors, resistance thermometers, quartz thermometers, which all include a metallic coil inductor. However, these temperature sensors have certain drawbacks. For example, these temperature sensors cannot be used in high temperature environments (e.g., 800° C. to 1400° C.) for prolonged periods of time due to oxidation of the metallic coil inductor, or can only be used under wired measurement conditions, and therefore are not suitable for in-flight monitoring. As a result, these temperature sensors can provide only limited evaluation of M&M systems.

It therefore would be desirable to provide improved temperature sensors that overcome one or more of the foregoing limitations. In particular, it would be desirable to provide a temperature sensor that can withstand high temperatures for prolonged periods of time, along with the ability to wirelessly transmit real-time, in-flight temperature data of M&M systems.

Similarly, real-time, online pressure monitoring is desired for many harsh-environment applications, such as gas turbines for power generation, to maintain operational effectiveness and safety. However, in such applications, suitable pressure sensors need to withstand corrosive gas environments having high temperatures (e.g., 1000° C. to 1400° C.) and high pressures (e.g., 300 psi to 600 psi).

Typical conventional pressure sensors used in these applications include passive pressure sensors based on resistive or capacitive sensing mechanisms. However, these pressure sensors have certain drawbacks. For example, wire interconnection is required to interrogate these sensors, and these sensors cannot operate effectively in high temperature environments. Moreover, pressure sensors that utilize a patch antenna operate within a limited temperature range, e.g., −55° C. to 125° C., because of the metallic wire used with the patch antenna. As a result, the application of these common pressure sensors is limited.

It therefore would be desirable to provide improved pressure sensors that overcome one or more of the foregoing limitations. In particular, it would be desirable to provide a pressure sensor that can withstand high temperatures and pressures for prolonged periods, along with the ability to wirelessly transmit real-time pressure data.

## SUMMARY

In one aspect, a temperature sensor is provided which includes: a ceramic coil inductor having a first end plate and a second end plate, wherein the ceramic coil inductor is formed of a ceramic composite that comprises carbon nanotubes, carbon nanofibers, or a combination thereof dispersed in a ceramic matrix; and a thin film polymer-derived ceramic (PDC) nanocomposite disposed between the first and the second end plates, wherein the thin film PDC nanocomposite has a dielectric constant that increases monotonically with temperature.

In another aspect, a pressure sensor is provided including: a ceramic coil inductor having a first end plate and a second end plate, wherein the ceramic coil inductor is formed of a ceramic composite that comprises carbon nanotubes, or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers thereof dispersed in a ceramic matrix; and a PDC nanocomposite structure disposed between the first and the second end plates, wherein the PDC nanocomposite structure has walls that define an internal cavity having a first cavity surface and an opposed second cavity surface, wherein the first and second cavity surfaces are spaced a distance from one another and the distance varies proportionally to the atmospheric pressure outside of the pressure sensor.

In another aspect, a method for making a wireless sensor is provided, the method including: disposing a PDC nanocomposite between a first end plate and a second end plate of a ceramic coil inductor, wherein the ceramic coil inductor comprises carbon nanotubes, or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers thereof dispersed in a ceramic matrix, wherein the sensor is a temperature sensor or a pressure sensor.

In another aspect, a method of detecting a change in temperature is provided, the method including: placing one or more temperature sensors described above in an environment; and measuring a frequency shift of an electromagnetic signal induced in the ceramic coil to detect a change in temperature of the environment.

In another aspect, a method of detecting a change in pressure is provided, the method including: placing one or more pressure sensors described above in an environment; and measuring a frequency shift of an electromagnetic signal induced in the ceramic coil inductor to detect a change in pressure of the environment.

## BRIEF DESCRIPTION OF THE DRAWINGS

The detailed description is set forth with reference to the accompanying drawings. The use of the same reference numerals may indicate similar or identical items. Various embodiments may utilize elements and/or components other than those illustrated in the drawings, and some elements and/or components may not be present in various embodiments. Elements and/or components in the figures are not necessarily drawn to scale.

FIG. **1**A is a top plan view of a temperature sensor in accordance with an embodiment of the present disclosure.

FIG. **1**B is an elevated side view of the temperature sensor in FIG. **1**A.

FIG. **1**C is a bottom plan view of the temperature sensor in FIG. **1**A.

FIG. **2** is a graph showing the dielectric constant of polymer-derived ceramic material as a function of temperature at 1 MHz.

FIG. **3** is a schematic of an exemplary temperature sensor represented as a passive resistor-inductor-capacitor (RLC) circuit.

FIG. **4**A is a graph illustrating the mechanical and electrical properties of a ceramic composite of an exemplary temperature sensor of the present disclosure compared to other representative CNT-reinforced ceramic composites and graphite.

FIG. **4**B is a graph showing a change in measured electrical conductivity of a ceramic composite of an exemplary temperature sensor of the present disclosure as a function of temperature.

FIG. **5**A is a top perspective view of a pressure sensor in accordance with an embodiment of the present disclosure.

FIG. **5**B is a cross-sectional view of the pressure sensor in FIG. **5**A.

FIG. **5**C is a bottom perspective view of the pressure sensor in FIG. **5**A.

FIG. **6** is a schematic of an exemplary pressure sensor represented as an evanescent-mode cavity resonator.

FIG. **7** is a schematic of a temperature sensor of the present disclosure integrated within an exemplary missile and munition (M&M) system.

FIG. **8** is an elevated side view of a temperature sensor according to an embodiment of the present disclosure.

FIG. **9** is an elevated side view of a pressure sensor according to an embodiment of the present disclosure.

## DETAILED DESCRIPTION

New temperature and pressure sensors are provided herein that may include a ceramic coil inductor having ceramic material and a relatively high volume fraction of carbon nanotubes. The combination leverages the remarkable electrical and mechanical properties (stiff and strong) of carbon nanotubes (CNTs) and the thermal properties (temperature sensitivity) of ceramic materials.

In some embodiments, the temperature sensors provided herein are high temperature, wireless sensors having one or more of the following advantages: (i) the ability to provide real-time, in-flight monitoring of M&M systems; (ii) the ability to maintain safety and effectiveness of critical parts and materials of the M&M systems without the need for extensive non-destructive evaluation (NDE), thereby reducing cost and time; and (iii) on-demand tracking and assessing of the status of the M&M systems over extended periods, based upon changing conditions.

Similarly, in some embodiments, the pressure sensors provided herein are wireless and can operate in harsh, corrosive gaseous environments having high temperatures and pressures. These sensors have one or more of the following advantages: (i) the ability to provide real-time, monitoring of systems that operate in high temperature and pressure environments; (ii) the ability to maintain safety and effectiveness of critical parts and materials of these systems, thereby reducing cost and time; and (iii) on-demand tracking and assessing of the status of systems over extended periods, based upon changing conditions.

### Temperature Sensors

In some embodiments, the temperature sensors include a ceramic coil inductor that is formed of a ceramic composite and a thin film polymer-derived ceramic (PDC) nanocomposite having a dielectric constant that increases monotonically with temperature.

An exemplary embodiment is illustrated in FIGS. **1**A-**1**C. In this embodiment, the temperature sensor **100** includes a ceramic coil inductor **110** having a first end plate **120** and a second end plate **130**. The temperature sensor **100** further includes a PDC nanocomposite **140** that is disposed between the first and second end plates, **120**, **130**.

In certain embodiments, the ceramic coil inductor **110** is configured to communicate with an external radio frequency antenna. In other embodiments, the temperature sensor **100** includes a patch antenna that is attached to the first end plate **120** of the ceramic coil inductor **110** and is configured to communicate with an external radio frequency antenna. Therefore, by using wireless transmission, the signal transmission distance can be accomplished over a network of RF links, such as satellite, the Internet, and/or infrared data links, or any other desired communication path.

FIG. **8** illustrates an elevated side view of a temperature sensor **800** according to another embodiment of the present disclosure. In this embodiment, the temperature sensor **800** includes a ceramic coil inductor **810** having a first end plate **820** and a second end plate **830**. The temperature sensor **800** further includes a PDC nanocomposite **840** that is disposed between the first and second end plates, **820**, **830**.

The temperature sensor **800** further includes a patch antenna **850** that is attached to the first end plate **820** of the ceramic coil inductor **810** and is configured to communicate with an external radio frequency antenna. Therefore, by using wireless transmission, the signal transmission distance can be accomplished over a network of RF links, such as satellite, the Internet, and/or infrared data links, or any other desired communication path.

Polymer-derived ceramic (PDC) materials are synthesized by thermal decomposition of polymeric precursors, instead of by conventionally sintering ceramic powder compacts. The polymeric precursor is in liquid form, and solidified into a polymer phase and then further pyrolyzed into a ceramic phase.

It has been demonstrated that the electrical conductivity of PDC materials can be greatly varied by tailoring the composition of the PDC materials from being an insulator to a semiconductor. When in the insulator state, PDC materials possess a dielectric constant that increases monotonically with temperature. This is desired because, when the dielectric constant can be determined, the environmental temperature the sensor is experiencing can be calculated. As shown in FIG. **2**, this trend has been verified for temperatures up to 1000 K (727° C.) at 1 MHz.

In embodiments, the present temperature sensors can be represented as a passive resistor-inductor-capacitor (RLC) circuit, which receives electromagnetic energy from an external transmitter/receiver as shown in FIG. **3**.

The permittivity ε of the PDC nanocomposite is a function of temperature as indicated in Equation (1):

$$\varepsilon=\varepsilon(T) \quad (1)$$

This results in the capacitance C of the RLC circuit being temperature dependent as indicated in Equation 2:

$$C = \varepsilon\frac{A}{d} \tag{2}$$

where A is the area of the end plate that serves as the bottom plate of the ceramic coil inductor, e.g., the second end plate **130**, and d is the distance between two plates (and is also the thickness of ceramic material).

Since the inductance L is a constant, the frequency f of the RLC circuit can then be expressed as Equation 3:

$$f = \frac{1}{2\pi\sqrt{CL}} \tag{3}$$

Therefore, the frequency electromagnetic wave generated by the sensor will change as a function of the temperature. This change in frequency can be transmitted by either the ceramic coil inductor itself or by a patch antenna attached thereto and received by a remotely placed RF reader antenna.

In embodiments, the ceramic composite comprises a ceramic matrix and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and nanofibers dispersed in the ceramic matrix. In some embodiments, the ceramic matrix comprises a polymer-derived ceramic (PDC) material.

In some embodiments, the carbon nanotubes comprise single-walled carbon nanotubes, multi-walled carbon nanotubes, or a combination thereof.

The ceramic composites provided herein generally may include a relatively high volume fraction of carbon nanotubes. As shown in FIG. **4**A, it has been found that high volume fraction of carbon nanotubes in combination with a PDC material result in ceramic composites having greater electrical conductivity compared to other CNT-reinforced ceramic composites and to graphite. Therefore, high electrical conductivity, which is desirable, may be provided, at least in part, by the high volume of carbon nanotubes.

In embodiments, the volume fraction of carbon nanotubes in the composite material is about 15% to about 90%, for example about 15%, about 20%, about 25%, about 30%, about 35%, about 40%, about 45%, about 50%, about 55%, about 60%, about 65%, about 70%, about 75%, about 80%, about 85%, about 90%, or any ranges therebetween. In some embodiments, the volume fraction of carbon nanotubes in the composite material is about 30% to about 80%. In some embodiments, the volume fraction of carbon nanotubes in the composite material is about 40% to about 70%. In some embodiments, the volume fraction of carbon nanotubes in the composite material is about 60%.

Additionally, as illustrated in FIG. **4**B, the present ceramic composites are lighter and possess a desirable amount of electrical conductivity, along with having the ability to withstand high temperatures. FIG. **4**B compares the electrical conductivity changes with elevated temperature for an exemplary ceramic composite compared to copper. As seen in FIG. **4**B, the electrical conductivity of the ceramic composite increases as the temperature increases to 750° C. This trend is desirable not only because the higher the electrical conductivity of the sensor, the greater the distance the sensor signal can be transmitted by the ceramic coil inductor itself or by the patch antenna, but also because elevated temperatures may not adversely affect the performance of the sensor.

