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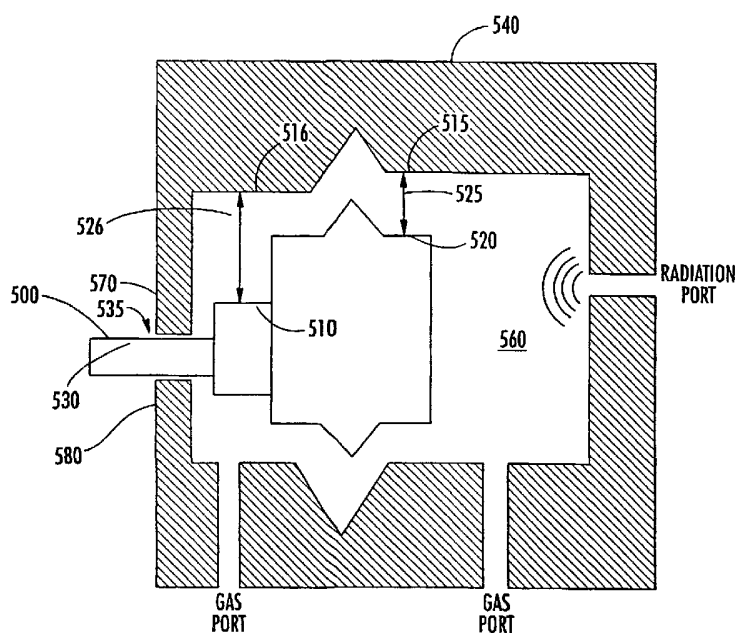
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(54) Title: CAVITY SHAPES FOR PLASMA-ASSISTED PROCESSING



(57) Abstract: Methods and apparatus for selectively processing objects with a plasma formed in a cavity with electromagnetic radiation. In one embodiment, a method can be provided that includes placing the object in the cavity such that a first gap is formed, having a thickness less than about $\lambda/4$, between a first surface region of the object and the inner surface of the cavity, and a second gap is formed, having a thickness at least about $\lambda/4$, between a second surface region and the inner surface, introducing gas into the cavity; and irradiating the cavity with the radiation to form a plasma in the second gap but not in the first gap.



For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

CAVITY SHAPES FOR PLASMA-ASSISTED PROCESSING

CROSS-REFERENCE OF RELATED APPLICATIONS

[001] Priority is claimed to U.S. Provisional Patent Application No. 60/378,693, filed May 8, 2002, No. 60/430,677, filed December 4, 2002, and No. 60/435,278, filed December 23, 2002, all of which are fully incorporated herein by reference.

FIELD OF THE INVENTION

[002] This invention relates to methods and apparatus for plasma-processing one or more objects and particularly to processing one or more portions of such objects in various types of cavities.

BACKGROUND

[003] It is known that a plasma can be ignited by subjecting a gas to a sufficient amount of electromagnetic radiation. In addition, radiation-induced plasmas may be used to process objects.

[004] A plasma-processing cavity may be used to confine a plasma to more efficiently process parts. Use of conventional plasma-processing cavities, however, can limit manufacturing flexibility.

BRIEF SUMMARY OF A FEW ASPECTS OF THE INVENTION

[005] Methods and apparatus for plasma-assisted processing of one or more parts in cavities are provided.

[006] In one embodiment consistent with this invention, a method is provided for selectively processing at least one object using a plasma induced by radiation having a wavelength of λ . The method can include placing the object in a cavity having at least one inner surface, arranging the object so that a location on

the object intended for reduced heating is spaced from the inner surface by a distance of less than about $\lambda/4$, introducing gas into the cavity, and irradiating the cavity with radiation to form a plasma in the cavity in an area other than the location on the object intended for reduced heating.

[007] In another embodiment consistent with this invention, an apparatus is provided for processing at least one object using plasma. The apparatus can include a source for generating radiation having a wavelength of λ , a vessel in which a cavity is formed, the cavity being arranged to be irradiated by the source, the cavity having at least one inner surface and being shaped to hold the object in a manner such that a portion of the object is spaced from the inner surface by a distance of less than about $\lambda/4$, and a portion of the object is spaced from another portion of the inner surface by a distance of at least about $\lambda/4$. The apparatus can also include a conduit for introducing gas into the cavity, such that in the presence of radiation, at least a portion of the gas becomes a plasma and the plasma is formed in regions other than those where the spacing between the inner surface of the cavity and the object is less than about $\lambda/4$.

