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Okojie

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(54) **MATERIAL DAMAGE SYSTEM AND METHOD FOR DETERMINING SAME**

(71) Applicant: **Robert S. Okojie**, Strongsville, OH (US)

(72) Inventor: **Robert S. Okojie**, Strongsville, OH (US)

(73) Assignee: **The United States of America as Represented by the Administrator of National Aeronautics and Space Administration**, Wahington, DC (US)

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(51) **Int. Cl.**

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G01B 7/02	(2006.01)
G01N 17/04	(2006.01)
G01B 7/06	(2006.01)
G01N 3/56	(2006.01)
G01N 27/20	(2006.01)
G01N 27/24	(2006.01)

(52) **U.S. Cl.**

CPC ***G01B 7/02*** (2013.01); ***G01B 7/044*** (2013.01); ***G01B 7/06*** (2013.01); ***G01B 7/08*** (2013.01); ***G01N 17/04*** (2013.01); *G01N 3/56* (2013.01); *G01N 27/20* (2013.01); *G01N 27/24* (2013.01)

(58) **Field of Classification Search**

CPC G01B 7/02; G01B 7/044; G01N 27/20; G01N 17/04; G01N 27/24; G01N 3/56; H01C 3/08

See application file for complete search history.

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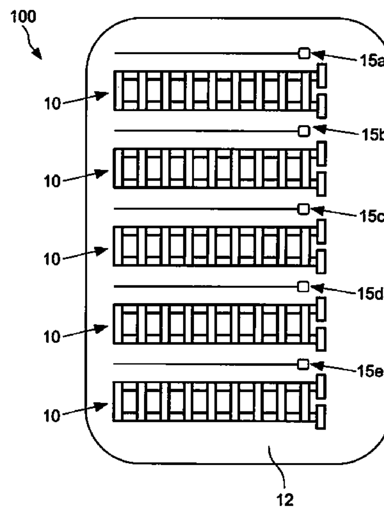
Primary Examiner — Roy Y Yi
Assistant Examiner — Lynne Anderson
(74) *Attorney, Agent, or Firm* — Robert H. Earp, III; William M. Johnson

(57) **ABSTRACT**

A system and method for determining a change in a thickness and temperature of a surface of a material are disclosed herein. The system and the method are usable in a thermal protection system of a space vehicle, such as an aeroshell of a space vehicle. The system and method may incorporate micro electric sensors arranged in a ladder network and capacitor strip sensors. Corrosion or ablation causes a change in an electrical property of the sensors. An amount of or rate of the corrosion or the ablation and a temperature of the material is determined based on the change of the electrical property of the sensors.

18 Claims, 7 Drawing Sheets



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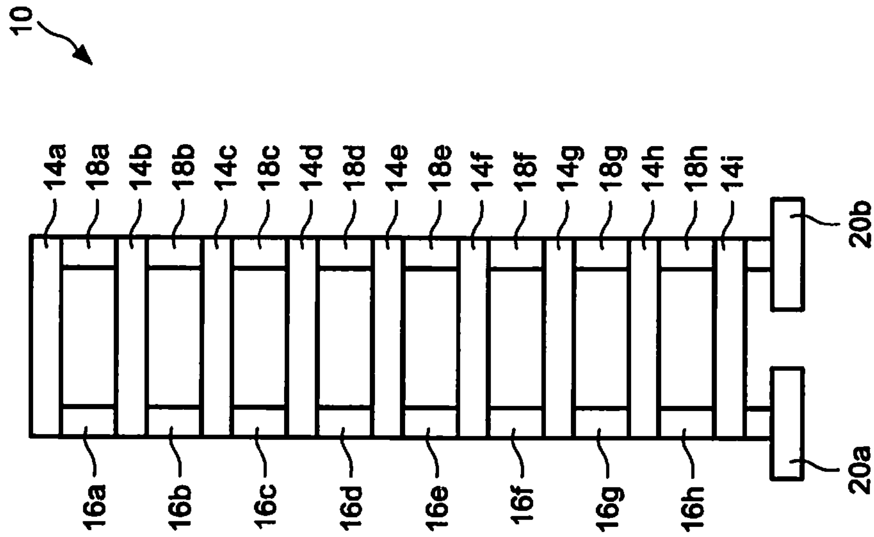


