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(54) **SYSTEMS AND METHODS OF MONITORING THIN FILM DEPOSITION**

(75) Inventors: **John D. Larson, III**, Palo Alto, CA (US); **Herbert L. Ko**, Mountain View, CA (US); **Richard K. Karlquist**, Cupertino, CA (US); **Mark A. Hueschen**, Palo Alto, CA (US); **Kent W. Carey**, Palo Alto, CA (US)

(73) Assignee: **Agilent Technologies, Inc.**, Palo Alto, CA (US)

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(51) **Int. Cl.**[7] **G01N 33/00**; G01N 29/00
(52) **U.S. Cl.** **73/61.62**; 73/64.53; 73/24.06; 73/28.01; 427/10
(58) **Field of Search** 427/10; 73/64.53, 73/31.05, 24.06, 28.01, 61.62

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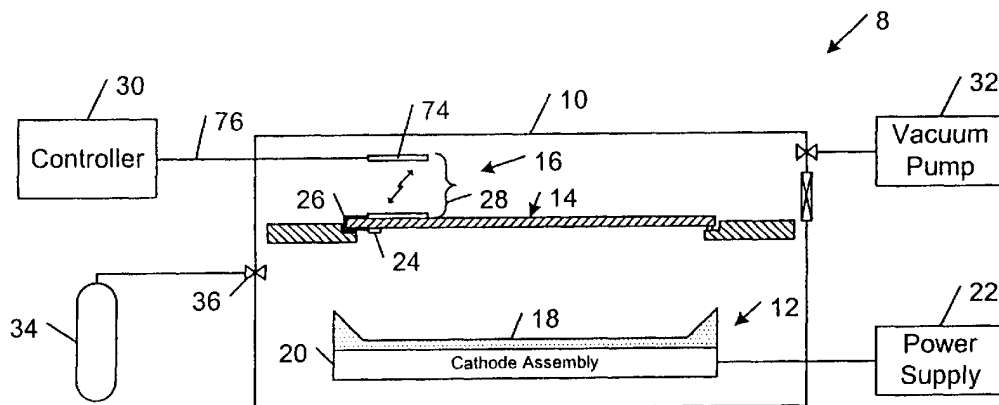|					
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Primary Examiner—Edward Lefkowitz
Assistant Examiner—Michael Cygan

(57) **ABSTRACT**

Systems and methods of monitoring thin film deposition are described. In one aspect, a thin film deposition sensor includes an acoustical resonator (e.g., a thin film bulk acoustical resonator) that has an exposed surface and is responsive to thin film material deposits on the exposed surface. A substrate clip may be configured to attach the thin film deposition sensor to a substrate. A transceiver circuit may be configured to enable the thin film deposition sensor to be interrogated wirelessly. A method of monitoring a thin film deposition on a substrate also is described.
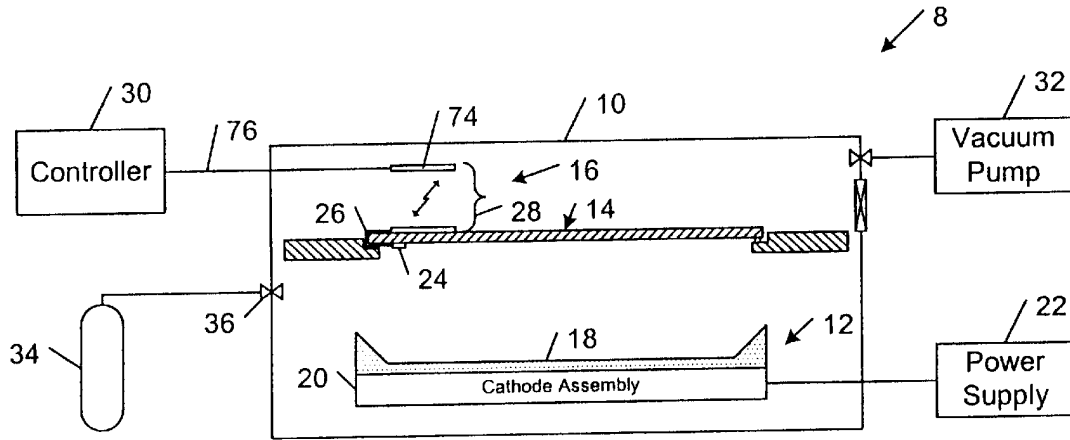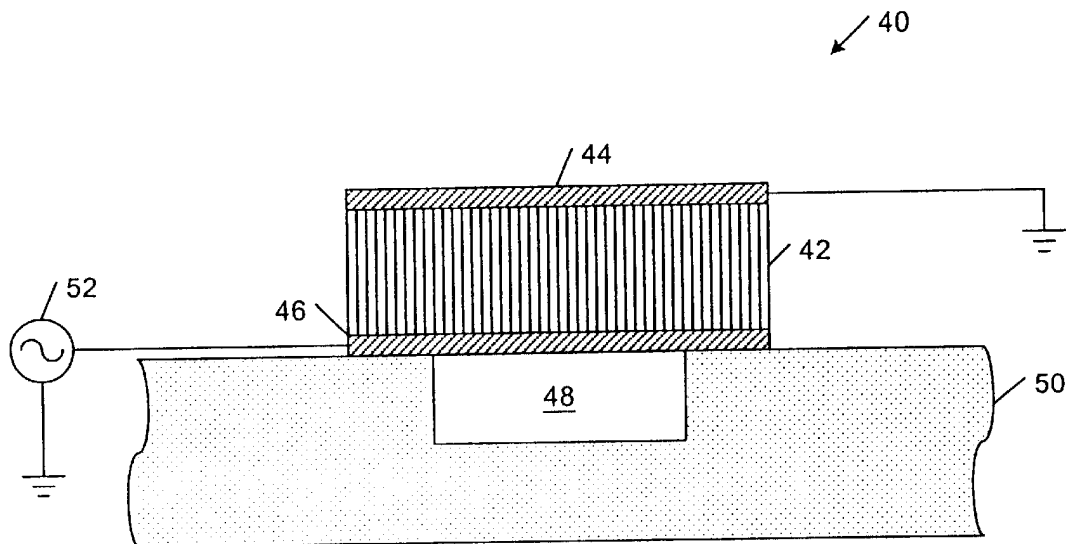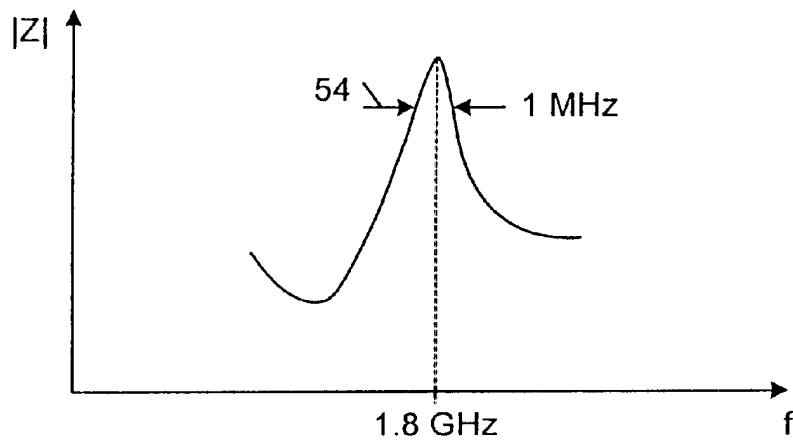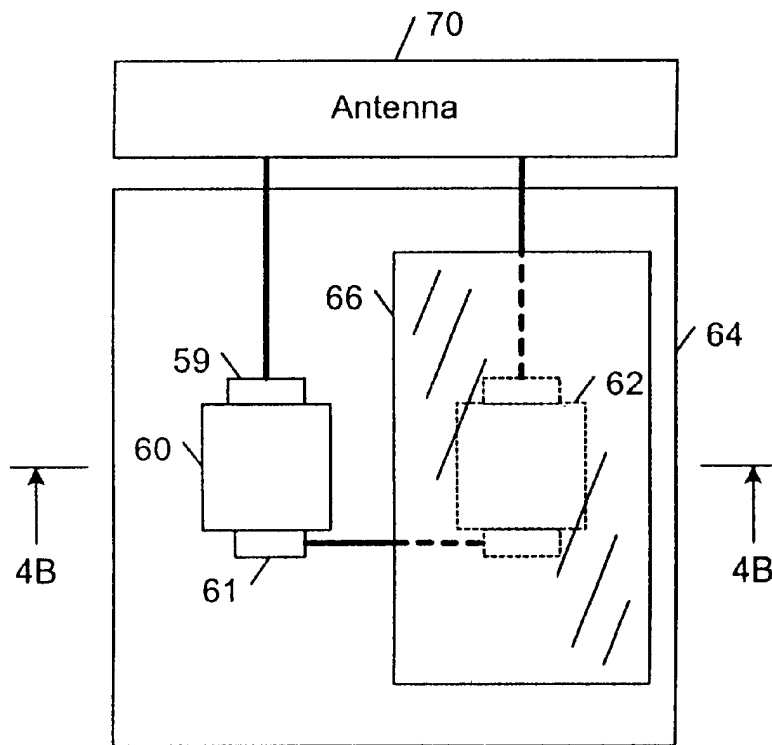
25 Claims, 6 Drawing Sheets