Pressure Sensors

Generally, the pressure sensors comprise a ceramic coil inductor formed of a ceramic composite, which has carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers dispersed in a ceramic matrix, and a polymer-derived ceramic (PDC) nanocomposite. In some embodiments, the ceramic matrix comprises a polymer-derived ceramic (PDC) material.

An exemplary embodiment of a pressure sensor is illustrated in FIGS. **5**A-**5**C. In this embodiment, the pressure sensor **200** includes a ceramic coil inductor **210** having a first end plate **220** and a second end plate **230**. The pressure sensor **200** further includes a PDC nanocomposite structure **240** that is disposed between the first and second end plates **220**, **230**. The PDC nanocomposite structure **240** has two opposed, generally disk shaped walls and an outer ring wall that together define an internal cavity **250**. The internal cavity **250** is bounded, in part, by a first cavity surface **260**, which includes a generally centrally-located elevated regional surface **290**, and a second cavity surface **280**. The elevated regional surface **290** is part of protrusion **270**. The elevated regional surface **290** of the first cavity surface **260** is not in contact with the second cavity surface **280**. Instead, the elevated regional surface **290** is spaced a distance D from the second cavity surface **280**. The distance D will vary based on the differential between the pressure within the internal cavity **250** and the pressure of the external environment in which the pressure sensor **200** is located. The distance D will vary inversely proportional to the environmental pressure. In some embodiments, the protrusion **270** is generally in the shape of a cylindrical disk.

In certain embodiments, the ceramic coil inductor **210** is configured to communicate with an external radio frequency antenna. Therefore, by using wireless transmission, the signal transmission distance can be accomplished over a network of RF links, such as satellite, the Internet, and/or infrared data links, or any other desired communication path.

FIG. **9** illustrates an elevated side view of a pressure sensor **900** according to another embodiment of the present disclosure. In this embodiment, the pressure sensor **900** includes a ceramic coil inductor **910** having a first end plate **920** and a second end plate **930**. The pressure sensor **900** further includes a PDC nanocomposite structure **940** that is disposed between the first and second end plates **920**, **930**. The PDC nanocomposite structure **940** has two opposed, generally disk shaped walls and an outer ring wall that together define an internal cavity **950**. The internal cavity **950** is bounded, in part, by a first cavity surface **960**, which includes a generally centrally-located elevated regional surface **290**, and a second cavity surface **280**. The elevated regional surface **990** is part of protrusion **970**. The elevated regional surface **990** of the first cavity surface **960** is not in contact with the second cavity surface **980**. Instead, the elevated regional surface **990** is spaced a distance D from the second cavity surface **980**. The distance D will vary based on the differential between the pressure within the internal cavity **950** and the pressure of the external environment in which the pressure sensor **900** is located. The distance D will vary inversely proportional to the environmental pressure. In some embodiments, the protrusion **970** is generally in the shape of a cylindrical disk.

The pressure sensor **900** further includes a patch antenna **995** that is attached to the first end plate **920** of the ceramic coil inductor **910** and is configured to communicate with an external radio frequency antenna. Therefore, by using wireless transmission, the signal transmission distance can be accomplished over a network of RF links, such as satellite, the Internet, and/or infrared data links, or any other desired communication path.

In embodiments, the present pressure sensors can be represented as an evanescent-mode cavity resonator, which receives electromagnetic energy from an external transmitter/receiver as shown in FIG. **6**.

The resonant frequency of the evanescent-mode resonator can be expressed as Equation (4):

$$f_r = \frac{1}{2\pi\sqrt{L(C_p + C_r)}} \tag{4}$$

where $C_p$ represents parallel-plate capacitance between the second cavity surface and the protrusion, $C_r$ is the remaining fringing capacitance, and L is the equivalent inductance.

The parallel-plate capacitance $C_p$ between the second cavity and the protrusion is expressed as indicated in Equation 5:

$$C_p = \frac{\varepsilon_o A}{\text{gap}} \tag{5}$$

where εo is the permittivity of the PDC nanocomposite at room temperature, A is the area of the first surface of the protrusion, and the gap is the distance between the second cavity surface and the first surface of the protrusion.

With pressure being applied to the pressure sensor, $C_p$ increases with the reduced gap due to the cavity deformation of the PDC nanocomposite, and therefore the gap is inversely proportional to pressure. Therefore, the frequency electromagnetic wave generated by the pressure sensor will change as a function of the applied pressure. This change in frequency can be transmitted by the ceramic coil inductor and received by a remotely placed RF reader antenna.

In some embodiments, the carbon nanotubes comprise single-walled carbon nanotubes, multi-walled carbon nanotubes, or a combination thereof.

As discussed above, the ceramic composites provided herein generally may include a relatively high volume fraction of carbon nanotubes. In embodiments, the volume fraction of carbon nanotubes in the composite material is about 20% to about 90%. In other embodiments, the volume fraction of carbon nanotubes in the composite material is about 30% to about 80%. In some particular embodiments, the volume fraction of carbon nanotubes in the composite material is about 40% to about 70%. In some embodiments, the volume fraction of carbon nanotubes in the composite material is about 60%.

Methods of Manufacture

Generally, the methods for making the wireless temperature and pressure sensors described herein include disposing a PDC nanocomposite between a first end plate and a second end plate of a ceramic coil inductor. The ceramic coil inductor comprises carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers dispersed in a ceramic matrix.

Temperature Sensors

In some embodiments, the PDC nanocomposite is in the form of a thin film and has a dielectric constant that increases monotonically with temperature. In such embodiments, the method may further comprise attaching a patch antenna to the first end plate of the ceramic coil inductor.



In some embodiments, the method of making a wireless temperature sensor further includes forming the ceramic coil inductor and/or the PDC nanocomposite via an additive manufacturing process. Exemplary additive manufacturing processes are disclosed in U.S. Patent Application Publication No. 2017/0341297 A1, which is incorporated by reference herein.

In some embodiments, the additive manufacturing process includes (i) providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers; (ii) disposing the mixture on a support; (iii) exposing the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer; and (iv) subjecting the mixture to pyrolysis at a temperature and time effective to form the ceramic coil inductor or the PDC nanocomposite.

In some embodiments, the additive manufacturing process includes (i) providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers; (ii) disposing a first portion of the mixture on a support; (iii) exposing the first portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the first portion; (iv) disposing a second portion of the mixture on the first portion; (v) exposing the second portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the second portion; and (vi) subjecting the first and second portions of the mixture to pyrolysis at a temperature and time effective to form the ceramic coil inductor or the PDC nanocomposite.

In some variations of the foregoing embodiments, the curing step may be effected by application of other suitable wavelengths of light and/or by heating the mixture.

In some embodiments, a 3D printing process is used to place the mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers, onto a support. 3D printing systems are known in the art and may be readily adapted to dispose the mixture on a support to form a ceramic coil inductor of the present temperature sensors.

In some embodiments, the support is maintained at a temperature equal to or less than the freezing point of the liquid-state pre-ceramic polymer. Not wishing to be bound by any particular theory, it is believed that a support maintained at such a temperature may allow the dimensions of the liquid-state pre-ceramic polymer disposed on the substrate to be at least substantially controlled.

In one embodiment, one or more additives are added to the mixture. The one or more additives may include powders, a UV sensitizer, or a combination thereof. The powders may include metal powders.

In embodiments, the liquid-state pre-ceramic polymer is a paste. In some particular embodiments, the liquid-state pre-ceramic polymer is an aqueous paste.

In one embodiment, the liquid-state pre-ceramic polymer is formed by mixing a pre-ceramic material and water. Proper mixing may be used to ensure that the mixture will be soluble enough to ease the deposition of the liquid-state pre-ceramic polymer, such as with 3D printing, with no entrapped gas in it.

In some embodiments, the liquid-state pre-ceramic polymer includes polysilazane.

The mixture may be formed by mixing the components in a suitable container (e.g., a beaker or other processing or reaction vessel), with mechanical stirring, such as with a magnetic mixer, for a period effective to substantially uniformly disperse the components with the mixture.

The viscosity of the liquid-state pre-ceramic polymer may be tested. Based on the viscosity, mixing may be continued as necessary, or the proportions of the components may be adjusted to achieve a desired viscosity, or a combination thereof.

When the liquid-state pre-ceramic polymer is a paste, the paste, in embodiments, should not be too thick or too watery, so that the paste can be suitably transported and deposited, and otherwise processed as described herein. Not wishing to be bound by any particular theory, it is believed that a relatively thick paste may make extrusion/printing/disposing more difficult to perform and/or may lead to cracks, while paste that is not viscous enough may make extrusion/printing/disposing hard to control and also may add time to the curing and/or pyrolysis steps. Viscosity checks, if necessary, may be performed frequently as mixing proceeds, and mixing stopped when a suitable viscosity is achieved.

Once the mixture is obtained, the mixture may be collected into a syringe or other device, for loading into a 3D printer or other apparatus configured to dispose the mixture on a substrate.

In some embodiments, the performance of the temperature sensors described herein may be tested using arc-jet facilities, such as a short-take and vertical landing (STOVL) jet facility, or wind tunnels.

Pressure Sensors

In some embodiments, the PDC nanocomposite defines an internal cavity having a first cavity surface from which a protrusion extends, but does not contact, a second cavity surface. The protrusion has a first surface that is spaced at a distance from the second cavity surface in which the distance is inversely proportional to pressure.

In some embodiments, the method for making the present wireless pressure sensors further includes forming the ceramic coil inductor and/or the PDC nanocomposite via an additive manufacturing process. Exemplary additive manufacturing processes are disclosed in U.S. Patent Application Publication No. 2017/0341297 A1, which is incorporated by reference herein.

In some embodiments, the additive manufacturing process for forming the ceramic coil inductor includes (i) providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers; (ii) disposing the mixture on a support; (iii) exposing the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer; and (iv) subjecting the mixture to pyrolysis at a temperature and time effective to form the ceramic coil inductor.

In some embodiments, the additive manufacturing process for forming the ceramic coil inductor includes (i) providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers; (ii) disposing a first portion of the mixture on a support; (iii) exposing the first portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the first portion; (iv) disposing a second portion of the mixture on the first portion; (v) exposing the second portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the second portion; and (vi) subjecting the first and second portions of the mixture to pyrolysis at a temperature and time effective to form the ceramic coil inductor.

In some embodiments, the additive manufacturing process for forming the PDC nanocomposite includes (i) providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers; (ii) disposing a first portion of the mixture on a first support; (iii) exposing the first portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the first portion; (iv) subjecting the first portion of the mixture to pyrolysis at a temperature and time effective to form a first section of the PDC nanocomposite, wherein the first portion comprises a first cavity surface; (v) metallizing the first portion of the PDC nanocomposite; (vi) disposing a second portion of the mixture on a second support; (vii) exposing the second portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the second portion; (viii) subjecting the second portion of the mixture to pyrolysis at a temperature and time effective to form a second section of the polymer derived-ceramic nanocomposite, wherein the second portion comprises a second cavity surface; metallizing the second portion of the PDC nanocomposite; and (ix) joining the first portion with the second portion to form the PDC nanocomposite.

In some variations of the foregoing embodiments, the curing step may be effected by application of other suitable wavelengths of light and/or by heating the mixture.

In one embodiment, disposing the mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers on a support includes 3D printing the mixture on a support.

In one embodiment, the support is maintained at a temperature equal to or less than the freezing point of the liquid-state pre-ceramic polymer. Not wishing to be bound by any particular theory, it is believed that a support maintained at such a temperature may allow the dimensions of the liquid-state pre-ceramic polymer disposed on the substrate to be at least substantially controlled.

In one embodiment, one or more additives are added to the mixture. The one or more additives may include powders, a UV sensitizer, or a combination thereof. The powders may include metal powders.

In embodiments, the liquid-state pre-ceramic polymer is a paste. In particular embodiments, the liquid-state pre-ceramic polymer is an aqueous paste.

In one embodiment, the liquid-state pre-ceramic polymer is formed by mixing a pre-ceramic material and water. Proper mixing may be used to ensure that the mixture will be soluble enough to ease the deposition of the liquid-state pre-ceramic polymer, such as with 3D printing, with no entrapped gas in it.

In one embodiment, the liquid-state pre-ceramic polymer comprises polysilazane.