FIG. 2

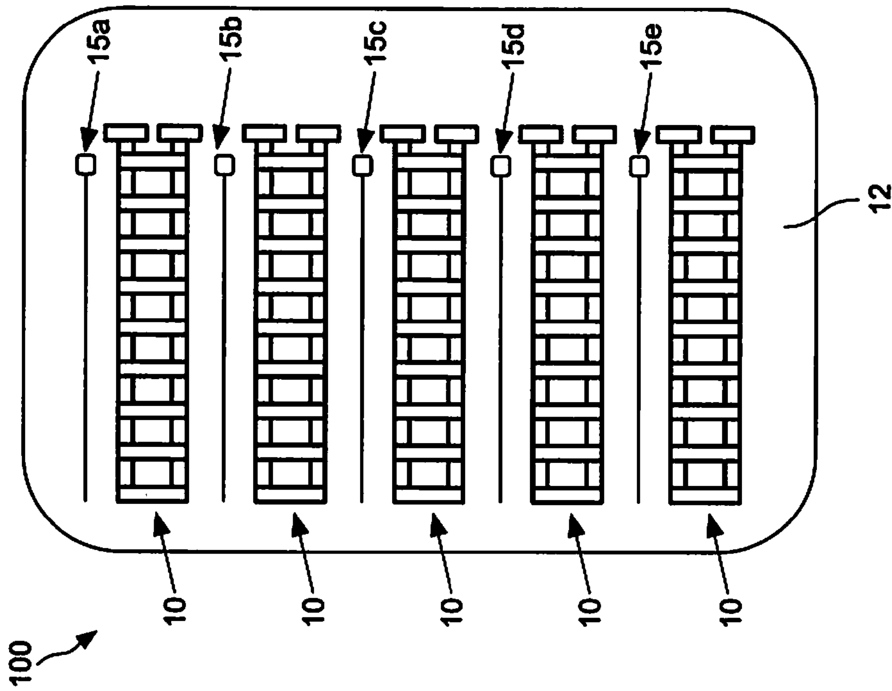


FIG. 1

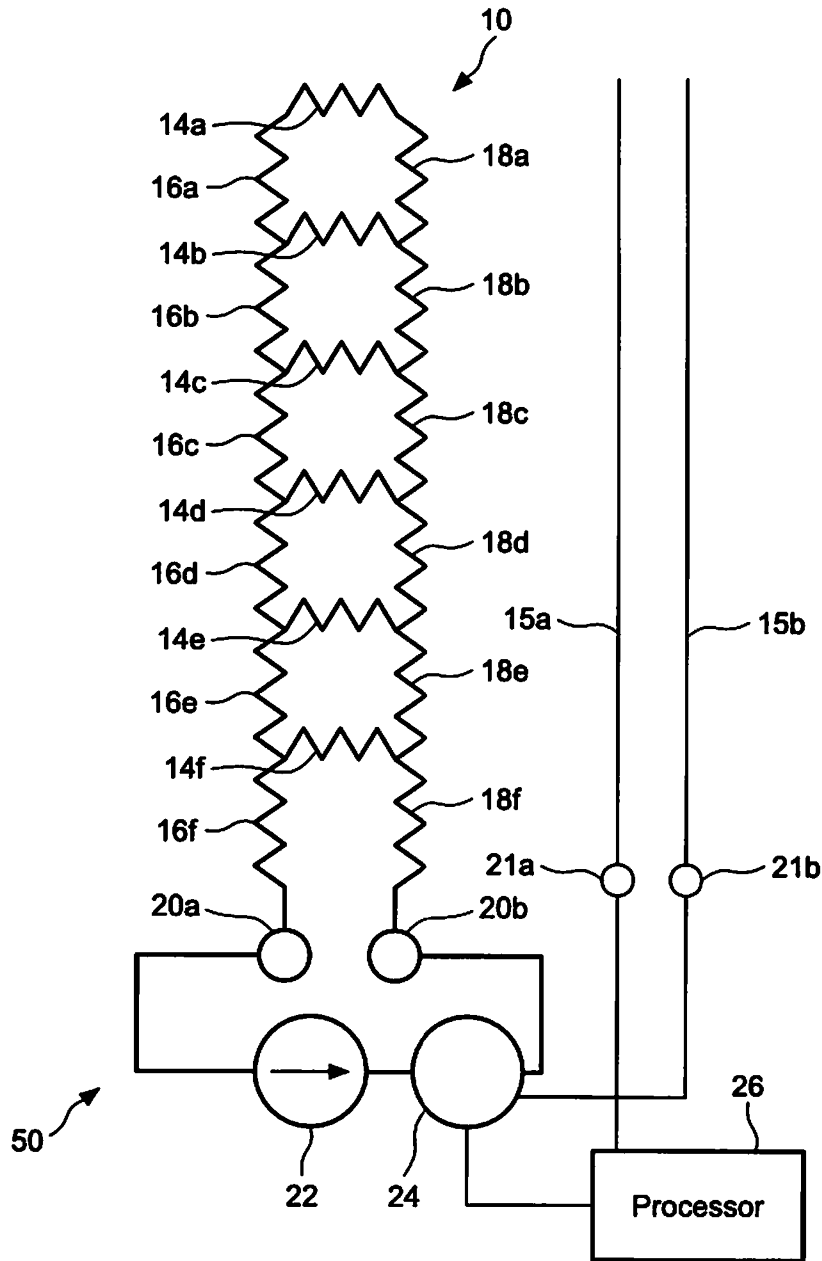


FIG. 3

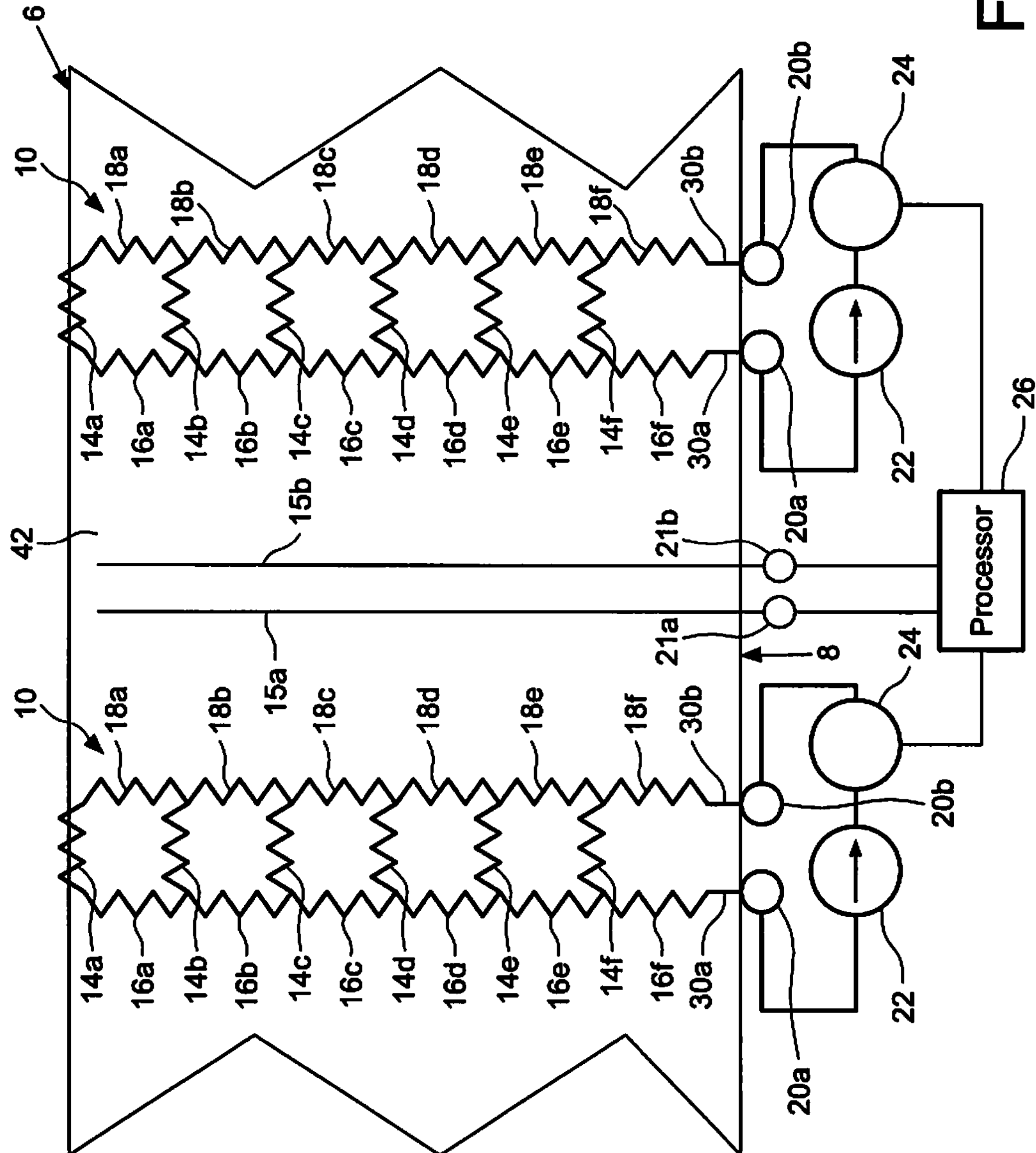
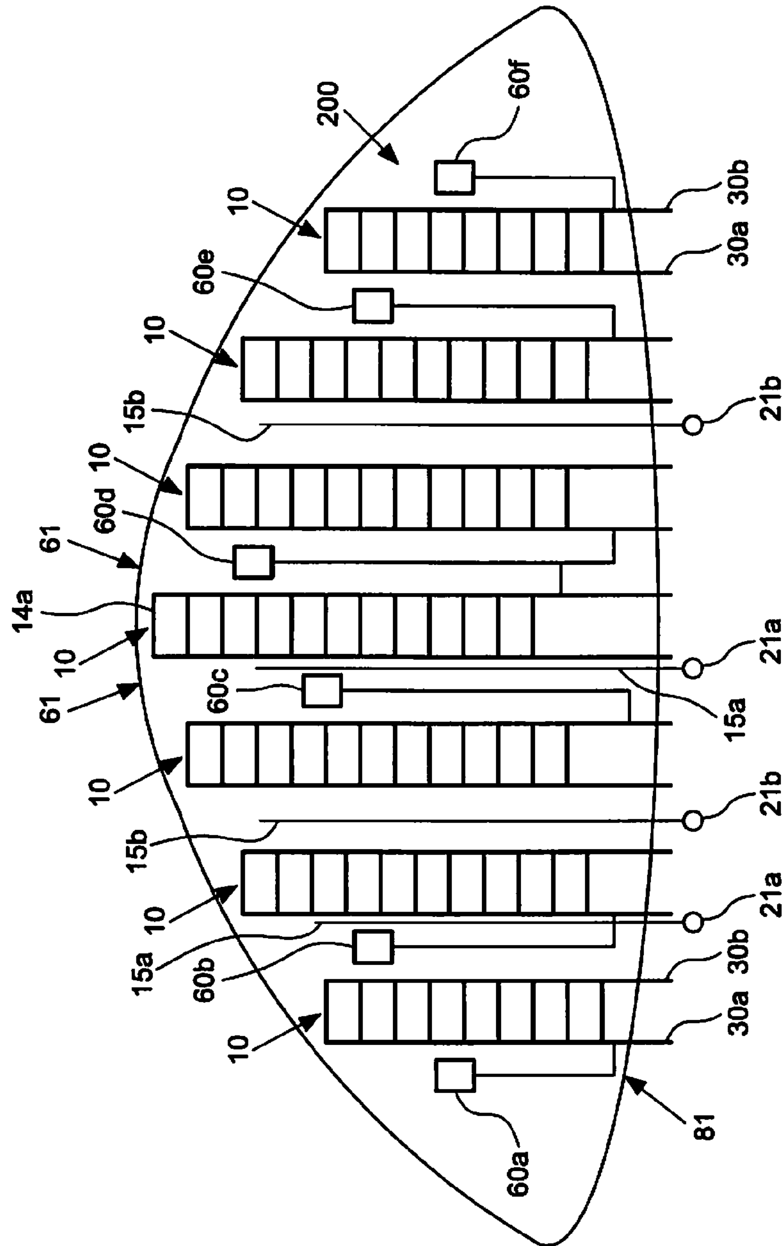


FIG. 4


200
60f
10
30b
30a
60e
10
21b
15b
10
60d
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14a
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21a
61
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10
21b
15b
10
21a
15a
60b
30b
10
30a
81
60a
FIG. 5