FIG. 1

FIG. 2
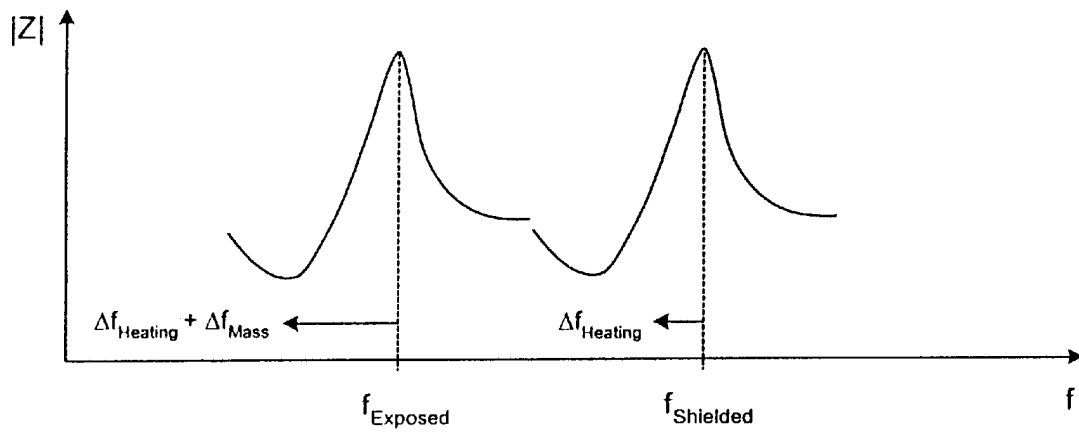
FIG. 3

FIG. 4A

FIG. 4B

FIG. 4C

$|Z|$

$\Delta f_{Heating} + \Delta f_{Mass}$ $\Delta f_{Heating}$

$f_{Exposed}$ $f_{Shielded}$ f

FIG. 5

80

88

90

86

82   84

FIG. 6A

100

106

108

110

102   104

FIG. 6B

8

30
Controller

120 122 28 10

124

26 16

24 14

34 36

18

20

20   Cathode Assembly

32
Vacuum
Pump

22
Power
Supply

FIG. 7

124

140

126

138

128

130

132

134

Antenna

136

FIG. 8

150

66   158   66   66

60   60   60

62   62   62

152   154   156

FIG. 9

Interrogator Circuit

170

178

Non-Volatile
Memory

172

176

Power Converter/
Transceiver

Modulator/
Demodulator

Frequency
Discrimator

174

FIG. 10

SYSTEMS AND METHODS OF MONITORING THIN FILM DEPOSITION

This is a Divisional of copending application Ser. No. 09/840,401, filed on Apr. 23, 2001, the entire disclosure of which is incorporated herein by reference.
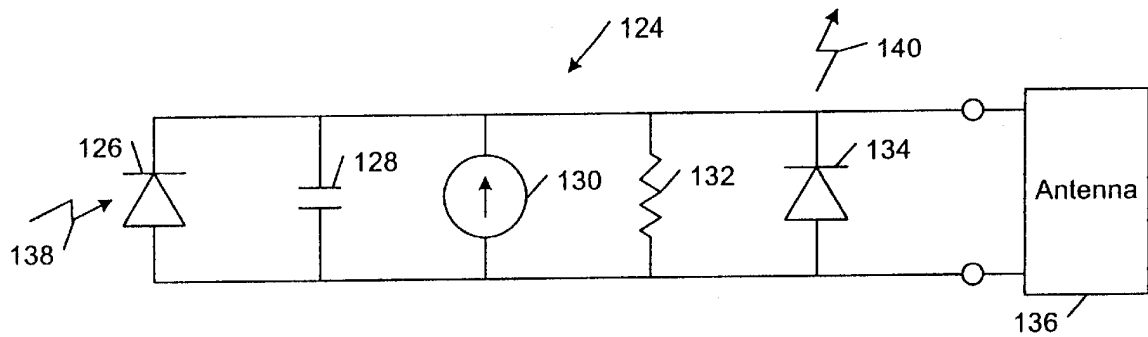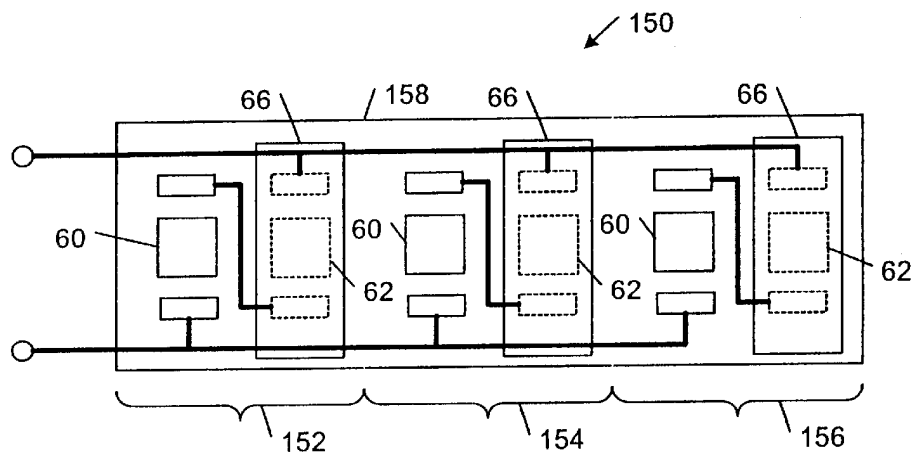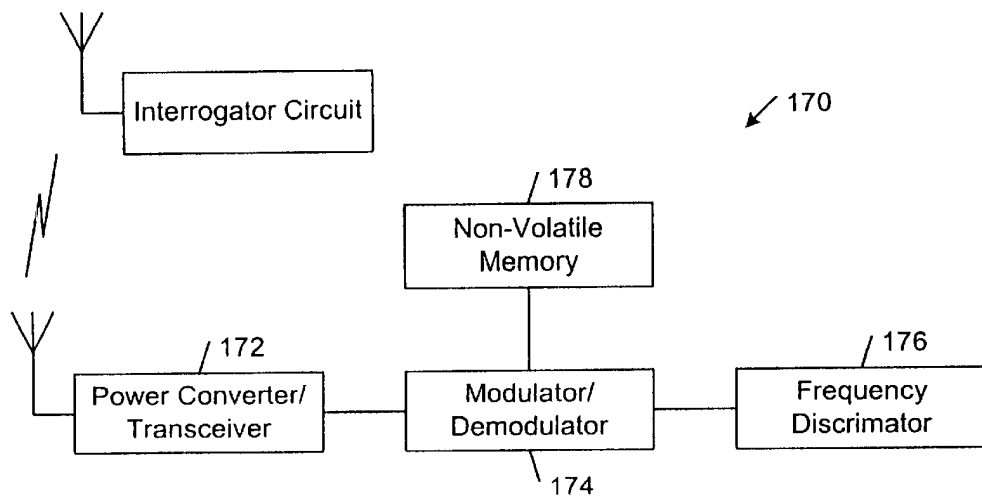
TECHNICAL FIELD

This invention relates to systems and methods of monitoring thin film deposition.

BACKGROUND

Monitoring and controlling the deposition of thin films, for example, by vapor deposition or sputtering, are required steps in the production of high quality thin film devices. Quartz crystal deposition monitors typically are used to monitor the deposition process and to control the amount of material deposited on a substrate and the rate at which material is deposited on the substrate. In practice, a quartz crystal monitor is mounted on a water-cooled holder that is positioned inside a vacuum deposition chamber where material may deposit on the exposed monitor surface while a thin film is deposited on a substrate that is located near the exposed monitor surface. Due to the large size of the monitor crystal and the associated holder, the monitor often is mounted at a location that is offset from the substrate. As a result, the monitor typically is exposed to different deposition conditions than the substrate. This difference often is corrected by a tooling factor.

