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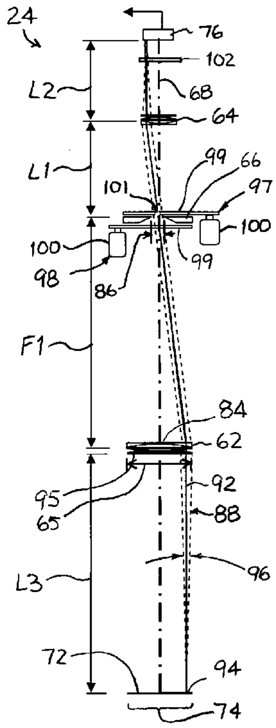

FIG. 4

(57) **Abstract**: Apparatuses for reducing radiation thermometry bias errors in enclosures such as CVD reactors. In one embodiment, a radiation thermometer utilizes an off-focus telecentric lens arrangement. The off-focus telecentric arrangement is focused at infinity, but is utilized to capture radiation from a relatively proximate target (e.g., within a couple meters) that is out of focus. The capture of collimated radiation from the target diminishes the contribution of stray radiation. In another embodiment, scattered radiation originating from a designated segment of a peripheral heating element can be reduced locally by one of several mechanisms, including reducing the emission (e.g., operating temperature) of the designated segment, or capturing or deflecting a portion of the radiation originating from the designated segment. Radiation thermometers fixed proximate an axis that extends from the center of the wafer carrier and across the designated segment are subject to less stray radiation, thus providing a more reliable temperature reading.

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REDUCTION OF RADIATION THERMOMETRY BIAS ERRORS IN A CVD REACTOR

BACKGROUND

Metalorganic Chemical Vapor Deposition (MOCVD) is a chemical vapor deposition technique for growing crystalline layers in processes such as the production of semiconductors. The MOCVD process is implemented in a reactor chamber with specially designed flow flanges that deliver uniform reactor gas flows to the reactor chamber.

The temperature of the crystalline layers during the MOCVD process are typically measured using non-contact devices such as radiation thermometers or pyrometers. Such crystalline growth materials include silicon carbide (SiC), zinc selenide (ZnSe), and gallium nitride (GaN) based materials such as GaN and AlGaN. Certain substrates crystalline growth materials have emission characteristics that limit the wavelength of operation for radiation thermometry. For example, GaN, grown on a sapphire substrate, can have a transmittance greater than 50% for wavelengths longer than 450 nanometers (nm) at process temperatures. Thus, at wavelengths longer than 450 nm, a substantial fraction of the radiation leaving the surface of a GaN layer originates from the structure beneath the substrate that is in the line of sight of the radiation thermometer (e.g., a wafer carrier). Radiation that passes through the GaN layer is not indicative of the temperature of the GaN layer. Accordingly, radiation thermometers have been developed that detect radiation at wavelengths lengths shorter than 450 nm (corresponding roughly to the blue, violet and ultraviolet wavelengths). See, e.g., U.S. Patent Application Publication No. 2011/0064114 to Zettler et al. (hereinafter “Zettler”), disclosing a pyrometer adapted to detect radiation in the range of 250 nm to 450 nm.

An issue with the use radiation thermometers is the detection of unwanted radiation. One source of unwanted radiation is unfiltered radiation that is detected from outside the desired band pass of detection. Zettler describes an apparatus and technique that accounts for the contribution of unfiltered radiation. Zettler points out that narrow band pass filters do not totally block infrared radiation. The unblocked infrared radiation can be problematic at the temperatures of operation (about 800 °C) because the spectral blackbody emissive power of the target in the infrared portion of the electromagnetic spectrum is about 9 orders of magnitude higher than in the primary band pass (i.e., the desired spectral band pass for inferring target temperature) of the narrow band pass filter. The method of Zettler involves the use of a detector that is sensitive over a broad wavelength range (from ultraviolet to the infrared) and filtering the incoming radiation with a narrow band pass filter centered near 410 nm. A long pass filter is then used to effectively block the primary band pass of the narrow band pass filter, but still allow the radiation unfiltered by the narrow band pass filter in the infrared and the near-infrared portions of the electromagnetic spectrum to pass. Zettler infers the radiation that passes through the primary band pass of the narrow band pass filter as the difference between the two measurements, i.e., between the signal attained with only the narrow band pass filter and the signal attained with both the narrow band pass filter and the long pass filter.

Another source of unwanted radiation is the contribution of "stray radiation." Stray radiation is reflected radiation that is redirected onto the target by the enclosure or other structures therein via inter-reflection and reflected into the line-of-sight of the radiation thermometer. Consider a wafer carrier with GaN wafers that are being heated to an elevated temperature of 800 °C by, for example, a microwave heating process. The components operating at the elevated temperature, such as the wafer carrier and wafers, will emit radiation in all directions, causing radiation to inter-reflect within the chamber. Some of the inter-reflected radiation will be incident on the surface targeted by the radiation thermometer and contribute to the radiation detected by the radiation thermometer. For GaN crystalline layers at 800 °C, the reflectivity at 410 nm is approximately 0.2. The stray radiation contribution can significantly bias the temperature value indicated by the radiation thermometer.

Stray radiation is enough of an issue when the target is at or near the maximum temperatures within the chamber, which is the case in microwave heating systems. However, when measuring radiation at or near the short wavelengths of the visible spectrum (i.e., in the blue, violet or ultraviolet wavelengths), the problem becomes exacerbated when there are other sources within the chamber that are operating at substantially higher temperatures than the target. Such a heating arrangement transfers heat in accordance with the first law of thermodynamics, which requires that the resistance heating element operate at a temperature that is significantly higher than the crystalline growth layer. An advantage of thermal radiative heating is that the radiation intensity can be tailored to have a profile across the wafer carrier that promotes uniformity of the temperature.

Consider, for example, the blackbody radiation of a crystalline growth layer at 800 °C. According to Planck's law, the blackbody spectral emissive power at 410 nm and 800 °C is about 2.0×10^{-4} watts/m^2·μm. Now consider a heating source such as a resistance heating element that transfers heat to the crystalline growth layer via radiation and convection that operates at 1800 °C. The blackbody spectral emissive power at 410 nm and 1800 °C is about 1.4×10^{3} watts/m^2·μm. That is an increase of about 7 orders of magnitude over the blackbody spectral emissive power at 800 °C (a typical operating temperature for crystalline growth layer during CVD operations) at the wavelength of interest (FIG. 1). Accordingly, even if only a fraction of a percent of the radiation at the 410 nm wavelength finds its way onto the detector of the radiation thermometer, the bias to the indicated temperature can be significant. Thus, the stray radiation contribution in chambers that utilize resistance heating elements can be of the same order of magnitude as the unfiltered radiation contribution identified by Zettler.

Zettler, however, is silent with respect to the contribution of stray radiation, or the effects of having radiation sources within a chamber that can effectively overwhelm the radiation that is emitted from the target. Rather, Zettler treats the target as though it is freely radiating (i.e., has no reflected contribution). In fact, a target within a CVD chamber at that is operating at the temperatures required for crystalline growth is not freely radiating.

A radiation thermometer tailored to reduce the effects of unwanted radiation, not only due to unfiltered radiation, but also due to stray radiation, would be welcomed.

SUMMARY

Various embodiments of the disclosure utilize a so-called "telecentric" optical arrangement, but in an off-focus manner, to limit the contribution of reflected stray radiation in at least three different aspects. First, in a telecentric optical arrangement, the chief rays that are captured from the target are substantially parallel to the optical axis, which substantially limits the stray radiation contribution, particularly if the target has a strong specular reflectivity component. Second, telecentric optical arrangements can also be tailored so that the solid angle subtended by each point on the target is quite small, which also reduces the contribution of stray radiation. Third, the telecentric optical arrangement can be configured to capture a collimated beam of radiation that is emitted from the target, which further reduces the solid angle of radiation captured by the radiation thermometer while increasing the size of the target (and the subsequent signal-to-noise ratio) to the effective diameter of the forward optical elements. In capturing the collimated beam of radiation, the telecentric optical arrangement is utilized in an "off-focus" manner, i.e., is not used for high quality imaging of the surface of the target. Therefore, the components utilized in the telecentric optical arrangement need not be of the superior quality typically associated with commercially available telecentric lens systems.

Various embodiments of the disclosure alternatively or additionally reduce the contribution of stray radiation that is detected by a radiation thermometer by configuring the reactor chamber and appurtenances therein so that there is less stray radiation incident on the target of the radiation thermometer. In analyzing stray radiation for the present work, it was determined that the peripheral heating elements in a heater array account for the greatest contribution to stray radiation detected by the radiation thermometer. It has also been verified by both ray trace modeling and by verification experiments that providing a discontinuity in the portion of the peripheral heating element nearest the target area of the radiation thermometer significantly reduces the bias error caused by stray radiation.

"Off-Focus" Telecentric Optics

Commercially available telecentric lens systems are utilized, for example, in machine vision systems to provide clear, crisp images of high magnification. These telecentric lens systems provide uniform magnification of all points within an image, regardless of the location of the point within that image. That is, telecentric lens systems used in machine vision systems provide images that are substantially isometric, as opposed to perspective images that are provided with standard imaging systems. One advantage of commercially available telecentric lens systems is that the isometric image can substantially reduce parallax within the image.

However, the effective range over which a telecentric lens system can provide an isometric image at a given setting is quite limited. This effective range is commonly referred to as the "telecentric depth" (see, e.g., Petrozzo et al., "Telecentric Lenses Simplify Non-Contact Metrology," Test & Measurement World, October 15, 2001, p.5). Thus, a paradigm of telecentric lens systems is that they are operable over a narrow range centered about the object plane. The optical components of a machine vision telecentric lens system are of high quality to provide crisp, clear images over the entire image. Furthermore, commercially available telecentric lens systems typically utilize high quality mountings to provide the ability to adjust the focal depth of the object plane. The precise imaging capabilities of commercially available telecentric lens systems drive up the cost.

For various embodiments of the disclosure, the telecentric concept is utilized in a way that machine vision systems are not. In one embodiment, the telecentric optical arrangement is configured for focusing at infinity while being arranged only a few centimeters from the target. The advantage of this arrangement is that the radiation from each points on the target have substantially the same angle entering the optical system. High quality imaging and the costly optics associated therewith is not needed because the objective is radiation collection and detection rather than object imagery. That is, the telecentric optical arrangement is utilized in an out-of-focus or "off-focus" manner to effectively capture a collimated beam of radiation that is emitted from the target surface. Such an arrangement requires neither high quality imaging optics nor sophisticated mountings for fine tuning an image.

Structurally, in various embodiments of the disclosure, an off-focus telecentric optical arrangement includes an aperture stop and a first or "object" optical component (herein referred to as the "object assembly") of one or more optical components. The aperture stop and object assembly can define an optical axis and a first focal length relative to a reference point within the object assembly, the reference point being located on the optical axis. In one embodiment, the aperture stop is located at a distance from the reference point of the object assembly that is substantially equal to the first focal length of the object assembly. By locating the aperture stop at the focal length of the object assembly, the object assembly is focused effectively at infinity for transfer of substantially collimated radiation from an off-focus target through the object assembly and for focusing of the radiation from the off-focus target onto the aperture stop.

In some embodiments, a second or "image" optical component assembly (herein referred to as the "image assembly") of one or more optical components can be located opposite said object assembly from said aperture stop and arranged to receive radiation transferred from the object assembly through the aperture stop along the optical axis, the image assembly defining a second focal length relative to a second reference point within the image assembly, the second reference point being located on the optical axis.

In one embodiment, a “bilateral” telecentric optical arrangement is implemented, in which the chief rays of both the target and the image are parallel to the optical axis. In the bilateral arrangement, the focal length of the object assembly defines approximately the target distance, the aperture stop being located at essentially the back focal plane of the object assembly and at the front local plane of the image assembly. In a bilateral telecentric arrangement, not only is the radiation collected through the object optical component assembly substantially collimated, but the radiation transferred from the image optical component assembly to the detector is also substantially collimated. An advantage of collimating the radiation between the image optical component assembly and the detector is additional rejection of stray light.

In various embodiments, the off-focus telecentric optical arrangement is provided as a kit for implementation with a new or an existing radiation thermometer in chemical vapor deposition systems. In one embodiment, a telecentric lens arrangement is provided that includes an aperture stop and a forward optical component assembly for collecting radiation from a target, the telecentric lens arrangement being adapted for positioning the aperture stop at the focal length of the forward optical component assembly. Manufacturer-supplied instructions are also provided that instruct the user to orient the forward optical component assembly to intercept radiation emitted from a target within a chemical vapor deposition chamber. In one embodiment, coupling the telecentric lens arrangement with a radiation detector and/or the positioning the aperture stop at the focal length of the forward optical component assembly is performed by the manufacturer; in other embodiments, the step of positioning the aperture stop at the focal length of the forward optical component assembly and/or positioning the aperture is provided on the manufacturer-supplied instructions.

Dual Wavelength Pyrometers

Various of the disclosed embodiments also include a dual wavelength pyrometer that utilizes the off-focus telecentric concept to measure radiation in the visible/ultraviolet or “visible/UV” spectrum and in the infrared spectrum. (For purposes of this disclosure, the “visible/UV” spectrum, alternatively referred to as the “optical” spectrum, is inclusive of the 300 nm to the 700 nm wavelengths, the “visible” spectrum is inclusive of the 400 nm to 700 nm wavelengths, and the “infrared” spectrum is inclusive of wavelengths greater than 700 nm to about 10,000 nm.) A common solution for inferring temperature from a radiation measurement is the so-called “ratio” pyrometer. A ratio pyrometer includes measures the radiation emitted from a target at two distinct wavelength band passes, and operates on the principle of correlating the ratio of the signals obtained against the temperature. For a gray body emitter (i.e., a target having the same emissivity across both of the distinct wavelength band passes), the effect of the emissivity is effectively cancelled out by the quotient of the ratio, so that the signal ratios vs. temperature are the same as for a blackbody calibration. Schemes have also been developed to correct the indicated temperature of a ratio pyrometer when the target viewed is not a gray body.

The distinct wavelength band passes of standard ratio pyrometers tend to be relatively close to each other on the electromagnetic spectrum, under the general presumption that wavelength band passes that are close to each other have a better chance of having the same emissivity (i.e., exhibit gray body behavior) than do wavelength band passes that are farther apart. However, for certain processes, it is desirable to obtain information from different portions of the wavelength spectrum in order to properly control the process. For example, for depositing GaN on sapphire substrates in a MOCVD reactor, one way to control the process is to infer the temperature of the wafer carrier using an infrared pyrometer for primary temperature control, and to infer the temperature of the GaN layer of the wafer using an optical pyrometer for secondary control. Conventional ratio pyrometers are not suited for this purpose because both wavelength band passes are typically in the same electromagnetic regime—either the optical or the infrared.

With the dual wavelength pyrometer embodiments of the present disclosure, a pair of radiation thermometers measure radiation from identically viewed targets at different wavelength band passes. The center wavelengths of the band passes can be in different portions of the electromagnetic spectrum, with the first of the wavelength band passes being in the visible/UV spectrum and the second of the wavelength band passes being in the infrared spectrum. In one embodiment, the central wavelengths for the infrared and the optical wavelength band passes are approximately 900 nm and 400 nm, respectively, (e.g., 930 nm and 405 nm). The dual wavelength pyrometer of the present disclosure combines the optical (i.e., visible/UV spectrum) and infrared detectors in a single package, so that both measurements are made through a common view port. Accordingly, provision for both an optical and an infrared radiation measurement does not require the use of two view ports. A further advantage is that the radiation captured for both the optical and the infrared measurements can be captured simultaneously from the same identical target through the same location on the view port window, thus eliminating certain discrepancies that can arise from non-simultaneous measurements acquired from different targets through different view port windows. Incorporation of the off-focus telecentric optics further reduces the contribution of scattered radiation, which reduces the bias error of the temperature measurements.

Some of the dual wavelength pyrometer arrangements disclosed herein optionally include a reflectometer arrangement for emissivity compensation. Inferring temperature from a radiation signal requires either knowledge of or compensation for the emissivity of the target. A wafer in a CVD chamber can undergo substantial and non-monotonic changes in emissivity as the layers build up on the wafer, causing intermittent destructive interference to reflect from the different wafer layers, resulting in a periodic variation in the reflectivity and emissivity. Certain embodiments of the present disclosure include a reflectometer integrated into the radiation thermometer, including one or both of the radiation thermometers of the dual wavelength pyrometer. The reflectometer can be implemented to infer the emissivity of the target and provide a correction to the indicated temperature. Incorporation of the off-focus telecentric optics further reduces the contribution of scattered radiation, which reduces the bias error of the emissivity determination.

Structurally, the disclosed telecentric dual wavelength pyrometer can comprise an object assembly of one or more optical components for transfer of radiation from an off-focus target, the object assembly defining a focal length relative to a reference point within the object assembly. In this embodiment, a first aperture stop is arranged to receive radiation transferred from the object assembly, the object assembly and the first aperture stop defining a first optical axis that passes through the reference point, the first aperture stop being located at a distance from the reference point that is substantially equal to the focal length of the object assembly for focusing of a first detected portion of the radiation onto the first aperture stop. Also in this embodiment, a second aperture stop is arranged to receive radiation transferred from the object assembly, the object assembly and the second aperture stop defining a second optical axis that passes through the reference point, the second aperture stop being located at a distance from the reference point that is substantially equal to the focal length of the object assembly for focusing of a second detected portion of the radiation onto the second aperture stop. A first electromagnetic radiation detector arranged can be detect the first detected portion of the radiation transferred from the object assembly through the first aperture stop. Likewise, a second electromagnetic radiation detector can be arranged to detect the second detected portion of the radiation transferred from the object assembly through the second aperture stop, the first electromagnetic radiation detector and the second electromagnetic radiation detectors for generation of a first signal and a second signal, respectively, for inferring a temperature of the off-focus targets.

The telecentric dual wavelength pyrometer can further comprise a first reflectometer subassembly including a first radiation source for generation of a first beam of electromagnetic radiation and a first beam splitter, the first beam splitter being arranged for propagation of a portion of the first beam along the first optical axis for irradiation of the off-focus target. A second reflectometer subassembly including a second radiation source for generation of a second beam of electromagnetic radiation and a second beam splitter can also be included, the second beam splitter being arranged for propagation of a portion of the second beam along the second optical axis for irradiation of the off-focus target.

In one embodiment, the first detected portion of radiation is in the infrared spectrum of electromagnetic radiation and the second detected portion of radiation is in the visible spectrum of electromagnetic radiation. The second detected portion of radiation can define a wavelength band pass that is centered at a wavelength that is greater than or equal to 400 nm and less than or equal to 410 nm. The first detected portion of radiation can define a wavelength band pass that includes the 930 nm wavelength. A reduced aperture assembly can also be arranged for selectively reducing one of the first detected portion of the radiation that is detected by the first electromagnetic radiation detector and the second detected portion of the radiation that is detected by the second electromagnetic radiation detector.

Multi-Channel Pyrometers

Embodiments of the present disclosure further include a “multi-channel” pyrometer system for inferring a spatial temperature distribution that provide a plurality of off-focus telecentric radiation thermometers for determining the temperature profile of the wafers during fabrication. Uniform wafer temperatures are desirable to increase wafer yield. While the bulk temperature of the wafer carrier and wafers are controlled by the heating elements, various secondary parameters are available to the operator to improve the uniformity of the temperature between wafers as well as the temperature uniformity within a wafer. The present disclosure includes an arrangement for measuring the uniformity of the wafer temperature. The plurality of radiation thermometers are each oriented to view a different target at a different location on a given wafer, with the data from each target being acquired simultaneously. The target sizes can be tailored to provide nearly full coverage of the subject wafer for infer temperature distribution across the wafer. Temperature uniformity maps can be generated and their accuracy improved by utilizing statistical averages of synchronized data over a selected time interval (e.g., 1 minute). Incorporation of the off-focus telecentric optics further reduces the contribution of radiation scattered within the chamber, which can vary substantially with the location of the target on the wafer. The reduction of the scattered radiation contribution reduces the bias error of the individual temperature measurements and the resultant temperature profile.