The mixture may be formed by mixing the components in a suitable container (e.g., a beaker or other processing or reaction vessel), with mechanical stirring, such as with a magnetic mixer, for a period effective to substantially evenly mix the components.

The viscosity of the liquid-state pre-ceramic polymer may be tested. Based on the viscosity, mixing may be continued as necessary, or the proportions of the components may be adjusted to achieve a desired viscosity, or a combination thereof.

When the liquid-state pre-ceramic polymer is a paste, the paste, in embodiments, must not be too thick, nor too watery. Not wishing to be bound by any particular theory, it is believed that a relatively thick paste may make extrusion/printing/disposing more difficult to perform and/or may lead to cracks, while paste that is not viscous enough may make extrusion/printing/disposing hard to control and also may add time to the curing and/or pyrolysis steps. Viscosity checks, if necessary, may be performed frequently as mixing proceeds, and mixing may be stopped when good viscosity is achieved.

Once the mixture is obtained, the mixture may be collected into a syringe or other device, for loading into a 3D printer or other apparatus configured to dispose the mixture on a substrate.

Method of Use

Generally, the wireless temperature sensors described herein are used to detect a change in temperature of an environment, such as an in-flight environment of an M&M system. Similarly, the wireless pressure sensors described herein are used to detect a change in pressure of an environment, such as an operational environment of a gas turbine.

Temperature Sensors

In some embodiments, the method of detecting a change in temperature comprises placing one or more temperature sensors as described herein in an environment; and measuring a frequency shift of an electromagnetic signal induced in the ceramic coil inductor to detect a change in temperature of the environment.

As described herein, the change in permittivity of the ceramic matrix of the ceramic coil inductor is a function of temperature within the environment. In embodiments, the change in permittivity of the ceramic matrix results in the frequency shift of the electromagnetic signal.

In some embodiments, the one or more temperature sensors are configured to detect the change in temperature in the environment with a temperature in the range from about 800° C. to about 1000° C., for example, about 810° C., about 825° C., about 850° C., about 900° C., about 925° C., about 950° C., about 980° C., and any ranges therebetween. In some embodiments, the one or more temperature sensors are configured to detect the change in temperature in the environment with a temperature in the range of from about 25° C. to about 1000° C., for example about 25° C., about 100° C., about 200° C., about 300° C., about 400° C., about 500° C., about 600° C., about 700° C., about 800° C., about 900° C., about 100° C., and any ranges therebetween.

FIG. **7** shows an exemplary system of a present temperature sensor integrated into an M&M system. The system **700** includes an aircraft **702**, and a wireless ceramic temperature sensor **704** for in-flight heath monitoring. The wireless ceramic temperature sensor includes a wireless sensor **706** and an RF antenna **708**. Using the RF antenna **708**, the sensor **704** communicates with several field programmable gate arrays ("FPGA"). For example, the sensor **704** communicates with a DSP processing FPGA **710** and a control FPGA **712**, each of which communicates with a processor interface FPGA **714**. The processor interface **714** in turn communicates with a processor **716** and a secure communication FPGA **718**. The control FPGA **712** communicates with a roll/pitch/altitude sensor **720** and a control motor **722**, which may control parts of the aircraft **702**.

Pressure Sensors

In some embodiments, the method of detecting a change in pressure comprises placing one or more pressure sensors as described herein in an environment; and measuring a frequency shift of an electromagnetic signal induced in the ceramic coil inductor to detect a change in pressure of the environment.

As described herein, the change in distance is a function of pressure within the environment. In embodiments, the change in the distance between the first surface of the protrusion and the second cavity surface results in the frequency shift.

In some embodiments, the one or more pressure sensors are configured to detect the change in pressure in the environment with a pressure in the range from about 0 psi to about 40,000 psi, for example about 1 psi, about 10 psi, about 50 psi, about 100 psi, about 150 psi, about 200 psi, about 300 psi, about 400 psi, about 500 psi, about 600 psi, about 700 psi, about 800 psi, about 900 psi, about 1,000 psi, about 2,000 psi, about 3,000 psi, about 4,000 psi, about 5,000 psi, about 6,000 psi, about 7,000 psi, about 8,000 psi, about 9,000 psi, about 10,000 psi, about 15,000 psi, about 20,000 psi, about 25,000 psi, about 30,000 psi, about 35,000 psi, about 40,000 psi, and any ranges therebetween.

It should be apparent that the foregoing relates only to certain embodiments of the present disclosure and that numerous changes and modifications may be made herein without departing from the spirit and the scope of the disclosure as defined by the following claims and equivalents thereof.

We claim:

**1**. A temperature sensor comprising:

a ceramic coil inductor having a first end plate and a second end plate, wherein the ceramic coil inductor is formed of a ceramic composite that comprises carbon nanotubes, carbon nanofibers, or a combination thereof dispersed in a ceramic matrix; and

a thin film polymer-derived ceramic (PDC) nanocomposite disposed between the first and the second end plates, wherein the thin film PDC nanocomposite has a dielectric constant that increases monotonically with temperature.

**2**. The temperature sensor of claim **1**, wherein the ceramic coil inductor is configured to communicate with an external radio frequency antenna.

**3**. The temperature sensor of claim **1**, further comprising a patch antenna configured to communicate with an external radio frequency antenna, wherein the patch antenna is attached to the first end plate of the ceramic coil inductor.

**4**. The temperature sensor of claim **1**, wherein the volume fraction of carbon nanotubes in the ceramic composite is about 15% to about 70%.

**5**. The temperature sensor of claim **1**, wherein the ceramic matrix comprises a PDC material.

**6**. The temperature sensor of claim **1**, wherein the ceramic composite comprises single-walled carbon nanotubes, multi-walled carbon nanotubes, or a combination thereof.

**7**. A method of detecting a change in temperature, the method comprising:

placing one or more temperature sensors of claim **1** in an environment; and

measuring a frequency shift of an electromagnetic signal induced in the ceramic coil to detect a change in temperature of the environment.

**8**. The method of claim **7**, wherein the one or more temperature sensors are configured to detect the change in temperature in the environment with a temperature in the range from about 25° C. to about 1000° C.

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## Description

### Cross-Reference to Related Applications

**[0001]** This application claims priority to U.S. Provisional Patent Application No. 62/443,103, filed on January 6, 2017.

### Statement Regarding Federally Sponsored Research or Development

**[0002]** This invention was made with government support under contract number N00014-11-1-0706 awarded by the Office of Naval Research. The government has certain rights in the invention.

### Background

**[0003]** Maintaining situational awareness of the weapon environment is desirable for developing the next generation of robust missile and munition (M&M) systems that can withstand the extreme acceleration, temperature, and pressure conditions that are presented by traditional fighter and hypersonic aircraft. Conventional techniques for remotely monitoring munition assets are primarily performed by proximate environmental monitoring by fuel sensors, accelerometers, surface acoustic wave sensors, chemical resistors, and temperature sensors, which unfortunately are limited to storage and transportation purposes. In addition, conventional temperature testing for M&M surveillance is performed over a limited temperature range, e.g., -55 °C to 125 °C.

**[0004]** Typical conventional temperature sensors used in the evaluation of M&M systems include thermocouples, thermistors, resistance thermometers, quartz thermometers, which all include a metallic coil inductor. However, these temperature sensors have certain drawbacks. For example, these temperature sensors cannot be used in high temperature environments (e.g., 800 °C to 1400 °C) for prolonged periods of time due to oxidation of the metallic coil inductor, or can only be used under wired measurement conditions, and therefore are not suitable for in-flight monitoring. As a result, these temperature sensors can provide only limited evaluation of M&M systems.

**[0005]** It therefore would be desirable to provide improved temperature sensors that overcome one or more of the foregoing limitations. In particular, it would be desirable to provide a temperature sensor that can withstand high temperatures for prolonged periods of time, along with the ability to wirelessly transmit real-time, in-flight temperature data of M&M systems.

**[0006]** Similarly, real-time, online pressure monitoring is desired for many harsh-environment applications, such as gas turbines for power generation, to maintain operational effectiveness and safety. However, in such applications, suitable pressure sensors need to withstand corrosive gas environments having high temperatures (e.g., 1000 °C to 1400 °C) and high pressures (e.g., 300 psi to 600 psi, being about 20.7-41.4 bar).

**[0007]** Typical conventional pressure sensors used in these applications include passive pressure sensors based on resistive or capacitive sensing mechanisms. However, these pressure sensors have certain drawbacks. For example, wire interconnection is required to interrogate these sensors, and these sensors cannot operate effectively in high temperature environments. Moreover, pressure sensors that utilize a patch antenna operate within a limited temperature range, e.g., -55 °C to 125 °C, because of the metallic wire used with the patch antenna. As a result, the application of these common pressure sensors is limited.

**[0008]** It therefore would be desirable to provide improved pressure sensors that overcome one or more of the foregoing limitations. In particular, it would be desirable to provide a pressure sensor that can withstand high temperatures and pressures for prolonged periods, along with the ability to wirelessly transmit real-time pressure data.

**[0009]** US 6 278 379 B1; US 2016/009741 A1, US 2010/321191 A1; Xun Gong et al "Wireless passive sensor development for harsh environment applications", Antenna Technology (IWAT), March 2012 , pages 140-143; and Haitao Cheng et al "Evanescent-mode-resonator-based and antenna-integrated wireless passive pressure sensors for harsh-environment applications", Sensors and Actuators A 220 (2014) 22-23, 1 December 2014, pages 22-23; and US 2015/028889 A1 disclose temperature and pressure sensors of prior art.

### Summary

**[0010]** In one aspect, a temperature sensor is provided which includes: a ceramic coil inductor having a first end plate and a second end plate, wherein the ceramic coil inductor is formed of a ceramic composite that comprises carbon nanotubes, carbon nanofibers, or a combination thereof dispersed in a ceramic matrix; and a thin film polymer-derived ceramic (PDC) nanocomposite disposed between the first and the second end plates, wherein the thin film PDC nanocomposite has a dielectric constant that increases monotonically with temperature.

**[0011]** In another aspect, a method for making a wireless temperature sensor is provided, the method including: disposing a thin film PDC nanocomposite between a first end plate and a second end plate of a ceramic coil inductor, wherein the ceramic coil inductor comprises carbon nanotubes, or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers thereof dispersed in a ceramic matrix, wherein the thin film PDC nanocomposite has a dielectric constant that increases monotonically with temperature.

**[0012]** In another aspect, a method of detecting a change in temperature is provided, the method including: placing one or more temperature sensors described above in an environment; and measuring a frequency shift of an electromagnetic signal induced in the ceramic coil inductor to detect a change in temperature of the environment.

**Brief Description of the Drawings**

**[0013]** The detailed description is set forth with reference to the accompanying drawings. The use of the same reference numerals may indicate similar or identical items. Various embodiments may utilize elements and/or components other than those illustrated in the drawings, and some elements and/or components may not be present in various embodiments. Elements and/or components in the figures are not necessarily drawn to scale.

**FIG. 1A** is a top plan view of a temperature sensor in accordance with an embodiment of the present disclosure.

**FIG. 1B** is an elevated side view of the temperature sensor in **FIG. 1A.**

**FIG. 1C** is a bottom plan view of the temperature sensor in **FIG. 1A**.

**FIG. 2** is a graph showing the dielectric constant of polymer-derived ceramic material as a function of temperature at 1 MHz.

**FIG. 3** is a schematic of an exemplary temperature sensor represented as a passive resistor-inductor-capacitor (RLC) circuit.

**FIG. 4A** is a graph illustrating the mechanical and electrical properties of a ceramic composite of an exemplary temperature sensor of the present disclosure compared to other representative CNT-reinforced ceramic composites and graphite.

**FIG. 4B** is a graph showing a change in measured electrical conductivity of a ceramic composite of an exemplary temperature sensor of the present disclosure as a function of temperature.

**FIG. 5A** is a top perspective view of a pressure sensor in accordance with an example which does not form part of the present invention.

**FIG. 5B** is a cross-sectional view of the pressure sensor in **FIG. 5A**.

**FIG. 5C** is a bottom perspective view of the pressure sensor in **FIG. 5A**.

**FIG. 6** is a schematic of an exemplary pressure sensor , which does not form part of the present invention, represented as an evanescent-mode cavity resonator.

**FIG. 7** is a schematic of a temperature sensor of the present disclosure integrated within an exemplary missile and munition (M&M) system.