In general, as material is deposited onto the exposed surface of a quartz crystal monitor, the resonant frequency of the monitor decreases. Quartz crystal is characterized by a relatively high quality factor (Q), which enables quartz crystal monitors to make high resolution frequency measurements and, thereby, allows such monitors to detect small changes in the deposited mass. For example, a monolayer of copper added to a 6 MHz quartz crystal monitor reduces the resonance frequency by approximately 20 Hz, which is on the order of the bandwidth of the resonator. To a first order approximation, the gauge factor (MHz/nm) of a quartz crystal monitor is proportional to the density of the deposited material. Typical thin film monitor quartz crystals have quality factors that are on the order of 200,000 and, consequently, are characterized by a 3 dB line width and a frequency shift resolution that are on the order of 20 Hz. Typical commercial instruments (e.g., a quartz crystal thin film deposition monitor available from Inficon of East Syracuse, N.Y., U.S.A.) have resolutions that are on the order of 0.1–0.2 nm for film thicknesses in the range of 100 nm, or less. The absolute thickness accuracy of such systems is on the order of 1–2%.

In a typical instrumentation arrangement, the resonant frequency of a quartz crystal monitor is determined by placing the monitor in the feedback loop of an external oscillator circuit as a frequency control element. The quartz crystal monitor is connected to the oscillator circuit by a cable that extends through a vacuum feed-through in a wall of the deposition chamber. Since the equivalent electrical impedance of the quartz crystal is pure real and maximized at its parallel resonance frequency and is minimized at its series resonance frequency, the oscillator circuit tends to produce an output signal at one of the other of the crystal resonance frequencies, as determined by the external oscillator circuit. As a result, changes in the crystal resonance frequency produce corresponding changes in the oscillator circuit output frequency, which may be monitored by an is external control circuit.

SUMMARY

The invention provides a novel scheme (systems and methods) for monitoring thin film thickness or substrate temperature, or both.

In one aspect, the invention features a system for monitoring a thin film deposition that includes a thin film deposition sensor comprising an acoustical resonator that has an exposed surface exposed and is responsive to thin film material deposits on the exposed surface.