In still other embodiments of the present disclosure, both the multi-channel arrangement and the dual wavelength concepts (with optional reflectance measurement capabilities) are combined in the same system. By this arrangement, the temperature profiles can include the enhanced accuracy provided by the dual wavelength and/or the emissivity compensation arrangements.

Structurally, the multi-channel pyrometer system for inferring a spatial temperature distribution is disclosed, comprising a plurality of radiation thermometers arranged to view a corresponding plurality of adjacent off-focus targets, each of the plurality of radiation thermometers including a first telecentric optical arrangement. The first telecentric optical arrangement includes an object assembly of one or more optical components for transfer of radiation, the object assembly defining a focal length relative to a reference point within the object assembly. Each of the plurality of radiation thermometers further includes a first aperture stop is arranged to receive radiation transferred from the object assembly, the object assembly and the first aperture stop defining a first optical axis that passes through the reference point, the first aperture stop being located at a distance from the reference point that is substantially equal to the focal length of the object assembly for focusing of the first detected portion of the radiation from the respective one of the corresponding plurality of adjacent off-focus targets onto the first aperture stop. Each of the plurality of radiation thermometers further includes a first electromagnetic radiation detector arranged to detect the first detected portion of the radiation transferred from the object assembly through the first aperture stop, the first electromagnetic radiation detector generating a first signal from which a temperature of the respective one of the corresponding plurality of adjacent off-focus targets is inferred. The plurality of radiation thermometers can be arranged for viewing a wafer on a wafer carrier, the wafer carrier being arranged within a chemical vapor deposition chamber, and wherein the plurality of adjacent off-focus targets are completely subtended by the wafer. The subtending of the off-focus targets by the wafer is periodic due to rotation of the wafer carrier.

At least one of the plurality of radiation thermometers can include a first reflectometer subassembly including a first beam splitter and a first radiation source for generation of a first beam of electromagnetic radiation. The first beam splitter can be arranged for propagation of a portion of the first beam along the first optical axis for irradiation of the respective one of the corresponding plurality of adjacent off-focus targets. A second reflectometer subassembly including a second beam splitter and a second radiation source for generation of a second beam of electromagnetic radiation can also be included, the second beam splitter being arranged for propagation of a portion of the second beam along the second optical axis for irradiation of the respective one of the corresponding plurality of adjacent off-focus targets. In some embodiments, one or both of the first and second reflectometer subassembly or subassemblies modulates the first beam with a chopper. Also, at least one of the plurality of radiation thermometers can include a reduced aperture assembly arranged for selectively reducing the first detected portion of the radiation that is detected by the first electromagnetic radiation detector.

In one embodiment, at least one of the plurality of radiation thermometers of the pyrometer system further includes a second telecentric optical arrangement that includes a second aperture stop arranged to receive radiation from the object assembly, the object assembly and the second aperture stop defining a second optical axis that passes through the reference point, the second aperture stop being located at a distance from the reference point that is substantially equal to the focal length of the object assembly for focusing of the second detected portion of the radiation from the respective one of the corresponding plurality of adjacent off-focus targets onto the second aperture stop; and a second electromagnetic radiation detector arranged to detect the second detected portion of the radiation transferred from the object assembly through the second aperture stop, the second electromagnetic radiation detector generating a second signal from which the temperature of the respective one of the corresponding plurality of adjacent off-focus targets is inferred. The first detected portion of radiation can be in the infrared spectrum of electromagnetic radiation and the second detected portion of radiation is in the visible spectrum of electromagnetic radiation. In one embodiment, a cold mirror is disposed along the first optical axis and the second optical axis, the cold mirror transmitting the first detected portion of radiation and reflecting the second detected portion of radiation. The second detected portion of radiation can define a wavelength band pass that is centered at a wavelength that is greater than or equal to 400 nm and less than or equal to 410 nm, and the first detected portion of radiation can define a wavelength band pass that includes the 930 nm wavelength.

Stray Radiation Control

An operating principle of various embodiments is to locally reduce the contribution of radiation from the peripheral heating element in the vicinity of the target of the radiation thermometer. In one embodiment, the local reduction in the radiation contribution is achieved by including a low heat flux portion on the peripheral heating element so that the radiant heat emitted therefrom at the operating wavelength of the radiation thermometer is significantly less than from other portions of the peripheral heating element or elements (e.g., more than two orders of magnitude lower). The low heat flux portion eliminates emission of radiation at the wavelengths of operation (e.g., in the visible/UV spectrum) so that, locally, the peripheral heating element does not contribute to the stray radiation at the operating wavelengths of the radiation thermometer. Analysis and experimentation for this work have revealed that reducing the spectral radiation contribution proximate the target area of the radiation thermometer in this way significantly reduces the bias error due to stray radiation.

In another embodiment, local reduction of the stray radiation contribution is achieved with a radiation trap positioned proximate the peripheral heating element. Much of the radiation originating from the peipheral heating element from the segment proximate the radiation trap is thereby captured and does not contribute to the stray radiation contribution.

In another embodiment, local reduction of the stray radiation contribution is achieved by redirecting the radiation originating from a segment of the peripheral heating element. In this embodiment, a deflection surface is positioned proximate the peripheral heating element that deflects radiation originating from a portion of the peripheral heating element away from the target area of the radiation thermometer. In this way, the stray radiation contribution is reduced locally.

In one embodiment, a system for limiting stray radiation received by a radiation thermometer is described, including a chemical vapor deposition (CVD) chamber, a wafer carrier configured for rotation about a rotation axis, the wafer carrier including a top surface, a bottom surface and an outer edge, the top surface being substantially planar and defining a target plane. A plurality of heating elements are disposed beneath the wafer carrier, the plurality of heating elements being arranged to irradiate the bottom surface of the wafer carrier. The plurality of heating elements can include a peripheral heating element proximate the outer edge of the wafer carrier. The peripheral heating element can substantially surround the other heating of the plurality of heating elements, or comprised two or more heating elements that surround the other heating elements. The peripheral heating element can include a low heat flux portion along a designated portion of the peripheral heating element, the low heat flux portion operating at a substantially reduced temperature relative to other portions of the peripheral heating element. In one embodiment, the low heat flux portion configured to operate at a temperature that is at least 300 °C less than any other portion of the heating element when operating at a maximum operating temperature.

In one embodiment, a radiation thermometer is arranged for viewing of a target that is proximate an "axis of reduced scattered radiation," the axis of reduced scattered radiation being coplanar with the target plane and extending from the rotation axis and over the low heat flux portion of the heating element. The low heat flux portion of the peripheral heating element can include an electrical connector.

In one embodiment, the target is within a rectangular region on the wafer plane that includes a portion of the axis of reduced scattered radiation, the rectangular region extending from the spindle to an outer edge of the wafer carrier, the rectangular region having a width that is approximately the same width as the tangential dimension of the designated portion of the peripheral heating element.

The system can further comprise a cylinder disposed within the CVD chamber, the cylinder defining a cylinder axis that is substantially concentric with the rotation axis, the cylinder having an interior surface and an exterior surface, the interior surface defining an inner cylinder diameter, the exterior surface defining an outer cylinder diameter, the cylinder having a top edge defining an upper plane that is substantially normal to the cylinder axis. The wafer carrier can define a carrier outer diameter that is greater than the inner cylinder diameter of the cylinder. The system can also include a spindle disposed within the CVD chamber, the spindle being concentric with the rotation axis and having a distal portion adapted for coupling with the wafer carrier. In one embodiment, the radiation thermometer is configured to detect radiation in the visible/UV portion of the electromagnetic spectrum.

In various embodiments of the disclosure, different mechanisms for reducing scattered radiation that is emitted from a designated portion of a peripheral heating element are presented. In one embodiment, the mechanism includes one of a radiation trap and a radiation deflector located proximate the designated portion of the peripheral heating element.

In other embodiments, a method for limiting stray radiation received by a radiation thermometer viewing a target in a chemical vapor deposition chamber is presented, the method comprising providing a wafer carrier and a heater array configured for operation within the chemical vapor deposition chamber, the wafer carrier being configured for rotation about a rotation axis and having a lower surface and a substantially planar upper surface, the upper surface defining a target plane, the heater array including a peripheral heating element that includes a low heat flux portion along a designated portion of the peripheral heating element. Instructions on a tangible medium are also provided, including the steps of:

- disposing the heater array within the chemical vapor deposition chamber;
- disposing the wafer carrier within the chemical vapor deposition chamber above the heater array and with the upper surface facing upward;
- aligning a radiation thermometer to view a target proximate an axis of reduced scattered radiation, the axis of reduced scattered radiation being coplanar with the target plane and

extending from the rotation axis and over the low heat flux portion of the heating element.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a graph of spectral blackbody emissive power according to Planck's law at various temperatures;

FIG. 2 is a sectional view of an off-focus telecentric radiation thermometer operatively coupled to a MOCVD chamber in a disclosed embodiment;

FIG. 3 is a sectional view of an off-focus telecentric radiation thermometer and light trap operatively coupled to a MOCVD chamber in a disclosed embodiment;

FIG. 4 is an off-focus telecentric optical arrangement in a disclosed embodiment;

FIG. 5 is a sectional view of an off-focus telecentric radiation thermometer operatively coupled to a MOCVD chamber utilizing a flow extender in an a disclosed embodiment;

FIG. 5A is an enlarged partial sectional view of the MOCVD chamber and flow extender of FIG. 5;

FIGS. 6A through 6C depict multi-channel arrangements for acquiring spatial temperature distributions of a wafer in a disclosed embodiment;

FIG. 7A is a sectional view of a MOCVD chamber with radiation thermometer;

FIG. 7B is a three-dimensional cutaway view of the MOCVD chamber of FIG. 7A with the various appurtenances for modeling radiation scattering in a disclosed embodiment;

FIG. 8 is a schematic of the radiation emitted from a portion of the peripheral heating element of FIG. 7A;

FIG. 9 is a plan view of a heating element arrangement within a reactor chamber (wafer carrier removed) in a disclosed embodiment;

FIG. 10 is a graph comparing the response of an infrared radiation thermometer and an optical radiation thermometer, both viewing a wafer carrier during a heating cycle of a heater array;

FIG. 11 is the plan view of FIG. 9, depicting the alignment of the targets relative to the heater array for a stray radiation detection experiment in a disclosed embodiment;

FIG. 12A is a graph comparing the response of a radiation thermometer arranged to view outer radial positions of a wafer carrier proximate a high heat flux portion of a peripheral heating element and proximate a low heat flux portion of a peripheral heating element in a disclosed embodiment;

FIG. 12B is a graph comparing the response of a radiation thermometer arranged to view mid-span radial positions of a wafer carrier proximate a high heat flux portion of a peripheral heating element and proximate a low heat flux portion of a peripheral heating element in a disclosed embodiment;

FIG. 13A is a partial plan view of a wafer carrier within a reactor chamber, the reactor chamber including a local radiation trap in a disclosed embodiment;

FIG. 13B is a sectional view of the local radiation trap of FIG. 13A;

FIG. 14 is a schematic of a chamber utilizing a local radiation deflector in a disclosed embodiment;

FIG. 15 is a schematic of a dual wavelength pyrometer viewing a wafer through a view port in a disclosed embodiment;

FIGS. 16A and 16B are representative diagrams of composite signals received by a pyrometer utilizing a reflectometer subassembly in a disclosed embodiment; and

FIG. 17 depicts a multi-channel arrangement that utilizes dual wavelength pyrometers for acquiring spatial temperature distributions of a wafer in a disclosed embodiment.

DETAILED DESCRIPTION

Referring to FIG. 1, a family of curves 10 depicting the spectral blackbody emissive power in accordance with Planck's law at various temperatures is presented. The visible spectral region 12, coinciding approximately with the 400 nm to 700 nm wavelength band, is also identified in FIG. 1. In relation to the previous discussion of the effect of temperature on the blackbody emissive power at 410 nm, first and second reference points 14 and 16 are identified in FIG. 1 at 1073 K and 2073 K, respectively (corresponding to 800 °C and 1800 °C, respectively).

Referring to FIGS. 2 and 3, a MOCVD reactor system 20 utilizing a radiation thermometer 22 having an off-focus telecentric optical arrangement 24 is depicted in disclosed embodiments. The MOCVD reactor system 20 includes a reactor chamber 26 operatively coupled with a flow flange 28 to define an enclosure 30. The flow flange 28 includes laminar flow plates 31 through which the gases for the MOCVD process are introduced into the reactor chamber 26. Disposed within the reactor chamber 26 is a wafer carrier 32 having a top surface 34 defining wafer pockets 35 and a bottom surface 36 and operatively coupled with a spindle 38 that defines a rotation axis 40. Each of the wafer pockets 35 are configured for disposition of a wafer 41 therein. A body shutter 42 can be removably inserted adjacent the interior wall of the reactor chamber 26 and surrounds the wafer carrier 32.

A resistance heating array 44 is disposed beneath the wafer carrier 32 for radiative coupling with the bottom surface 36 of the wafer carrier 32. The resistance heating array 44 can include a peripheral heating element 45 and can be surrounded by a cylinder 46 and also bounded beneath with a reflector plate 48 to enhance radiative coupling between the resistance heating array 44 and the wafer carrier 32.

The radiation thermometer 22 is mounted atop the flow flange 28 and oriented to view the top surface 34 of the wafer carrier 32 through a view port window 52. In one embodiment, the view port window 52 is disposed in a recess 54, which can be actively cooled.

The off-focus telecentric optical arrangement 24 includes a first or forward optical component assembly 62 (herein referred to as the "object assembly" 62) and a second or rearward optical component assembly 64 (herein referred to as the "image assembly" 64). The object assembly 62 is characterized as having an effective radial dimension 65 (FIG. 4), i.e., the maximum radial dimension over which the object assembly 62 effectively transfers radiation onto an aperture stop 66.

The aperture stop 66 is disposed between the object and image assemblies 62 and 64. In one embodiment, the object and image assemblies 62 and 64 and the aperture stop 66 are arranged concentrically along an optical axis 68. The optical axis 68 is the axis about which radiation detected by the radiation thermometer 22 propagates. The optical axis 68 can be straight, such as depicted herein, or can be tortuous, for example when planar or focusing mirrors are implemented for the transfer of radiation. The optical axis 68 can be centered about an off-focus target 72, characterized as having an off-focus target area 74. The radiation thermometer 22 also includes a detector 76 for detecting electromagnetic radiation.

It is noted that, for purposes of this disclosure, an "optical component assembly" can comprise a plurality of optical components (as depicted), or can comprise a single optical component such as a single lens. While the optical components depicted herein comprise lenses, it is understood that other optical components, such as focusing mirrors and fiber optic bundles can also be utilized to achieve the radiation transfer.

In one embodiment, the radiation thermometer 22 is oriented so that the optical axis 68 is substantially normal to the top surface 34 of the wafer carrier 32 (FIG. 2). In another embodiment, the radiation thermometer 22 is oriented so that the optical axis 68 is at an acute angle 78 relative to a direction normal to the top surface 34 of the wafer carrier 32 (FIG. 3). In one embodiment, a light trap 82 is arranged at a mirrored angle of the optical axis 68 (FIG. 3) in three-dimensional space. That is, the light trap 82 is arranged to subtend a reflection of the optical axis 68 from a hypothetical mirrored surface at the top surface 34 of the wafer carrier 32.

Referring to FIG. 4, the off-focus telecentric optical arrangement 24 of the radiation thermometer 22 is described in greater detail. The object assembly 62 is characterized as having a focal length F1 that is measured from a reference point 84 on the optical axis that is on or within the object assembly 62. A "focal length" is the distance from the reference point 84 at which rays parallel to the optical axis 68 passing through by the object assembly 62 are focused. For the off-focus telecentric optical arrangement 24, the aperture stop 66 is positioned at this convergence point, i.e., at the focal length F1 of the object assembly.

The off-focus telecentric optical arrangement 24 is further depicted as having a distance L1 between the image assembly and the aperture stop and a distance L2 between the image assembly 64 and the detector 76. The aperture stop 66 is also characterized as having a major dimension 86. Herein, the "major dimension" 86 is the diameter of a circular aperture or the largest dimension of a non-circular aperture (e.g., the diagonal of a rectangular aperture).

In one embodiment, the distance L1 is substantially equal to the focal length of the image assembly 64, such that the radiation transferred by the image assembly 64 to the detector 76 is substantially collimated. This arrangement is herein referred to as a "bilateral" telecentric optical arrangement. In a bilateral telecentric arrangement, not only is the radiation collected through the object assembly 62 substantially collimated, but the radiation transferred from the image assembly 64 to the detector 76 is also substantially collimated (as depicted in the figures). An advantage of collimating the radiation transferred from the image assembly 64 to the detector 76 is that additional stray light is rejected. Such scattered radiation can originate on the surfaces of the various optical components in the system, as well as off-axis radiation that enters the radiation thermometer 22. The collimation of the radiation between the image assembly 64 and the detector 76 rejects more of the radiation entering the image assembly 64 at angles that are not parallel to the optical axis 68.

In one embodiment, the distance L2 can also be substantially equal to the focal length of the image assembly 64. However, L2 is not constrained to any particular dimension in a bilateral telecentric optical arrangement.

A ray bundle 88 is characterized as a cluster of rays including a central or "chief" ray 92, all originating from an infinitesimal point 94 on the target 72. The ray bundle 88 comprises all the rays originating from the infinitesimal point 94 that are within a solid angle 96 centered about the chief ray 92. The chief ray 92 is parallel to but offset from the optical axis 68. Each infinitesimal point 94 within the target area 74 emits a similar bundle of rays that are collected by the object assembly 62.

The solid angle 96 is a function of the major dimension 86 and a target distance L3, which is the distance from a forward-most surface 95 of the object assembly 62 to the target 72. The smaller the solid angle 96 of the ray bundle 88, the closer the rays in the ray bundle 88 are to being parallel with the optical axis 68, and the greater the rejection of stray light. For a given target distance L3, the smaller the major dimension 86 the smaller the solid angle 96. Also, for a given major dimension 86 of the aperture stop 66, a longer target distance L3 will provide a smaller solid angle 96 for enhanced rejection of stray light. Generally, the target distance L3 is not of specified dimension because of the off-focus, parallel ray collection. Non-limiting examples of the target distance L3 for MOCVD chambers is less than two meters. In one embodiment, the target distance L3 is substantially the focal length of the object assembly 62, which acts to substantially focus the rays of a given ray bundle 88 as it passes through the aperture stop 66, as depicted in FIG. 4. In one embodiment, the target distance L3 is on the order of 200 mm to 300 mm (for example, 250 mm).

Optionally, the radiation thermometer 22 can be equipped with a reduced size aperture assembly 97 and/or a shutter assembly 98. In one embodiment, the reduced size aperture assembly 97 and the shutter assembly 98 each include a plate 99 mounted to an actuator 100. For the reduced size aperture assembly 97, the plate 99 includes an aperture 101 that is of a reduced size compared to the aperture of the aperture stop 66, thereby interfering with at least the major dimension 86 of the aperture stop 66. The plate 99 of the shutter assembly 98, on the other hand, is blank.