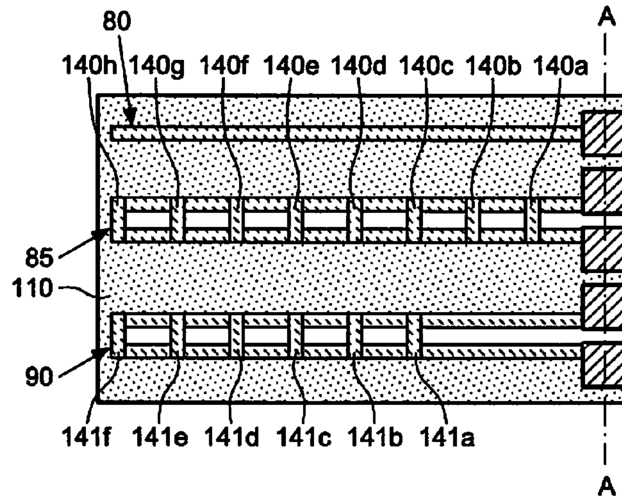

FIG. 6A

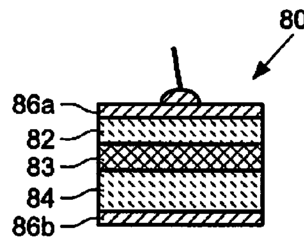

FIG. 6B

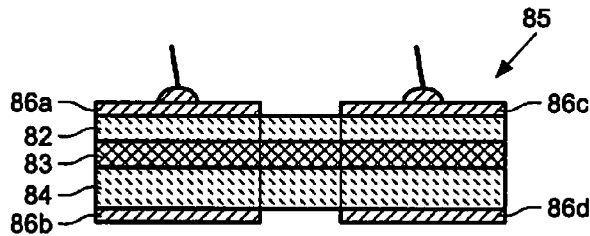

FIG. 6C

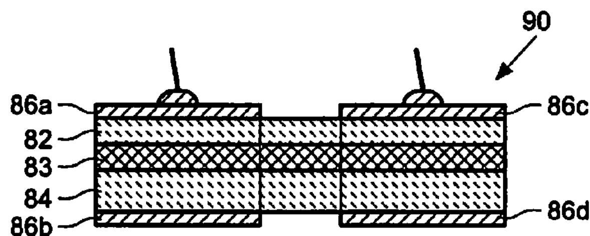

FIG. 6D

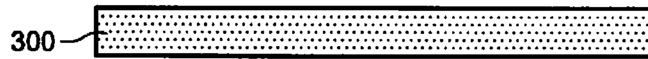

FIG. 7A

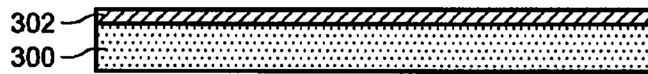

FIG. 7B

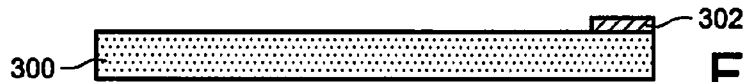

FIG. 7C

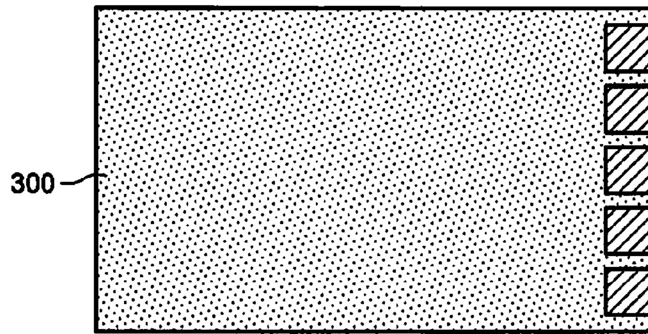

FIG. 7D

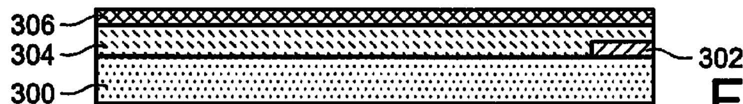

FIG. 7E

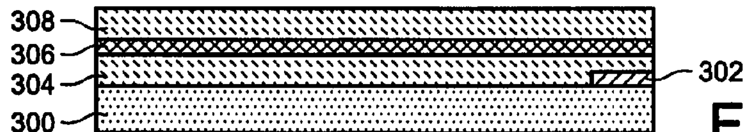

FIG. 7F

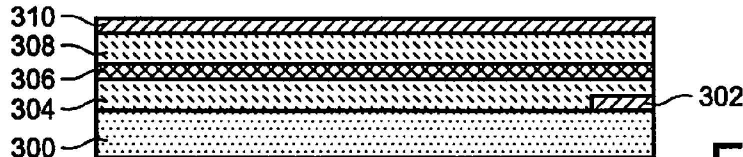

FIG. 7G

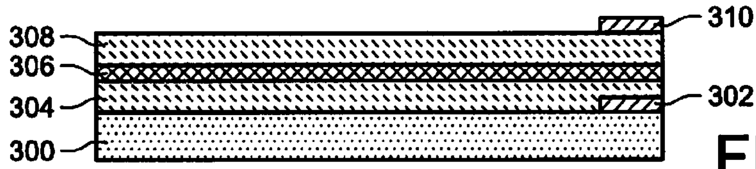

FIG. 8A

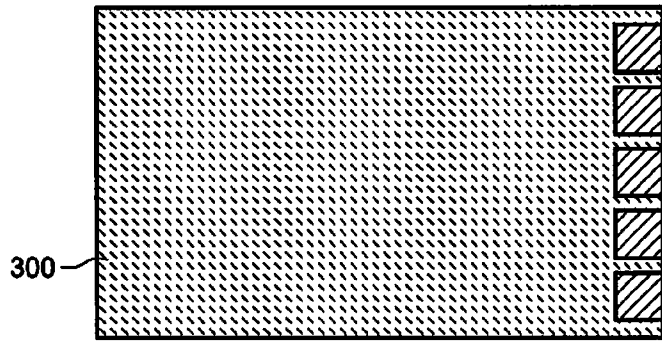

FIG. 8B

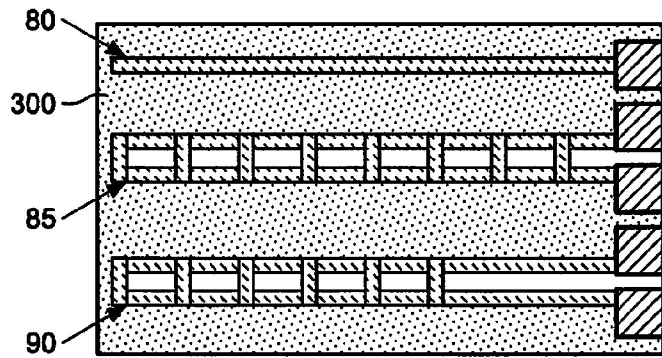

FIG. 8C

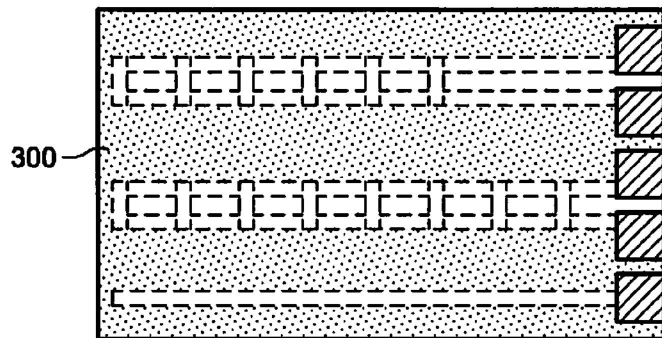

FIG. 8D

MATERIAL DAMAGE SYSTEM AND METHOD FOR DETERMINING SAME

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a Continuation Application claiming the benefit of priority from U.S. patent application Ser. No. 13/301,249, entitled "Material Damage System and Method for Determining Same", filed on Nov. 21, 2011, pending, each of which is hereby incorporated by reference in its entirety.

ORIGIN OF THE INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government for Government purposes without the payment of any royalties thereon or therefore.

BACKGROUND OF THE DISCLOSURE

Damage to materials due to use and environmental conditions is problematic in many industries. Corrosion, ablation and erosion are examples of material damage that effect industrial applicability and use resulting in increased maintenance costs, compromised safety, higher production costs and other negative results. In order to mitigate this damage, corrosion monitoring is necessary.

In the aeronautical industry, for example, thermal protection systems are critical for the protection of space vehicles and payloads during re-entry. The thermal protection system is usually attached to the entire front surface of the aero-shell that bears the major blunt of atmospheric re-entry. The mission success of the space vehicle is fundamentally dependent on the thermal protection system material protecting the aero-shell from the aggressive conditions encountered during entry. Several entry conditions (e.g. radiation, shock and ionization) combine to ablate the thermal protection system material and their effects increase as the anticipated size and mass of future vehicles destined for planets with atmosphere increases. It is, therefore, important to determine the temperature and rate at which the thermal protection system material recedes toward the aero-shell due to ablation.

The current state of the art of instrumentation of the thermal protection system uses conventional thermocouples and resistors to sense temperature and resistance, respectively. These thermocouples and resistors are manually placed in cylindrical plugs that are made from the temperature protection system material. The plugs are subsequently inserted in holes drilled in the main thermal protection system material that is incorporated into the aero-shell. The purpose of the thermocouples is to measure the temperature spatial and temporal temperature gradient along the trajectory axis of the thermal protection system material and also over the surface of the thermal protection system. The resistor measures the ablation of the char layer of the thermal protections system material. The sensors are embedded in the plug with the thermocouple and then inserted into the main thermal protection system material.

There are several problems with these sensor arrangements. First, these instrumented plugs are time consuming to manufacture and problematic to integrate into a space vehicle. Integration requires machining holes to accommodate these instrumented cylindrical plugs. The cost and time to integrate plugs into a heat shield of the space vehicle can have significant cost and schedule impacts. Presently, insertion and gluing of the plug into the thermal protection system material leaves a circular boundary of homogeneous material discontinuity between the plug and the main thermal protection system. The circular boundary is defined by the glue material. During entry phase, the boundary layer shock/thermal protection system interaction could preferentially ablate this circular boundary section, leading to enhanced turbulence and accelerated ablation. The potential result would be the disgorging of the plug and exposure of the aero-shell, thus compromising the safety of the vehicle. To dramatically reduce the impact of incorporating instrumentation into a thermal protection system of the space vehicle, a new measurement system and methodology is needed.

Second, the plug approach limits the number of thermocouple and resistor carrying plugs that can be positioned in the thermal protection system. Too many plugs, for the purpose of improving area coverage and resolution, could potentially affect the structural and mechanical integrity of the thermal protection system material. It could also increase the number of possible sites for shock induced damage. Also, the manual arrangement of the sensors within the plug severely reduces the number of sensors needed for high resolution profiling of the temperature gradient and the ablation recession rate. Additionally, due to the limited number of sensors, a high resolution, large area tomographic profile of the thermal protection system is impossible to obtain.

It is anticipated that the thermal protection system area will continue to increase with increasing payload, a tomographic profile of the condition of the thermal protection system becomes important in monitoring entry and actively changing the entry axis to avoid risks. Accordingly, to improve thermal protection systems of space vehicles as well as detecting damage to materials of other surfaces, whether caused by corrosion, ablation or the like, a new system and method of use is needed.

SUMMARY OF THE DISCLOSURE

In an embodiment of the disclosure, a system is disclosed having a material susceptible to corrosion or ablation and having a thickness defined between a first end and a second end. The first sensor and a second sensor are on the material and extend along the thickness adjacent the first end and toward the second end. The first sensor has an electrical component that changes an electrical property of the sensor as temperature of the material changes. The second sensor has an electrical property that is substantially constant with respect to changes in temperature of the material. An electrical circuit coupled to the first sensor and the second sensor determines the change in the electrical property of each of the first sensor and the second sensor. A processor determines a thickness and a temperature of the material based on the change of the electrical property of the first sensor and the second sensor.