Embodiments in accordance with this aspect of the invention may include one or more of the following features.

The acoustical resonator preferably is a thin film bulk acoustical resonator (FBAR). The thin film deposition sensor preferably further comprises a second acoustical resonator thermally coupled to the first acoustical resonator and shielded from deposition of thin film material. The first and second acoustical resonators may be coupled electrically in series or in parallel, or may be addressed individually. The first and second acoustical resonators may be coupled together by an electrical connection that is shielded from thin film material deposits. In one embodiment, a plurality of pairs of exposed and shielded acoustical resonators are disposed on an elongated substrate.

The monitoring system preferably includes an antenna configured to enable the thin film deposition sensor to be interrogated wirelessly. Alternatively, an optical coupler may be used to interrogate the thin film deposition sensor wirelessly.

In another aspect, the invention features a thin film deposition monitoring system that includes a thin film deposition sensor and a substrate clip that is configured to attach the thin film deposition sensor to the substrate. In this way, the monitor may be exposed to substantially the same deposition conditions as the substrate, in which case convention tooling factor corrections may not be needed.

Embodiments in accordance with this aspect of the invention may include one or more of the following features.

The substrate clip may include an antenna.

In another aspect of the invention, a thin film deposition monitoring system includes a thin film deposition sensor and a transceiver circuit that is configured to enable the thin film deposition sensor to be interrogated wirelessly.

Embodiments in accordance with this aspect of the invention may include one or more of the following features.

In some embodiments, the monitoring system may include a first antenna coupled to the thin film deposition sensor and a second antenna coupled to the transceiver circuit.

The transceiver circuit may include an energy storage element and an opto-electronic transducer.

In one embodiment, the transceiver is an RFID tag circuit.

In another aspect, the invention features a method of monitoring a thin film deposition on a substrate. In accordance with this inventive method, a thin film deposition sensor comprising an acoustical resonator is disposed within a deposition chamber, and a surface of the acoustical resonator is exposed to a thin film deposition.

Embodiments in accordance with this aspect of the invention may include one or more of the following features.

The thin film deposition sensor preferably is interrogated wirelessly to determine the resonant frequency of the acoustical resonator. The thin film deposition sensor preferably further comprises a second acoustical resonator that is shielded from the thin film deposition. The thin film depo-

sition sensor preferably is interrogated wirelessly to determine the resonant frequencies of the first and second acoustical resonators.

In some embodiments, an optical signal may be transmitted through an optical port of the deposition chamber.

The thin film deposition sensor may be disposed within the deposition chamber by attaching the thin film deposition sensor to the substrate.

Among the advantages of the invention are the following.

The invention provides a novel thin film deposition monitoring system that may be used to monitor thin film thickness or substrate temperature, or both. The use of a pair of exposed and shielded acoustical resonators, which respond to temperature changes in substantially the same way, enables a controller to distinguish temperature-induced changes in resonant frequency from mass-induced changes in resonant frequency. This feature avoids the need to maintain the thin film deposition sensor at a constant controlled temperature and, thereby, avoids the need for a water-cooled holder and associated cooling equipment (e.g., water pipes).

In addition, the novel substrate clip provides a convenient way to implement a thin film deposition sensor as a single-use, disposable thin film thickness and temperature monitor. This feature avoids the need to periodically replace monitors and the associated risk that effluent build-up might flake off and contaminate the vacuum deposition system. Also, because the thin film deposition sensor may be clipped directly to the substrate, the invention allows a controller to monitor the film growth at the substrate surface. This feature avoids inaccuracies that could result from monitoring deposition conditions at a location displaced from the substrate, conditions which may not correlate well with the actual deposition conditions at the substrate surface. Thus, conventional tooling factor corrections may be eliminated for the most part.

Furthermore, because the novel acoustical resonators are characterized by relatively small dimensions, multiple redundant thin film deposition sensors may be disposed within a vacuum chamber to provide a plurality of data points that enable a controller to monitor and control the deposition process with greater accuracy. In this way, the deposition uniformity at the substrate surface may be monitored and controlled dynamically (e.g., in vacuum deposition systems that include multiple independently controllable material sources).

Other features and advantages of the invention will become apparent from the following description, including the drawings and the claims.

DESCRIPTION OF DRAWINGS

FIG. **1** is a diagrammatic side view of a vacuum deposition system that includes a target assembly for sputtering a thin film onto a substrate, and a system for monitoring the thin film deposition.

FIG. **2** is a diagrammatic cross-sectional side view of a thin film bulk acoustical resonator (FBAR).

FIG. **3** is a graph of the magnitude of electrical impedance (|Z|) of the FBAR of FIG. **2** plotted as a function of frequency (f) and indicating the series and shunt resonant frequencies.

FIG. **4A** is a diagrammatic top view of a thin film deposition sensor incorporating two FBARs that are connected electrically in series.

FIG. **4B** is a diagrammatic cross-sectional side view of the thin film deposition sensor of FIG. **4A** and a substrate clip that is configured to attach the thin film deposition sensor to a substrate.

FIG. **4C** is a diagrammatic bottom view of the thin film deposition sensor of FIG. **4A** and the substrate clip of FIG. **4B**.

FIG. **5** is a graph of the magnitude of electrical impedance (|Z|) of the thin film deposition sensor of FIG. **4A** plotted as a function of frequency (f) during a thin film deposition.

FIG. **6A** is a diagrammatic cross-sectional side view of another thin film deposition sensor.

FIG. **6B** is a diagrammatic cross-sectional side view of another thin film deposition sensor.

FIG. **7** is a diagrammatic side view of a vacuum deposition system that includes an optical system for interrogating the thin film deposition sensor of FIG. **4A**.

FIG. **8** is a circuit diagram of an interrogation transceiver circuit that is configured to enable the optical system of FIG. **7** to interrogate the thin film deposition sensor of FIG. **4A** wirelessly.

FIG. **9** is a diagrammatic top view of an elongated thin film deposition sensor that includes multiple FBAR series pairs that are connected electrically in parallel.

FIG. **10** is a block diagram of an RFID tag circuit.

DETAILED DESCRIPTION

In the following description, like reference numbers are used to identify like elements. Furthermore, the drawings are intended to illustrate major features of exemplary embodiments in a diagrammatic manner. The drawings are not intended to depict every feature of actual embodiments nor relative dimensions of the depicted elements, and are not drawn to scale.