In operation, the plates 99 can be independently positioned to either stand clear of the radiation passing through the aperture stop 66 or to partially or totally obstruct the radiation passing through the aperture stop 66. For the reduced size aperture assembly 97, the aperture 101 can be centered about the optical axis 68 when in a deployed position, thereby partially obstructing the radiation and reducing the effective aperture of the radiation thermometer 22. For the shutter assembly 98, positioning the plate 99 from the standby to the deployed position totally blocks target radiation from reaching the detector 76. Both the reduced size aperture assembly 97 and the shutter assembly 98 are depicted in the deployed position in FIG. 4. In one embodiment, the aperture 101 has a diameter in the range of 1 to 12 mm.

Functionally, the reduced size aperture assembly 97 can be implemented to prevent saturation of the detector as the temperature increases. As discussed above, the blackbody spectral emissive power can increase several orders of magnitude, particularly in the visible/UV spectrum. The reduced size aperture assembly 97 can be utilized to reduce the level of radiation reaching the detector 76, thereby preventing saturation. Likewise, the shutter assembly 98 can be used to protect the detector 76 from damage in extreme conditions radiation conditions.

The depicted actuator(s) 100 are of a rotational type that rotate the plate(s) 99 into the optical axis 68 when in the deployed position and rotated the plate(s) 100 away from the optical axis when in the standby position. It is understood that this arrangement is not limiting, as any of a number of actuator arrangements can be implemented, including a translating arrangement that linearly translates the plate(s) 99 into and out of the optical path, or an adjustable iris device for active control of the aperture size.

The artisan will recognize that there is a tradeoff between the magnitude of the solid angle 96 required and the magnitude of the target area 74 required to achieve a given signal-to-noise ratio. That is, for a given target distance L3, smaller solid angles 96 (e.g., smaller major dimensions 86) can be utilized for larger target areas 74, generally enhancing the rejection of stray radiation, whereas larger solid angles 96 (e.g., larger major dimensions 86) are required for smaller target areas 74. Target size is limited by other factors, including the dimension of the view port window 52, the effective radial dimension of the image assembly 64, and the desired field of view of the target 72 on the wafer carrier 32. Thus, for smaller target areas 74 that require a larger major dimension 86 of the aperture stop 66, and at shorter target distances L3, the stray light rejection of the off-focus telecentric optical arrangement 24 can be vitiated.

In certain non-limiting embodiments, the major dimension 86 of the aperture stop 66 is approximately 1/3 or less of the effective radial dimension 65 of the object assembly 62. In one embodiment, the major dimension 86 of the aperture stop 66 is in the range of 1 mm to 20 mm.

For a typical target of crystalline growth material, inter-reflected radiation that is reflected from the target 72 has a strong specular component. That is, a large fraction of the radiation incident on the surface of the crystalline growth structure will be reflected at the same angle as the angle of incidence. Accordingly, a disproportionate amount of the stray radiation that enters standard radiation thermometers (i.e., one without at telecentric optical arrangement) is reflected off the target 72 at angles that are not parallel to the optical axis 68. Accordingly, by reducing the solid angle 96 of the ray bundle 88, the contribution of stray radiation is also substantially reduced.

Consider the orientation of the radiation thermometer 22 in FIG. 2. Radiation that is specularly reflected from the target 72 and into the radiation thermometer 22 must have first been inter-reflected or emitted from the view port window 52. The viewport can be configured to reduce the amount of reflected radiation therefrom, for example by the use of antireflective coatings and/or by disposing the view port window 52 within the recess 54, which can be actively cooled, to limit the amount of radiation incident upon the view port window 52.

Consider the orientation of the radiation thermometer 22 in FIG. 3. The light trap 82, arranged as generally described and as depicted in FIG. 3, functions to trap radiation that would otherwise be incident on the target 72 at the angle of specular reflection for the optical axis 68. The light trap 82 can also be configured as discussed above—e.g., with an antireflective window within a recess 54—to limit transfer of inter-reflected radiation onto the target 72.

To verify the theory of operation of the off-focus telecentric optical arrangement 24, the geometry and operating conditions of the enclosure 30 as substantially depicted in FIG. 2 and described herein was modeled using the Advanced System Analysis Program (ASAP), a three-dimensional ray tracing program provided by the Breault Research Organization, Inc. of Tucson, Arizona, U.S.A. The ASAP model was executed to identify stray radiation paths and to analyze stray radiation entering the view port window 52. The peripheral heating element 45 was set as a radiation source operating at a temperature of 1800 °C. The wafer carrier 32 (modeled as including wafers in the wafer pockets 35) was modeled as both a radiation source at 800 °C and as a scattering media. The wafer pockets 35 were assumed to be carrying wafers 41 having an emittance of 0.8 at the wavelengths of interest. The blackbody emissive power for the radiation sources was established based on Planck's law at a wavelength of 405 nm. The interior walls of the enclosure 30 (including the body shutter 42, laminar flow plates 31 and view port window 52 were also modeled as scattering media.

The radiation thermometer 22 was modeled for two different collection optics: a "standard" optical arrangement having a target diameter of 10 mm at a 1:1 magnification; and the off-focus telecentric optical arrangement as depicted and described herein, with a target diameter of approximately 30 mm. The amount of 405 nm radiation emitted from the target 24 and directly entering the radiation thermometer 22 ("signal radiation") was compared with the amount of 405 nm radiation inter-reflected within the enclosure 30 and entering the radiation thermometer 22 ("stray radiation") for each optical arrangement. The results are presented in Table 1.

Table 1: ASAP model results predicting the fraction of radiation wavelength attributed to signal and stray radiation at 405 nm for a standard and a telecentric optical arrangement (target at 800 °C; peripheral heating element at 1800 °C)

	Standard Optics	**Off-Focus Telecentric Optics**
Signal Radiation	30%	61%
Stray Radiation	70%	39%
Temperature Error at 405 nm wavelength	41 °C	16 °C

The ASAP model predicted that, for a radiation thermometer utilizing standard optics, about 70% of the radiation flux at the 405 nm wavelength on the detector is attributed to stray radiation. Utilization of the off-focus telecentric optical arrangement 24, however, reduced the stray radiation contribution to 39%. These stray light contributions cause temperature bias errors of approximately 41 °C and 16 °C, respectively. That is, the bias error of the temperature measurement for the off-focus telecentric optical arrangement 24 is almost 2/3 less for the off-axis telecentric optical arrangement than for a standard lens system.

Referring to FIGS. 5 and 5A, the performance of the off-focus telecentric optical arrangement 24 was also verified experimentally. For this experiment, a MOCVD reactor system utilizing a flow extender 104. The flow extender 104 includes an upper end 106 that extends above the top surface 34 of the wafer carrier 32 and is attached to the body shutter 42 using connectors 108. Flow extenders are utilized to improve the flow and thermal characteristics crystalline growth environment, but also tend to dramatically increase the stray radiation signal received by radiation thermometers viewing the wafer carrier 32 and wafers 41. The reactor system was operated at approximately 800 °C for an extended period of time with the wafer carrier (including GaN crystalline growth material on the wafers in the wafer pockets) so that the thermal environment within the enclosure was at quasi-steady state (i.e., the components of the MOCVD reactor system were thermally saturated). A measurement with a radiation thermometer was made with the resistance heating array energized. Then, the power to the resistance heating array was cut, and a second measurement made with the radiation thermometer within a ten second time period. At the 405 nm wavelength, the stray radiation from the resistance heating array ceases almost immediately upon the power being cut, whereas the target continues to emit radiation at essentially the same emissive power as immediately prior to the power termination because of the thermal capacitance of the target. Accordingly, it was assumed that the first measurement included a stray radiation component from the resistance heating array at the 405 nm wavelength, whereas the second measurement did not. The experiment was performed for both a standard optical pyrometer utilizing a standard in-focus optical arrangement, as well as for a radiation thermometer utilizing the off-focus telecentric optical arrangement 24. Both radiation thermometers were operated nominally at the 405 nm wavelength. The results are presented in Table 2.

Table 2: Measurement results estimating the fraction of radiation wavelength attributed to signal and stray radiation at 405 nm for a standard and a telecentric optical arrangement (target at 800 °C; chamber with flow extender)

	Standard Optics	Off-Focus Telecentric Optics
Signal Radiation	36%	69%

Stray Radiation	64%	31%
Temperature Error at 405 nm wavelength	34°C	12 °C

The measurement results show that, for a radiation thermometer utilizing standard optics, about 64% of the radiation flux at the 405 nm wavelength on the detector is attributed to stray radiation. Utilization of the off-focus telecentric optical arrangement 24, on the other hand, reduced the stray radiation contribution to about 31%. These stray light contributions cause temperature bias errors of approximately 34 °C and 12 °C, respectively. Again, the bias error of the temperature measurement for the off-focus telecentric optical arrangement 24 is about 2/3 less for the off-axis telecentric optical arrangement than for a standard lens system.

In one embodiment, the detector 76 comprises a photon counter (i.e., photomultiplier tube, or PMT) having a cut off wavelength of 700 nm, and thus is insensitive to infrared radiation. Therefore, the use of a PMT as the detector largely eliminates the concerns of inadequate filtering in the infrared portion of the spectrum identified in Zettler. A filtering device 102 can be used to filter the PMT so that only wavelengths primarily in the region of blue, violet or ultraviolet light are detected.

Another advantage of the PMT is the fast time response that it provides, which is a factor for CVD chambers that utilize high rotational speeds of the wafer carrier, such as the TURBODISC systems manufactured by Veeco Instruments of Somerset, New Jersey, U.S.A. The TURBODISC system is described generally at Mitrovic, et. al., "Reactor Design Optimization Based on 3D CFD Modeling of Nitrides Deposition in MOCVD Vertical Rotating Disc Reactors," June 2005 (available at http://www.wpi.edu/academics/che/HMTL/CFD_in_CRE_IV/Mitrovic.pdf, last visited 16 June 2012). The high rotation rates of such systems can require data acquisition rates from the radiation detector 76 on the order of 10 kHz, which PMTs can provide.

Non limiting examples of the spectra transmitted by the filtering device includes a center wavelength in the range of 380 nm to 420 nm and a band width (full width at half maximum) in the range of 10 nm to 70 nm. In one embodiment, the filtering device 102 further comprises a band pass filter in combination with a colored glass filter. A non-limiting example of a filter combination is the 10BPF25-400 band pass filter from Newport (center wavelength of 400 ±3.5 nm; full width at half maximum of 25 ±3.5 nm) with a FGB25 colored glass filter from Thorlabs (local cut-off wavelength of 400 nm), which combine to define a primary band pass that passes radiation nominally in the 390 nm to 420 nm band pass.

In one embodiment, a non-limiting example of the component sizing and layout for the off-focus telecentric optical arrangement 24 includes: the object assembly 62 comprising a plano-convex lens having a 50.8 mm diameter and a focal length of 249.2 mm (e.g., LA1301-A from Thorlabs, Inc.) located a distance F1 of 249.2 mm from the aperture stop 66; the image assembly 64 comprising a plano-convex lens having a 25.4 mm diameter and a focal length of 75.0 mm (e.g., LA1608-A from Thorlabs, Inc.) located at a distance L1 of 75 mm from the aperture stop 66 and a distance L3 of 75 mm from the detector. In another embodiment, the object assembly 62 further comprises an achromatic doublet having a 50.8 mm diameter and a focal length of 100 mm (e.g., AC508-100-A from Thorlabs) in combination with the plano-convex lens above to shorten the focal length F1 of the object assembly to approximately 87 mm, as well as to shorten the overall length of the assembly. In this latter arrangement, an achromatic doublet having a shorter focal length (e.g., 30 mm) can, for example, be utilized as the image assembly 64 for closer proximity to the aperture (e.g., AC254-030-A from Thorlabs).

The lenses in the above-referenced examples can comprise any material suitable for transmitting radiation in the visible/UV spectrum of the electromagnetic spectrum, such as borosilicate glass, barium fluoride and fused silica. They can also be coated with anti-reflective coatings.

Alternatively, other filtering devices and techniques can be implemented in combination with the off-focus telecentric optical arrangement 24 presented herein. For example, the detector and filtering arrangement Zettler can be implemented. In some embodiments, a water cooled CCD or a solid state detector such as an avalanche photodiode can be utilized.

In operation, the wafer carrier is rotated about the rotation axis 40 while being radiantly heated by the heating array 44. The rotation rate of the wafer carrier 32 about the rotation axis 40 can vary substantially, depending on the operating parameters and design criteria of the MOCVD reactor system 20.

The radiation thermometer 22 and off-focus telecentric optical arrangement 24 are not limited to systems that implement heating sources other than resistance-type heaters. The various embodiments of the disclosure can be utilized, for example, some CVD reactor systems utilize microwave heating sources.

Referring to FIGS. 6A and 6B, multi-channel arrangements 110 and 111 for detection of spatial temperature variation on the wafer 41 is depicted in an embodiment of the disclosure. In the depicted embodiment, a plurality of radiation thermometers 22a, 22b and 22c, each implementing the off-focus telecentric optical arrangement 24, are situated to simultaneously view respective targets 72a, 72b and 72c on the wafer 41 as the wafer 41 rotates past the view port 52. The plurality of radiation thermometers 22a, 22b and 22c can be configured and arranged so that all of the targets 72a, 72b and 72c are subtended by the wafer 41 when the wafer carrier 32 is in a given rotational orientation about the rotation axis 40.

In one embodiment, the plurality of radiation thermometers 22a, 22b and 22c are arranged so that the targets 72a, 72b and 72c are centered along a line 112 that extends substantially along a radial coordinate R that extends radially outward from the rotation axis 40 and passes through the center of wafer 41 (FIG. 6A). In another embodiment, the plurality of radiation thermometers 22a, 22b and 22c are arranged so that the targets 72a, 72b and 72c are centered along a line 114 that is substantially perpendicular to the radial coordinate r and through the center of wafer 41 (FIG. 6B). Still other embodiments can define other patterns, such as targets that form a non-linear pattern or that lie along a line that defines an acute angle relative to the radial coordinate r.

Referring to FIG. 6C, a multi-channel cluster 120 of radiation thermometers 22a through 22e are depicted in a disclosed embodiment, for measurement of a pattern of targets 72a through 72e. The multi-channel cluster 120 can provide two-dimensional information regarding the temperature distribution of the wafer 41, e.g., along lines 112 and 114.

The various embodiments depicted in FIGS. 6A through 6C can implement a “blue light” wavelength centered at a wavelength that falls, for example, within the wavelength range of 400 nm to 410 nm (e.g., at 405 nm). In one embodiment, the plurality of radiation detectors (e.g., radiation detectors 22a through 22c of FIG. 6A) utilize a single holder for radiation collection lenses, shutters/apertures, filters and detector lenses to provide a more compact design for better spatial resolution. In one non-limiting embodiment, the size of the targets 72 (e.g., 72a through 72e of FIG. 6C) can be 11 mm x 22 mm and still provide adequate signal-to-noise ratios. Allowing for spaces of 1.5 mm to 10 mm between the targets, such an arrangement enables the use of a row of radiation thermometers 22 at a density of one radiation thermometer 22 or less for approximately each inch of diameter of the wafer 41 (i.e., a row of three thermometers for a 3 in. wafer, a row of six thermometers for a 6 in. wafer, a row of eight thermometers for an 8 in. wafer and so on).

The output signals from the radiation thermometers 22a, 22b and 22c can be acquired and stored on a data acquisition system 115. In one embodiment, the data acquisition system comprises a signal processor 116 that conditions and digitizes the signals from the radiation thermometers 22a, 22b and 22c, a memory device 117 that stores the digitized data, and a controller 118 such as a computer. The time vs. signal data from each of the radiation thermometers 22a, 22b and 22c can be acquired and stored in the memory device 117. The controller 118 can also perform tasks in real time, such as conversion of the signal data to temperatures, calculations of averages and standard deviations, and plotting of the temperature profiles of the wafers 41 and/or wafer carrier 32. The data acquisition system 115 is depicted for use in the configuration of FIG. 6A, but can be used with any of the radiation thermometers depicted herein. Also, various systems available to the artisan are suitable for the data acquisition.

The data acquisition system 115 can also be configured to synchronize the data streams for processing of data that is acquired when a given wafer 41 is properly oriented in view of the radiation thermometers. Synchronization enables extraction of the relevant portions of the data stream that correspond to the signals received when viewing, for example, the targets 72a, 72b and 72c. These relevant portions of the data stream can be averaged over time for statistical treatment. In one embodiment, the synchronization as well as the statistical treatment of the data is done in real time. An example synchronization routine is disclosed in U.S. Patent No. 6,349,270 to Gurary, et al. ("Gurary").

Referring to FIGS. 7A and 7B, a MOCVD reactor system 220 utilizing a radiation thermometer 222 arranged to view a target 224 within the MOCVD reactor system 220 is depicted. The MOCVD reactor system 220 includes a reactor chamber 226 operatively coupled with a flow flange 228 to define an enclosure 230. The flow flange 228 includes laminar flow plates 231 through which the gases for the MOCVD process are introduced into the reactor chamber 226. Disposed within the reactor chamber 226 is a wafer carrier 232 having a top surface 234 that defines a target plane 233 on which the target 224 of the radiation thermometer is substantially fixed. The top surface also defines wafer pockets 235 for holding substrates or wafers 237. The wafer carrier 232 also includes a bottom surface 236 and is operatively coupled with a spindle 238 that defines a rotation axis 240. A body shutter 242 can be removably inserted adjacent the interior wall of the reactor chamber 226 and surrounds the wafer carrier 232.

A heater array 244 is disposed beneath the wafer carrier 232 for radiative coupling with the bottom surface 236 of the wafer carrier 232. The heater array 244 can be surrounded by a cylinder 246 and also bounded beneath with a filament mounting plate 248 to enhance radiative coupling between the heater array 244 and the wafer carrier 232. The cylinder 246 defines a cylinder axis 250 substantially concentric with the rotation axis 240.

The radiation thermometer 222 is mounted atop the flow flange 228 and oriented to view the top surface 234 of the wafer carrier 232 through a view port window 252. In one embodiment, the view port window 252 is disposed in a recess 254, which can be actively cooled.

The heater array 244 can include a peripheral heating element 264. The peripheral heating element 264 is so-named because it defines the outer periphery of the heater array 244. While the peripheral heating element 264 depicted herein is a single heating element, a heater arrangement wherein peripheral (i.e., outermost) heating elements are comprised of two or more heating elements is also contemplated.

To promote uniform heating, the peripheral heating element 264 in the depicted embodiment is located proximate an interior surface 266 of the cylinder 246. A plurality of rays 2` are depicted as being emitted from the peripheral heating element 264, inter-reflecting within the enclosure 230, and entering the radiation thermometer 222.

Referring to FIG. 8, the region near a top edge 272 of the cylinder 246 and an outer edge 274 of the wafer carrier 232 is depicted in a disclosed embodiment. A gap 276 is defined between the outer edge 274 and the top edge 272 to enable the wafer carrier 232 to freely rotate. Rays 268a, 268b and 268c, depicted as being emitted from the peripheral heating element 264, represent three kinds of radiation that exit the gap 276: ray 268a represents direct radiation that exits the gap 276 without being reflected; ray 268b represents radiation that is scattered off the interior surface 266 of the cylinder 246 and the outer edge 274 of the wafer carrier 232; and ray 268c represents the radiation that is scattered off the bottom surface 236 of the wafer carrier 232 and the filament mounting plate 248.