In another embodiment of the disclosure, a method is disclosed positioning a first micro electric sensor and a second micro electric sensor within a susceptible material. The method further includes applying a current or voltage to the first micro electric sensor and the second micro electric sensor. Furthermore, the method includes exposing the susceptible material to a substance causing a change in a temperature and thickness of the susceptible material. In addition, the method includes determining the temperature

of the susceptible material from an electrical property of the first micro electric sensor. Moreover, the method includes determining the thickness of the susceptible material from an electrical property of the second micro electric sensor. The electrical property of the first micro electric sensor changes substantially more with temperature than the second micro electric sensor.

In yet another embodiment of the disclosure, a method is disclosed for embedding a plurality of sensors within a material. The plurality of sensors have at least a first ladder sensor, a second ladder sensor, and a capacitor strip. The second ladder sensor has more rungs than the first ladder sensor. Further, the second ladder sensor has electrical components that are less temperature sensitive than electrical components of the first ladder sensor. The method also includes applying a current or voltage to each of the plurality of sensors, and exposing the material to a change in temperature causing a change in an electrical property of at least the second ladder sensor. Furthermore, the method includes ablating a portion of the material to change an electrical property of at least the first ladder sensor and the capacitor strip. Still further, the method includes determining a temperature of the material based on the change in the electrical property of the first ladder sensor and the second ladder sensor. Moreover, the method includes determining a thickness of the material based on the change of the electrical property of the capacitor strip and the change of the electrical property of the second ladder sensor.

DESCRIPTION OF DRAWINGS

FIG. **1** illustrates a plurality of sensors on a material in an embodiment of the present disclosure.

FIG. **2** illustrates a sensor in an embodiment of the disclosure.

FIG. **3** illustrates a sensor connected to a sensing device, source and processor in an embodiment of the disclosure.

FIG. **4** illustrates a first sensor and a second sensor connected to a processor in an embodiment of the disclosure.

FIG. **5** illustrates a plurality of sensors within a material in an embodiment of the present disclosure.

FIG. **6**A illustrates a first sensor, a second sensor, and a third sensor on a material in another embodiment of the present disclosure.

FIG. **6**B illustrates a cross-sectional view of the first sensor along the line A-A as shown in FIG. **6**A.

FIG. **6**C illustrates a cross-sectional view of the second sensor along the line A-A as shown in FIG. **6**A.

FIG. **6**D illustrates a cross-sectional view of the third sensor along the line A-A as shown in FIG. **6**A.

FIGS. **7**A-**7**G illustrate embodiments of steps of manufacturing one or more sensors in an embodiment of the disclosure.

FIGS. **8**A-**8**D illustrate embodiments of additional steps of manufacturing one or more sensors in an embodiment of the disclosure.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE DISCLOSURE

Embodiments of the present disclosure generally describe a system and method for determining temperature and/or thickness of a surface of a susceptible material. The susceptible material may be susceptible to a change in thickness by exposure to extreme temperatures, radiactive sources, corrosive substances, or other sources that may damage the surface of and/or structure of the susceptible material. While embodiments of the present disclosure are described as being implemented with a sensor having a ladder network, the present disclosure should not interpreted as limited as requiring the use of a ladder network. The present disclosure describes sensors that may be implemented within the spirit of the invention that are not arranged in a ladder network.

In addition, the present disclosure should not be deemed as limited to use on a space vehicle or in the aerospace industry. Those having ordinary skill in the art will appreciate that the present disclosure has various applications in many industries. For example, the embodiments disclosed herein have broad applications across any industry where it is desirous to determine corrosion, erosion, ablation, recession, and surface temperature of a material.

In at least some embodiments, the present disclosure provides temperature and recession rate measurements of a susceptible material. For example, the present disclosure may utilize or employ a sensor comprising an electrical circuit having components the cause a change in an electrical property upon corrosion, ablation or a change in temperature of the susceptible material.

FIG. **1** illustrates an embodiment of a system **100** comprised of a plurality of sensors **10** and a plurality of sensors **15***a*-**15***e* arranged on a substrate **12**. The system **100** may utilize the substrate **12** in order to fabricate the sensors **10**, **15***a*-**15***e*. For example, the system **100** may be a micro electromechanical system ("MEMS") whereby the sensors **10**, **15***a*-**15***e* are micro electric sensors. In such an embodiment, the substrate **12** may be used to fabricate one or more of the sensors **10**, **15***a*-**15***e*.

As one example of fabricating the sensors **10**, **15***a*-**15***e*, the substrate **12** may be selectively removed in order to realize miniaturized components. Such micromachining may be accomplished using chemical or physical means. For example, a bulk micromachining technique may be used, such as chemical wet etching that involves immersion of a substrate, such as the substrate **12**, into a reactive chemical solution. As a result of immersion in the reactive chemical solution, the exposed regions of the substrate **12** may be etched at measurable rates. Chemical wet etching may be used to provide a relatively high etch rate and permit selective etching.

Surface micromachining is another method that may be used for the fabrication sensors **10**, **15***a*-**15***e* on the substrate **12** in an embodiment where the sensors **10**, **15***a*-**15***e* are micro electric devices or MEMS devices. Generally, surface micromachining may involve deposition of a film material to act as a temporary mechanical layer onto which the actual device layers are built. Next, a structural layer may be deposited and patterned on the film material followed by the removal of the temporary layer to release the mechanical structure layer from the constraint of the underlying layer. As a result, the structural layer may be freed. One of the reasons surface micromachining may be used is that it provides for precise dimensional control.

A person having ordinary skill in the art will appreciate many methods of fabricating the sensors **10**, **15***a*-**15***e*. The invention should not be deemed as limited to any specific fabrication technique. In addition, the sensors **10**, **15***a*-**15***e* being micro electric sensors and/or MEMS sensors are an embodiment and the disclosure is not limited thereto.

As shown in FIG. **1**, each of the sensors **10** may have a plurality of electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h*. One or more of the sensors **15***a*-**15***h* may be positioned adjacent each of the sensors **10**. In an embodiment, the sensors **15***a*-**15***h* each have a capacitor strip configured to ablate, recess or otherwise have its length

change in response to ablation, recession, corrosion or erosion of the thickness of the substrate **12**. In such an embodiment, the capacitor strip may comprise a pair of opposing electrodes, a pair of electric wires, a coaxial cable, micro sized capacitors positioned in series or in parallel, a single wire, a pair of opposing plates, or any type of capacitive device that will change its capacitance with length or surface area. The sensors **15***a*-**15***h* may not be temperature dependent such that any change in the temperature of the substrate **12** will have substantially zero effect on electrical properties of the sensors **15***a*-**15***h*. Accordingly, the sensors **15***a*-**15***h* may be positioned into a device to measure changes in dimension, such as changes in a thickness of the substrate **12**.

FIG. **2** illustrates the sensor **10** having the plurality of electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* that may be used in the system **100**. The electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* of the sensor **10** may be in electrical communication to form an electrical network. The electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* may comprise conducting lines, conducting wires, resistors, and/or inductors. The electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* may be in parallel or in series as shown in FIG. **2**. In an embodiment, each of the electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* has at least one resistor or inductor. The electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* may have at least one resistor, or inductor in addition to or alternative to a conducting line or wire.

The arrangement of the electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* may be in a ladder network configuration as shown in FIG. **2**. The ladder network configuration may permit a portion of the electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* to become electrically separated while permitting electrical communication between the other portion of the electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* to terminals **20***a*, **20***b*, as shown in FIG. **2**. As an example, the electrical component **14***a* may be removed, may be destroyed, or may otherwise be electrically separated from the other electrical components **14***b*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h*. Electrically disconnecting the electrical component **14***a*, for example, may change a resistance, or a current in the sensor **10**. Conversely, a break, ablation or the like in the sensor **15** may change the capacitance to correspond with a new thickness of the eroding material.

As mentioned, the electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* may be electrically connected to the terminals **20***a*, **20***b*, as shown in FIG. **2**. As a portion of the electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* are electrically separated from the electrical network, the resistance or the current as measurable from the terminals **20***a*, **20***b* may change.

In addition, the electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* may be temperature sensitive such that a change in a temperature of at least one of the electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* causes a change in the electrical property of the sensor **10**. The electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h* may have a positive or negative temperature coefficient. In the case of a positive temperature coefficient, a resistance or capacitance of one or more of the electrical components **14***a*-**14***i*, **16***a*-**16***h*, or **18***a*-**18***h*, may increase with an increase in temperature. On the other hand, a negative temperature coefficient results in a decrease in resistance or capacitance as temperature increases. It should also be noted that a zero temperature coefficient is also a possible coefficient of the electrical components **14***a*-**14***i*, **16***a*-**16***h*, and **18***a*-**18***h*.

FIG. **3** illustrates an embodiment of the sensor **10** and the sensors **15***a*, **15***b*. For explanatory purposes, the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* are shown as each having a resistor. The electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* are connected to the terminals **20***a*, **20***b* and arranged in a ladder network. The electrical component **16***f* is electrically connected to the terminal **20***a* and may extend substantially parallel to the electrical component **18***f*, which is electrically connected to the terminal **20***b*. The electrical component **14***f* is electrically connected to the electrical components **16***f*, **18***f*. The electrical component **14***f* may be substantially perpendicular to the electrical components **16***f*, **18***f*. The electrical components **16***e* and **18***e* may be electrically connected to the electrical components **14***f*, **16***f*, **18***f* and extend away from the terminals **20***a*, **20***b*. The other electrical components **14***a*-**14***e*, **16***a*-**16***e*, and **18***a*-**18***d* may be electrically connected in a similar manner as shown in FIG. **3**.