**FIG. 8** is an elevated side view of a temperature sensor according to an embodiment of the present disclosure.

**FIG. 9** is an elevated side view of a pressure sensor according to an example which does not form part of the present invention.

**Detailed Description**

**[0014]** New temperature and pressure sensors are provided herein that may include a ceramic coil inductor having ceramic material and a relatively high volume fraction of carbon nanotubes. The combination leverages the remarkable electrical and mechanical properties (stiff and strong) of carbon nanotubes (CNTs) and the thermal properties (temperature sensitivity) of ceramic materials.

**[0015]** In some embodiments, the temperature sensors provided herein are high temperature, wireless sensors having one or more of the following advantages: (i) the ability to provide real-time, in-flight monitoring of M&M systems; (ii) the ability to maintain safety and effectiveness of critical parts and materials of the M&M systems without the need for extensive non-destructive evaluation (NDE), thereby reducing cost and time; and (iii) on-demand tracking and assessing of the status of the M&M systems over extended periods, based upon changing conditions.

**[0016]** Similarly, in some examples which do not form part of the present invention, the pressure sensors provided herein are wireless and can operate in harsh, corrosive gaseous environments having high temperatures and pressures. These sensors have one or more of the following advantages: (i) the ability to provide real-time, monitoring of systems that operate in high temperature and pressure environments; (ii) the ability to maintain safety and effectiveness of critical parts and materials of these systems, thereby reducing cost and time; and (iii) on-demand tracking and assessing of the status of systems over extended periods, based upon changing conditions.

Temperature Sensors

**[0017]** In some embodiments, the temperature sensors include a ceramic coil inductor that is formed of a ceramic composite and a thin film polymer-derived ceramic (PDC) nanocomposite having a dielectric constant that increases monotonically with temperature.

**[0018]** An exemplary embodiment is illustrated in **FIGS. 1A-1C**. In this embodiment, the temperature sensor **100** includes a ceramic coil inductor **110** having a first end plate **120** and a second end plate **130**. The temperature sensor **100** further includes a PDC nanocomposite **140** that is disposed between the first and second end plates, **120**, **130**.

**[0019]** In certain embodiments, the ceramic coil inductor **110** is configured to communicate with an external radio frequency antenna. In other embodiments, the temperature sensor **100** includes a patch antenna that is attached to the first end plate **120** of the ceramic coil inductor **110** and is configured to communicate with an external radio frequency antenna. Therefore, by using wireless transmission, the signal transmission distance can be accomplished over a network of RF links, such as satellite, the Internet, and/or infrared data links, or any other desired communication path.

**[0020]** **FIG. 8** illustrates an elevated side view of a temperature sensor **800** according to another embodiment of the present disclosure. In this embodiment, the temperature sensor **800** includes a ceramic coil inductor **810** having a first end plate **820** and a second end plate **830**. The temperature sensor **800** further includes a PDC nanocomposite **840** that is disposed between the first and second end plates, **820**, **830**.

**[0021]** The temperature sensor **800** further includes a patch antenna **850** that is attached to the first end plate **820** of the ceramic coil inductor **810** and is configured to communicate with an external radio frequency antenna. Therefore, by using wireless transmission, the signal transmission distance can be accomplished over a network of RF links, such as satellite, the Internet, and/or infrared data links, or any other desired communication path.

**[0022]** Polymer-derived ceramic (PDC) materials are synthesized by thermal decomposition of polymeric precursors, instead of by conventionally sintering ceramic powder compacts. The polymeric precursor is in liquid form, and solidified into a polymer phase and then further pyrolyzed into a ceramic phase.

**[0023]** It has been demonstrated that the electrical conductivity of PDC materials can be greatly varied by tailoring the composition of the PDC materials from being an insulator to a semiconductor. When in the insulator state, PDC materials possess a dielectric constant that increases monotonically with temperature. This is desired because, when the dielectric constant can be determined, the environmental temperature the sensor is experiencing can be calculated. As shown in **FIG. 2**, this trend has been verified for temperatures up to 1000 K (727 °C) at 1 MHz.

**[0024]** In embodiments, the present temperature sensors can be represented as a passive resistor-inductor-capacitor (RLC) circuit, which receives electromagnetic energy from an external transmitter/receiver as shown in **FIG. 3**.

**[0025]** The permittivity $\varepsilon$ of the PDC nanocomposite is a function of temperature as indicated in Equation (1):

$$\varepsilon = \varepsilon(T) \qquad (1)$$

**[0026]** This results in the capacitance C of the *RLC* circuit being temperature dependent as indicated in Equation 2:

$$\mathrm{C} = \varepsilon \frac{A}{d} \qquad (2)$$

where *A* is the area of the end plate that serves as the bottom plate of the ceramic coil inductor, e.g., the second end plate **130**, and *d* is the distance between two plates (and is also the thickness of ceramic material).

**[0027]** Since the inductance *L* is a constant, the frequency *f* of the *RLC* circuit can then be expressed as Equation 3:

$$f = \frac{1}{2\pi\sqrt{CL}} \qquad (3)$$

**[0028]** Therefore, the frequency electromagnetic wave generated by the sensor will change as a function of the temperature. This change in frequency can be transmitted by either the ceramic coil inductor itself or by a patch antenna attached thereto and received by a remotely placed RF reader antenna.

**[0029]** In embodiments, the ceramic composite comprises a ceramic matrix and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and nanofibers dispersed in the ceramic matrix. In some embodiments, the ceramic matrix comprises a polymer-derived ceramic (PDC) material.

**[0030]** In some embodiments, the carbon nanotubes comprise single-walled carbon nanotubes, multi-walled carbon nanotubes, or a combination thereof.

**[0031]** The ceramic composites provided herein generally may include a relatively high volume fraction of carbon nanotubes. As shown in **FIG. 4A**, it has been found that high volume fraction of carbon nanotubes in combination with a PDC material result in ceramic composites having greater electrical conductivity compared to other CNT-reinforced ceramic composites and to graphite. Therefore, high electrical conductivity, which is desirable, may be provided, at least in part, by the high volume of carbon nanotubes.

**[0032]** In embodiments, the volume fraction of carbon nanotubes in the composite material is about 15% to about 90%, for example about 15%, about 20%, about 25%, about 30%, about 35%, about 40%, about 45%, about 50%, about 55%, about 60%, about 65%, about 70%, about 75%, about 80%, about 85%, about 90%, or any ranges therebetween. In some embodiments, the volume fraction of carbon nanotubes in the composite material is about 30% to about 80%. In some embodiments, the volume fraction of carbon nanotubes in the composite material is about 40% to about 70%. In some embodiments, the volume fraction of carbon nanotubes in the composite material is about 60%.

**[0033]** Additionally, as illustrated in **FIG. 4B**, the present ceramic composites are lighter and possess a desirable amount of electrical conductivity, along with having the ability to withstand high temperatures. **FIG. 4B** compares the electrical conductivity changes with elevated temperature for an exemplary ceramic composite compared to copper. As seen in **FIG. 4B**, the electrical conductivity of the ceramic composite increases as the temperature increases to 750 °C. This trend is desirable not only because the higher the electrical conductivity of the sensor, the greater the distance the sensor signal can be transmitted by the ceramic coil inductor itself or by the patch antenna, but also because elevated temperatures may not adversely affect the performance of the sensor.

## Pressure Sensors not forming part of the present invention

**[0034]** Generally, the pressure sensors comprise a ceramic coil inductor formed of a ceramic composite, which has carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers dispersed in a ceramic matrix, and a polymer-derived ceramic (PDC) nanocomposite. In some embodiments, the ceramic matrix comprises a polymer-derived ceramic (PDC) material.

**[0035]** An exemplary embodiment of a pressure sensor which does not form part of the present invention is illustrated in **FIGS. 5A-5C**. In this embodiment, the pressure sensor **200** includes a ceramic coil inductor **210** having a first end plate **220** and a second end plate **230**. The pressure sensor **200** further includes a PDC nanocomposite structure **240** that is disposed between the first and second end plates **220**, **230**. The PDC nanocomposite structure **240** has two opposed, generally disk shaped walls and an outer ring wall that together define an internal cavity **250**. The internal cavity **250** is bounded, in part, by a first cavity surface **260**, which includes a generally centrally-located elevated regional surface **290**, and a second cavity surface **280**. The elevated regional surface **290** is part of protrusion **270**. The elevated regional surface **290** of the first cavity surface **260** is not in contact with the second cavity surface **280**. Instead, the elevated regional surface **290** is spaced a distance **D** from the second cavity surface **280**. The distance **D** will vary based on the differential between the pressure within the internal cavity **250** and the pressure of the external environment in which the pressure sensor **200** is located. The distance **D** will vary inversely proportional to the environmental pressure. In some embodiments, the protrusion **270** is generally in the shape of a cylindrical disk.

**[0036]** In certain embodiments, the ceramic coil inductor **210** is configured to communicate with an external radio frequency antenna. Therefore, by using wireless transmission, the signal transmission distance can be accomplished over a network of RF links, such as satellite, the Internet, and/or infrared data links, or any other desired communication path.

**[0037]** **FIG. 9** illustrates an elevated side view of a pressure sensor **900** according to another embodiment which does not form part of the present invention.

**[0038]** In this embodiment, the pressure sensor **900** includes a ceramic coil inductor **910** having a first end plate **920** and a second end plate **930**. The pressure sensor **900** further includes a PDC nanocomposite structure **940** that is disposed between the first and second end plates **920**, **930**. The PDC nanocomposite structure **940** has two opposed, generally disk shaped walls and an outer ring wall that together define an internal cavity **950**. The internal cavity **950** is bounded, in part, by a first cavity surface **960**, which includes a generally centrally-located elevated regional surface **290**, and a second cavity surface **280**. The elevated regional surface **990** is part of protrusion **970**. The elevated regional surface **990** of the first cavity surface **960** is not in contact with the second cavity surface **980**. Instead, the elevated regional surface **990** is spaced a distance **D** from the second cavity surface **980**. The distance **D** will vary based on the differential between the pressure within the internal cavity **950** and the pressure of the external environment in which the pressure sensor **900** is located. The distance **D** will vary inversely proportional to the environmental pressure. In some embodiments, the protrusion **970** is generally in the shape of a cylindrical disk.

**[0039]** The pressure sensor **900** further includes a patch antenna **995** that is attached to the first end plate **920** of the ceramic coil inductor **910** and is configured to communicate with an external radio frequency antenna. Therefore, by using wireless transmission, the signal transmission distance can be accomplished over a network of RF links, such as satellite, the Internet, and/or infrared data links, or any other desired communication path.

**[0040]** In embodiments, the present pressure sensors can be represented as an evanescent-mode cavity resonator, which receives electromagnetic energy from an external transmitter/receiver as shown in **FIG. 6**.

**[0041]** The resonant frequency of the evanescent-mode resonator can be expressed as Equation (4):

$$f_r = \frac{1}{2\pi\sqrt{L(C_p + C_r)}} \qquad (4)$$

where $C_p$ represents parallel-plate capacitance between the second cavity surface and the protrusion, $C_r$ is the remaining fringing capacitance, and L is the equivalent inductance.

**[0042]** The parallel-plate capacitance $C_p$ between the second cavity and the protrusion is expressed as indicated in Equation 5:

$$C_p = \frac{\varepsilon_o A}{gap} \qquad (5)$$

where $\varepsilon_O$ is the permittivity of the PDC nanocomposite at room temperature, A is the area of the first surface of the protrusion, and the gap is the distance between the second cavity surface and the first surface of the protrusion.

**[0043]** With pressure being applied to the pressure sensor, $C_p$ increases with the reduced gap due to the cavity deformation of the PDC nanocomposite, and therefore the gap is inversely proportional to pressure. Therefore, the frequency electromagnetic wave generated by the pressure sensor will change as a function of the applied pressure. This change in frequency can be transmitted by the ceramic coil inductor and received by a remotely placed RF reader antenna.

**[0044]** In some embodiments, the carbon nanotubes comprise single-walled carbon nanotubes, multi-walled carbon nanotubes, or a combination thereof.