In operation, the wafer pockets 235 can be loaded with substrates 237 (e.g., sapphire). The wafer carrier 232 is rotated about the rotation axis 240 and the heater array 244 energized to a temperature of approximately 1800 °C. Gases are introduced through the laminar flow plates 231 to form a crystalline growth material (e.g., GaN) on the wafer carrier 232, including the wafer pockets 235 and any substrate 237 contained therein. The temperature of the crystalline growth material during operation is on the order of 800 °C.

The operating conditions of the enclosure 230 as substantially depicted in FIGS. 7A and 7B was modeled using a three-dimensional ray tracing program. The ray tracing model was executed to identify stray radiation paths and to analyze stray radiation entering the view port window 252. The peripheral heating element 264 was assumed to be continuous and set as a radiation source operating at a temperature of 1800 °C. The wafer carrier 232 (modeled as including wafers 237 in the wafer pockets 235) was modeled as both a radiation source at 800 °C and as a scattering media. The blackbody emissive power for the radiation sources was established based on Planck’s law at a wavelength of 405 nm. The interior walls of the enclosure 230 (including the body shutter 242, laminar flow plates 231 and view port 252) were also modeled as scattering media.

The radiation thermometer 222 was modeled at two different positions: an “outer” position at a radius R proximate the center of the outermost wafer pockets 235 (depicted in FIG. 7A); and a “mid-span” position centered at approximately $^2/_3$ R between the outer position and the rotation axis 240. The amount of 405 nm radiation emitted from the target 224 and directly entering the radiation thermometer 222 (“signal radiation”) was compared with the amount of 405 nm radiation inter-reflected within the enclosure 230 and entering the radiation thermometer 222 (“stray radiation”). The results are presented in Table 3.

Table 3: Predicted fraction of radiation wavelength attributed to signal and stray radiation at 405 nm (target at 800 °C; peripheral heating element at 1800 °C)

	Outer Position	**Middle Position**
Signal Radiation	3%	30%
Stray Radiation	97%	70%
Temperature Error at 405 nm wavelength	127 °C	41 °C

The ray tracing model predicted that, for a peripheral heating element 264 that forms a continuous ring and for the radiation thermometer 222 centered at the outer position, about 97% of the radiation flux at the 405 nm wavelength on the detector of a standard radiation thermometer is attributed to stray radiation. At the middle position, stray radiation is predicted to account for about 70% of the total signal. These stray radiation contributions cause temperature bias errors of approximately 127 °C and 41 °C, respectively. Furthermore, the results of the ray tracing model indicate that about 92% of the stray radiation reaching the detector of the radiation thermometer originates from radiation scattered off the bottom surface 236 of the wafer carrier 232 and the filament mounting plate 248 (as represented by ray 268c in FIG. 8).

Referring to FIG. 9, a heater array 244a including an interior heating element 304 and a peripheral heating element 264a is depicted in a disclosed embodiment. The flow flange 228 and wafer carrier 232 are removed from this view to clearly show the layout of the heater array 244a. The spindle 238, body shutter 242 and filament mounting plate 248 are also visible in this view. The heating elements 264a and 304 include electrical connectors 306 and 308, respectively.

The terminal connection 306 occupies an arc segment 310 of the peripheral heating element 264a wherein the electrical resistance is substantially reduced in comparison to other arc segments of the peripheral heating element of equal length. That is, the arc segment 310 constitutes a low heat flux portion 312 of the peripheral heating element 264a. The terminal connection 306 operates at a substantially reduced temperature from the high resistance portion of the peripheral heating element 264a. For example, in one non-limiting embodiment, the peripheral heating element 264a operates at a maximum operating temperature of nominally 2000 °C. At this operating condition, the terminal connection 306 operates at approximately 1500 °C and the nominal temperature across the arc segment 310 is believed to operate at 1700 °C or less, or at least 300 °C less than the operating temperature of the high resistance portion of the peripheral heating element 264a. Thus, in terms of operating temperature, the low heat flux portion 312 (i.e., the electrical connector 306) of the peripheral heating element 264a operates at a substantially lower temperature than the remainder of the peripheral heating element 264a, so that the radiation contribution of the low heat flux portion 312 at 405 nm is about two orders of magnitude less than the high resistance portion of the peripheral heating element 264a (see FIG. 1).

The interior heating element 304 of the heater array 244a is arranged so that a first half-length 314 is within a first semicircle and a second half-length 316 is within a second semicircle. Accordingly, there is a line of discontinuity 318 that lies between the first and second half-lengths 314 and 316, bridged only at one location near the spindle 238 and the electrical connector 308.

An experiment was conducted to determine the relative contribution of the peripheral heating element 264a to the stray radiation contribution at the 405 nm wavelength as compared to the heater array 244a as a whole. The interior heating element 304 and the peripheral heating element 264a were fully energized and controlled to maintain the wafer carrier 232 at a steady state temperature near 800 °C, as would be done in a normal crystalline growth operation. Then, the power to the peripheral heating element 264a was capped so that the peripheral heating element 264a could operate only at about half capacity, while still controlling the system to heat the wafer carrier 232 at or near the 800 °C temperature. In this way, the radiation contribution of peripheral heating element 264a at the 405 nm wavelength was reduced to negligible, while the wafer carrier 232 remained essentially at temperature and the interior heating element 304 actually operated at a somewhat higher temperature to make up for the reduced heat input from the peripheral heating element 264a. Then, the power to the interior heating element 304 was also capped at approximately half capacity. A measurement was made with the radiation thermometer 222 at all three operating conditions, with the third condition (both the peripheral heating element 264a and the interior heating element 304 at half capacity) being taken immediately after capping the capacity of the interior heating element 304. Based on these measurements, it was determined that the peripheral heating element 264a contributed between 80% and 90% of the stray radiation received by the radiation thermometer 222. Thus, the simplification of modeling only the radiation originating from the peripheral heating element 264 instead of the entire heater array 244 of FIG. 7A was validated.

A theory was developed that, because such a large fraction of the stray radiation originates from the peripheral heating element 264, stray radiation may be controlled locally by limiting the emission of the peripheral heating element locally. That is, if the target 224 of the radiation thermometer 222 is fixed on a region of the target plane 233 that is proximate a zone of the peripheral heating element 264 of which emitted radiation is largely reduced, captured or transferred away, the stray radiation received by the radiation thermometer should be reduced.

A stray radiation detection experiment was conducted to test this theory. The radiation thermometer 222 was configured to detect electromagnetic radiation across a narrow band pass centered nominally at 405 nm. A second, infrared radiation thermometer 320 (FIG. 7A) was configured to detect electromagnetic radiation across a band pass centered nominally at 900 nm. Recall, as described *supra*, the change in the spectral blackbody emissive power is extremely sensitive to temperature changes at 405 nm (numerical references 14 and 16, FIG. 1). Accordingly, the radiation thermometer 222 configured to detect radiation nominally at 405 nm is extremely sensitive to stray radiation originating from the peripheral heating element 264. However, at the 900 nm wavelength (referring again to FIG. 1 and Planck's law), in the temperature region of interest (nominally 2100 K), the change in the spectral blackbody emissive power is very insensitive to temperature change at 900 nm (see numerical reference 322, FIG. 1). Accordingly, the infrared radiation thermometer 320 operating at 900 nm is substantially less sensitive to stray radiation originating from the peripheral heating element 264, and instead is more sensitive to changes in the temperature of the wafer carrier 232 (nominally at 1100 K; see numerical reference 324, FIG. 1).

Therefore, the stray radiation detection experiment is based on a comparison of the indicated temperatures from a detector that is highly sensitive to stray radiation (the radiation thermometer 222) and the indicated temperatures from a reference device that is insensitive to stray radiation (the infrared radiation thermometer 320).

Referring to FIG. 10, a typical stray radiation signature 330 is depicted. The stray radiation signature 330 is based on comparison of an infrared temperature signal 332 produced by the infrared radiation thermometer 320 and an optical or "blue light" temperature signal 334 produced by the radiation thermometer 222 detecting radiation at nominally 405 nm. For the data presented in FIG. 10, both the radiation thermometer 222 and the infrared radiation thermometer 320 viewed target locations on the target plane 233 that are similarly situated (i.e., at similar radii from the rotation axis 240). Also, the data in FIG. 10 has been normalized so that the initial temperatures shown in initial cool down (first zone I of FIG. 10) track the same.

For the stray radiation detection experiment, the MOCVD reactor system 220 was operated to bring the wafer carrier to a first control temperature. Then the control temperature was adjusted downward to a lower set point temperature below the first elevated temperature. A first zone I of the stray radiation signature 330 depicts the cooling of the wafer carrier 232 as a steady drop in the temperature signals 332 and 334. A second zone II of the stray radiation signature 330 depicts a recovery of the temperature signals 332 and 334 as the temperature controller of the MOCVD system 220 establishes a controlled equilibrium at the lower set point temperature.

The infrared temperature signal 332 substantially traces the true temperature profile of the wafer carrier during the above-described process. That is, the true temperature of the wafer carrier 232 undergoes a gradual inflection 336 followed by a substantially monotonic rise 338 in temperature in the zone II portion of the stray radiation signature 330. The gradual inflection 336 and monotonic rise in temperature 338 are a result of the thermal mass of the wafer carrier 232.

The optical temperature signal 334, however, is characterized by a sharp inflection 342 followed by a substantial overshoot 344 and a slight undershoot 346 in the zone II portion of the stray radiation signature 330 before settling at a controlled equilibrium temperature 348. The optical temperature signal 334 is a convolution of the emitted signal from the wafer carrier 232 and the stray radiation incident on the target 224 of the target plane 233 and reflected into the radiation thermometer 222. The overshoot 344 and undershoot 346 is characteristic of a proportional gain temperature profile experienced by the heater array 244 when responding to a new set point. It is believed that the optical temperature signal 334 closely tracks the control temperature profile of the heater array 244 because the optical temperature signal 334 is dominated by the stray radiation component, as predicted by the ray tracing model.

Therefore, one can qualitatively determine whether the radiation received by the radiation thermometer 222 has a strong scattered radiation component. Temperature signals that follow a profile similar to the infrared radiation signal 332 (gradual inflection with monotonic rise) are not dominated by scattered radiation, whereas temperature signals that follow a profile similar to the optical radiation signal 332 (sharp inflection with substantial overshoot) are dominated by scattered radiation.

Referring to FIG. 11, the stray radiation detection experiment was repeated by viewing targets 224a, 224b, 224c and 224d at several different locations on the target plane 233 with the radiation thermometer 222, again configured to detect radiation at the 405 nm nominal wavelength. While FIG. 11 depicts an exposed heater array 244a, it is understood that during the stray radiation detection experiment the wafer carrier 232 was in place and operating in a rotating mode. Accordingly, FIG. 11 depicts the orientation of the heater array 244a in relation to where the targets 224a through 224d fall on the target plane 233 located above the heater array 244a.

To test the theory that stray radiation is reduced proximate a low heat flux portion of the peripheral heating element 264a, the heater array 244a was arranged so that the low heat flux portion 312 was proximate targets 224a and 224b, while the portion of the peripheral heating element 264a proximate the targets 224c and 224d was a continuous portion 350 and having a high heat flux. Targets 224a and 224d, though diametrically opposed, were both centered at a radial distance of approximately 195 mm (7.68 inches) from the rotation axis 240. Likewise, targets 224b and 224c, though diametrically opposed, were both centered at a radial distance of approximately 142 mm (5.6 inches) from the rotation axis 240.

Referring to FIGS. 12A and 12B, the results of the tests are presented. Optical temperature signals 352 and 354 of FIG. 12A were acquired from targets 224a and 224d, i.e., at an outer radial position. Note that the optical temperature signal 354, acquired proximate a continuous, high heat flux portion of the peripheral heating element 264a, has a temperature profile characteristic of a high stray radiation component (sharp inflection 342a with a strong overshoot 344a). However, the optical temperature signal 352, acquired proximate the low heat flux zone 312 of the peripheral heating element 264a, has the same temperature profile characteristics as the infrared radiation signal 332 of FIG. 10 (gradual inflection 336a with monotonic rise in temperature 338a).

With respect to FIG. 12B, optical temperature signals 356 and 358 were acquired from targets 224b and 224c, respectively, i.e., at mid-span positions. The optical temperature signal 358, acquired at a mid-span position proximate the continuous, high heat flux portion of the peripheral heating element 264a, also has a temperature profile characteristic of a high stray radiation component (sharp inflection 342b with a strong overshoot144b). However, the optical temperature signal 356, acquired at a mid-span position proximate the low heat flux zone 312 of the peripheral heating element 264a, has the same temperature profile characteristics as the infrared radiation signal 332 of FIG. 10 (gradual inflection 336b with monotonic rise in temperature 338b).

Accordingly, an axis of reduced scattered radiation 362 (FIG. 11) is defined on the target plane 233 as extending radially from the rotation axis 240 and over the center of the low heat flux zone 312. Targets 224 on the target plane 233 that are proximate the axis 362 have a reduced stray radiation component, thus incurring a reduced bias in the temperature determination compared to targets acquired elsewhere on the target plane 233. In one embodiment, the target 224 is centered along or otherwise touches or overlaps the axis 362. In another embodiment, the target 224 falls within a rectangular zone 364 of reduced stray radiation, defined as having a length 366 that extends from the rotation axis 240 to the outer edge 274 of the wafer carrier 232 (not depicted in FIG. 11) and having an approximate width 368 defined by the chord of the arc segment 310.

Referring to FIGS. 13A and 13B, a radiation trap 372 for capturing a portion of the radiation that is emitted from a designated portion 374 of the peripheral heating element 264 is depicted in a disclosed embodiment. In one embodiment, the radiation trap 372 comprises a cavity 376 defined in the body shutter 242 having a tangential dimension 378. In one embodiment, the designated portion 374 of the peripheral heating element 264 is defined as the arc segment that is immediately adjacent the radiation trap 372 and having the same tangential dimension 378.

In operation, a portion of the radiation 380 emitted from the designated portion 374 is transferred into the cavity 376, either by direct radiation or by reflection off the various surfaces proximate the radiation trap 372. The radiation trap 372 thus limits the propagation of radiation locally by capturing the radiation 380. In this embodiment, the axis of reduced scattered radiation 362 is defined on the target plane 233 and extends from the rotation axis 240 and through the tangential center of the cavity 376. The width 368 of rectangular zone 364 of reduced stray radiation is defined by the chord of the tangential dimension 378.

Referring to FIG. 14, a radiation deflector 392 for deflecting a portion of the radiation that is emitted from a designated portion 394 of the peripheral heating element 264 is depicted in a disclosed embodiment. In one embodiment, the radiation deflector 392 comprises a convexity 396 that protrudes radially inward proximate the outer edge 274 of the wafer carrier 232. The convexity 396 can be characterized as having a tangential dimension 398. In one embodiment, the designated portion 394 of the peripheral heating element 264 is defined as the arc segment that is immediately adjacent the radiation deflector 392 and having the same tangential dimension 398 of the convexity 396.

In operation, a portion of the radiation 402 emitted from the designated portion 374 is transferred into the convexity 396, either by direct radiation or by reflection off the various surfaces proximate the radiation deflector 392. The radiation deflector 392 thus limits the incidence of radiation locally by scattering the radiation 402 away from a plane 404 that is defined by the rotation axis 240 and passing through the convexity 396. In this embodiment, the axis of reduced scattered radiation 362 is defined by the confluence of the target plane 233 and plane 404 and extends from the rotation axis 240 through the radiation deflector 392. The width 368 of rectangular zone 364 of reduced stray radiation is defined by the chord of the tangential dimension 398 of the radiation deflector 392.

In one disclosed embodiment, the heating element is provided with hardware for implementing at least one of the techniques for locally reducing stray radiation presented herein. A set of instructions is also provided on a tangible medium (e.g., written paper copy or computer accessible), the instructions describing how to align a radiation thermometer relative to the orientation of the heating element for a reduced stray radiation component, as described herein. Such a combination can be utilized, for example, for retrofitting existing CVD reactor systems.

Referring to FIG. 15, a dual wavelength pyrometer 420 is depicted in a disclosed embodiment. The dual wavelength pyrometer 420 comprises two radiation thermometers 422 and 424, each configured to view a different central wavelength—for example, the 930 nm and the 405 nm wavelengths, respectively. Each of the radiation thermometers 422 and 424 can also include the off-focus telecentric optical arrangement 24, the components of which are identified in FIG. 15 with the same numerical references as previously presented.

In one embodiment, the radiation thermometers 422 and 424 of the dual wavelength pyrometer 420 share a common object assembly 62. A cold mirror 426 can be utilized to transfer (reflect) a visible/UV spectrum radiation beam 434 to the radiation thermometer 424 while transmitting an infrared radiation beam 432 to the radiation thermometer 422. Alternatively, a beam splitter (not depicted) can be utilized instead of the cold mirror 426.

Functionally, the dual wavelength pyrometer 420 as depicted enables the simultaneous measurement of the radiation signal emitted from a common target 72. The cold mirror 426 enables a large fraction of visible/UV spectrum radiation to be transferred to the radiation thermometer 424 while passing a large fraction of the infrared radiation through the radiation thermometer 422. For example, cold mirrors are available that reflect over 90% of the radiation in the visible or visible/UV spectrum while maintaining a minimum of 83% transmission for wavelengths greater than 800 nm. See "Cold Mirrors," DichroTec Thin Films LLC (available at http://www.dtthinfilms.com/cold-mirrors.html, last visited on May 30, 2013). For embodiments where the filtered wavelengths of both radiation thermometers 422 and 424 are in either the visible/UV or the infrared spectrum, an appropriate beam splitter can instead be utilized. The reduced size aperture assembly 97 can also be utilized as described above, and as depicted for radiation thermometer 424 in FIG. 15, for one or both radiation thermometers 422, 424.

In various embodiments, one or both of the radiation thermometers 422, 424 can be equipped with a reflectometer subassembly 442. The reflectometer subassembly 442 can comprise a radiation source 444 (designated as radiation source 444a and 444b for the radiation thermometers 422 and 424, respectively), a detector 446 and a beam splitter 448. The radiation sources 444a and 444b are tailored or selected to emit a beam 452 that includes spectral emission within the wavelength band passed by the respective filtering device 102a and 102b of the respective radiation thermometer 422 or 424. The beams 452, as well as the optical axes 68, are distinguished from each other in FIG. 15 as beam 452a and 452b and optical axes 68a and 68b for the radiation thermometers 422 and 424, respectively. The beams 452a and 452b are hereinafter referred to generically as beam 452 and collectively as beams 452. The detector 446 (designated as detector 446a and 446b for the radiation thermometers 422 and 424, respectively) is selected to respond to a wavelength within the band passed by the filtering device 102 of the respective radiation thermometer 422 or 424, and emitted by the respective radiation source 444a or 444b. In one embodiment, the reflectometer subassembly 442 includes a chopper 458 for modulating the beam 452 as it exits the radiation source 444.

In certain embodiments, the reflectometer subassembly 442 can also include one or more focusing elements 454, 456 such as lenses or spherical mirrors that focus or collimate the beam 452. In one embodiment, the focusing element 454 can comprise a lens cluster akin to object assembly 62 or image assembly 64 for telecentric operation.