The sensors **15***a*, **15***b* extend in a direction substantially parallel to the sensor **10**. The sensors **15***a*, **15***b* may, in an embodiment, each comprise a wire, a semiconductor, a doped ceramic, or a plate for storing a charge. In another embodiment, each of the sensors **15***a*, **15***b* may comprise a pair of wires, a pair of plates or one or more devices positioned along its length for storing a charge. The sensors **15***a*, **15***b* may be configured such that a change in its length will change an electrical property of the sensors **15***a*, **15***b*. The change in the electrical property may be related to a change in the length of sensors **15***a*, **15***b*.

An electric circuit **50** is connected to the sensor **10** via the terminals **20***a*, **20***b*. The electrical circuit **50** is electrically connected to the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f*, via the terminals **20***a*, **20***b*. For example, as shown in FIGS. **4** and **5**, conducting lines **30***a*, **30***b* may extend from each of the sensors **10** out of the second end **8** of the susceptible material **42** and connect to the terminals **20***a*, **20***b*. The electrical circuit **50** may be electrically connected to the sensor **10** via the terminals **20***a*, **20***b*. The electrical circuit **50** may also be connected to the sensors **15***a*, **15***b* via terminals **21***a*, **21***b*. Several other alternative series/parallel connections exist, but the above is for illustrative purposes.

The electrical circuit **50** may comprise an electrical energy source **22** electrically connected to the terminals **20***a*, **20***b* and/or the terminals **21***a*, **21***b*. The electrical energy source **22** may deliver a current and/or a voltage to the sensor **10** and/or the sensors **15***a*, **15***b*. For example, the electrical energy source **22** may deliver a constant voltage or a constant current to the sensor **10**, such as the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f*, via the terminals **20***a*, **20***b*. In the case of constant voltage, a change in a resistance of one of the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* results in a change in the current passing through the electric circuit **50**. An increase in a resistance, results in a lower current, while a decrease in resistance results in an increased current. The electrical energy source **22** may also deliver a voltage or current to the sensors **15***a*, **15***b*. In an embodiment where the sensors **15***a*, **15***b* are capacitors, a change in length of the sensors **15***a*, **15***b* may change an electrical property of the sensors **15***a*, **15***b*. For example, as the length of the sensors **15***a*, **15***b* decrease, a capacitance of the sensors **15***a*, **15***b* may decrease.

The electrical circuit **50** may have a measuring device **24** to measure an electrical property of the electrical circuit **50**, the sensor **10** and/or the sensors **15***a*, **15***b*. The measuring device **24** may be positioned between the terminals **20***a*,

20*b*. The measuring device **24** or a second measuring device (not shown) may be in electrical communication with the terminals **21***a*, **21***b* of the sensors **15***a*, **15***b*. The measuring device **24** may determine and/or may measure a current or voltage of the sensor **10** and the sensors **15***a*, **15***b*. In an embodiment, the measuring device **24** may be an ammeter, or digital meter, to measure and/or determine an amount of current passing therethrough. The measuring device **24** may instead or in addition to current measure voltage.

A processor **26** may be electrically connected to the measuring device **24** to receive measurement data from the measuring device **24**. FIG. **4** illustrates an embodiment of the processor **26** connected to the measuring device **24** of each of the sensors **10**. The processor **26** may also be in communication with terminals **21***a*, **21***b* of the sensors **15***a*, **15***b*. In this embodiment, the terminals **21***a*, **21***b* may contain and/or may incorporate a measuring device for determining an electrical property of the sensors **15***a*, **15***b*, such as current, voltage or capacitance. The terminals **21***a*, **21***b* may communicate the electrical property to the processor **26** for determination of a length of the sensors **15***a*, **15***b*. The processor **26** may be positioned locally or remotely with respect to the electrical circuit **50** and the sensor **10**.

FIG. **4** also illustrates the sensors **10**, **15***a*, **15***b* positioned between a first end **6** and a second end **8** of a susceptible material **42**. The susceptible material **42** may be any material or device in which corrosion, ablation, erosion and/or surface temperature determination may be advantageous. Non-limiting examples of the susceptible material **42** include a braking material for a vehicle, a thermal protection system of a space vehicle, or a fluid conduit. A circuit method of multiplexing can be used to connect numerous sensors **10**, **15***a*, **15***b* so that sampling, such as high speed sampling, may be used to interrogate a plurality of the sensors **10**, **15***a*, **15***b* to allow for a real-time, or substantially real-time, topographic display of the erosion on a display (not shown).

The thickness of the susceptible material **42** may be defined between the first end **6** and the second end **8**. The first end **6** of the susceptible material **42** may be positioned adjacent to and/or exposed to a substance that may cause a change in the thickness of the susceptible material **42**. For example, the substance causing a change in thickness of the susceptible material **42** may be a fluid at an extreme temperature, a radiactive substance, a corrosive substance, or other substance that may cause a change in the thickness of the susceptible material, **42**, such as by damage to the surface of and/or structure of the susceptible material **42**.

The substance may change the thickness of the susceptible material **42** causing separation of a portion of the sensor **10** from a remaining portion of the sensor **10** and a change in length of the sensors **15***a*, **15***b*. For example, the substance may decrease the thickness of the susceptible material **42** and electrically separate one or more of the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f*, such as the electrical component **14***a*, from the sensor **10**. Additionally, the substance may decrease the thickness of the susceptible material **42** and electrically separate a portion of the sensors **15***a*, **15***b* and/or decrease a length of the sensors **15***a*, **15***b*. As a result, the measuring device **24** may measure a change in the electrical property of the electrical circuit **50**, such as a change in the current. In an embodiment, upon electrical separation of the electrical component **14***a*, the current measured at the measuring device **24** may decrease due to an increased resistance of the electrical circuit **50**, if, for example, the electrical component **14***a* is a resistor. If, for example, the sensors **15***a*, **15***b* are capacitor strips, a decrease in length of the sensors **15***a*, **15***b* may decrease a capacitance. The processor **26** may be in electrical and/or data communication with the measuring device **24** to relate a change in the electrical property of the sensor **10** and the sensors **15***a*, **15***b* to a change in the thickness of the susceptible material **42**. In an embodiment, the processor **26** may compare a computed change in thickness of the susceptible material **42** from the sensors **10** with a computed change in thickness of the susceptible material **42** from the sensors **15***a*, **15***b*.

Turning again to FIG. **4**, the substance changing the thickness of the susceptible material **42** may cause a greater change to the susceptible material **42** at one of the sensors **10**, **15***a*, **15***b* than one of the other sensors **10**, **15***a*, **15***b*. In such an event, the processor **26** may receive data and/or communication from the measuring device **24** and determine the thickness of the susceptible material **42** at each of the sensors **10**, **15***a*, **15***b*. Advantageously, the sensors **10**, **15***a*, **15***b* may be spaced at predetermined locations to measure a change of thickness, such as due to corrosion or ablation. While FIG. **4** only illustrates two of the sensors **10**, any number of the sensors **10** may be positioned at predetermined locations along the susceptible material **42** resulting in information related to the thickness at each location of each of the sensors **10**.

In addition to the change of thickness of the susceptible material **42**, the sensor **10** may determine a temperature of the susceptible material **42**. The change in temperature of the susceptible material **42** may cause a change in temperature of one or more of the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f*. As the temperature of one of the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* changes, an electrical property of the sensor **10** changes. For example, the electric property of the sensor **10** may be a resistance or capacitance that may change with temperature. The change in the capacitance of resistance of the sensor **10** may be the result of the change in temperature. Changing the electrical property may result in a change in current passing through the sensor **10** and/or current at the measuring device **24**.

As set forth above, the change in the temperature and the change in the thickness of the susceptible material **42** may cause a change in the electrical property of the sensor **10**. The processor **26** may determine the change in the electrical property due to the temperature and the change in the electrical property due to the change in thickness of the susceptible material **42**. The processor **26** may have information and/or may determine a relationship of the electrical property of each of the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* and temperature. In addition, the processor **26** may have information and/or may determine a relationship of the electrical property of each of the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* and a change in the thickness of the susceptible material **42**. The measuring device **24** and/or the processor **26** may determine a change in the electrical property of the sensor **10**. As mentioned, the change in the electrical property of the sensor **10** may be a change in current, voltage or the like. The processor **26** may then determine the change in electrical property due to the temperature change and the change in the electoral property due to the change in thickness of the susceptible material **42**.

As in the example of FIG. **4**, the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* may be resistors. If these resistors have a negative temperature coefficient, an increase in temperature of the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* may cause a decrease in resistance. Simultaneously if the increase in temperature causes a decrease of thickness of the susceptible material **42** by ablating a portion

of the susceptible material **42** and the electrical component **14***a*, then the resistance of the sensor **10** may increase. The measuring device **24** may measure a change in current as a result of the change in resistance. For explanatory purposes, if the overall resistance increases, then the current at the measuring device **24** may decrease. However, the current at the measuring device **24** may be higher than expected if the electrical component **14***a* is separated from electrical communication with the other electrical components **14***b*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f*. The current may be higher than expected as the temperature increase may cause the resistance in the other electrical components **14***b*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* to decrease. The processor **26** may determine the change of thickness of the susceptible material **42** and the change in temperature of the susceptible material **42** due to the decrease in the current.