[008] A plasma catalyst for initiating, modulating, and sustaining a plasma is also provided. The catalyst can be passive or active. A passive plasma catalyst can include any object capable of inducing a plasma by deforming a local electric field (including an electromagnetic field) consistent with this invention, without necessarily adding additional energy. An active plasma catalyst, on the other hand, is any particle or high energy wave packet capable of transferring a sufficient amount of energy to a gaseous atom or molecule to remove at least one electron from the gaseous atom or molecule in the presence of electromagnetic radiation. In both cases, a plasma catalyst can improve, or relax, the environmental conditions required to ignite a plasma.

[009] In another embodiment, a method can be provided that includes placing the object in the cavity such that a first gap is formed, having a thickness less than about $\lambda/4$, between a first surface region of the object and the inner surface of the cavity, and a second gap is formed, having a thickness at least about $\lambda/4$, between a second surface region and the inner surface, introducing gas

into the cavity; and irradiating the cavity with the radiation to form a plasma in the second gap but not in the first gap.

[010] Additional plasma catalysts, and methods and apparatus for igniting, modulating, and sustaining a plasma consistent with this invention are provided. Additional cavity shapes, and methods and apparatus for selectively plasma-processing in general, are also provided.

BRIEF DESCRIPTION OF THE DRAWINGS

[011] Further aspects of the invention will be apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts throughout, and in which:

[012] FIG. 1 shows a schematic diagram of an illustrative plasma system consistent with this invention;

[013] FIG. 2 shows an illustrative embodiment of a portion of a plasma system for adding a powder plasma catalyst to a plasma cavity for igniting, modulating, or sustaining a plasma in a cavity consistent with this invention;

[014] FIG. 3 shows an illustrative plasma catalyst fiber with at least one component having a concentration gradient along its length consistent with this invention;

[015] FIG. 4 shows an illustrative plasma catalyst fiber with multiple components at a ratio that varies along its length consistent with this invention;

[016] FIG. 5 shows another illustrative plasma catalyst fiber that includes a core under layer and a coating consistent with this invention;

[017] FIG. 6 shows a cross-sectional view of the plasma catalyst fiber of FIG. 6, taken from line 5--5 of FIG. 5, consistent with this invention;

[018] FIG. 7 shows a side cross-sectional view of an illustrative embodiment of another portion of a plasma system including an elongated plasma catalyst that extends through ignition port consistent with this invention;

[019] FIG. 8 shows an illustrative embodiment of an elongated plasma catalyst that can be used in the system of FIG. 7 consistent with this invention;

[020] FIG. 9 shows another illustrative embodiment of an elongated plasma catalyst that can be used in the system of FIG. 7 consistent with this invention; and

[021] FIG. 10 shows a side cross-sectional view of an illustrative embodiment of a portion of a plasma system for directing ionizing radiation into a radiation chamber consistent with this invention.

[022] FIG. 11 shows a side cross-sectional view of an illustrative embodiment of a cavity and an object partially inserted into the cavity consistent with this invention;

[023] FIG. 12 shows a side cross-sectional view of an illustrative embodiment of a cavity that covers only a portion of an object where the object itself partially seals the cavity consistent with this invention; and

[024] FIG. 13 shows a side cross-sectional view of an illustrative embodiment of a plasma cavity that also serves as a radiation chamber consistent with this invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[025] This invention may relate to cavity shapes for plasma-assisted processing one or more objects using plasma for a variety of applications, including, for example, heat-treating, synthesizing and depositing carbides, nitrides, borides, oxides, and other materials, doping, carburizing, nitriding, and carbo-nitriding, sintering, multi-part processing, joining, sintering, decrystallizing, making and operating furnaces, gas exhaust-treating, waste-treating, incinerating, scrubbing, ashing, growing carbon structures, generating hydrogen and other gases, forming electrodeless plasma jets, plasma processing in assembly lines, sterilizing, etc. In particular, various cavity shapes, and methods for their use, including controllably initiating, modulating, and sustaining a plasma are provided.