**[0045]** As discussed above, the ceramic composites provided herein generally may include a relatively high volume fraction of carbon nanotubes. In embodiments, the volume fraction of carbon nanotubes in the composite material is about 20 % to about 90 %. In other embodiments, the volume fraction of carbon nanotubes in the composite material is about 30 % to about 80 %. In some particular embodiments, the volume fraction of carbon nanotubes in the composite material is about 40 % to about 70 %. In some embodiments, the volume fraction of carbon nanotubes in the composite material is about 60 %.

## Methods of Manufacture

**[0046]** Generally, the methods for making the wireless temperature and pressure sensors described herein include disposing a PDC nanocomposite between a first end plate and a second end plate of a ceramic coil inductor. The ceramic coil inductor comprises carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers dispersed in a ceramic matrix.

### *Temperature Sensors*

**[0047]** In some embodiments, the PDC nanocomposite is in the form of a thin film and has a dielectric constant that increases monotonically with temperature. In such embodiments, the method may further comprise attaching a patch antenna to the first end plate of the ceramic coil inductor.

**[0048]** In some embodiments, the method of making a wireless temperature sensor further includes forming the ceramic coil inductor and/or the PDC nanocomposite via an additive manufacturing process. Exemplary additive manufacturing processes are disclosed in U.S.

**[0049]** Patent Application Publication No. 2017/0341297 A1.

**[0050]** In some embodiments, the additive manufacturing process includes (i) providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers; (ii) disposing the mixture on a support; (iii) exposing the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer; and (iv) subjecting the mixture to pyrolysis at a temperature and time effective to form the ceramic coil inductor or the PDC nanocomposite.

**[0051]** In some embodiments, the additive manufacturing process includes (i) providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers; (ii) disposing a first portion of the mixture on a support; (iii) exposing the first portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the first portion; (iv) disposing a second portion of the mixture on the first portion; (v) exposing the second portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the second portion; and (vi) subjecting the first and second portions of the mixture to pyrolysis at a temperature and time effective to form the ceramic coil inductor or the PDC nanocomposite.

**[0052]** In some variations of the foregoing embodiments, the curing step may be effected by application of other suitable wavelengths of light and/or by heating the mixture.

**[0053]** In some embodiments, a 3D printing process is used to place the mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers, onto a support. 3D printing systems are known in the art and may be readily adapted to dispose the mixture on a support to form a ceramic coil inductor of the present temperature sensors.

**[0054]** In some embodiments, the support is maintained at a temperature equal to or less than the freezing point of the liquid-state pre-ceramic polymer. Not wishing to be bound by any particular theory, it is believed that a support maintained at such a temperature may allow the dimensions of the liquid-state pre-ceramic polymer disposed on the substrate to be at least substantially controlled.

**[0055]** In one embodiment, one or more additives are added to the mixture. The one or more additives may include powders, a UV sensitizer, or a combination thereof. The powders may include metal powders.

**[0056]** In embodiments, the liquid-state pre-ceramic polymer is a paste. In some particular embodiments, the liquid-state pre-ceramic polymer is an aqueous paste.

**[0057]** In one embodiment, the liquid-state pre-ceramic polymer is formed by mixing a pre-ceramic material and water. Proper mixing may be used to ensure that the mixture will be soluble enough to ease the deposition of the liquid-state pre-ceramic polymer, such as with 3D printing, with no entrapped gas in it.

**[0058]** In some embodiments, the liquid-state pre-ceramic polymer includes polysilazane.

**[0059]** The mixture may be formed by mixing the components in a suitable container (e.g., a beaker or other processing or reaction vessel), with mechanical stirring, such as with a magnetic mixer, for a period effective to substantially uniformly disperse the components with the mixture.

**[0060]** The viscosity of the liquid-state pre-ceramic polymer may be tested. Based on the viscosity, mixing may be continued as necessary, or the proportions of the components may be adjusted to achieve a desired viscosity, or a combination thereof.

**[0061]** When the liquid-state pre-ceramic polymer is a paste, the paste, in embodiments, should not be too thick or too watery, so that the paste can be suitably transported and deposited, and otherwise processed as described herein. Not wishing to be bound by any particular theory, it is believed that a relatively thick paste may make extrusion/printing/disposing more difficult to perform and/or may lead to cracks, while paste that is not viscous enough may make extrusion/printing/disposing hard to control and also may add time to the curing and/or pyrolysis steps. Viscosity checks, if necessary, may be performed frequently as mixing proceeds, and mixing stopped when a suitable viscosity is achieved.

**[0062]** Once the mixture is obtained, the mixture may be collected into a syringe or other device, for loading into a 3D printer or other apparatus configured to dispose the mixture on a substrate.

**[0063]** In some embodiments, the performance of the temperature sensors described herein may be tested using arc-jet facilities, such as a short-take and vertical landing (STOVL) jet facility, or wind tunnels.

*Pressure Sensors not forming part of the present invention*

**[0064]** In some embodiments, the PDC nanocomposite defines an internal cavity having a first cavity surface from which a protrusion extends, but does not contact, a second cavity surface. The protrusion has a first surface that is spaced at a distance from the second cavity surface in which the distance is inversely proportional to pressure.

**[0065]** In some embodiments, the method for making the present wireless pressure sensors further includes forming the ceramic coil inductor and/or the PDC nanocomposite via an additive manufacturing process. Exemplary additive manufacturing processes are disclosed in U.S. Patent Application Publication No. 2017/0341297 A1.

**[0066]** In some embodiments, the additive manufacturing process for forming the ceramic coil inductor includes (i) providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers; (ii) disposing the mixture on a support; (iii) exposing the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer; and (iv) subjecting the mixture to pyrolysis at a temperature and time effective to form the ceramic coil inductor.

**[0067]** In some embodiments, the additive manufacturing process for forming the ceramic coil inductor includes (i) providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers; (ii) disposing a first portion of the mixture on a support; (iii) exposing the first portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the first portion; (iv) disposing a second portion of the mixture on the first portion; (v) exposing the second portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the second portion; and (vi) subjecting the first and second portions of the mixture to pyrolysis at a temperature and time effective to form the ceramic coil inductor.

**[0068]** In some embodiments, the additive manufacturing process for forming the PDC nanocomposite includes (i) providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers; (ii) disposing a first portion of the mixture on a first support; (iii) exposing the first portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the first portion; (iv) subjecting the first portion of the mixture to pyrolysis at a temperature and time effective to form a first section of the PDC nanocomposite, wherein the first portion comprises a first cavity surface; (v) metallizing the first portion of the PDC nanocomposite; (vi) disposing a second portion of the mixture on a second support; (vii) exposing the second portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the second portion; (viii) subjecting the second portion of the mixture to pyrolysis at a temperature and time effective to form a second section of the polymer derived-ceramic nanocomposite, wherein the second portion comprises a second cavity surface; metallizing the second portion of the PDC nanocomposite; and (ix) joining the first portion with the second portion to form the PDC nanocomposite.

**[0069]** In some variations of the foregoing embodiments, the curing step may be effected by application of other suitable wavelengths of light and/or by heating the mixture.

**[0070]** In one embodiment, disposing the mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers on a support includes 3D printing the mixture on a support.

**[0071]** In one embodiment, the support is maintained at a temperature equal to or less than the freezing point of the liquid-state pre-ceramic polymer. Not wishing to be bound by any particular theory, it is believed that a support maintained at such a temperature may allow the dimensions of the liquid-state pre-ceramic polymer disposed on the substrate to be at least substantially controlled.

**[0072]** In one embodiment, one or more additives are added to the mixture. The one or more additives may include powders, a UV sensitizer, or a combination thereof. The powders may include metal powders.

**[0073]** In embodiments, the liquid-state pre-ceramic polymer is a paste. In particular embodiments, the liquid-state pre-ceramic polymer is an aqueous paste.

**[0074]** In one embodiment, the liquid-state pre-ceramic polymer is formed by mixing a pre-ceramic material and water. Proper mixing may be used to ensure that the mixture will be soluble enough to ease the deposition of the liquid-state pre-ceramic polymer, such as with 3D printing, with no entrapped gas in it.

**[0075]** In one embodiment, the liquid-state pre-ceramic polymer comprises polysilazane.

**[0076]** The mixture may be formed by mixing the components in a suitable container (e.g., a beaker or other processing or reaction vessel), with mechanical stirring, such as with a magnetic mixer, for a period effective to substantially evenly mix the components.

**[0077]** The viscosity of the liquid-state pre-ceramic polymer may be tested. Based on the viscosity, mixing may be continued as necessary, or the proportions of the components may be adjusted to achieve a desired viscosity, or a combination thereof.

**[0078]** When the liquid-state pre-ceramic polymer is a paste, the paste, in embodiments, must not be too thick, nor too watery. Not wishing to be bound by any particular theory, it is believed that a relatively thick paste may make extrusion/printing/disposing more difficult to perform and/or may lead to cracks, while paste that is not viscous enough may make extrusion/printing/disposing hard to control and also may add time to the curing and/or pyrolysis steps. Viscosity checks, if necessary, may be performed frequently as mixing proceeds, and mixing may be stopped when good viscosity is achieved.

**[0079]** Once the mixture is obtained, the mixture may be collected into a syringe or other device, for loading into a 3D printer or other apparatus configured to dispose the mixture on a substrate.

## Method of Use

**[0080]** Generally, the wireless temperature sensors described herein are used to detect a change in temperature of an environment, such as an in-flight environment of an M&M system. Similarly, the wireless pressure sensors described herein are used to detect a change in pressure of an environment, such as an operational environment of a gas turbine.

### *Temperature Sensors*

**[0081]** In some embodiments, the method of detecting a change in temperature comprises placing one or more temperature sensors as described herein in an environment; and measuring a frequency shift of an electromagnetic signal induced in the ceramic coil inductor to detect a change in temperature of the environment.

**[0082]** As described herein, the change in permittivity of the ceramic matrix of the ceramic coil inductor is a function of temperature within the environment. In embodiments, the change in permittivity of the ceramic matrix results in the frequency shift of the electromagnetic signal.

**[0083]** In some embodiments, the one or more temperature sensors are configured to detect the change in temperature in the environment with a temperature in the range from about 800 °C to about 1000 °C, for example, about 810 °C, about 825 °C, about 850 °C, about 900 °C, about 925 °C, about 950 °C, about 980 °C, and any ranges therebetween. In some embodiments, the one or more temperature sensors are configured to detect the change in temperature in the environment with a temperature in the range of from about 25 °C to about 1000 °C, for example about 25 °C, about 100 °C, about 200 °C, about 300 °C, about 400 °C, about 500 °C, about 600 °C, about 700 °C, about 800 °C, about 900 °C, about 100 °C, and any ranges therebetween.

**[0084]** **FIG. 7** shows an exemplary system of a present temperature sensor integrated into an M&M system. The system **700** includes an aircraft **702**, and a wireless ceramic temperature sensor **704** for in-flight heath monitoring. The wireless ceramic temperature sensor includes a wireless sensor **706** and an RF antenna **708**. Using the RF antenna **708**, the sensor **704** communicates with several field programmable gate arrays ("FPGA"). For example, the sensor **704** communicates with a DSP processing FPGA **710** and a control FPGA **712**, each of which communicates with a processor interface FPGA **714**. The processor interface **714** in turn communicates with a processor **716** and a secure communication FPGA **718**. The control FPGA **712** communicates with a roll/pitch/altitude sensor **720** and a control motor **722**, which may control parts of the aircraft **702**.

*Pressure Sensors not forming part of the present invention*

**[0085]** In some embodiments, the method of detecting a change in pressure comprises placing one or more pressure sensors as described herein in an environment; and measuring a frequency shift of an electromagnetic signal induced in the ceramic coil inductor to detect a change in pressure of the environment.

**[0086]** As described herein, the change in distance is a function of pressure within the environment. In embodiments, the change in the distance between the first surface of the protrusion and the second cavity surface results in the frequency shift.