As another example, the sensors **10** as shown in FIG. **4** may be arranged such that any change in thickness of the susceptible material **42** at one of the sensors **10** will cause the same or a substantially similar change in thickness of the susceptible material **42** at the other sensor **10**. In order to separate the change in electrical property due to temperature from the change in electrical property due to the change in thickness, one of the sensors **10** may have the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* that do not change with temperature. In yet another embodiment, one of the sensors **10** may have the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* with positive temperature coefficients and the other sensor **10** may have the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* with negative temperature coefficients. The electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f* of the sensors **10** may have the same number of resistors, capacitors and electrical conductors such that the sensors **10** are similar. Alternatively, the sensors **10** may have a distinct number, type, location and/or arrangement of the electrical components **14***a*-**14***f*, **16***a*-**16***f*, and **18***a*-**18***f*. In either case, the processor **26** may utilize this information to determine a change in thickness of the susceptible material **42** and/or a temperature of the susceptible material **42**. These embodiments are not mutually exclusive and may be used in combination in order to determine temperature and thickness of the susceptible material **42** at each of the sensors **10**.

In an embodiment, the sensors **15***a*, **15***b* may be used to determine a change in thickness of the susceptible material **42**. In order to ensure accurate measurement of the change in thickness, the sensors **15***a*, **15***b* may not vary with temperature. Accordingly, the entire change, or at least a substantial amount of the change, in electrical property of the sensors **15***a*, **15***b* may be attributed to a change in thickness of the susceptible material **42**. Again, the processor **26** may determine the change in thickness of the susceptible material **42** based on the change in the electrical property of the sensors **15***a*, **15***b*. The temperature of the susceptible material **42** may be determined from the sensors **10**, such as by the processor **26** computing the temperature based on a change in the electrical property of the sensor **10**. Accordingly, a temperature and thickness of the susceptible material **42** may be determined. The temperature and thickness of the susceptible material **42** may be determined along an entire surface to generate a tomographic image of the susceptible material **42**.

In addition to utilizing the sensor **10** to determine the temperature of the susceptible material **42**, the change in thickness of the susceptible material **42** may be determined from a change in electrical property of the sensor **10**. The processor **26** may determine the change in thickness of the susceptible material **42** from the sensor **10** and the sensors **15***a*, **15***b* independently or using a combination. In the event these are independently measured, the values may be compared and resolved to improve accuracy, such as by determining the likelihood of each measurement. It may be determined that one of the sensors **10**, **15***a*, **15***b* is more accurate at certain temperature ranges than at other temperature ranges.

As another example, one could assume that the sensors **10** of FIG. **4** are spaced such that properties of the susceptible material **42** are identical or substantially similar at each location of a first sensor **10** and a second sensor **10**. For example, the thickness and temperature of the susceptible material **42** at the first sensor **10** may not differ much, if at all, from the thickness and temperature of the susceptible material **42** at the second sensor **10**. The processor **26** may determine the thickness, the rate of thickness change, and/or the temperature of the susceptible material **42** of each of the sensors **10** independently. If, for example, the first sensor **10** does not vary its electrical property with temperature while the second sensor **10** does vary with temperature, then the processor **26** may determine the amount of change of the electrical property due to temperature. The change in the electrical property due to temperature may then be correlated to a thickness or a change in thickness of the susceptible material **42**. Similarly, the sensors **10** may be used to independently compute the thickness of the susceptible material **42** to compare and improve the measurement. Use of the sensors **10** along or within the susceptible material **42** may permit the processor **26** to generate a tomographic image or other representation of the temperature and/or a tomographic image of the thickness (or change of the thickness, such as ablation, erosion, corrosion or the like) of the susceptible material **42**.

FIG. **5** illustrates an embodiment of the disclosure of the sensors **10**, **15***a*, **15***b* embedded into a thermal protection system **200** of a space vehicle, such as a heat shield of an aeroshell. The thickness of the aeroshell **200** is defined by a first end **61** and a second end **81**. The sensors **10**, **15***a*, **15***b* may be micro scale sensors fabricated in materials that are compatible with the material of the thermal protection system **200**. Any numbers of the sensors **10**, **15***a*, **15***b*, such as hundreds, are fabricated in the substrate **12** and may be released into the material prior to final forming of the thermal protection system **200**. In an embodiment, at least one of the sensors **15***a*, **15***b* may be used for each of the sensors **10**. For example, each of the sensors **10** may have at least one of the sensors **15***a*, **15***b* positioned adjacent thereto. Each of the sensors **10**, **15***a*, **15***b* and/or each of the substrates **12** may be positioned transversely in strategic locations of the thermal protection system **200** before final casting, molding, or compression. In an embodiment, the sensors **10**, **15***a*, **15***b* are positioned so that each of the sensors **10**, **15***a*, **15***b* extends along the thickness of the thermal protection system **200**. Each of the conducting lines **30***a*, **30***b* may be connected to terminals **20**, **20***b* as shown in FIGS. **2-4**. In the case of the thermal protection system **200**, the conducting lines **30***a*, **30***b* are extending out of a cold end, the second end **81**, of the thermal protection system **200**. In other words, the first end **61** is generally the end exposed to high temperatures during reentry. The conducting lines **30***a*, **30***b* and the terminals **21***a*, **21***b* of the sensors **15***a*, **15***b* are subsequently connected to an electronic circuit, such as the electric circuit **50** shown in FIGS. **3** and **4**, that is used to generate a tomographic image of the surface temperature and recession rate of the thermal protection system **200**. The processor **26** may be connected. The processor **26** may be

connected to transfer data or information from the thermal protection system **200** to other locations of the space vehicle.

Thermoelectric devices **60***a*-**60***f* may be embedded or otherwise positioned in the thermal protection system **200**. It should be understood that the thermoelectric devices **60***a*-**60***f* may be located on and/or may be embedded in the substrate **12**. The thermoelectric devices **60***a*-**60***f* (as well as the other features of the thermal protection system **200**) may be used with, in addition to and/or as an alternative to features of the aforementioned embodiments of the disclosure.

The thermoelectric devices **60***a*-**60***f* may scavenge thermal energy of the thermal protection system **200**. For example, during reentry to Earth, the space vehicle and, in turn, the thermal protection system **200** may encounter extremely high temperatures permitting thermal energy to be converted to electrical energy by the thermoelectric devices **60***a*-**60***f*. The thermoelectric devices **60***a*-**60***f* may be electrically connected to one or more of the sensors **10**, **15***a*, **15***b* to provide power or current to the sensors **10**, **15***a*, **15***b*. As shown in FIG. **5**, the thermoelectric devices **60***a*-**60***f* may be positioned at different locations along the thickness of the aeroshell so that ablation of the aeroshell may not eliminate at least some of the thermoelectric devices **60***a*-**60***f*. The thermoelectric devices **60***a*-**60***f* may generate sufficient power for one or more of the sensors **10**, **15***a*, **15***b*. The thermoelectric devices **60***a*-**60***f* may be in thermal contact with the heat source and thermally insulated from a heat sink by a cavity, for example, in the substrate **12**, or other thermal insulation device in the thermal protection system **200**.

FIG. **6**A illustrates another embodiment of a substrate **110** having a first sensor **80**, a second sensor **85**, and a third sensor **90**. The substrate **110** may be susceptible to corrosion, ablation and/or temperature changes. The substrate **110** may have qualities and features similar to the substrate **12**. A first sensor **80** may be positioned on and/or etched into the substrate **110**. In an embodiment, the first sensor **80** may be substantially resistant to temperature changes. For example, the properties of the first sensor **80** may be substantially constant with respect to temperature. As a non-limiting example, the first sensor **80** may be a capacitor strip providing a decrease in capacitance as the first sensor **80** is shortened, such as by ablation, corrosion or the like. To this end, the first sensor **80** may provide a measurement related to ablation or other change in thickness of the substrate **12**, **110** and/or the susceptible material **42**. The measurement from the first sensor **80** may be a capacitance that relates to a dimension of the first sensor **80**, the substrate **12**, **110** and/or the susceptible material **42**. For example, the measurement may indicate that a length of the first sensor **80** has decreased, indicating corrosion or ablation of the susceptible material **42**.

The first sensor **80** may comprise a first electrode **82** and a second electrode **84** as shown in FIG. **6**B. A dielectric **83** may separate the first electrode **82** from the second electrode **84**. The dielectric **83** may be, for example, an electric insulator or any substance capable of substantially preventing electrical charges from passing therethrough. The dielectric **83** defines the gap or separation between the first electrode **82** and the second electrode **84**, which of course may be customized based on application. A potential difference may be created across the first electrode **82** and the second electrode **84**. The surface area of the first electrode **82** and the second electrode **84** may decrease as corrosion or ablation occurs on the substrate **110** and/or the susceptible material **42**. As a result, in an embodiment where the first sensor **80** is a capacitor, the decrease in surface area of the electrodes **82**, **84** decrease a capacitance.

Bondpads **86***a*, **86***b* may be positioned at opposing sides of the first sensor **80**. For example, the bondpads **86***a*, **86***b* are positioned on opposite sides of the first electrode **82** and the second electrode **84**. The bondpads **86***a*, **86***b* may be made of a material that can be incorporated into, attached to and/or secured to the susceptible material **42**. The first bondpad **86***a* may be positioned on the first electrode **82**, and the second bondpad **86***b* may be positioned on the second electrode **84**, as shown in FIG. **6**B.

FIGS. **6**C and **6**D illustrate a cross-sectional view of the second sensor **85** and the third sensor **90**, respectively. The second sensor **85** and the third sensor **90** may each have bondpads **86***a*-**86***d* positioned on the first electrode **82** and the second electrode **84**, respectively. The bond pads **86***c* and **86***d* may be separated a distance from bondpads **86***a* and **86***b*. The first electrode **82**, the second electrode **84** and the dielectric **83** may extend between the bondpads **86***c*, **86***d* and the bond pads **86***a*, **86***b*.