Referring to FIG. **1**, in one embodiment, a vacuum deposition system **8** includes a vacuum chamber **10**, a target assembly **12** for sputtering a thin film onto a substrate **14**, and a system **16** for monitoring the thin film deposition. Target assembly **12** includes a target **18** that is located on a cathode assembly **20** and is formed from material (e.g., aluminum) to be deposited onto substrate **14**. Cathode assembly **20** is powered by a power supply **22**. Monitoring system **16** includes a thin film deposition sensor **24** that is attached to substrate **14** by a substrate clip **26**, and a wireless interrogation system **28** that is configured to enable a controller **30** to wirelessly interrogate thin film deposition sensor **24**.

In operation, a vacuum pump **32** evacuates vacuum chamber **10**. A sputtering gas (e.g., argon) from a gas supply **34** is introduced into vacuum chamber **10** at a low pressure through a control valve **36**. If reactive sputtering is to be performed, a reactive gas also is introduced into vacuum chamber **10**. An electrical potential is created within vacuum chamber **10** between a system ground (anode) and target **18** and cathode assembly **20**. The electrical potential may be established by grounding vacuum chamber **10** and holding the cathode at a negative potential relative to the ground potential. The resulting electric field between the cathode and the anode ionizes the support gas to form a plasma. Cathode assembly **20** generates magnetic fields that confine plasma electrons to a region between target **18** and substrate **14**, thereby increasing the ion population within the plasma. The positive ions in the plasma collide with target **18**, causing target material to be ejected from the surface of target **18**. A portion of the ejected target material impinges onto the exposed surface of substrate **14** to form a thin film. A portion of the ejected target material also impinges onto an exposed surface of thin film deposition sensor **24**, which is responsive to thin film material deposits on the exposed

surface. Controller **30** may interrogate thin film deposition sensor **24** wirelessly during the thin film deposition to determine the thickness of the deposited thin film, the rate at which target material is deposited onto substrate **14**, and the local substrate temperature in the vicinity of thin film deposition sensor **24**. Controller **30** may use this information to control the thin film deposition process.

Referring to FIG. **2**, the thin film deposition sensor **24** of FIG. **1** includes one or more acoustical resonators that are configured to enable controller **30** to monitor the thin film deposition process within vacuum deposition system **8**. In one embodiment, thin film deposition sensor **24** includes a thin film bulk acoustical resonator (FBAR) **40**, which is formed from a thin film piezoelectric layer **42** that is sandwiched between a pair of electrodes **44, 46**. Piezoelectric layer **42** may be formed from, e.g., aluminum nitride, and electrodes **44, 46** may be formed from, e.g., molybdenum. The sandwich structure is suspended over a cavity **48** that is formed in a substrate **50**. FBAR **40** may be fabricated using conventional silicon micromachining techniques. In operation, a voltage supply **52** applies an electric field between electrodes **44, 46**. Thin film piezoelectric layer **42** converts a portion of the applied electrical energy into mechanical energy in the form of sound waves. The sound waves propagate in the direction of the applied electric field and reflect off the interface between cavity **48** and electrode **46**, return through piezoelectric layer **42** and re-reflect off the interface between the air and electrode **44**. FBAR **40** is characterized by a mechanical resonant frequency corresponding to the frequency at which the half wavelength of a sound wave propagating in the device is approximately equal to the total thickness of the device for a given velocity of sound in the FBAR.

Further details regarding the construction and operation of thin film acoustical resonators may be obtained from U.S. Pat. Nos. 5,587,620, 5,873,153 and 6,060,818, each of which is incorporated herein by reference.

As shown in FIG. **3**, at the mechanical resonance, FBAR **40** appears to be an electronic resonator with an electrical impedance (Z) that peaks at the resonant frequency (e.g., 1.8 GHz). The resonant frequency is established, at least in part, by the physical dimensions of FBAR **40**. For applications in the microwave frequency range (e.g., about 1.8 GHz to about 5 GHz), FBAR **40** may have physical dimensions on the order of 150 μm×150 μm in area and 0.5 μm to 5 μm thickness. In operation, FBAR **40** is characterized by a relatively high gauge factor as a result of its relatively high resonant frequency. For example, FBARs with a resonant frequency of about 1.8 GHz typically exhibit quality factors on the order of about 2,000, which is equivalent to a line-width **54** that is on the order of about 1 MHz and a gauge factor to deposited film thicknesses that is on the order of about 1 MHz frequency shift per 0.5 μm of deposited film thickness. Such an FBAR construction may produce a detectable frequency shift corresponding to a few tenths of a nm of deposited material. For example, a deposition of 200 nm of molybdenum typically produces a 400 MHz downshift in resonant frequency (i.e., a 22% downshift from the initial resonant frequency of 1.8 GHz). Such a resonant frequency downshift may be detected by any one of a wide variety of microwave instrumentation techniques. In addition, since FBAR **40** converts the deposited film thickness increase into a change in resonant frequency, controller **30** may convert the thickness and deposition rate information automatically into digital values that may be used in subsequent data processing steps.

Referring to FIGS. **4A–4C** and **5**, in one embodiment, thin film deposition sensor **24** includes a pair of FBARs **60, 62**,

which are mounted on a thermally conductive substrate **64** (e.g., a silicon substrate) with an areal dimension of about 1 mm×1 mm. FBARs **60, 62** are connected electrically in series. In other embodiments, FBARs **60, 62** may be connected in parallel or addressed individually. FBARs **60, 62** are configured to enable controller **30** to distinguish temperature-induced changes in resonant frequency from mass-induced changes in resonant frequency. In particular, FBAR **60** is exposed to receive material deposits from target **18**, whereas FBAR **62** is shielded from such deposits by a deposition shield **66**. Referring to FIG. **5**, during a thin film deposition, exposed FBAR **60** would be subject to the frequency downshifting effects of mass loading ($\Delta f_{Exposed, Mass}$) and heating ($\Delta f_{Exposed, Heating}$), which is approximately 5 MHz downshift per 100° C. increase in temperature. Shielded FBAR **60**, on the other hand, would be subject to only the frequency downshifting effects of heating ($\Delta f_{Shielded, Heating}$). Because the exposed and shielded FBARs **60, 62** are matched and thermally coupled together, the heat-induced frequency downshifts observed in exposed FBAR **60** track the frequency downshifts observed in shielded FBAR **62**. Controller **30** may compute the amount of material deposited on substrate **14** and the rate at which material is deposited on substrate **14** based upon the difference between the resonant frequencies of the exposed and shielded FBARs **60, 62**:

$$\Delta f_{Exposed} - \Delta f_{Shielded} = \Delta f_{Exposed, Mass} + \Delta f_{Exposed, Heating} - \Delta f_{Shielded, Heating} = \Delta f_{Exposed, Mass}$$

In addition, controller **30** may track the resonant frequency of shielded FBAR **62** to determine the local temperature of substrate **14**. Thin film deposition sensor **24** may be characterized by a temperature resolution of approximately 1–2° C. and a linearity up to at least 100° C. At temperatures above 100° C., the temperature of thin film deposition sensor **24** may be determined from an empirically derived lookup table. In this way, thin film deposition sensor **24** may act as a thin film thickness monitor and a temperature monitor.