**[0087]** In some embodiments, the one or more pressure sensors are configured to detect the change in pressure in the environment with a pressure in the range from about 0 psi to about 40,000 psi, for example about 1 psi, about 10 psi, about 50 psi, about 100 psi, about 150 psi, about 200 psi, about 300 psi, about 400 psi, about 500 psi, about 600 psi, about 700 psi, about 800 psi, about 900 psi, about 1,000 psi, about 2,000 psi, about 3,000 psi, about 4,000 psi, about 5,000 psi, about 6,000 psi, about 7,000 psi, about 8,000 psi, about 9,000 psi, about 10,000 psi, about 15,000 psi, about 20,000 psi, about 25,000 psi, about 30,000 psi, about 35,000 psi, about 40,000 psi, and any ranges therebetween. (1 psi is about 0.069 bar)

## Claims

1. A temperature sensor (100, 800) **characterized in that** it comprises:

   a ceramic coil inductor (110, 810) having a first end plate (120, 820) and a second end plate (130, 830), wherein the ceramic coil inductor (110, 810) is formed of a ceramic composite that comprises carbon nanotubes, carbon nanofibers, or a combination thereof dispersed in a ceramic matrix; and
   a thin film polymer-derived ceramic (PDC) nanocomposite (140, 840) disposed between the first (120, 820) and the second end plates (130, 830), wherein the thin film PDC nanocomposite (140, 840) has a dielectric constant that increases monotonically with temperature.

2. The temperature sensor (100, 800) of claim 1, wherein the ceramic coil inductor (110, 810) is configured to communicate with an external radio frequency antenna.

3. The temperature sensor (100, 800) of claim 1, further comprising a patch antenna (850) configured to communicate with an external radio frequency antenna, wherein the patch antenna (850) is attached to the first end plate (120, 820) of the ceramic coil inductor (110, 810).

4. The temperature sensor (100, 800) of claim 1, wherein the volume fraction of carbon nanotubes in the ceramic composite is about 15 % to about 70 %.

5. The temperature sensor (100, 800) of claim 1, wherein the ceramic matrix comprises a PDC material.

6. The temperature sensor (100, 800) of claim 1, wherein the ceramic composite comprises single-walled carbon nanotubes, multi-walled carbon nanotubes, or a combination thereof.

7. A method for making a wireless temperature sensor (100, 800), the method being **characterized in that** it comprises:

forming a ceramic coil inductor (110, 810) having a first end plate (120, 820) and a second end plate (130, 830), wherein the ceramic coil inductor (110, 810) comprises carbon nanotubes, carbon nanofibers, or a combination thereof dispersed in a ceramic matrix; and
providing a thin film polymer-derived ceramic (PDC) nanocomposite (140, 840) between the first end plate (120, 820) and the second end plate (130, 830), wherein the thin film PDC nanocomposite (140, 840) has a dielectric constant that increases monotonically with temperature. (140, 840)

8. The method of claim 8, further comprising attaching a patch antenna (850) to the first end plat (120, 820) of the ceramic coil inductor (110, 810).

9. The method of claim 7, wherein the ceramic matrix comprises a PDC material.

10. The method of any one of claims 7 to 10, wherein the manufacturing process comprises:

providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes, carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers;
disposing the mixture on a support;
exposing the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer; and
pyrolyzing the mixture at a temperature and for a time effective to form the ceramic coil inductor (110, 810) or the PDC nanocomposite (140, 840).

11. The method of any one of claims 7 to 10, wherein the manufacturing process comprises:

providing a mixture of a liquid-state pre-ceramic polymer and carbon nanotubes or carbon nanofibers, or a combination of carbon nanotubes and carbon nanofibers;
disposing a first portion of the mixture on a support;
exposing the first portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the first portion;
disposing a second portion of the mixture on the first portion;
exposing the second portion of the mixture to ultraviolet light effective to substantially cure the liquid-state pre-ceramic polymer of the second portion; and
pyrolyzing the first and second portions of the mixture at a temperature and for a time effective to form the ceramic coil inductor (110, 810) or the PDC nanocomposite (140, 840).

12. A method of detecting a change in temperature, the method being **characterized in that** it comprises:

placing one or more temperature sensors (100, 800) of any one of claims 1 to 6 in an environment; and
measuring a frequency shift of an electromagnetic signal induced in the ceramic coil inductor (110, 810) to detect a change in temperature of the environment, wherein the one or more temperature sensors (100, 800) are configured to detect the change in temperature in the environment with a temperature in the range from about 25 °C to about 1000 °C.

## Patentansprüche

1. Ein Temperatursensor (100, 800), **dadurch gekennzeichnet, dass** er umfasst:

einen keramischen Spuleninduktor (110, 810) mit einer ersten Endplatte (120, 820) und einer zweiten Endplatte (130, 830), wobei der keramische Spuleninduktor (110, 810) aus einem keramischen Verbundwerkstoff gebildet ist, der Kohlenstoff-Nanoröhrchen, Kohlenstoff-Nanofasern oder eine Kombination davon, dispergiert in einer keramischen Matrix, umfasst; und
einem Dünnfilm-PDC-Nanokomposit (140, 840), der zwischen der ersten (120, 820) und der zweiten Endplatte (130, 830) angeordnet ist, wobei der Dünnfilm-PDC-Nanokomposit (140, 840) eine Dielektrizitätskonstante aufweist, die monoton mit der Temperatur zunimmt.

2. Temperatursensor (100, 800) nach Anspruch 1, wobei die keramische Spuleninduktivität (110, 810) so konfiguriert

ist, dass sie mit einer externen Hochfrequenzantenne kommuniziert.

**3.** Temperatursensor (100, 800) nach Anspruch 1, der ferner eine Patch-Antenne (850) umfasst, die so konfiguriert ist, dass sie mit einer externen Hochfrequenzantenne kommuniziert, wobei die Patch-Antenne (850) an der ersten Endplatte (120, 820) des Keramikspuleninduktors (110, 810) angebracht ist.

**4.** Temperatursensor (100, 800) nach Anspruch 1, wobei der Volumenanteil der Kohlenstoff-Nanoröhren in dem keramischen Verbundstoff etwa 15 % bis etwa 70 % beträgt.

**5.** Temperatursensor (100, 800) nach Anspruch 1, wobei die Keramikmatrix ein PDC-Material umfasst.

**6.** Temperatursensor (100, 800) nach Anspruch 1, wobei der keramische Verbundwerkstoff einwandige Kohlenstoff-Nanoröhren, mehrwandige Kohlenstoff-Nanoröhren oder eine Kombination davon umfasst.

**7.** Verfahren zur Herstellung eines drahtlosen Temperatursensors (100, 800), wobei das Verfahren **dadurch gekennzeichnet ist, dass** es umfasst:

Bilden eines keramischen Spuleninduktors (110, 810) mit einer ersten Endplatte (120, 820) und einer zweiten Endplatte (130, 830), wobei der keramische Spuleninduktor (110, 810) Kohlenstoff-Nanoröhren, Kohlenstoff-Nanofasern oder eine Kombination davon, dispergiert in einer keramischen Matrix, umfasst; und
Bereitstellen eines Dünnschicht-PDC-Nanokomposits (140, 840) zwischen der ersten Endplatte (120, 820) und der zweiten Endplatte (130, 830), wobei das Dünnschicht-PDC-Nanokomposit (140, 840) eine Dielektrizitätskonstante aufweist, die monoton mit der Temperatur zunimmt.

**8.** Verfahren nach Anspruch 7, ferner umfassend das Anbringen einer Patch-Antenne (850) an der ersten Endplatte (120, 820) der Keramikspuleninduktivität (110, 810).

**9.** Verfahren nach Anspruch 7, wobei die Keramikmatrix ein PDC-Material umfasst.

**10.** Verfahren nach einem der Ansprüche 7 bis 10, wobei der Herstellungsprozess umfasst:

Bereitstellen einer Mischung aus einem vorkeramischen Polymer im flüssigen Zustand und Kohlenstoff-Nanoröhren, Kohlenstoff-Nanofasern oder einer Kombination aus Kohlenstoff-Nanoröhren und Kohlenstoff-Nanofasern;
Anordnen des Gemischs auf einem Träger;
Bestrahlen des Gemisches mit ultraviolettem Licht, um das vorkeramische Polymer im flüssigen Zustand im Wesentlichen zu härten; und
pyrolysieren der Mischung bei einer Temperatur und für eine Zeit, die wirksam sind, um den keramischen Spuleninduktor (110, 810) oder den PDC-Nanokomposit (140, 840) zu bilden.

**11.** Verfahren nach einem der Ansprüche 7 bis 10, wobei das Herstellungsverfahren umfasst:

Bereitstellen eines Gemischs aus einem vorkeramischen Polymer im flüssigen Zustand und Kohlenstoff-Nanoröhrchen oder Kohlenstoff-Nanofasern oder einer Kombination aus Kohlenstoff-Nanoröhrchen und Kohlenstoff-Nanofasern;
Anordnen eines ersten Teils des Gemischs auf einem Träger;
Bestrahlen des ersten Teils der Mischung mit ultraviolettem Licht, um das vorkeramische Polymer im flüssigen Zustand des ersten Teils im Wesentlichen zu härten;
Anordnen einer zweiten Portion der Mischung auf der ersten Portion;
Bestrahlen des zweiten Teils des Gemisches mit ultraviolettem Licht, das bewirkt, dass das vorkeramische Polymer des zweiten Teils im flüssigen Zustand im Wesentlichen aushärtet; und
pyrolysieren des ersten und zweiten Teils der Mischung bei einer Temperatur und für eine Zeit, die wirksam sind, um den keramischen Spuleninduktor (110, 810) oder den PDC-Nanokomposit (140, 840) zu bilden.

**12.** Verfahren zum Erfassen einer Temperaturänderung, **dadurch gekennzeichnet, dass** es umfasst:

Anbringen eines oder mehrerer Temperatursensoren (100, 800) nach einem der Ansprüche 1 bis 6 in einer Umgebung; und

Messen einer Frequenzverschiebung eines elektromagnetischen Signals, das in der keramischen Spuleninduktivität (110, 810) induziert wird, um eine Temperaturänderung in der Umgebung zu erfassen, wobei der eine oder die mehreren Temperatursensoren (100, 800) so konfiguriert sind, dass sie die Temperaturänderung in der Umgebung mit einer Temperatur im Bereich von etwa 25 °C bis etwa 1000 °C erfassen.

## Revendications

1. Capteur de température (100, 800) **caractérisé en ce qu'**il comprend :

   un inducteur de bobine en céramique (110, 810) ayant une première plaque d'extrémité (120, 820) et une seconde plaque d'extrémité (130, 830), dans lequel l'inducteur de bobine en céramique (110, 810) est formé d'un composite céramique qui comprend des nanotubes de carbone, des nanofibres de carbone, ou une combinaison de ceux-ci dispersés dans une matrice céramique ; et
   un nanocomposite céramique dérivé de polymère (PDC) en film mince (140, 840) disposé entre la première (120, 820) et la seconde plaque d'extrémité (130, 830), dans lequel le nanocomposite PDC en film mince (140, 840) a une constante diélectrique qui augmente de façon monotone avec la température.

2. Capteur de température (100, 800) de la revendication 1, dans lequel l'inducteur à bobine céramique (110, 810) est configuré pour communiquer avec une antenne radiofréquence externe.

3. Capteur de température (100, 800) de la revendication 1, comprenant en outre une antenne patch (850) configurée pour communiquer avec une antenne radiofréquence externe, dans lequel l'antenne patch (850) est fixée à la première plaque d'extrémité (120, 820) de l'inducteur à bobine en céramique (110, 810).

4. Capteur de température (100, 800) de la revendication 1, dans lequel la fraction volumique de nanotubes de carbone dans le composite céramique est d'environ 15 % à environ 70 %.

5. Capteur de température (100, 800) de la revendication 1, dans lequel la matrice céramique comprend un matériau PDC.

6. Capteur de température (100, 800) de la revendication 1, dans lequel le composite céramique comprend des nanotubes de carbone à paroi unique, des nanotubes de carbone à paroi multiple, ou une combinaison de ceux-ci.

7. Procédé de fabrication d'un capteur de température sans fil (100, 800), le procédé étant **caractérisé en ce qu'**il comprend :

   la formation d'une bobine d'induction en céramique (110, 810) ayant une première plaque d'extrémité (120, 820) et une seconde plaque d'extrémité (130, 830), dans laquelle la bobine d'induction en céramique (110, 810) comprend des nanotubes de carbone, des nanofibres de carbone, ou une combinaison de ceux-ci, dispersés dans une matrice céramique ; et
   fournir un nanocomposite de céramique dérivée de polymère (PDC) en film mince (140, 840) entre la première plaque d'extrémité (120, 820) et la seconde plaque d'extrémité (130, 830), dans lequel le nanocomposite PDC en film mince (140, 840) a une constante diélectrique qui augmente de façon monotone avec la température.