The second sensor **85** may have any number of electrical components **141***a*-**141***f*. In the embodiment shown in FIG. **6**A, the second sensor **85** may be utilized to determine an ablation, corrosion or other change in thickness of the substrate **110** and/or the susceptible material **42**. As a result, the second sensor **85** may position the electrical components **141***a*-**141***f* at predetermined positions representative of the degree of measurement of the thickness of the substrate **110** and/or the susceptible material **42** that is desired or required. For example, the electrical components **141***a*-**141***f* may be positioned such that one of the electrical components **141***a*-**141***f* is separated from the second sensor **85** at each position or thickness in which it may be beneficial to determine a thickness, ablation or corrosion of the substrate **110** and/or the susceptible material **42**.

For example, the second sensor **85** may be arranged as a resistor ladder network where at least a portion of the electrical components **141***a*-**141***f* is positioned at rungs of the ladder, for example. The separation, disconnection or destruction of a rung of the ladder network changes the electrical properties of the second sensor **85**. For example, if the electrical components **141***a*-**141***f* comprise resistors, one less resistor may be connected to the ladder network as each run of the ladder is destroyed or broken. As each of the electrical components **141***a*-**141***f* are separated (or destroyed) from the second sensor **85**, the resistance of the second sensor **85** may change, such as increase. The change in the electrical property of the second sensor **85** may be substantially related to a change in thickness of the substrate **110** and/or the susceptible material **42**. Accordingly, in an embodiment, the electrical components **141***a*-**141***f* have a minimal change with respect to temperature. As a result, the second sensor **85** may output or measure the ablation or corrosion of the substrate **110** and/or susceptible material **42** with minimal effects on temperature.

The third sensor **90** may be temperature dependent such that an output or measurement of the third sensor **90** changes based on temperature. For example, the third sensor **90** may comprise one or more electrical components **141***a*-**141***f* that change with respect to temperature. In an embodiment, at least a portion of the electrical components **141***a*-**141***f* may comprise resistors that change resistance based on temperature. The second sensor **85** may be arranged such that one or more of the electrical components **141***a*-**141***f* are separated upon ablation or corrosion of the substrate **110**. For example, the third sensor **90** may be arranged in a ladder configuration as shown in FIG. **6**A where one or more of the electrical

components **141**a-**141**f is separated based on ablation or corrosion of the substrate **110**. In an embodiment where the third sensor **90** primarily measures temperature and the second sensor **85** primarily measures ablation, the third sensor **90** may have less rungs in the ladder network and/or have electrical components that are more temperature dependent.

The third sensor **90** may have any number of electrical components **141**a-**141**f that may be arranged at predetermined distances along the third sensor **90** in order to cause separation of one or more of the electrical components **141**a-**141**f. Accordingly, any degree of ablation or corrosion may be monitored by positioning the electrical components **141**a-**141**f at predetermined positions.

In an embodiment, the separation (or destruction) of one or more of the electrical components **140**a-**140**h from the second sensor **85** changes the electrical property as does changes in temperature of the second sensor **85**. As there may be a number of variables in the changes in the output or measurement of the second sensor **85**, the measurement or output of the second sensor **85** may be compared to the output or the measurement from the first sensor **80** and the third sensor **90**, and vice versa. In an embodiment where the first sensor **80** is a capacitor strip, the first sensor **80** may provide a relatively accurate measurement of the thickness or the susceptible material **42**. This measurement of the thickness of the susceptible material **42** may be used to determine or predict an amount of change in the electrical properties of the second sensor **85** and the third sensor **90** due to the change in thickness. For example, in an embodiment where the second sensor **85** is a resistor ladder sensor, the change in thickness may destroy or otherwise electrically separate one of the resistors causing a change in the electrical property, such as a change in resistance, of the second sensor **85**.

As the second sensor **85** and the third sensor **90** may be sensitive to temperature such that electrical properties of the second sensor **85** and the third sensor **90** change with temperature, the electrical properties or measurements of the second sensor **85** and the third sensor **90** may be compared. However, the electrical properties of the second sensor **85** and the third sensor **90** may also change due to ablation or corrosion of the susceptible material **42**. In order to determine an amount of change of the electrical properties of the second sensor **85** and the third sensor **90** due to temperature, the measurements may be compared in addition to the measurement of the first sensor **80**. The comparison may be an analysis, applying a logic, algorithm or the like using a processor, such as the processor **26**.

In an embodiment the first sensor **80**, the second sensor **85** and the third sensor **90** may be incorporated into a network whereby numerous sets of the first sensor **80**, the second sensor **85** and the third sensor **90**. In an embodiment, each set of the sensors **80**, **85**, **90** may be incorporated into a network or circuit. Each set or each of the sensors **80**, **85**, **90** may operate similar to a node of a circuit and/or may be connected to a multiplex. The multi-plex may communicate with and interrogate with each sensor and may be addressable to each sensor by using an address of each sensor. A demultiplex may be used to display the sets of sensors **80**, **85**, **90** as an array on a display. For example, the display may show a temperature and thickness at each node, such as at each set of the sensors **80**, **85**, **90**.

FIGS. **7**A-**7**G illustrate an embodiment of fabricating and/or manufacturing the first sensor **80**, the second sensor **85** and the third sensor **90**. It will also be appreciated by those having ordinary skill in the art that the embodiment of fabrication and manufacturing methods FIGS. **7**A-**7**G may be utilized for the sensors **10**, **15**a-**15**e. It should also be appreciate that the description of the manufacturing and fabrication process is for explanatory purposes, and the present disclosure should not be deemed as limited to this fabrication process or any specific fabrication process.

FIG. **7**A illustrates a side view of a wafer **300** which may be utilized in an embodiment of the disclosure. The wafer **300** may be, for example, a high resistivity p-type substrate, or a semi-insulating substrate. The wafer **300** of the disclosure should not be deemed as limited to any type of substrate dimensions, but at least in an embodiment may have a thickness of approximately 200 microns. The wafer **300** may be cleaned using a solvent to remove organics, and then the wafer **300** may be dipped in a chemical solution to remove any trace metals, such as a solution of hydrogen peroxide and sulfuric acid. As a non-limiting example, the wafer **300** is dipped into a chemical solution comprising substantially equal volumes of hydrogen peroxide and sulfuric acid for 15 minutes. The wafer **300** may be rinsed, such as by use of de-ionized water. In addition, the wafer **300** may be blown dry with a gas, such as nitrogen.

FIG. **7**B illustrates deposition of a layer **302** on the wafer **300**. The layer **302** may be positioned on the wafer **300** by any process known to those having ordinary skill in the art, including microfabrication techniques, such as sputtering. In an embodiment, the layer **302** may be metallic, such as gold. The layer **302** may then be annealed in a gas, such as nitrogen. For example, the layer **302** may be annealed in nitrogen at 200 degrees Celsius for about thirty minutes. Photoresist or other light sensitive material may be applied on the layer **302** and spun, such as at 3000 revolutions per minute for thirty seconds. Next, the wafer **300** with the layer **302** may be baked at 90 degrees Celsius in a gas, such as nitrogen ambient for a duration, such as five minutes. Next, a bondpad mask is placed over the photoresist and exposed under ultra violet light, such as for ten seconds. The wafer **300** may then be inserted in a developer for about one and a half minutes to develop the photoresist. The wafer **300** may be rinsed in de-ionized, blow dried, and baked again for five minutes in nitrogen ambient at 90 degrees Celsius.

FIG. **7**C illustrates that the layer **302** is etched in 10:9:1 volume ratio of H_2O:HCl:HNO_3 at 40 degrees Celsius until a portion of the layer **302** is dissolved, leaving only the bondpad gold under the protective photoresist. Next, the photoresist is dissolved in acetone and the wafer and rinsed in de-ionized water. The layer **302** may be one of the bondpads **86**a-**86**d as shown in FIGS. **6**B-**6**D. FIG. **7**D illustrates a top view of the wafer **300** of FIG. **7**C.

A layer **304** may be deposited on the wafer **300** and the layer **302** as shown in FIG. **7**E by any microfabrication technique, such as sputtering. The layer **304** may be an electrode, such as a metal, for example platinum, and may have any dimension, but in this example is approximately 400 nanometers. A silicon or other bonding agent may be deposited on the layer **304** to promote sealing with the layer **306**. Next, the layer **306** is deposited by any known microfabrication technique. The layer **306** may be a dielectric material, such as silicon dioxide. The layer **306** may, in an embodiment, be the dielectric **83** as shown in FIGS. **6**B-**6**D.

A layer of silicon or other bonding agent is deposited on the layer **306** to promote adhesion. The silicon may be a thin layer, such as 10 nanometers. The layer **308** is then deposited on the layer **306**, as shown in FIG. **7**F by any known microfabrication technique. The layer **308** may be made of an electrode, such as a metal, for example, platinum. The

layer **308** in this embodiment is about three nanometers. The layer **308** may be the electrode **82** as shown in FIGS. **6**B-**6**D.

Next, a layer **310** is deposited on the layer **308** using a known microfabrication technique, as shown in FIG. **7**G. The layer **310** may be a metallic layer, such as gold. The layer **310** may be about 200 nanometers. Photoresist or other light sensitive material may be applied on the layer **310** and spun, such as at 3000 revolutions per minute for thirty seconds. Next, the wafer **300** with the layer **302** may be baked at 90 degrees Celsius in a gas, such as nitrogen ambient for a duration, such as five minutes. Next, a bondpad mask is placed over the photoresist and exposed under ultra violet light, such as for ten seconds. The wafer **300** may then be inserted in a developer for about one and a half minutes to develop the photoresist. The wafer **300** may be rinsed in de-ionized, blow dried, and baked again for five minutes in nitrogen ambient at 90 degrees Celsius.