In operation, the beam 452 from the radiation source 444 of the reflectometer subassembly 442 is passed through the beam splitter 448. In one embodiment, a first portion 462a or 462b of the beam 452 passes through the beam splitter 448 and is incident on the detector 446. The signal generated by the detector 446 provides an indication of the intensity of the beam 452. Because of the orientation of the beam splitter 448, the detector 446 effectively does not see radiation that either originates from or is reflected from the target 72. A second portion 464 (referred to as 464a and 464b for radiation thermometers 422 and 424, respectively, and referred to generically as 464) of the beam 452 is reflected by the beam splitter 448 and directed to propagate substantially along the respective optical axis 68a or 68b and onto the target 72 via the cold mirror 426. A fraction of the second portion 464 of the beam 452 is then reflected from the target 72, back along the respective optical axis 68a or 68b of the respective radiation thermometer 422 or 424 via the cold mirror 426, passing through the beam splitter 448 and filtering device 102 for detection by the respective detector 76a, 76b of the radiation thermometer 422 or 424.

In one embodiment, the layout and components of the reflectometer subassembly or subassemblies 442 are specified so that, in combination with the two passes through the object assembly 62 and the pass through the respective image assembly 64a or 64b, the second portion 464 of the beam 452 is brought to focus on the image plane of the respective detector 76a, 76b. Also, the reflectometer subassembly 442 can be specified so that the reflectometer irradiation "underfills" the target 72. That is, the area of the target 72 irradiated by the radiation from the reflectometer subassembly 442 is smaller than and totally contained within the target 72.

Functionally, the underfilling of the target 72 provides spatial tolerance during the reflectivity measurement for misalignment that may occur. In brief explanation, during the CVD process, the wafer 41 can deform or "bow" due to the presence of thermal gradients within the wafer 41. The bowing can cause the fraction of the second portion 464 of the beam 452 that is reflected from the target 72 and received by the detector 76a or 76b to be redirected, particularly when the target is highly specular. The redirection of this reflected fraction causes the reflected radiation to laterally migrate at the image plane of the detector 76a or 76b. By underfilling the target 72, the reflected fraction can laterally migrate to some extent and still be fully subtended and therefore fully detected by the detector 76a or 76b.

While the depiction of FIG. 15 portrays reflectometer subassemblies 442 in both the radiation thermometers 422 and 424, it is understood that the refelectometer sources 442 are optional and can be implemented by both radiation thermometers 422 and 424, by only one radiation thermometer 422 or 424, or none of the radiation thermometers. Likewise, the use of the chopper 458 or other beam modulating device is also considered optional, and need not be implemented with the reflectometer subassembly or sources 442.

Referring to FIGS. 16A and 16B, respective composite signals 472a and 472b generated by the detector 76a or 76b viewing an emitted target 72 irradiated by the reflectometer subassembly 442 is depicted in a disclosed embodiment. The composite signal 472a is characteristic of a signal generated by a reflectometer subassembly 442 that implements the optional chopper 458 or other modulation means. The composite signal 472a can be characterized as having a modulated signal 474 that rides on a baseline signal 476. A baseline magnitude 478 of the baseline signal 476 is indicative of the emissive power of the target 72. A valley-to-peak amplitude 482 of the modulated signal 474 is indicative of the fraction of the second portion 464 of the beam 452 that is reflected from the target 72.

The composite signal 472b is characteristic of a signal generated by a refelctometer source 442 that does not modulate the beam 452. Rather, the composite signal 472b comprises a pulse or step signal 484 having a magnitude 485 that extends from the baseline signal 476. The step signal 484 can be generated by powering on the radiation source 444, in which case the step signal 484 may drift during the duration of the step signal 484. To compensate for the drift, the step signal 484 can be normalized against the signal from the detector 446, which tracks the intensity of the beam 452, to provide a normalized signal 486. The amplitude of the normalized signal 486 is indicative of the reflectivity of the target 72.

The reflectometer subassembly 442 can be implemented, for example, to compensate for changes in the emissivity of the target 72. The emissivity of the target can be inferred from the reflectivity measurement, for example, as described in U.S. Patent No. 6,349,270 to Gurary, et al. (“Gurary”), which discloses how to infer emissivity from a reflectivity measurement in the context of wafers on a wafer carrier in a CVD process. An indication of the target emissivity can be utilized to improve the accuracy of the temperature determination.

The fraction of the second portion 464 of the beam 452 that is sensed by the detector 76a or 76b is subject to the same collimation as the radiation emitted from the target 72, described above in the discussion attendant to FIG. 4. That is, only the reflected radiation from the second portion 464 that is reflected substantially parallel to a chief ray 92 (FIG. 4) is detected by the detector 76a or 76b, so that there will be very little if any contribution from radiation that is first scattered from the target 72 or the view port 52. Therefore, the contribution of scattered radiation that originated from the second portion 464 of the beam 452 is *de minimis*, regardless of where the target 72 is on the wafer 41. By essentially eliminating the scattered radiation component, the resultant indicated reflectivity characteristics between targets can be more consistent.

In the depicted arrangement of the dual wavelength pyrometer 420, the second portion 464 of the beams 452a and 452b are twice attenuated by the beam splitter 448, the cold mirror 426, the object assembly 62 and the view port 52, and once by the target 72, the filtering device 102 and the image assembly 64 before reaching the respective detector 76a, 76b. Accordingly, the second portion 464 of the beam 452 can undergo significant attenuation, thus requiring that the radiation source 444 be of sufficient power to provide a detectable reflectivity signal. A non-limiting example of a radiation source having sufficient power is a light-emitting diode (LED) operated in the range of approximately 1 mW to approximately 10 mW. Light-emitting diodes can be tailored to deliver energy in a narrow spectral range that passes through the filtering device 102 of the respective radiation detector 422 or 424. For example, for a filtering device 102 having a central wavelength of approximately 405 nm and a band pass on the order of 25 nm, a non-limiting example of a LED radiation source is the LED405E, manufactured by Thorolabs, Inc. of Newton, NJ, USA, which has a center wavelength of 405 nm ±10 nm and a spectral band pass (full width at half maximum) of about 15 nm. For a filtering device 102 having a central wavelength of approximately 930 nm and a band pass on the order of 10 nm, a non-limiting example of a LED radiation source is the OD-1390, manufactured by Opto Diode Corp. of Newbury Park, CA, USA, which has a center wavelength of approximately 943 nm and a spectral band pass (full width at half maximum) of about 60 nm.

Referring to FIG. 17, a combined multi-channel, dual wavelength system 490 is depicted in a disclosed embodiment. In the depicted embodiment, a plurality of dual wavelength pyrometers 420a, 420b and 420c are arranged to view targets 72a, 72b and 72c along the line 114. Each dual wavelength pyrometer 420a, 420b, 420c include a respective pair of radiation thermometers 422a/424a, 422b/424b, 422c/424c, each member of a given pair being configured to view a selected wavelength band pass as described in reference to FIG. 15.

The radiation thermometers 422 and 424 of the dual wavelength pyrometer 420 can be arranged on so that the propagation axes of the optical components are on a common plane (e.g., plane 492, depicted as passing through the elongate axes of radiation thermometers 422c and 424c in FIG. 17). Also, the internal components of the radiation thermometers 422 and 424 can be arranged so that a width 494 orthogonal to the common plane 492 is the same as the width of the radiation thermometers 22a, 22b and 22c of FIGS. 6A and 6B. Such an arrangement provides the dual wavelength pyrometer 420 with the same lateral footprint as the radiation thermometer 22, thereby enabling the dual wavelength pyrometers 420a, 420b and 420c to be arranged to view targets along any arbitrary line or in other patterns in the same manner as discussed above in relation to FIGS. 6A and 6B and as depicted in FIG. 17.

In an alternative embodiment, only one of the pyrometers of a multi-channel arrangement is dual wavelength. In this arrangement, an assumption is made that the temperature correction and/or emissivity compensation derived from the sole dual wavelength pyrometer applies to the entire wafer and therefore all of the targets.

Accordingly, the combined multi-channel, dual wavelength system 490 can deliver the enhanced accuracy of the dual wavelength, off-focus telecentric arrangement while providing spatial temperature uniformity information.

While the discussion herein focuses primarily on application in MOCVD reactor systems, it is noted that the principles explained herein can apply to other types of CVD chambers, as well as chambers generally in that utilize radiation thermometers. Also, for purposes of this disclosure, the terms “pyrometer” and “radiation thermometer” are synonymous, a “detector” is an electromagnetic radiation detector, and a “beam” is a beam of electromagnetic radiation.

References to relative terms such as upper and lower, front and back, left and right, or the like, are intended for convenience of description and are not limiting to any specific orientation.

All dimensions depicted in the figures may vary with a potential design and the intended use of a specific embodiment without departing from the scope thereof.

Each of the additional figures and methods disclosed herein may be used separately, or in conjunction with other features and methods, to provide improved devices, systems and methods for making and using the same. Therefore, combinations of features and methods disclosed herein may not be necessary to practice the disclosed embodiments in the broadest sense and are instead disclosed merely to particularly describe representative embodiments.

For purposes of interpreting the claims of the present application, it is expressly intended that the provisions of Section 112, sixth paragraph of 35 U.S.C. are not to be invoked unless the specific terms “means for” or “step for” are recited in the subject claim.

CLAIMS

What is claimed is:

1. A telecentric optical arrangement for a radiation thermometer, comprising:

an aperture stop;

an object assembly of one or optical components arranged for transfer of radiation to said aperture stop, said object assembly and said aperture stop defining an optical axis, said object assembly defining a first focal length relative to a first reference point within said object assembly, said first reference point being located on said optical axis at a distance from said aperture stop that is substantially equal to said first focal length of said object assembly for transfer of substantially collimated radiation from an off-focus target through said object assembly and for focusing of said radiation from said off-focus target onto said aperture stop; and

an electromagnetic radiation detector arranged to detect at least a portion of the radiation transferred from said object assembly through said aperture stop, said electromagnetic radiation detector generating a signal from which a temperature of said off-focus target is inferred.

2. The telecentric optical arrangement of claim 1, further comprising an image assembly of one or optical components disposed opposite said object assembly from said aperture stop and arranged to receive radiation transferred from said object assembly through said aperture stop along said optical axis, said image assembly defining a second focal length relative to a second reference point within said image assembly, said second reference point being located on said optical axis.

3. The telecentric optical arrangement of claim 2, wherein said second reference point of said image assembly is located at a distance from said aperture stop that is substantially equal to said second focal length of said image assembly for collimation of radition transferred from said aperture stop through said image assembly and onto said detector.

4. The telecentric optical arrangement of claims 1, 2 or 3 wherein said aperture stop defines a major dimension that is approximately 1/3 or less of an effective radial dimension of said object assembly.

5. The telecentric optical arrangement of any one of claims 1-4, wherein said electromagnetic radiation detector is a photon counter having a cutoff wavelength of approximately 700 nm.

6. The telecentric optical arrangement of any one of claims 1-5, further comprising a filtering device having a primary band pass at wavelengths less than 450 nm, said filtering device being arranged to filter radiation incident on a sensing region of said electromagnetic radiation detector.

7. The telecentric optical arrangement of claim 6, wherein said primary band pass of said filtering device has a center wavelength in the range of 380 nm to 420 nm and has a band width in the range of 20 nm to 50 nm.

8. The telecntric optical arrangement of claim 6, wherein said filtering device comprises a band pass filter.

9. The telecntric optical arrangement of any one of claims 1-8, wherein a distance between said off-focus target and said object assembly is less than two meters.

10. The telecentric optical arrangement of any one of claims 1-9, wherein said object assembly comprises at least one lens.

11. A method of reducing stray radiation bias in a radiation thermometer utilized in a chemical vapor deposition chamber, comprising:

providing a telecentric lens arrangement including an aperture stop and a first optical component assembly for collecting radiation from a target, said telecentric lens arrangement being adapted for positioning said aperture stop at the focal length of said first optical component assembly for capture of collimated radiation emitted from said target;

providing instructions on a tangible medium, said instructions comprising:

orienting said first optical component assembly to intercept radiation emitted from a target within said chemical vapor deposition chamber.

12. The method of claim 11, wherein said instructions provided in the step of providing instructions further comprise positioning said aperture stop at the focal length of said first optical component assembly.

13. The method of claim 11 or claim 12, wherein said instructions provided in the step of providing instructions further comprising operatively coupling said telecentric lens arrangement with an electromagnetic radiation detector.

14. The method of claim 11, 12 or 13, further comprising positioning said aperture stop at the focal length of said first optical component assembly.

15. The method of any one of claims 11-14, further comprising operatively coupling said telecentric lens arrangement with an electromagnetic radiation detector.

16. A system for measuring a temperature of a target in a chemical vapor deposition chamber, comprising:

a radiation thermometer operatively coupled with said chemical vapor deposition chamber, said radiation thermometer including means for defining an off-focus target inside said chemical vapor deposition chamber.

17. A pyrometer system for inferring a spatial temperature distribution, comprising:

a plurality of radiation thermometers arranged to view a corresponding plurality of adjacent off-focus targets, each of said plurality of radiation thermometers including a first telecentric optical arrangement that includes:

an object assembly of one or more optical components for transfer of radiation, said object assembly defining a focal length relative to a reference point within said object assembly;

a first aperture stop arranged to receive radiation transferred from said object assembly, said object assembly and said first aperture stop defining a first optical axis that passes through said reference point, said first aperture stop being located at a distance from said reference point that is substantially equal to said focal length of said object assembly for focusing of a first detected portion of said radiation from said respective one of said corresponding plurality of adjacent off-focus targets onto said first aperture stop; and

a first electromagnetic radiation detector arranged to detect said first detected portion of said radiation transferred from said object assembly through said first aperture stop, said first electromagnetic radiation detector generating a first signal from which a temperature of said respective one of said corresponding plurality of adjacent off-focus targets is inferred.

18. The pyrometer system of claim 17, wherein adjacent ones of said plurality of adjacent off-focus targets define a respective space therebetween.

19. The pyrometer system of claim 17, wherein said plurality of radiation thermometers are arranged for viewing a wafer on a wafer carrier, said wafer carrier being arranged within a chemical vapor deposition chamber, and wherein said plurality of adjacent off-focus targets are completely subtended by said wafer.

20. The pyrometer system of claim 19, wherein the subtending of said off-focus targets by said wafer is periodic.

21. The pyrometer system of any of claims 17-20, wherein at least one of said plurality of radiation thermometers includes a first reflectometer subassembly including a first beam splitter and a first radiation source for generation of a first beam of electromagnetic radiation, said first beam splitter being arranged for propagation of a portion of said first beam along said first optical axis for irradiation of said respective one of said corresponding plurality of adjacent off-focus targets.

22. The pyrometer system of claim 21, wherein said first reflectometer subassembly modulates said first beam.

23. The pyrometer system of claim 22, wherein said first reflectometer subassembly modulates said first beam with a chopper.

24. The pyrometer system of any one of claims 17-23, wherein at least one of said plurality of radiation thermometers includes a reduced aperture assembly arranged for selectively reducing said first detected portion of said radiation that is detected by said first electromagnetic radiation detector.

25. The pyrometer system of any one of claims 17 through 24, wherein at least one of said plurality of radiation thermometers including a second telecentric optical arrangement that includes:

a second aperture stop arranged to receive radiation from said object assembly, said object assembly and said second aperture stop defining a second optical axis that passes through said reference point, said second aperture stop being located at a distance from said reference point that is substantially equal to said focal length of said object assembly for focusing of said second detected portion of said radiation from said respective one of said corresponding plurality of adjacent off-focus targets onto said second aperture stop; and

a second electromagnetic radiation detector arranged to detect said second detected portion of said radiation transferred from said object assembly through said second aperture stop, said second electromagnetic radiation detector generating a second signal from which said temperature of said respective one of said corresponding plurality of adjacent off-focus targets is inferred.

26. The pyrometer system of claim 25, wherein said first detected portion of radiation is in the infrared spectrum of electromagnetic radiation and said second detected portion of radiation is in the visible spectrum of electromagnetic radiation.

27. The pyrometer system of claim 25 further comprising a cold mirror disposed along said first optical axis and said second optical axis, said cold mirror transmitting said first detected portion of radiation and reflecting said second detected portion of radiation.

28. The pyrometer system of claim 26 or claim 27, wherein said second detected portion of radiation defines a wavelength band pass that is centered at a wavelength that is greater than or equal to 400 nm and less than or equal to 410 nm.

29. The pyrometer system of claim 26, 27 or 28, wherein said first detected portion of radiation defines a wavelength band pass that includes the 930 nm wavelength.

30. The pyrometer system of any one of claims 21-29, wherein at least one of said plurality of radiation thermometers includes a second reflectometer subassembly including a second beam splitter and a second radiation source for generation of a second beam of electromagnetic radiation, said second beam splitter being arranged for propagation of a portion of said second beam along said second optical axis for irradiation of said respective one of said corresponding plurality of adjacent off-focus targets.

31. The pyrometer system of claim 30, wherein said second reflectometer subassembly modulates said second beam.

32. The pyrometer system of claim 31, wherein said second reflectometer subassembly modulates said second beam with a chopper.

33. A telecentric dual wavelength pyrometer, comprising:

an object assembly of one or more optical components for transfer of radiation from an off-focus target, said object assembly defining a focal length relative to a reference point within said object assembly;

a first aperture stop arranged to receive radiation transferred from said object assembly, said object assembly and said first aperture stop defining a first optical axis that passes through said reference point, said first aperture stop being located at a distance from said reference point that is substantially equal to said focal length of said object assembly for focusing of a first detected portion of said radiation onto said first aperture stop;

a second aperture stop arranged to receive radiation transferred from said object assembly, said object assembly and said second aperture stop defining a second optical axis that passes through said reference point, said second aperture stop being located at a distance from said reference point that is substantially equal to said focal length of said object assembly for focusing of a second detected portion of said radiation onto said second aperture stop;

a first electromagnetic radiation detector arranged to detect said first detected portion of said radiation transferred from said object assembly through said first aperture stop; and

a second electromagnetic radiation detector arranged to detect said second detected portion of said radiation transferred from said object assembly through said second aperture stop, said first electromagnetic radiation detector and said second electromagnetic radiation detectors for generation of a first signal and a second signal, respectively, for inferring a temperature of said off-focus target.

34. The telecentric dual wavelength pyrometer of claim 33, further comprising a first reflectometer subassembly including a first radiation source for generation of a first beam of electromagnetic radiation and a first beam splitter, said first beam splitter being arranged for propagation of a portion of said first beam along said first optical axis for irradiation of said respective one of said corresponding plurality of adjacent off-focus targets.

35. The telecentric dual wavelength pyrometer of claim 34, further comprising a second reflectometer subassembly including a second radiation source for generation of a second beam of electromagnetic radiation and a second beam splitter, said second beam splitter being arranged for propagation of a portion of said second beam along said second optical axis for irradiation of said respective one of said corresponding plurality of adjacent off-focus targets.

36. The telecentric dual wavelength pyrometer of any one of claims 33-35, wherein said first detected portion of radiation is in the infrared spectrum of electromagnetic radiation and said second detected portion of radiation is in the visible spectrum of electromagnetic radiation.

37. The telecentric dual wavelength pyrometer of any one of claims 33-36, wherein said second detected portion of radiation defines a wavelength band pass that is centered at a wavelength that is greater than or equal to 400 nm and less than or equal to 410 nm, and said first detected portion of radiation defines a wavelength band pass that includes the 930 nm wavelength.

38. The telecentric dual wavelength pyrometer of any one of claims 33-37, further comprising a reduced aperture assembly arranged for selectively reducing one of said first detected portion of said radiation that is detected by said first electromagnetic radiation detector and said second detected portion of said radiation that is detected by said second electromagnetic radiation detector.