[026] Metals and other types of electrical conductors are, generally, good reflectors of electromagnetic radiation. At normal incidence, the boundary conditions require that the electric field at the surface of the conductor be zero and the first maxima be formed at a quarter wavelength from the surface. Thus, little or no plasma will be formed in the gap formed between the surface of the object and

the inner wall of the cavity if the thickness of the gap is much smaller than a quarter wavelength of the radiation. Thus, the thickness of the plasma layer adjacent the surface of the object can be used to control the heating and the plasma processing rate at the surface.

[027] In the case of nonconductors, the thickness of the plasma layer at the surface can also be used to control the heating and processing rates because a thinner plasma layer will have a reduced ability to absorb radiation, and at least for this reason, the layer is less capable of heating and performing other plasma-dependent processes.

[028] The following commonly owned, concurrently filed U.S. patent applications are hereby incorporated by reference in their entireties: U.S. Patent Application No. 10/____,____ (Atty. Docket No. 1837.0008), No. 10/____,____ (Atty. Docket No. 1837.0009), No. 10/____,____ (Atty. Docket No. 1837.0010), No. 10/____,____ (Atty. Docket No. 1837.0011), No. 10/____,____ (Atty. Docket No. 1837.0012), No. 10/____,____ (Atty. Docket No. 1837.0013), No. 10/____,____ (Atty. Docket No. 1837.0015), No. 10/____,____ (Atty. Docket No. 1837.0016), No. 10/____,____ (Atty. Docket No. 1837.0017), No. 10/____,____ (Atty. Docket No. 1837.0018), No. 10/____,____ (Atty. Docket No. 1837.0020), No. 10/____,____ (Atty. Docket No. 1837.0021), No. 10/____,____ (Atty. Docket No. 1837.0023), No. 10/____,____ (Atty. Docket No. 1837.0024), No. 10/____,____ (Atty. Docket No. 1837.0025), No. 10/____,____ (Atty. Docket No. 1837.0026), No. 10/____,____ (Atty. Docket No. 1837.0027), No. 10/____,____ (Atty. Docket No. 1837.0029), No. 10/____,____ (Atty. Docket No. 1837.0030), No. 10/____,____ (Atty. Docket No. 1837.0032), and No. 10/____,____ (Atty. Docket No. 1837.0033).

[029] Illustrative Plasma System

[030] FIG. 1 shows illustrative plasma system 10 consistent with one aspect of this invention. In this embodiment consistent with this invention, plasma-processing cavity 12 is formed in vessel 13 that is positioned inside radiation chamber (i.e., applicator) 14. In another embodiment, shown in FIG. 2, vessel 13 and radiation chamber 14 are the same, thereby eliminating the need for two separate components. Vessel 13 in which cavity 12 is formed can include one or more radiation-transmissive insulating layers to improve thermal insulation

properties without significantly shielding cavity 12 from the radiation used to form a plasma. It will be appreciated that more than one cavity can be formed in vessel 13. In one embodiment, multiple cavities can be formed in vessel 13 and those cavities are in fluid communication with one another. As described more fully below, plasma-processing cavity 12 consistent with this invention can selectively generate plasma and prevent plasma formation inside the cavity

[031] As used herein, a plasma-processing cavity is any localized volume capable of igniting, modulating, and/or sustaining a plasma. Thus, it will be appreciated that a cavity consistent with this invention need not be completely closed, and may indeed be open. It is known that a plasma can be ignited by subjecting a gas to a sufficient amount of radiation. The plasma may then be modulated or sustained by direct absorption of the radiation, but may be assisted by a plasma catalyst during processing.

[032] In one embodiment, cavity 12 is formed in a vessel made of ceramic. Due to the extremely high temperatures that can be achieved with plasmas consistent with this invention, a ceramic capable of operating at about 3,000 degrees Fahrenheit can be used. The ceramic material can include, by weight, 29.8% silica, 68.2% alumina, 0.4% ferric oxide, 1% titania, 0.1% lime, 0.1% magnesia, 0.4% alkalies, which is sold under Model No. LW-30 by New Castle Refractories Company, of New Castle, Pennsylvania. It will be appreciated by those of ordinary skill in the art, however, that other materials, such as quartz, and those different from the one described above, can also be used consistent with the invention.