As mentioned above, thin film deposition sensor **24** also includes a substrate clip **26** that is formed from a resilient material and is configured to attach thin film deposition sensor **24** securely to substrate **14**. In one embodiment, substrate clip **26** is designed to clip onto the peripheral edge of substrate **14**. In operation, substrate clip **26** may be clipped to substrate **14** before substrate **14** is loaded into vacuum deposition chamber **10** and may be detached from substrate **14** and discarded after substrate **14** is unloaded from vacuum deposition chamber **10**. In this way, substrate clip **26** provides a convenient way to implement thin film deposition sensor **24** as a single-use, disposable thin film thickness and temperature monitor.

As shown in FIGS. **4A–4C**, substrate clip **26** also may incorporate an antenna **70** that is configured to enable controller **30** to interrogate thin film deposition sensor **24** wirelessly. Antenna **70** may be implemented as a loop antenna (e.g., a ¼ wavelength circumference loop antenna), as shown. Alternatively, antenna **70** may be implemented as a dipole antenna (e.g., a ½ wavelength dipole antenna) that preferably projects out of the plane of the backside of substrate **14** (although, in some embodiments, the dipole antenna may be oriented in a plane parallel to the backside of substrate **14**). For communications in the microwave range (e.g., at 1.88 GHz, 2.45 GHz, or the unlicensed bands around 5 GHz), antenna **70** may have dimensions on the order of a few centimeters. In operation, controller **30** may establish a microwave radio link with thin film deposition sensor **24** through an interrogation antenna **74**, which is

coupled to controller **30** by a coaxial cable **76** that extends through a vacuum feed-though in vacuum chamber **10** (see FIG. **1**). In one embodiment, controller **30** includes an interrogation transmitter and an interrogation receiver. The interrogation transmitter is configured to interrogate thin film deposition sensor **24** by transmitting a microwave signal of a few watts of input power that is a gated sine burst of the resonant frequency of exposed FBAR **60** or shielded FBAR **62**. The duration of the burst preferably is long enough to excite the resonator to be interrogated, but short enough to allow time to monitor the natural resonance of the resonator. For example, a burst of about 100–1,000 cycles of the resonant frequency of a desired resonator **60, 62** to be interrogated may be transmitted from interrogation antenna **74**. After the burst has been transmitted, the interrogation transmitter is turned off and signals from the interrogation receiver are monitored by controller **30** to detect the current natural ringing frequency (series or shunt resonance) of the excited resonator as it exponentially decays. Since the period of a 1.8 GHz sine wave is 556 picoseconds, a ten-cycle burst may be completed in 55.6 nanoseconds. On the other hand, the 1/e decay time of an FBAR with a quality factor of 2,000 is on the order of 1,000 nanoseconds. Thus, in this embodiment, the resonant frequency of an interrogated FBAR may be determined within a few microseconds. Consequently, the resonant frequencies of both FBARs **60, 62** may be determined with a data rate of approximately 50–100 kHz, with ample time between measurements to process data received from thin film deposition sensor **24**.

Other embodiments are within the scope of the claims.

The embodiment of FIGS. **4A–4C** and **5**, may be used to monitor the deposition of electrically insulating films. For the deposition of electrically conducting films, a thin dielectric layer may be disposed over sensor **24** to prevent shorting of the exposed electrode bonding pads **59, 61**.

Referring to FIG. **6A**, in another embodiment, a thin film deposition sensor **80** includes a pair of FBARs **82, 84**, which are mounted on a thermally conductive substrate **86** (e.g., a silicon substrate) with an areal dimension of about 1 mm×1 mm. FBARs **82, 84** are connected electrically in series. In other embodiments, FBARs **82, 84** may be connected in parallel or addressed individually. FBARs **82, 84** are configured to enable controller **30** to distinguish temperature-induced changes in resonant frequency from mass-induced changes in resonant frequency and may be used for depositions of electrically insulating and electrically conducting films without modification. In particular, FBARs **82** and **84** are mounted on the backside of substrate **86** such that their bonding pads and electrical connections are shielded from sputtered material deposits. However, the region of the top surface of substrate **86** corresponding to the front side of FBAR **82** is exposed to receive material deposits from target **18**, whereas the region of the top surface of substrate **86** corresponding to the front side of FBAR **84** is shielded from such deposits by a deposition shield **88** (e.g., an AlN thin film layer) that is formed over an isolation cavity **90**. Thus, during a thin film deposition, exposed FBAR **82** would be subject to the frequency downshifting effects of mass loading ($\Delta f_{Exposed, Mass}$) and heating ($\Delta f_{Exposed, Heating}$). Shielded FBAR **84**, on the other hand, would be subject to only the frequency downshifting effects of heating ($\Delta f_{Shielded, Heating}$). Because the exposed and shielded FBARs **82, 84** are matched and thermally coupled together, the heat-induced frequency downshifts observed in exposed FBAR **82** track the frequency downshifts observed in shielded FBAR **84**. Controller **30** may compute the amount of material deposited on substrate **14** and the rate at which

material is deposited on substrate **14** based upon the difference between the resonant frequencies of the exposed and shielded FBARs **82, 84**, as explained above. In addition, controller **30** may track the resonant frequency of shielded FBAR **84** to determine the local temperature of substrate **14**. In this way, thin film deposition sensor **80** may act as a thin film thickness monitor and a temperature monitor.