39. A system for limiting stray radiation received by a radiation thermometer, comprising:

a chemical vapor deposition (CVD) chamber;

a wafer carrier configured for rotation about a rotation axis and including a top surface, a bottom surface and an outer edge, said top surface being substantially planar and defining a target plane;

a plurality of heating elements disposed beneath said wafer carrier, said plurality of heating elements arranged to irradiate said bottom surface of said wafer carrier, said plurality of heating elements including a peripheral heating element proximate said outer edge of said wafer carrier, said peripheral heating element including a low heat flux portion along a designated portion of said peripheral heating element, said low heat flux portion operating at a substantially reduced temperature relative to other portions of said peripheral heating element; and

a radiation thermometer arranged for viewing a target that is proximate an axis of reduced scattered radiation, said axis of reduced scattered radiation being coplanar with said target plane and extending from said rotation axis and over said low heat flux portion of said heating element.

40. The system of claim 39, wherein said radiation thermometer is arranged to view a target that is within a rectangular region on said wafer plane that includes a portion of said axis of reduced scattered radiation, said rectangular region extending from said spindle to an outer edge of said

wafer carrier, said rectangular region having a width that is approximately the same width as the tangential dimension of said designated portion of said peripheral heating element.

41. The system of claim 39 or claim 40, wherein said low heat flux portion of said peripheral heating element includes an electrical connector.

42. The system of claim 39, 40 or 41, further comprising a cylinder disposed within said CVD chamber, said cylinder defining a cylinder axis that is substantially concentric with said rotation axis, said cylinder having an interior surface and an exterior surface, said interior surface defining an inner cylinder diameter, said exterior surface defining an outer cylinder diameter, said cylinder having a top edge defining an upper plane that is substantially normal to said cylinder axis.

43. The system of claim 42, wherein said wafer carrier defines a carrier outer diameter that is greater than said inner cylinder diameter of said cylinder.

44. The system of any one of claims 39-43, wherein said peripheral heating element substantially surrounds the other of said plurality of heating elements.

45. The system of any one of claims 39-44, wherien said radiation thermometer is configured to detect radiation in the visible/UV portion of the electromagnetic spectrum.

46. The system of any one of claims 39-45, further comprising a spindle disposed within said CVD chamber, said spindle being concentric with said rotation axis and having a distal portion adapted for coupling with said wafer carrier.

47. The system of any one of claims 39-46, wherein said low heat flux portion configured to operate at a temperature that is at least 300 °C less than any other portion of said heating element when operating at a maximum operating temperature.

48. A method for limiting stray radiation received by a radiation thermometer viewing a target in a chemical vapor deposition chamber, the method comprising:

providing a wafer carrier and a heater array configured for operation within said chemical vapor deposition chamber, said wafer carrier being configured for rotation about a rotation axis and having a lower surface and a substantially planar upper surface, said upper surface defining a target plane, said heater array including a peripheral heating element that includes a low heat flux portion along a designated portion of said peripheral heating element;

providing instructions on a tangible medium, said instructions comprising:

disposing said heater array within said chemical vapor deposition chamber;

disposing said wafer carrier within said chemical vapor deposition chamber above said heater array and with said upper surface facing upward;

aligning a radiation thermometer to view a target proximate an axis of reduced scattered radiation, said axis of reduced scattered radiation being coplanar with said target plane and extending from said rotation axis and over said low heat flux portion of said heating element.

49. The method of claim 48, wherein said target aligned in the step of aligning is within a rectangular region on said target plane that includes a portion of said axis of reduced scattered radiation, said rectangular region extending from said rotation axis to an outer edge of said wafer

carrier, said rectangular region having a width that is approximately the same width as the tangential dimension of said designated portion of said peripheral heating element.

50. The method of claim 48 or claim 49, wherein said target aligned in the step of aligning includes a portion of said axis.

51. A system for limiting stray radiation received by a radiation thermometer, comprising:

a chemical vapor deposition (CVD) chamber;

a cylinder disposed within said CVD chamber, said cylinder defining a cylinder axis and having an interior surface and an exterior surface, said interior surface defining an inner cylinder diameter, said exterior surface defining an outer cylinder diameter and, said cylinder having a top edge defining an upper plane that is substantially normal to said cylinder axis;

a peripheral heating element disposed within said cylinder and proximate said interior surface of said cylinder;

a spindle disposed within said cylinder and extending through peripheral heating element, said spindle having a distal portion that extends above said upper plane of said cylinder;

a wafer carrier having a top surface that is substantially planar and defining a target plane, said wafer carrier being configured for connection to said distal portion of said spindle for suspension above said peripheral heating element;

means for reducing scattered radiation that is emitted from a designated portion of said peripheral heating element, said means for reducing scattered radiation being located proximate said peripheral heating element; and

a radiation thermometer arranged to view a target on said target plane that is proximate an axis of reduced scattered radiation, said axis of reduced scattered radiation being coplanar with said target plane and having an origin at said rotation axis extending in a direction of said means for reducing scattered radiation.

52. The system of claim 51, wherein said target is within a rectangular region on said wafer plane that includes a portion of said axis of reduced scattered radiation, said rectangular region extending from said spindle to an outer edge of said wafer carrier, said rectangular region having a width that is approximately the same width as the tangential dimension of said means for reducing scattered radiation.

53. The system of claim 51 or claim 52, wherein said means for reducing scattered radiation comprises an electrical connector of said peripheral heating element.

54. The system of claim 51, 52 or 53, wherein said means for reducing scattered radiation includes one of a radiation trap and a radiation deflector located proximate said designated portion of said peripheral heating element.

55. A system for limiting stray radiation received by a radiation thermometer, comprising:

a chemical vapor deposition (CVD) chamber;

a wafer carrier configured for rotation about a rotation axis, said wafer carrier having a top surface, a bottom surface and a peripheral edge, said top surface defining a target plane substantially orthogonal to said rotation axis;

a heating element disposed adjacent said bottom surface of said wafer carrier, said heating element being proximate said peripheral edge of said wafer carrier, said heating element including a low heat flux portion configured to operate at a temperature that is at least 300 °C less than any other portion of said heating element when operating at a maximum operating temperature; and

a view port for a radiation thermometer, said viewport arranged for viewing a target that is proximate an axis of reduced scattered radiation, said axis of reduced scattered radiation being coplanar with said target plane and extending from said rotation axis and over said low heat flux portion of said heating element.

56. The system of claim 55, further comprising a radiation thermometer arranged to view a target through said view port, said target being proximate said axis of reduced scattered radiation.

57. The system of claim 56, wherein said radiation thermometer is configured to detect radiation in the visible/UV portion of the electromagnetic spectrum.

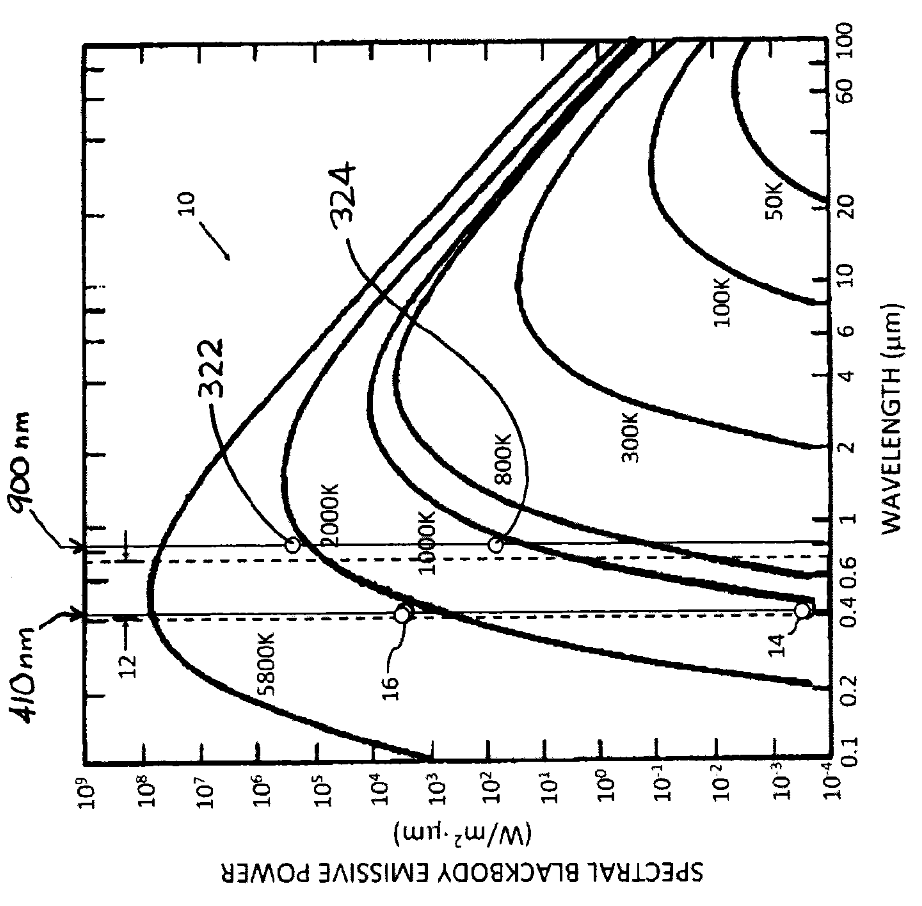
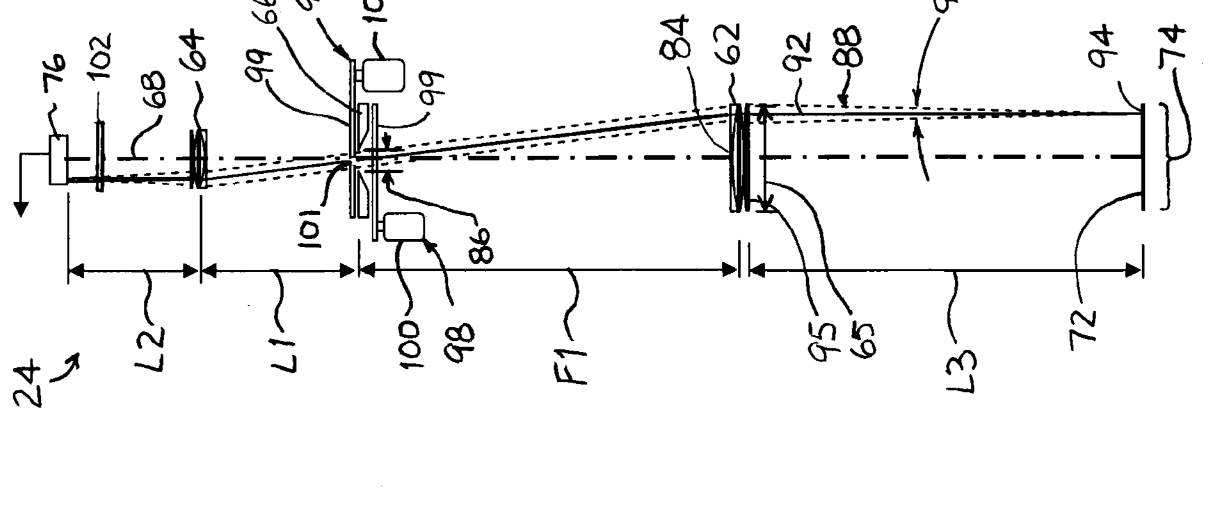

SPECTRAL BLACKBODY EMISSIVE POWER
(W/m²·μm)
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
WAVELENGTH (μm)
0.1
0.2
0.4
0.6
1
2
4
6
10
20
60
100
410nm
900nm
12
10
322
324
5800K
2000K
1000K
800K
300K
100K
50K
16
14

FIG. 1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68
64
99
66
97
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101
86
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62
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94
74
95
65
72
L2
L1
F1
L3

FIG. 4

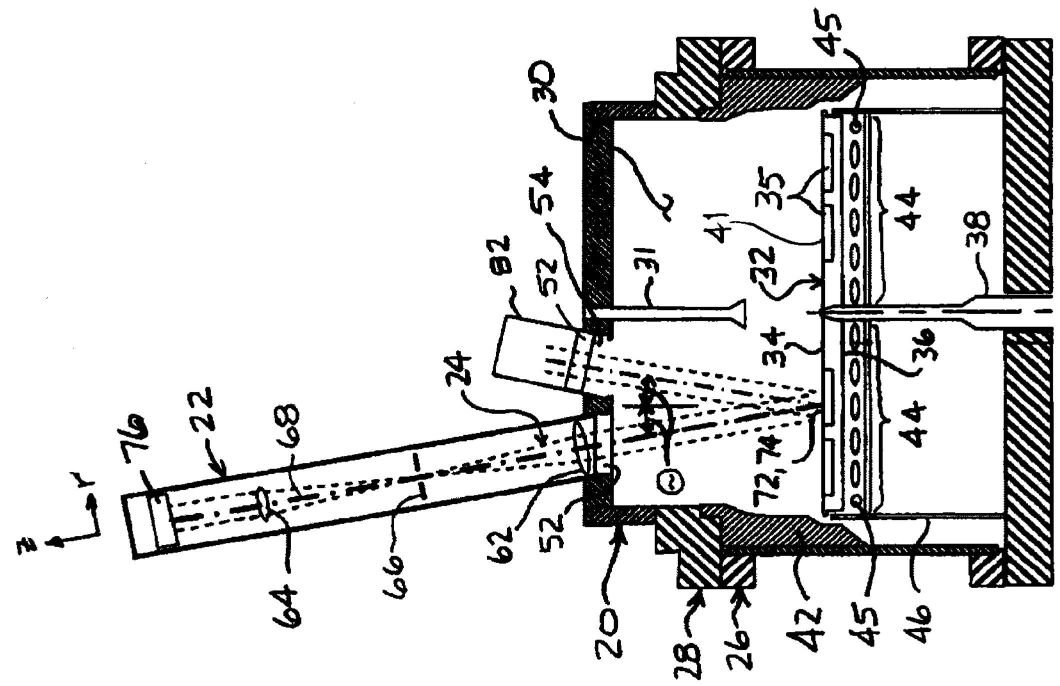
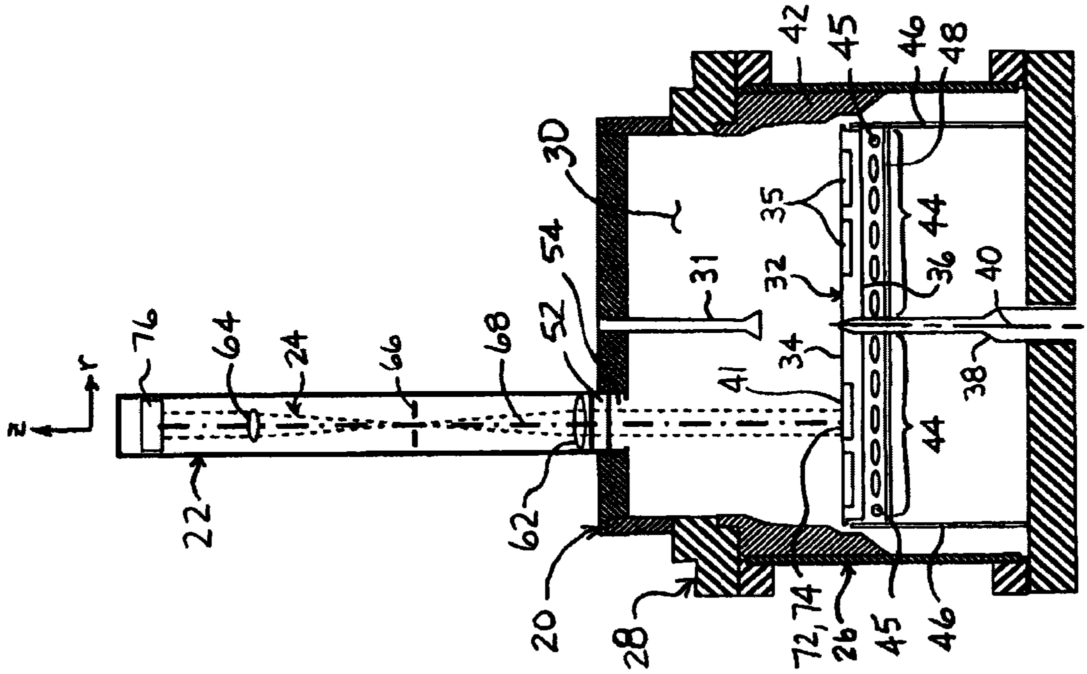

z
r
76
22
68
64
66
24
62
52
82
52
54
30
31
32
41
35
34
36
44
44
38
40
45
72, 74
θ
20
28
26
42
45
46

FIG. 3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r
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62
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28
72, 74
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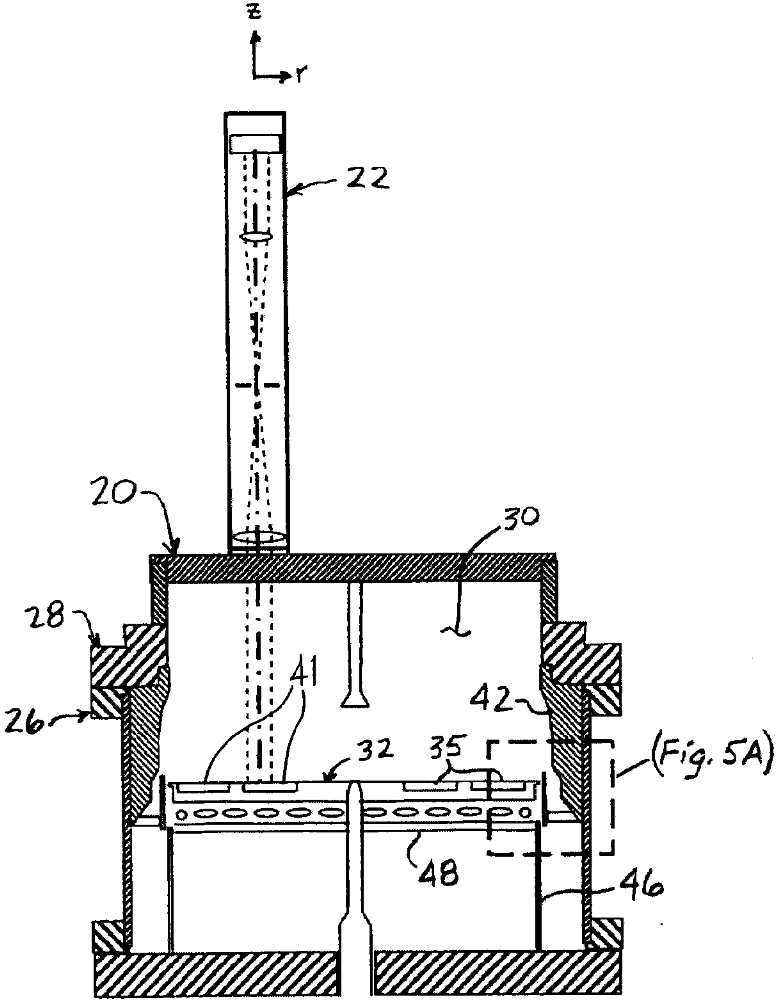
42
45
46
48

FIG. 2


z
r
22
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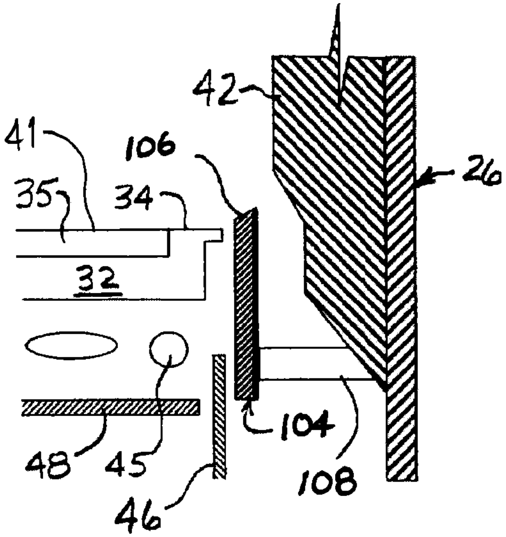
30
28
26
41
42
32
35
(Fig. 5A)
48
46