FIG. **8**A illustrates that the layer **310** is etched in 10:9:1 volume ratio of H_2O:HCl:HNO_3 at 40 degrees Celsius until a portion of the layer **310** is dissolved, leaving only the bondpad gold under the protective photoresist. Next, the photoresist is dissolved in acetone and the wafer and rinsed in de-ionized water. The layer **310** may be one of the bondpads **86***a*-**86***d* as shown in FIGS. **6**B-**6**D. FIG. **8**B illustrates a top view of the wafer **300** of FIG. **8**A.

A layer of aluminum may then be deposited on the surface by sputtering or e-beam technique. Photoresist is applied on the aluminum surface and spun at 3000 revolutions per minute for about thirty seconds. After applying the photoresist, the wafer **300** may be baked at 90 degrees Celsius in a gas, such as nitrogen ambient for about five minutes. A sensor element mask may be positioned over the photoresist and exposed under ultra violet light for about ten seconds. The wafer **300** is then inserted in a developer for about one and half minutes to develop the photoresist. The wafer **300** is rinsed in de-ionized, blow dried, and baked again for about five minutes in gas, such as nitrogen ambient, at about 90 degrees Celsius.

The aluminum layer may be etched using any known etching technique as will be appreciated by those of ordinary skill in the art. For example, the aluminum layer may be etched chemically using phosphoric acid at about 50 degrees Celsius under the field aluminum dissolves substantially or preferably completely, leaving the aluminum under the protective photoresist. To remove the photoresist, acetone may be used to dissolve the photoresist. Then, the wafer **300** may be reinsed in de-ionized water. Using the aluminum as the etch mask, the areas not protected by the aluminum are etched by reactive ion etching method to the wafer **300** as shown in FIG. **8**C. The residual aluminum surviving the reactive ion etching is dissolved in phosphoric acid at about 50 degrees Celsius, followed by rinsing with de-ionized water and blowing dry with a nitrogen gas.

The underside of the wafer **300** is etched by reactive ion etching to thin the wafer **300** to at least 100 microns. The front side of the wafer **300** is mounted to a carrier substrate with a thin layer of photoresist and backed at 90 degrees Celsius in nitrogen ambient for about 30 minutes. A seed layer of nickel may be deposited on the backside. Photoresist is applied to the nickel see layer and spun at 3000 revolutions per minute for about 30 seconds. This is followed by baking at 90 degrees Celsius in nitrogen ambient for about five minutes. Next, a backside contact mask is placed over the photoresist and exposed under ultra violet light for about ten seconds. The wafer **300** is then inserted in a developer for about one and a half minutes to develop the photoresist. The wafer **300** is rinsed in de-ionized, blow dried, and baked again for five minutes in nitrogen ambient at 90 degrees Celsius.

Nickel may be electroplated on the portion of the nickel seed layer not protected by the photoresist. The dissolution of the photoresist may be accomplished with acetone and subsequent rinsing in de-ionized water. Using the thick nickel as an etch mask, the backside of the wafer **300** is etched to expose the layer **302**, which is the first bondpad layer. The thickness of the electroplated nickel should be such that it is completely etched just before the bondpads are exposed. This permits a complete removal of the nickel and the etching continues on the entire backside of the wafer **300** until the bondpads are exposed. The wafer **300** is unmounted from the carrier by immersing in acetone.

During re-entry of the space vehicle into Earth, the thermal protection system **200** may encounter thermophysical effects (shock, radiation, ionization, non-equilibrium chemistry) that combine to lead to its ablation and subsequent recession. As the thermal protection system **200** recedes, the sensors **10**, **15***a*, **15***b*, **80**, **85**, **90** also recede. This results in a change in an electrical property of the sensors **10**, **15***a*, **15***b*, **80**, **85**, **90** such as a change in the capacitance or resistance of the sensors **10**, **15***a*, **15***b*, **80**, **85**, **90**. For example, if the sensor **10**, **85**, **90** is arranged in a ladder network, then the rate of breaks of the steps of the ladder network (or the rate at which one of the electrical components separates from the other electrical components) directly relates to the recession rate of the thermal protection system **200**. In cases where the recession across the thermal protection system **200** is asymmetric, such effect would be reflected on the sensor **10**, **15***a*, **15***b*, **80**, **85**, **90** that corresponds to that location.

In an embodiment, the system and method disclosed herein may be utilized to enhance temperature and recession measurements and/or may significantly aid in optimizing the geometric shape of the susceptible material **42**, such as an aero-shell of a space vehicle. Instead of having a few measurement plugs as in prior art devices, hence few measurement locations, the present disclosure provides a system and method permitting temperature and ablation recession sensors **10**, **15***a*, **15***b*, **80**, **85**, **90** to be arrayed over a larger surface area, such as a larger surface area of the thermal protection system material **200**. Each sensor **10**, **85**, **90** may comprise one or more resistors, such as a micro-millimeter scale resistor ladder network, fabricated in materials that are compatible with the susceptible material. The resistor ladder network may be fabricated in the substrate **12** and released. Each resistor ladder network is positioned along the thickness of the susceptible material **42**. The sensors **15***a*, **15***b*, **80** which may be capacitor strips, may be positioned adjacent each of the sensors **10** to determine a change in the thickness of the susceptible material (recession rate).

The invention claimed is:

1. A system comprising:

a material susceptible to corrosion or ablation and having a thickness defined between a first end and a second end;

a first sensor and a second sensor on the material and extending along the thickness adjacent the first end and toward the second end, wherein the first and second sensors extend parallel to one another and are both configured to change in length in response to corrosion or ablation of the susceptible material, wherein a first electrical property of the first sensor is dependent on a length of the first sensor, wherein a second electrical property of the second sensor is dependent on a length

of the second sensor, wherein the first electrical property has a different dependency on a temperature of the material than the second electrical property;

an electrical circuit coupled to the first sensor and the second sensor to determine changes in the first and second electrical properties; and

a processor configured to estimate the temperature and thickness based on the changes in the first and second electrical properties.

2. The system of claim **1**, wherein the first electrical property is resistance and the first sensor is a first ladder sensor comprising a first plurality of resistive elements disposed at various locations between the first end and the second end.

3. The system of claim **2**, wherein the second electrical property is capacitance and the second sensor comprises a capacitive strip, wherein the first electrical property is more dependent on the temperature than the second electrical property.

4. The system of claim **3**, wherein the processor is configured to determine the thickness based on a change in the second electrical property and determine the temperature based on a combination of the change in the first electrical property and a change in the second electrical property.

5. The system of claim **3**, wherein the second electrical property does not vary with the temperature.

6. The system of claim **2**, wherein the second electrical property is resistance and the second sensor is a second ladder sensor comprising a second plurality of resistive elements disposed at various locations between the first end and the second end.

7. The system of claim **6**, wherein each of the first plurality of resistive elements have positive temperature coefficients and each of the second plurality of resistive elements have negative temperature coefficients.

8. The system of claim **6**, further comprising a third sensor extending along the thickness adjacent the first end and toward the second end, wherein the third sensor comprises a capacitive strip having a capacitance that decreases in response to ablation or corrosion of the material.

9. The system of claim **8**, wherein the third sensor is disposed between the first sensor and the second sensor.

10. The system of claim **1**, wherein the first and second sensors are a part of a first grouping of sensors, wherein the system further comprises a plurality of additional groupings of sensors communicably coupled to the processor, wherein the processor is configured to receive signals from the plurality of additional sensors and estimate the thickness at a plurality of locations in the material based on the received signals.

11. A system comprising:

a material comprising a first surface and a second surface;

a first grouping of sensors embedded in the material, the first grouping of sensors comprising:

a first ladder sensor comprising a first plurality of electrical components extending between the first surface and the second surface, the first ladder sensor having a first electrical property that varies in response to a change in a thickness of the material at a first location and variations in a temperature of the material;

a second ladder sensor comprising a second plurality of electrical components extending between the first surface and the second surface, the second ladder sensor having a second electrical property that varies in response to a change in the thickness at a second location; and

a capacitive strip sensor extending between the first surface and the second surface, the capacitive strip sensor having a capacitance that varies in response to a change in the thickness at a third location, wherein the first ladder sensor, the second ladder sensor, and the capacitive strip sensor extend parallel to one another; and

a processor communicably coupled to the grouping of sensors, wherein the processor is configured to:

estimate the thickness of the material at the first, second, and third locations based on sensor signals generated via the first ladder sensor, the second ladder sensor, and the capacitive strip sensor, respectively; and

estimate the temperature of the material based on the sensor signal generated via the first ladder sensor.

12. The system of claim **11**, wherein the second electrical property also varies in response to variations in the temperature of the material.

13. The system of claim **12**, wherein a sensitivity of the second electrical property to the temperature of the material is different than a sensitivity of the first electrical property to the temperature of the material.

14. The system of claim **13**, wherein the processor is configured to isolate changes in the first and second electrical properties due to changes in the temperature from changes in the first and second electrical properties due to changes in the thickness based on a difference between the first and second sensor signals.

15. The system of claim **13**, wherein the first electrical property is more sensitive to the temperature of the material than the second electrical property, wherein the first plurality of electrical components has a lesser number of electrical components than the second plurality of electrical components.

16. The system of claim **11**, wherein the first and second electrical properties are resistance, wherein the first plurality of electrical components comprises a first plurality of resistors and the second plurality of electrical components comprises a second plurality of resistors.

17. The system of claim **16**, wherein each resistor in the first plurality of resistors has a positive temperature coefficient and each resistor in the second plurality of resistors has a negative temperature coefficient.

18. The system of claim **11**, wherein the processor is configured to estimate the temperature at the first location based on a combination of the first sensor signal and the third sensor signal and estimate the temperature at the second location based on a combination of the second sensor signal and the third sensor signal.

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