8. Procédé de la revendication 7, comprenant en outre la fixation d'une antenne patch (850) à la première plaque d'extrémité (120, 820) de l'inducteur à bobine céramique (110, 810).

9. Procédé de la revendication 7, dans lequel la matrice céramique comprend un matériau PDC.

10. Procédé de l'une quelconque des revendications 7 à 10, dans lequel le procédé de fabrication comprend :

    la fourniture d'un mélange d'un polymère précéramique à l'état liquide et de nanotubes de carbone, de nanofibres de carbone, ou d'une combinaison de nanotubes de carbone et de nanofibres de carbone ;
    disposer le mélange sur un support ;
    l'exposition du mélange à une lumière ultraviolette efficace pour durcir sensiblement le polymère précéramique à l'état liquide ; et
    pyrolyser le mélange à une température et pendant une durée efficaces pour former l'inducteur de bobine en

céramique (110, 810) ou le nanocomposite PDC (140, 840).

**11.** Procédé de l'une quelconque des revendications 7 à 10, dans lequel le procédé de fabrication comprend :

à fournir un mélange d'un polymère précéramique à l'état liquide et de nanotubes de carbone ou de nanofibres de carbone, ou d'une combinaison de nanotubes de carbone et de nanofibres de carbone ;
disposer une première partie du mélange sur un support ;
exposer la première partie du mélange à une lumière ultraviolette efficace pour durcir sensiblement le polymère précéramique à l'état liquide de la première partie ;
la disposition d'une seconde partie du mélange sur la première partie ;
l'exposition de la seconde partie du mélange à une lumière ultraviolette efficace pour durcir substantiellement le polymère précéramique à l'état liquide de la seconde partie ; et
pyrolyser les première et seconde parties du mélange à une température et pendant une durée efficaces pour former l'inducteur à bobine céramique (110, 810) ou le nanocomposite PDC (140, 840).

**12.** Procédé de détection d'un changement de température, le procédé étant **caractérisé en ce qu'**il comprend :

placer un ou plusieurs capteurs de température (100, 800) de l'une quelconque des revendications 1 à 6 dans un environnement ; et
mesurer un décalage de fréquence d'un signal électromagnétique induit dans l'inducteur à bobine céramique (110, 810) pour détecter un changement de température de l'environnement, dans lequel le ou les capteurs de température (100, 800) sont configurés pour détecter le changement de température dans l'environnement avec une température dans la gamme d'environ 25°C à environ 1000°C.

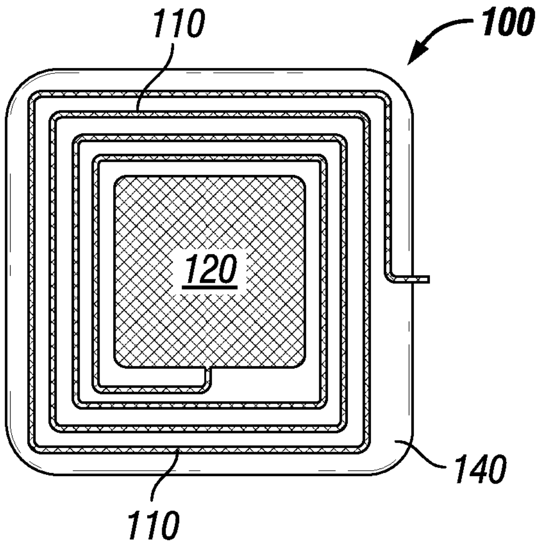


FIG. 1A

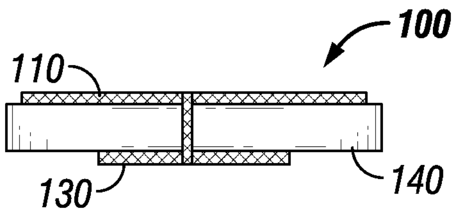


FIG. 1B

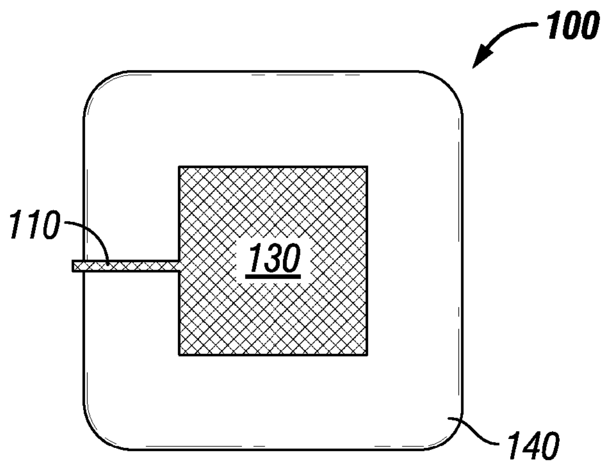


FIG. 1C

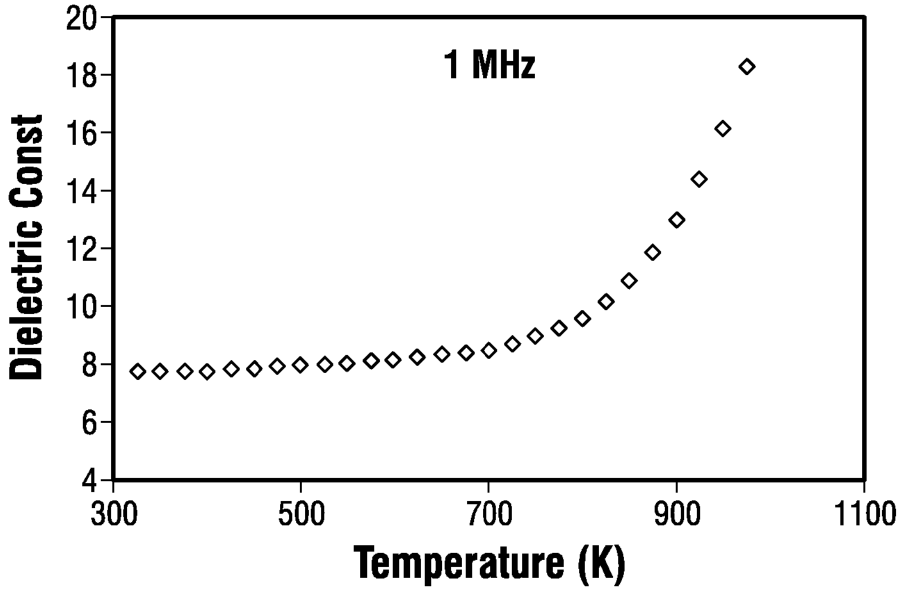
20
18
16
14
12
10
8
6
4
1 MHz
Dielectric Const
300
500
700
900
1100
Temperature (K)

*FIG. 2*

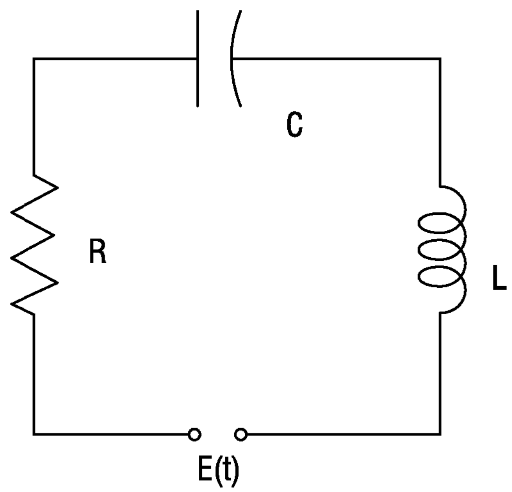
C
R
L
E(t)

*FIG. 3*

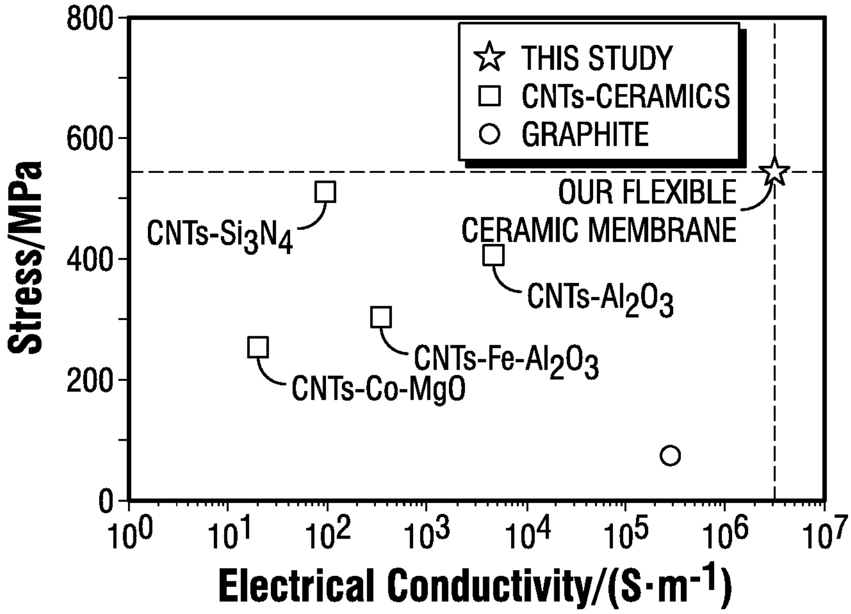
THIS STUDY
CNTs-CERAMICS
GRAPHITE
OUR FLEXIBLE CERAMIC MEMBRANE
CNTs-Si3N4
CNTs-Al2O3
CNTs-Fe-Al2O3
CNTs-Co-MgO
Stress/MPa
Electrical Conductivity/(S·m-1)

*FIG. 4A*

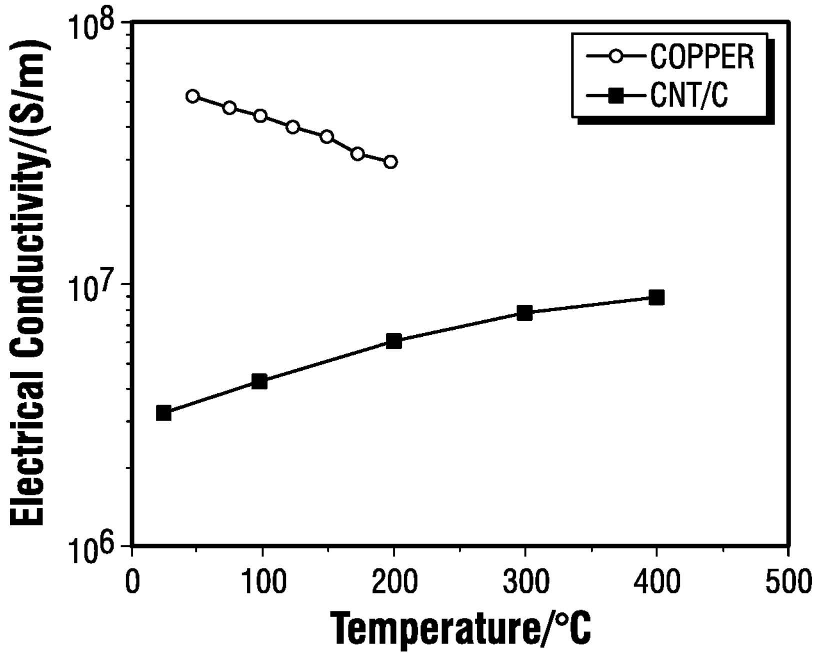
COPPER
CNT/C
Electrical Conductivity/(S/m)
Temperature/°C