FIG. 5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106
35
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32
104
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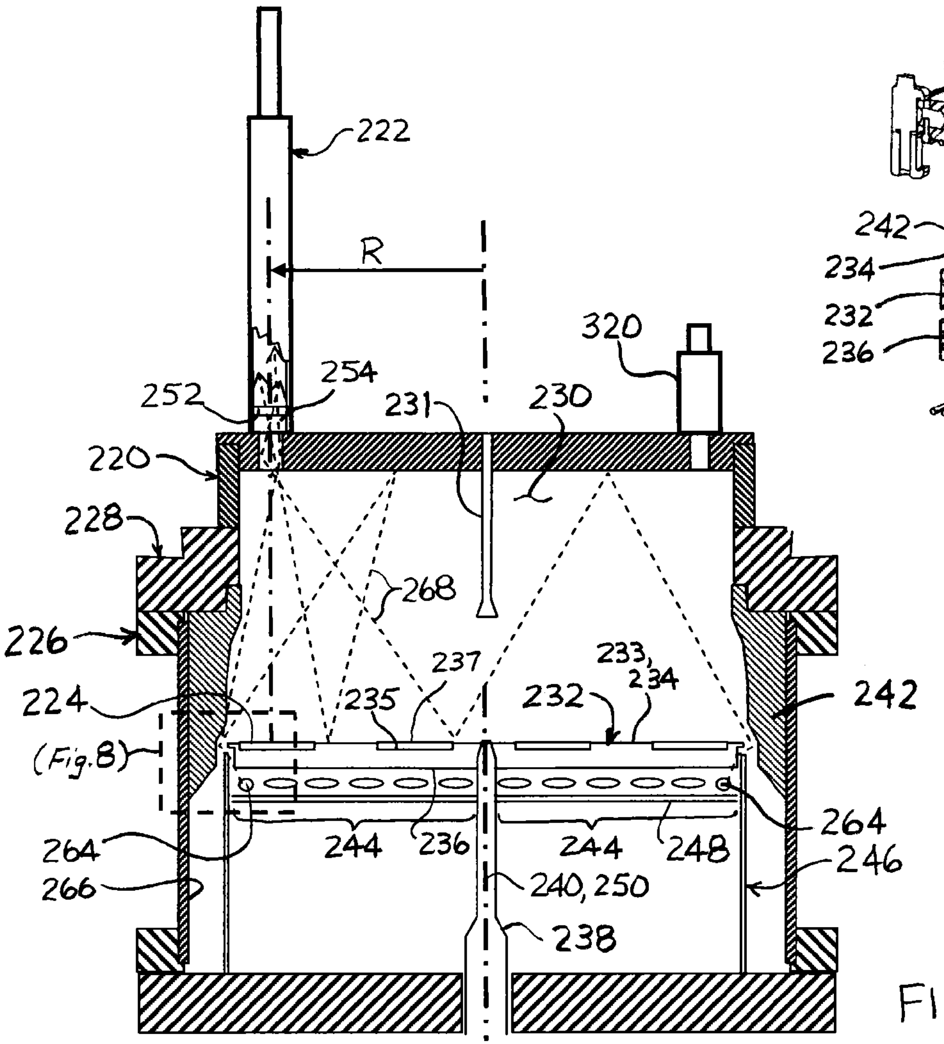
45
108
46

FIG. 5A


222
R
320
252
254
231
230
220
228
268
226
237
233, 234
235
232
242
224
(Fig. 8)
264
244
236
244
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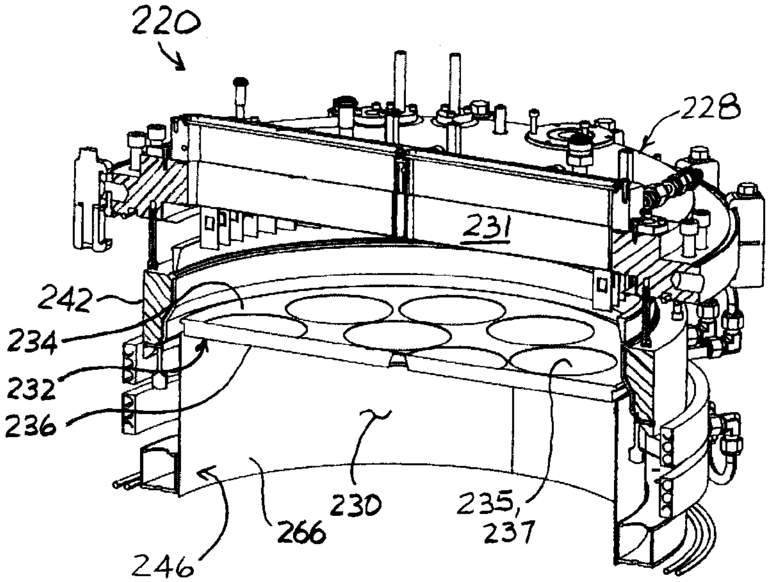
264
246
266
240, 250
238

FIG. 7A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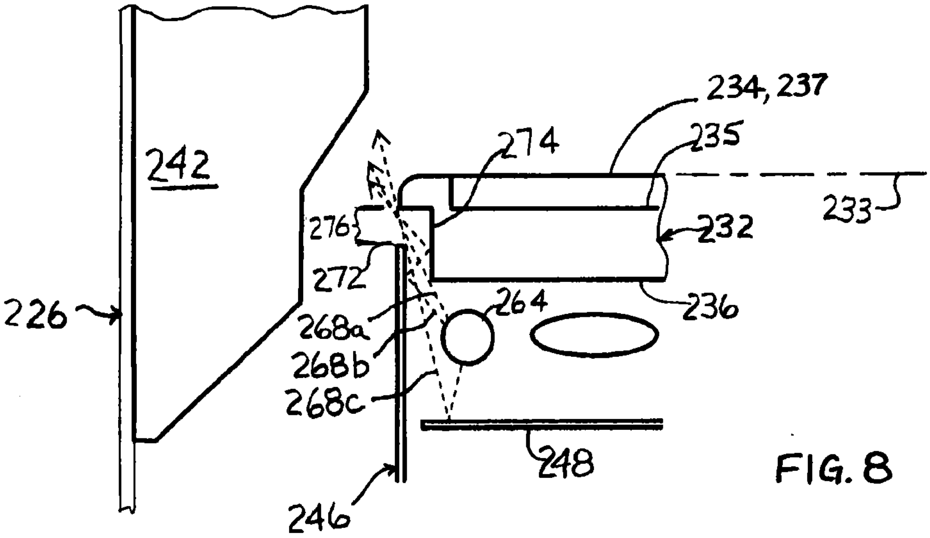
232
236
230
235, 237
266
246

FIG. 7B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274
235
242
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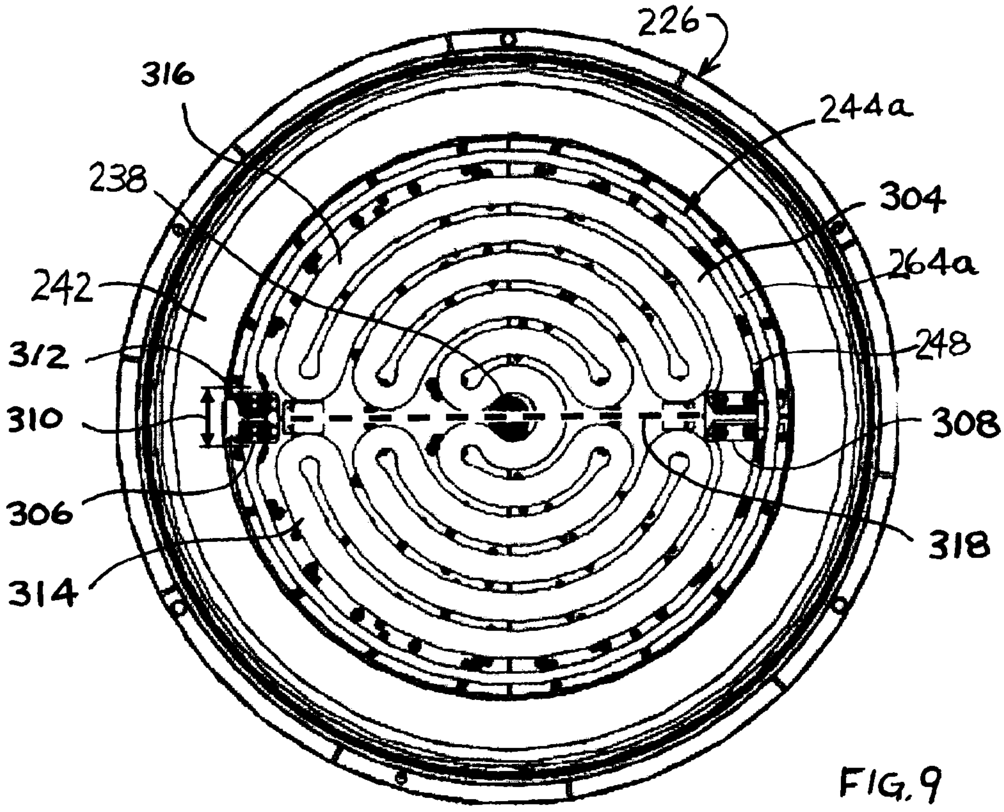
276
232
272
236
264
268a
226
268b
268c
248
246

FIG. 8


226
316
244a
238
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264a
242
248
312
310
308
306
318
314

FIG. 9

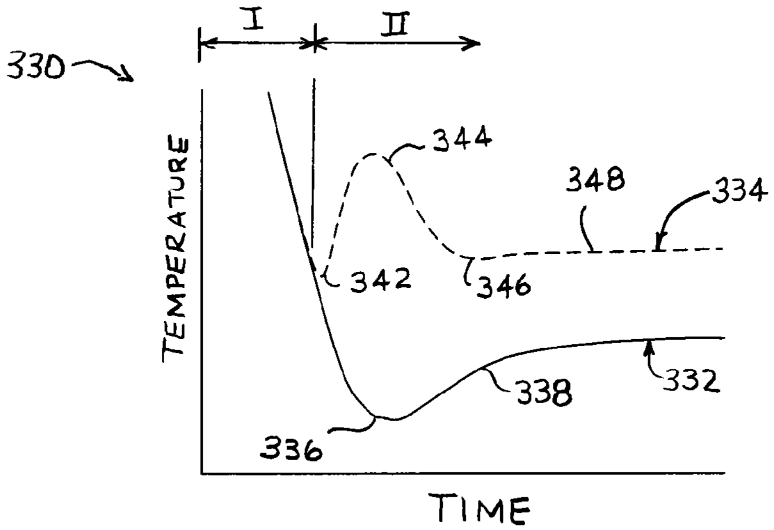
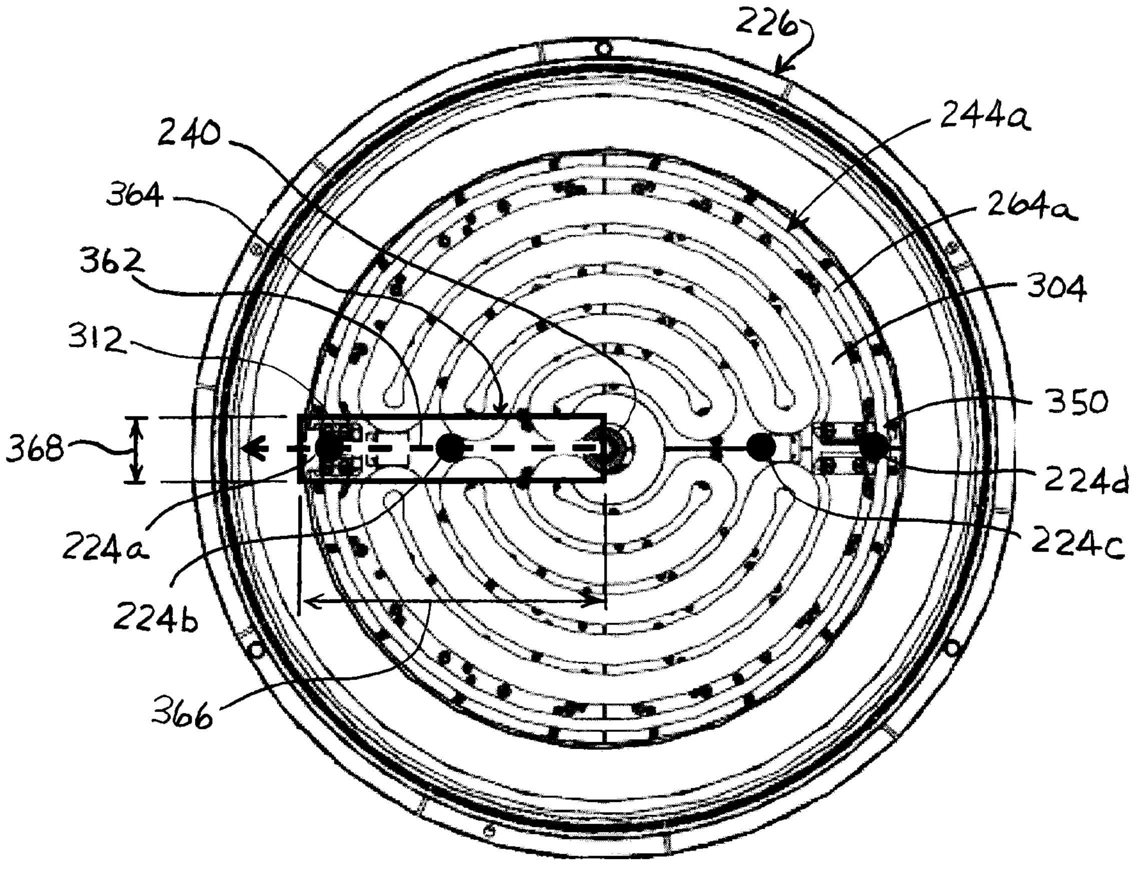

330
I
II
TEMPERATURE
TIME
344
348
334
342
346
338
332
336

FIG. 10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244a
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264a
364
304
362
312
350
368
224d
224a
224c
224b
366