As shown in FIG. **6B**, in another embodiment, a thin film deposition sensor **100** includes a pair of FBARs **102, 104**, which are mounted on a thermally conductive substrate **106** (e.g., a silicon substrate) with an areal dimension of about 1 mm×1 mm. FBARs **102, 104** are connected electrically in series. In other embodiments, FBARs **102, 104** may be connected in parallel or addressed individually. FBARs **102, 104** are configured to enable controller **30** to distinguish temperature-induced changes in resonant frequency from mass-induced changes in resonant frequency and may be used for depositions of electrically insulating and electrically conducting films without modification. In particular, FBARs **102** and **104** are mounted on the backside of substrate **106** such that their bonding pads and electrical connections are shielded from sputtered material deposits. However, the front side of FBAR **102** is exposed to receive material deposits from target **18** through a through-hole **108** in substrate **106**, whereas the front side of FBAR **104** is shielded from such deposits by the portion of substrate **106** above an isolation cavity **110**. Thus, during a thin film deposition, exposed FBAR **102** would be subject to the frequency downshifting effects of mass loading ($\Delta f_{Exposed, Mass}$) and heating ($\Delta f_{Exposed, Heating}$) Shielded FBAR **104**, on the other hand, would be subject to only the frequency downshifting effects of heating ($\Delta f_{Shielded, Heating}$). Because the exposed and shielded FBARs **102, 104** are matched and thermally coupled together, the heat-induced frequency downshifts observed in exposed FBAR **102** track the frequency downshifts observed in shielded FBAR **104**. Controller **30** may compute the amount of material deposited on substrate **106** and the rate at which material is deposited on substrate **106** based upon the difference between the resonant frequencies of the exposed and shielded FBARs **102, 104**, as explained above. In addition, controller **30** may track the resonant frequency of shielded FBAR **104** to determine the local temperature of substrate **106**. In this way, thin film deposition sensor **100** may act as a thin film thickness monitor and a temperature monitor.

Referring to FIGS. **7** and **8**, in one embodiment, wireless interrogation system **28** may be configured to communicate optically through an optical port **120** in vacuum chamber **10** and, thereby, avoid the vacuum feed-through that is required for a direct coaxial cable connection. In this embodiment, controller **30** communicates with an optical transceiver **122** that is configured to exchange light signals with an interrogation transceiver circuit **124** through optical port **120**.

As shown in FIG. **8**, optical transceiver circuit **124** includes an optical receiver **126** (e.g., an opto-electronic transducer, such as a p-i-n photodiode), a capacitor **128**, a current driver **130**, a resistor **132**, and an optical transmitter **134** (e.g., an opto-electronic transducer, such as a p-i-n photodiode). Current driver **130** is configured to drive an electrical current through an interrogation antenna **136** at a frequency that may be swept through a predetermined frequency range encompassing the resonant frequencies of FBARs **60, 62**. In operation, controller **30** directs optical transceiver **122** to transmit an optical signal **138** to interrogation transceiver circuit **124**. Optical receiver **136** converts the transmitted optical signal **138** into DC electrical energy,

which is stored in capacitor **128**. The transmitted optical signal **138** preferably charges capacitor **128** with sufficient energy to enable current driver **130** to sweep the current applied to antenna **136** through the predetermined frequency range one or more times. Interrogation antenna **136** converts the applied current into a microwave gated sine burst signal that may be used to interrogate thin film deposition sensor **24**, as described above. Resistor **132** converts the exponential decay signals received from the excited thin film deposition sensor **24** into corresponding voltage signals. Optical transmitter **134** transmits to optical transceiver **122** optical signals **140** corresponding to the voltage signals established across resistor **132**. Controller **30** may extract from optical signals **140** the resonant frequencies of FBARs **60, 62**, from which controller **30** may determine the amount of material deposited on substrate **14**, the rate at which material is deposited on substrate **14** and the temperature of substrate **14**, as described above.

In one embodiment, interrogation transceiver circuit **124** may be mounted on substrate clip **26** and electrically coupled to thin film deposition sensor **24**. In this embodiment, thin film deposition sensor antenna **70** and interrogation antenna **136** are not required. Optical transceiver **122** preferably supplies sufficient power to interrogation transceiver circuit **124** to excite FBARs **60, 62** directly.

In another embodiment, vacuum chamber **10** may include an interrogation arm that is configured to couple electrically to thin film deposition sensor **24** after substrate **14** has been loaded into the chamber. The interrogation arm may couple electrically to thin film deposition sensor **24** through substrate clip **26** or may directly contact electrical leads mounted on sensor substrate **64**. The interrogation arm may be coupled to a coaxial cable that extends through a vacuum feed-though in vacuum deposition chamber **10**. In this embodiment, controller **30** may interrogate thin film deposition sensor **30** directly through the interrogation arm.

As mentioned above, thin film deposition sensor **24** may include one or more acoustical resonators. In some embodiments, a thin film deposition sensor may include multiple, redundant pairs of exposed and shielded acoustical resonators. The redundant pairs of acoustical resonators may be arranged on the surface of a substrate in a wide variety of different ways. Referring to FIG. **9**, in one embodiment, a thin film deposition sensor **150** may include an array of sensor series pairs **152, 154, 156** that are connected electrically in parallel and disposed on an elongated substrate **158**. Thin film deposition sensor **150** may be attached to substrate **14** by substrate clip **26** and oriented radially along the exposed surface of substrate **14**. In this way, thin film deposition sensor **150** enables controller **30** to monitor variations in deposition thickness, deposition rate and temperature across the surface of substrate **14**. Thin film deposition sensor **150** may be used in combination with an elongated deposition shield with a window that is configured to selectively expose a single acoustical resonator to the sputtering conditions inside vacuum deposition chamber **10**.

Although the interrogation antennas **74, 136** are located within vacuum chamber **10** in the above-described embodiments, the interrogation antennas may be positioned outside vacuum deposition chamber **10** in other embodiments provided there is sufficient coupling between the interrogation antennas and antenna **70** of thin film deposition sensor **24**. Furthermore, more than one thin film deposition sensor **24** may be attached to substrate **14**.

The above-described thin film deposition sensors may be interrogated wirelessly in a ways that differ from the interrogation schemes described above.