*FIG. 4B*

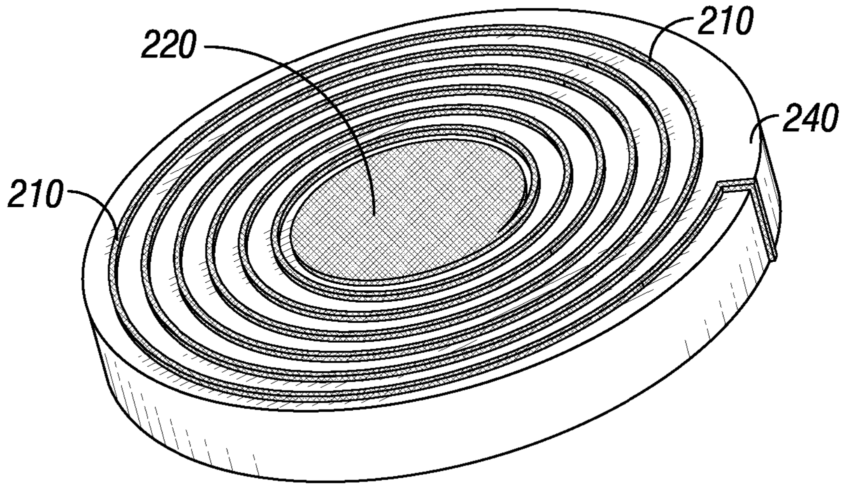
220
210
240
210

FIG. 5A

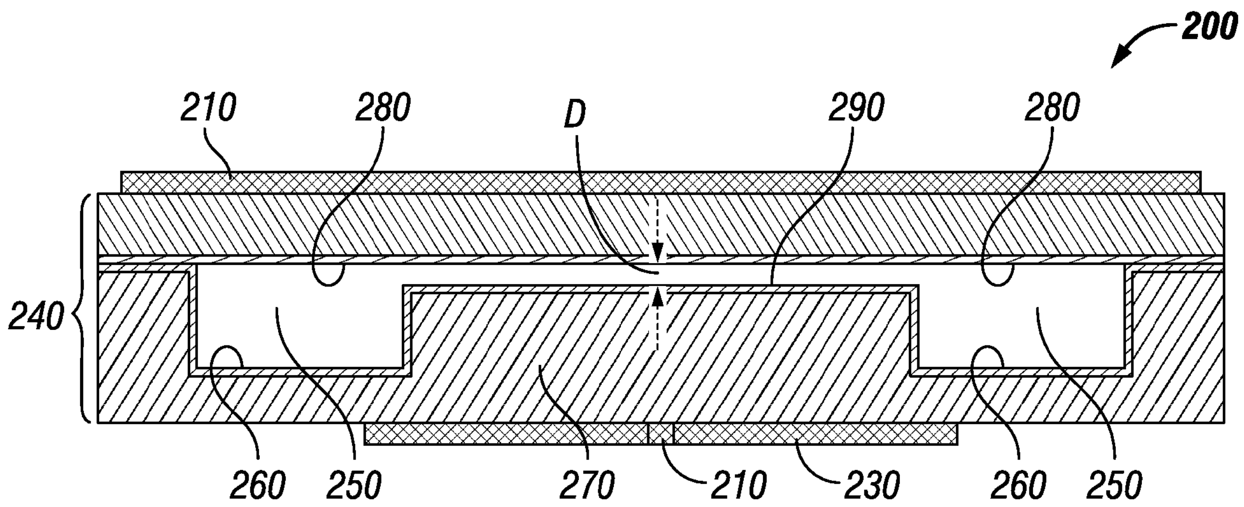
200
210
280
D
290
280
240
260
250
270
210
230
260
250

FIG. 5B

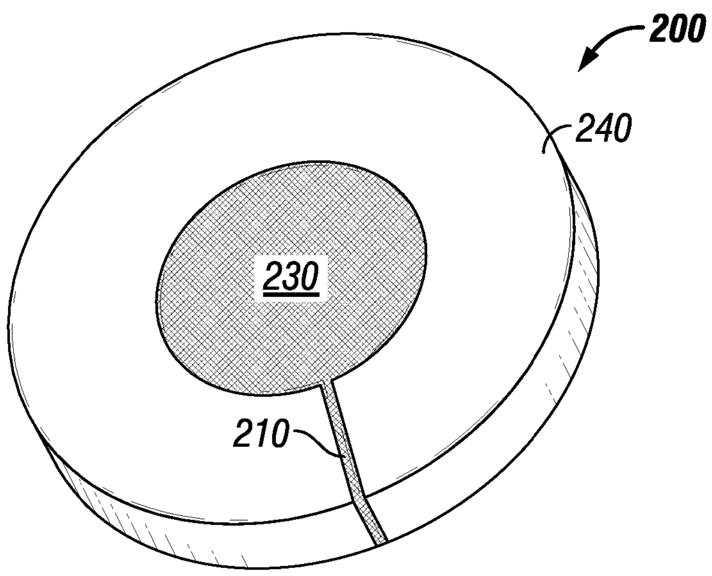


FIG. 5C

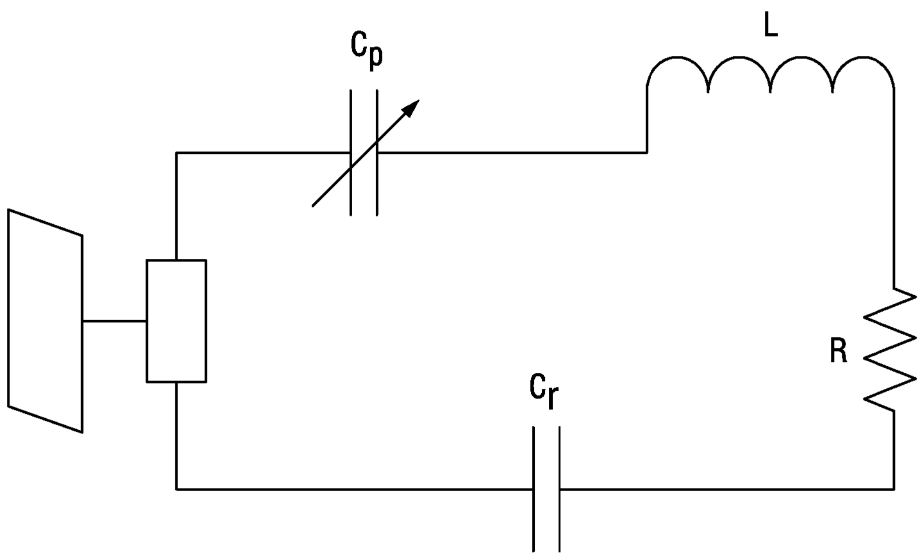


FIG. 6

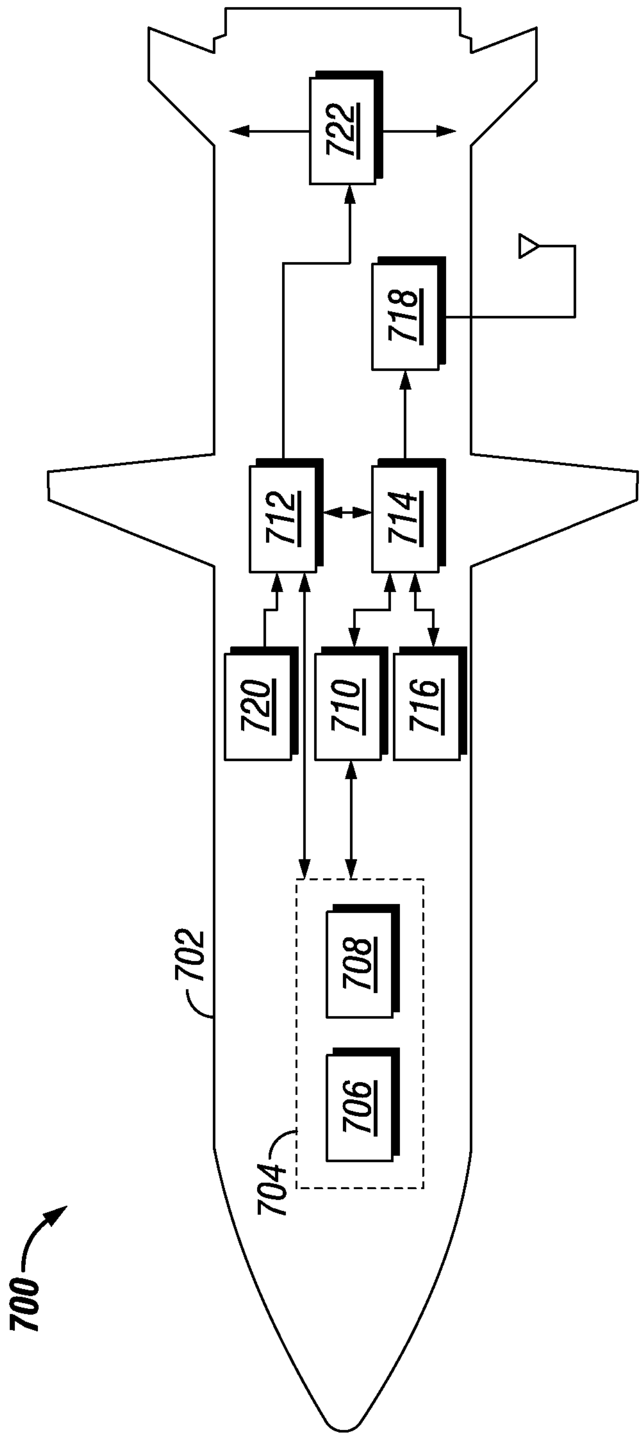


FIG. 7

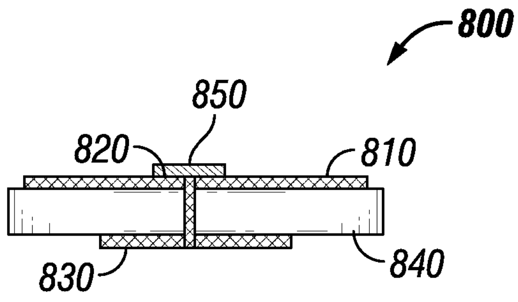
800
850
820
810
830
840

FIG. 8

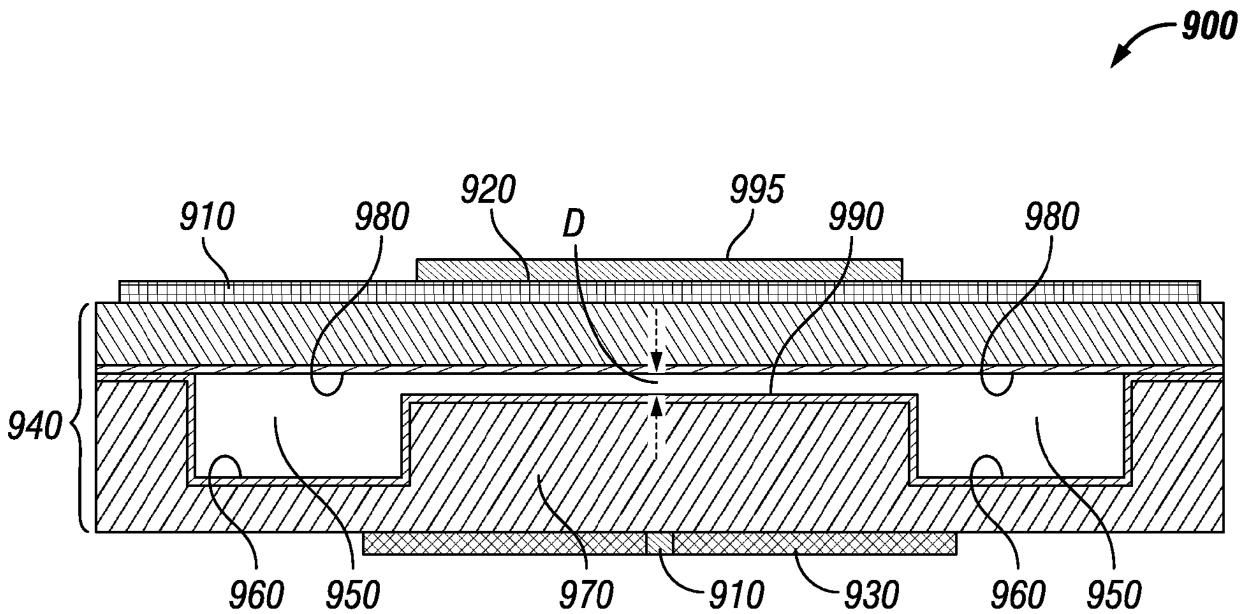
900
920
995
910
980
D
990
980
940
960
950
970
910
930
960
950

FIG. 9

## REFERENCES CITED IN THE DESCRIPTION

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