FIG. 11

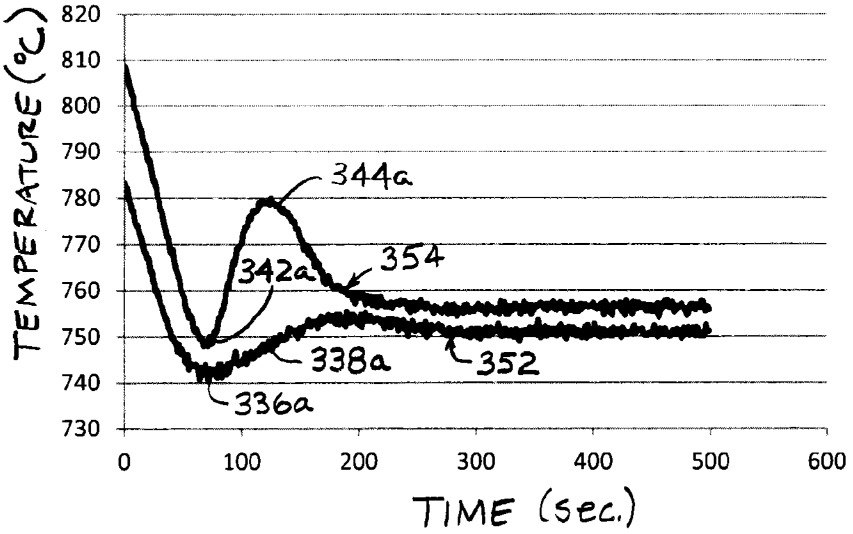


FIG. 12A

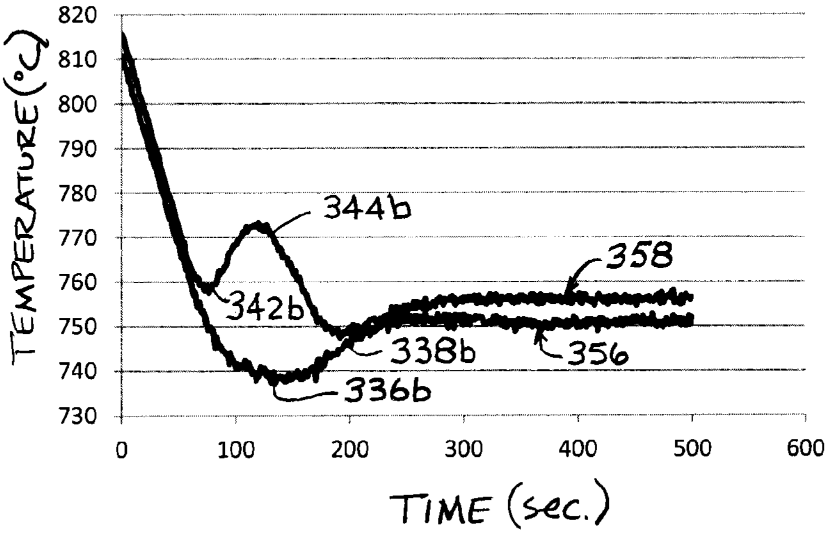


FIG. 12B

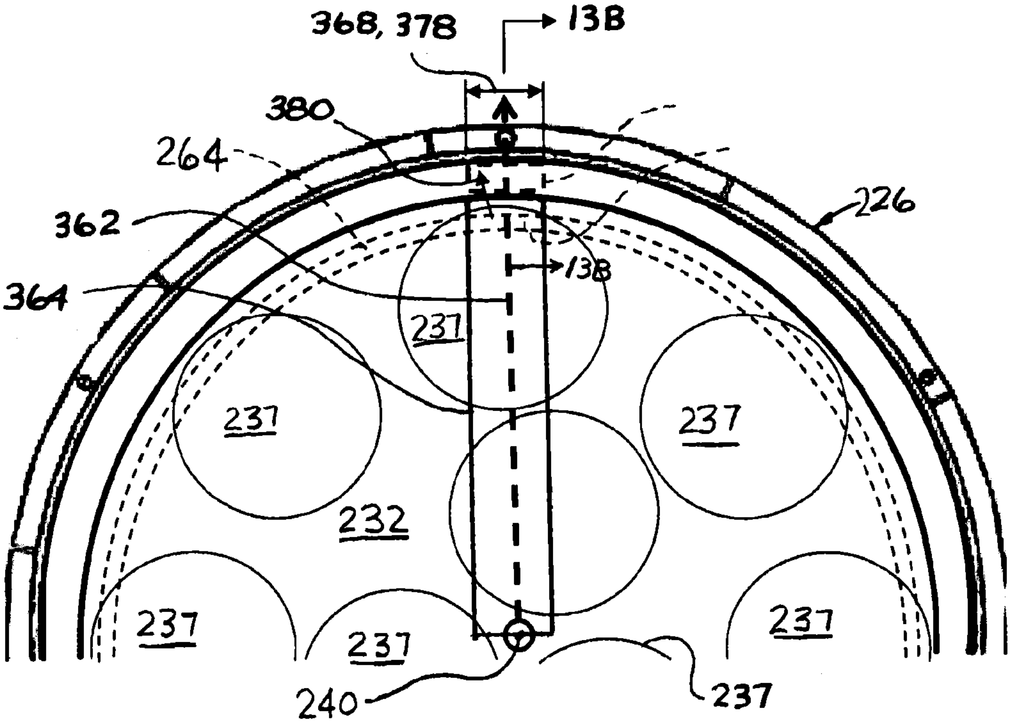


FIG. 13A

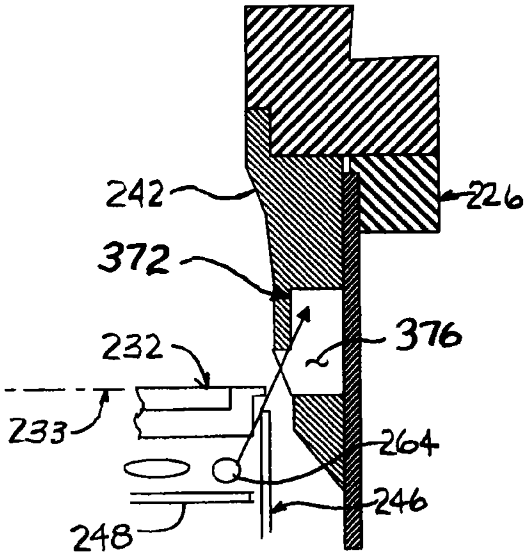


FIG. 13B

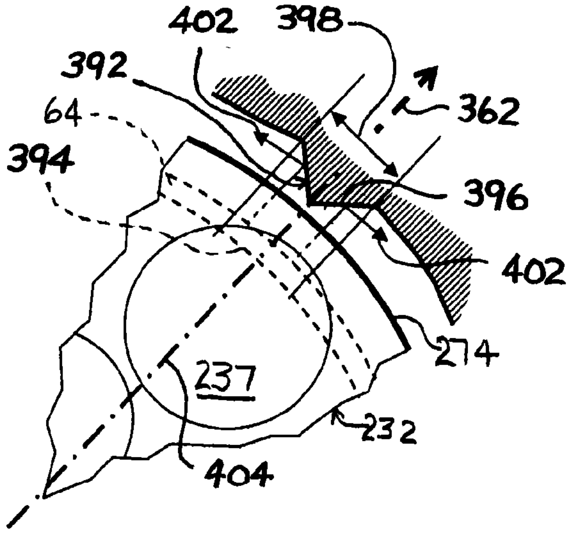
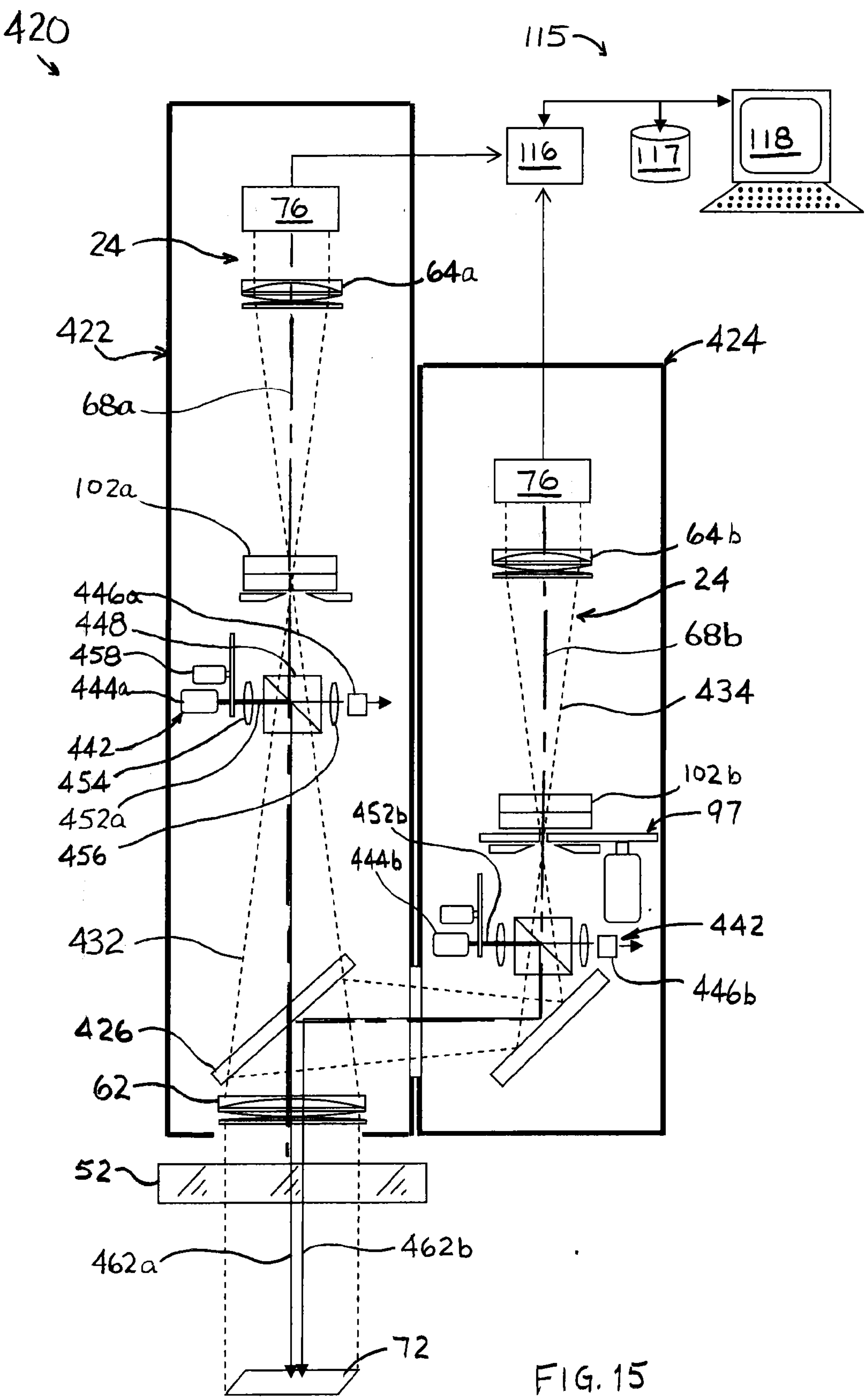


FIG. 14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68a
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102a
64b
24
446a
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444a
434
442
454
102b
452a
97
456
452b
444b
442
432
446b
426
62
52
462a
462b
72

FIG. 15

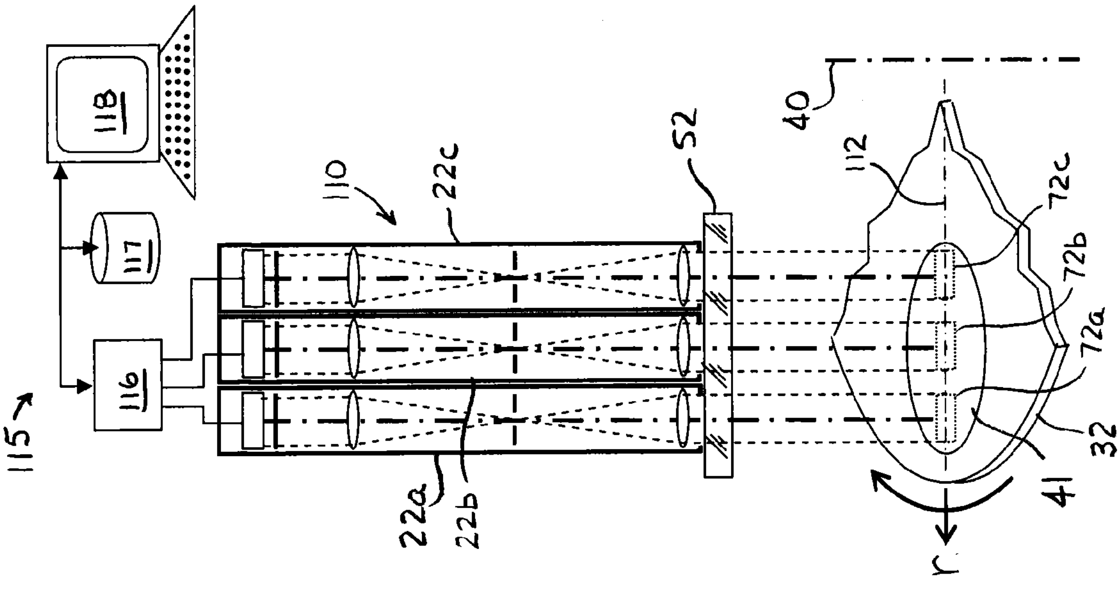

FIG.6A

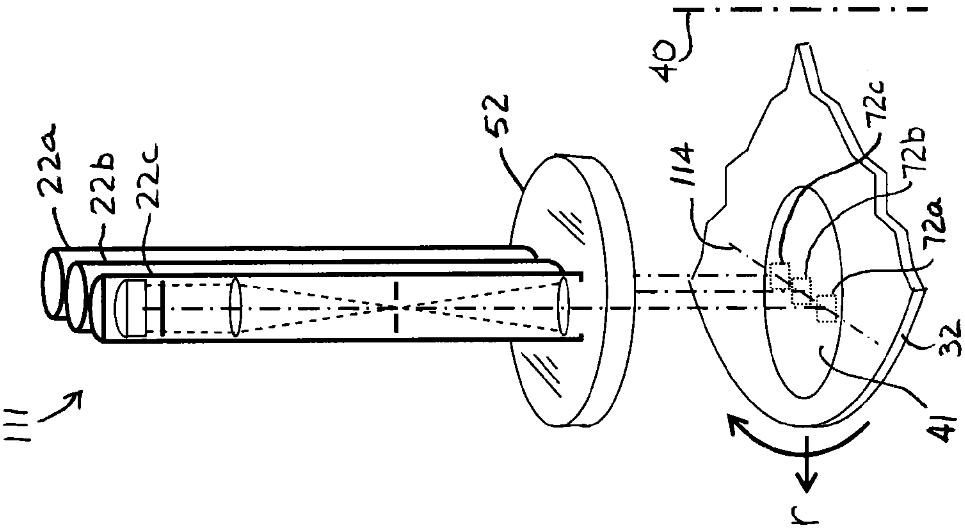

FIG.6B

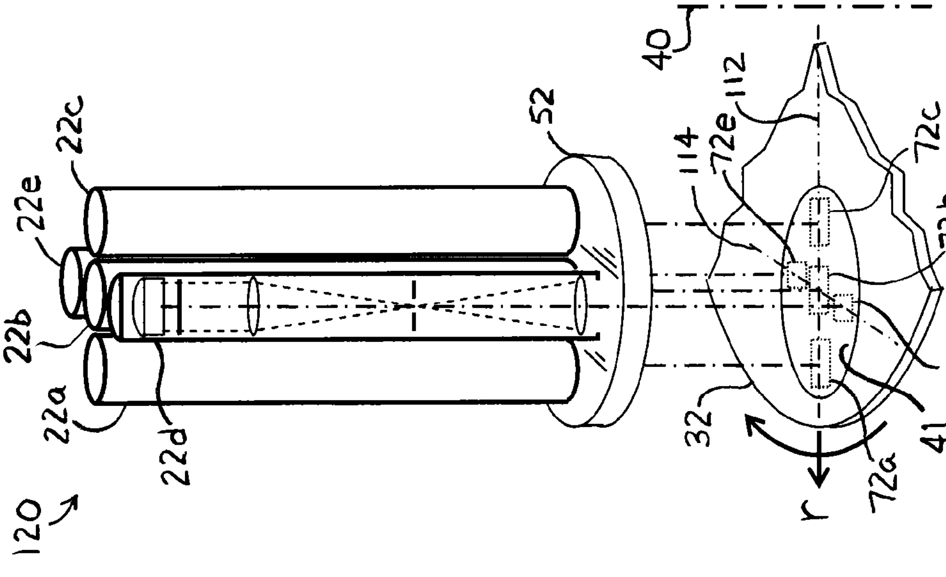

FIG. 6C

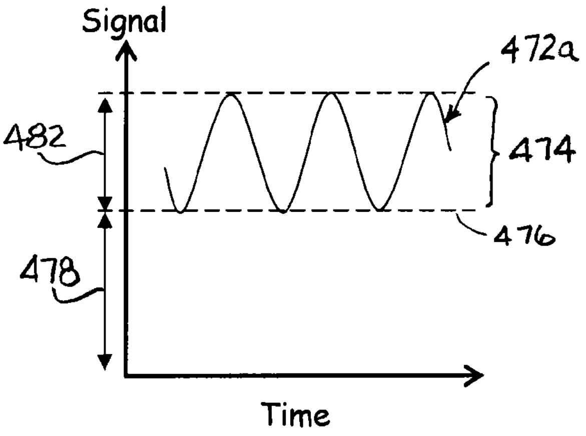

FIG. 16A

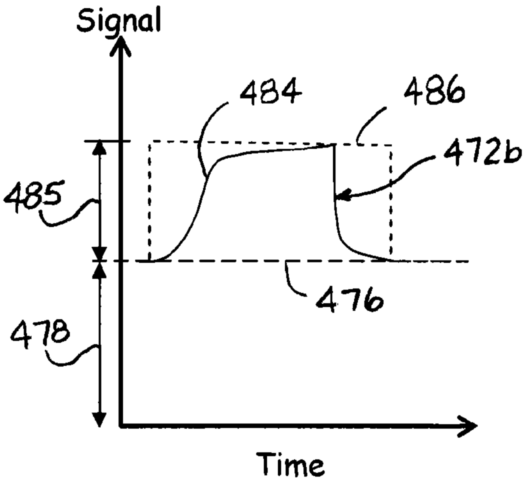

FIG. 16B

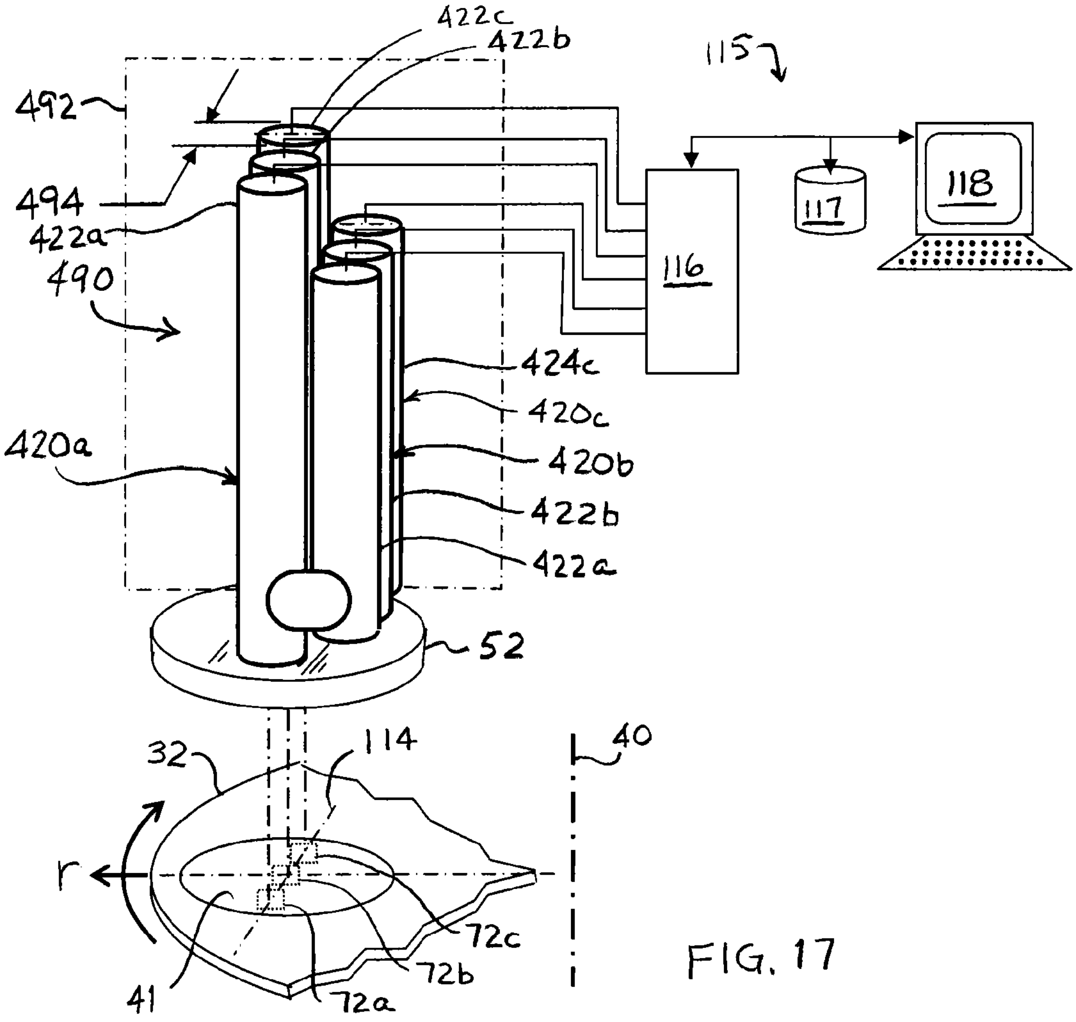

FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/047024

A. CLASSIFICATION OF SUBJECT MATTER

C23C 16/44(2006.01)i, C23C 16/50(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C23C 16/44; G01J 5/00; G01K 15/00; G01J 5/02; G01J 5/06; H05B 1/02; C23C 16/50

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: radiation thermometer, pyrometer, optical, aperture stop, collimate, detector, stray radiation, bias, lens, off-focus, and CVD

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2008-0198895 A1 (DAVIS et al.) 21 August 2008 See paragraphs [0037],[0039]; claims 1,5,6 and figure 6.	1-4,11-13,16-23,33-36,39-41,48-53,55-57
A	US 5209570 A (NEUHAUS, DIETMAR) 11 May 1993 See column 5, lines 8-58; claim 5 and figure 1.	1-4,11-13,16-23,33-36,39-41,48-53,55-57
A	US 2007-0291816 A1 (VOLF et al.) 20 December 2007 See paragraphs [0025],[0027],[0028],[0032]; claim 1 and figrue 1.	1-4,11-13,16-23,33-36,39-41,48-53,55-57
A	US 6310347 B1 (SHU et al.) 30 October 2001 See column 3, lines 21-64; claim 1 and figure 1.	1-4,11-13,16-23,33-36,39-41,48-53,55-57
A	US 6492625 B1 (BOGUSLAVSKIY et al.) 10 December 2002 See column 4, line 44 - column 5, line 27; claim 1 and figures 3-4.	1-4,11-13,16-23,33-36,39-41,48-53,55-57

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
24 September 2013 (24.09.2013)

Date of mailing of the international search report
25 September 2013 (25.09.2013)

Name and mailing address of the ISA/KR
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701, Republic of Korea
Facsimile No. +82-42-472-7140

Authorized officer
LEE Chang Ho
Telephone No. +82-42-481-8435

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/047024

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 7,8,26,27,31,32,43
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claims 7,8,26,27,31,32,43 are unclear, because they refer to multiple dependent claims which do not comply with PCT Rule 6.4(a).

3. ☒ Claims Nos.: 5,6,9,10,14,15,24,25,28-30,37,38,42,44-47,54
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Group I, claims 1-4,11-13,17-23,33-36, drawn to a telecentric optical arrangement, a method of reducing straty radiation bias, a pyrometer system, and a telecentric dual wavelength pyrometer.
Group II, claim 16, drawn to a system for measuring a temperature of a target in a chemical vapor deposition chamber.
Group III, claims 39-41,48-53,55-57, drawn to systems for limiting stray radiation and a method for limiting stray radiation.

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☒ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
☐ No protest accompanied the payment of additional search fees.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2008-0198895 A1	21/08/2008	CN 101542254 A	23/09/2009
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