Referring to FIG. **10**, in one wireless interrogation scheme, a thin film deposition sensor may be incorporated into an RFID tag circuit **170** that includes a power converter/transceiver **172**, a modulator/demodulator circuit **174**, a frequency discriminator **176**, and a non-volatile memory **178**. Power converter/transceiver **172** rectifies an RF signal received from an interrogator circuit to provide DC power to the components of RFID tag circuit **170**. In operation, non-volatile memory **178** may send to modulator/demodulator **174** data (e.g., a serial number) identifying the associated thin film deposition sensor. This data is transmitted to the interrogator circuit, which is configured to recover the data. Data corresponding to response signals from frequency discriminator **176** also is transmitted to the interrogator circuit. In particular, frequency discriminator **176** preferably is implemented as a Foster-Seeley discriminator that includes a pair of diodes and a sensor FBAR operating as bandpass filter. Frequency discriminator **176** preferably is configured such that the DC output is proportional to the frequency difference between the interrogation frequency and the sensor FBAR resonant frequency and is zero when interrogated at the sensor FBAR resonant frequency. Other embodiments may include different discriminator implementations. The interrogator circuit preferably includes a servo loop that is configured to tune the interrogation signal frequency to the resonant frequency of the acoustical resonator incorporated into the thin film deposition sensor. The frequency data produced by frequency discriminator **176** may be coded as two binary values of RF/no RF and high/low. Alternatively, the frequency discriminator data may be digitized by an analog-to-digital converter, in which case the interrogator circuit may be informed of the actual output voltage of frequency discriminator **176**. In some embodiments, the frequency discriminator output may be used to vary the duty cycle of a rectangular wave, where, for example, a 50% duty cycle may correspond to the sensor FBAR resonator frequency. An auxiliary "carrier detect" signal may be used to distinguish between the case where the interrogation frequency corresponds to the sensor FBAR resonant frequency and the case where the interrogation frequency is outside of the bandwidth of frequency discriminator **176**.

In another embodiment, an FBAR resonator may be frequency modulated at an audio frequency and the resulting FM sidebands may be detected. Two FBAR resonators operating at different frequencies may be switched to produce a frequency shift keying (FSK) modulation on the return signal. In one embodiment, an integrated circuit may be configured to switch between the two FBAR resonators. An interrogator circuit may be configured to synchronously demodulate the return signal by locking onto a pilot tone modulated on the interrogation beam so that the interrogator circuit may use the same clock to recover the modulation.

In another embodiment, the FSK modulation may be incorporated into the interrogation source.

Still other embodiments are within the scope of the claims.

What is claimed is:

1. A system for monitoring a thin film deposition on a substrate in a vacuum deposition chamber, comprising:

a thin film deposition sensor having an exposed surface and being responsive to thin film material deposits on the exposed surface; and

a substrate clip configured to attach the thin film deposition sensor to the substrate so that the thin film deposition sensor and the substrate are exposable to substantially similar conditions during the thin film deposition in the vacuum chamber.

2. The system of claim **1**, wherein the substrate clip is operable to be clipped onto a peripheral edge of the substrate.

3. The system of claim **2**, wherein the substrate clip is operable to be clipped onto a peripheral edge of a semiconductor wafer.

4. The system of claim **1**, wherein the thin film deposition sensor comprises an acoustical resonator having an exposed surface and being responsive to thin film material deposits on the exposed surface.

5. The system of claim **4**, the acoustical resonator is a thin film bulk acoustical resonator (FBAR).

6. The system of claim **5**, wherein the thin film deposition sensor further comprises a second FBAR thermally coupled to the first acoustical resonator and shielded from deposition of thin film material.

7. The system of claim **6**, wherein the first FBAR and the second FBAR are formed on a common semiconductor substrate.

8. The system of claim **6**, wherein the first and second acoustical resonators are coupled electrically in series.

9. The system of claim **6**, wherein the first and second acoustical resonators are coupled together by an electrical connection shielded from thin film material deposits.

10. The system of claim **6**, wherein each of the first FBAR and the second FBAR has a thin film stack structure formed on a first surface of the semiconductor substrate and comprises a piezoelectric layer disposed between a pair of electrode layers, the first FBAR including an isolation cavity formed on a second surface of the semiconductor substrate opposite the first surface and a deposition shield disposed over the isolation cavity and having an exposed surface corresponding to the exposed surface of the first FBAR.

11. The system of claim **6**, wherein each of the first FBAR and the second FBAR has a thin film stack structure formed on a first surface of the semiconductor substrate and comprises a piezoelectric layer disposed between a pair of electrode layers, the first FBAR including an isolation cavity extending through the semiconductor substrate to a second surface of the semiconductor substrate opposite the first surface, the thin film stack structure of second FBAR being disposed over an isolation cavity formed in the first surface of the semiconductor substrate.

12. The system of claim **6**, further comprising a plurality of pairs of exposed and shielded acoustical resonators disposed on an elongated substrate.

13. A system for monitoring a thin film deposition on a substrate, comprising:

a thin film deposition sensor having an exposed surface and being responsive to thin film material deposits on the exposed surface; and

a substrate clip configured to attach the thin film deposition sensor to the substrate, wherein the substrate clip comprises an antenna.

14. The system of claim **12**, wherein the FBARs of each pair are coupled electrically in series and the pairs of FBARs are inter-coupled electrically in parallel.

15. The system of claim **13**, wherein the antenna is a loop antenna.

16. A system for monitoring a thin film deposition on a substrate, comprising:

a thin film deposition sensor having an exposed surface and being responsive to thin film material deposits on the exposed surface; and

a substrate clip configured to attach the thin film deposition sensor to the substrate, wherein the substrate clip comprises a transceiver circuit configured to enable the thin film deposition sensor to be interrogated wirelessly.

17. The system of claim **16**, wherein the transceiver circuit comprises an opto-electronic transducer.

18. The system of claim **15**, wherein the antenna is on the order of a few centimeters in size.

19. The system of claim **16**, wherein the transceiver circuit is mounted within a thin film deposition chamber.

20. The system of claim **19**, wherein the substrate clip comprises a first antenna and further comprising a second antenna coupled to the transceiver circuit.

21. The system of claims **20**, wherein the second antenna is operable to transmit electromagnetic signals to the first antenna and to detect electromagnetic signals transmitted from the first antenna in response to excitation of the thin film deposition sensor by signals received from the second antenna.

22. The system of claim **16**, wherein the transceiver circuit is an RFID tag circuit.

23. The system of claim **22**, wherein the RFID circuit is electrically coupled to the thin film deposition sensor and comprises a power converter/transceiver, a modulator/demodulator circuit, a frequency discriminator, and a non-volatile memory.

24. A method of monitoring a thin film deposition on a substrate in a vacuum deposition chamber, comprising:

attaching a thin film deposition sensor to the substrate;

disposing the substrate and the attached thin film deposition sensor within the vacuum deposition chamber;

exposing the substrate and the attached thin film deposition sensor to a thin film deposition; and

interrogating the attached thin film deposition sensor to monitor the thin film deposition.

25. The method of claim **24**, further comprising detaching the thin film deposition sensor from the substrate after the thin film deposition is complete.

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