[033] In one successful experiment, a plasma was formed in a partially open cavity inside a first brick and topped with a second brick. The cavity had dimensions of about 2 inches by about 2 inches by about 1.5 inches. At least two holes were also provided in the brick in communication with the cavity: one for viewing the plasma and at least one hole for providing the gas. The size of the cavity can depend on the desired plasma process being performed. Also, the cavity can be at least be configured to prevent the plasma from rising/floating away from the primary processing region.

[034] As shown in FIG. 1, for example, Cavity 12 can be connected to one or more gas sources 24 (e.g., a source of argon, nitrogen, hydrogen, xenon, krypton) by line 20 and control valve 22, which may be powered by power supply 28. Line 20 may be tubing or any other device capable of delivering a gas. In one embodiment, the diameter of the tube is sufficiently small to prevent radiation leakage (e.g., between about 1/16 inch and about 1/4 inch, such as about 1/8"). Also, if desired, a vacuum pump (not shown) can be connected to the chamber to remove any fumes that may be generated during plasma processing. Although not shown in FIG. 1, chamber 14 can have a separate gas port for removing gas.

[035] A radiation leak detector (not shown) was installed near source 26 and waveguide 30 and connected to a safety interlock system to automatically turn off the radiation (e.g., microwave) power supply if a leak above a predefined safety limit, such as one specified by the FCC and/or OSHA (e.g., 5 mW/cm²), was detected.

[036] Radiation source 26, which may be powered by electrical power supply 28, directs radiation energy into chamber 14 through one or more waveguides 30. It will be appreciated by those of ordinary skill in the art that source 26 can be connected directly to chamber 14 or cavity 12, thereby eliminating waveguide 30. The radiation energy entering cavity 12 can be used to ignite a plasma within the cavity. This plasma can be substantially sustained and confined to the cavity by coupling additional radiation with the catalyst. Also, the frequency of the radiation is believed to be non-critical in many applications (see below).

[037] Radiation energy can be supplied through circulator 32 and tuner 34 (e.g., 3-stub tuner). Tuner 34 can be used to minimize the reflected power as a function of changing ignition or processing conditions, especially after the plasma has formed because radiation power, for example, will be strongly absorbed by the plasma.

[038] As explained more fully below, the location of radiation -transmissive cavity 12 in chamber 14 may not be critical if chamber 14 supports multiple modes, and especially when the modes are continually or periodically mixed. As also explained more fully below, motor 36 can be connected to mode-mixer 38 for

making the time-averaged radiation energy distribution substantially uniform throughout chamber 14. Furthermore, as shown in FIG. 1, for example, window 40 (e.g., a quartz window) can be disposed in one wall of chamber 14 adjacent to cavity 12, permitting temperature sensor 42 (e.g., an optical pyrometer) to be used to view a process inside cavity 12. In one embodiment, the optical pyrometer output can increase from zero volts as the temperature rises to within the tracking range.

[039] Sensor 42 can develop output signals as a function of the temperature or any other monitorable condition associated with a work piece (not shown) within cavity 12 and provide the signals to controller 44. Dual temperature sensing and heating, as well as automated cooling rate and gas flow controls can also be used. Controller 44 in turn can be used to control operation of power supply 28, which can have one output connected to source 26 as described above and another output connected to valve 22 to control gas flow into cavity 12. Although not shown in FIG. 1, chamber 14 can have a separate gas port for removing gas.

[040] The invention has been practiced with equal success employing microwave sources at both 915 MHz and 2.45 GHz provided by Communications and Power Industries (CPI), although radiation having any frequency less than about 333 GHz can be used. The 2.45 GHz system provided continuously variable microwave power from about 0.5 kilowatts to about 5.0 kilowatts. A 3-stub tuner allowed impedance matching for maximum power transfer and a dual directional coupler (not shown) was used to measure forward and reflected powers. Also, optical pyrometers were used for remote sensing of the sample temperature.

[041] As mentioned above, radiation having any frequency less than about 333 GHz can be used consistent with this invention. For example, frequencies, such as power line frequencies (about 50 Hz to about 60 Hz), can be used, although the pressure of the gas from which the plasma is formed may be lowered to assist with plasma ignition. Also, any radio frequency or microwave frequency can be used consistent with this invention, including frequencies greater than about 100 kHz. In most cases, the gas pressure for such relatively high frequencies need not be lowered to ignite, modulate, or sustain a plasma, thereby enabling many plasma-processes to occur at atmospheric pressures and above.

[042] The equipment was computer controlled using LabView 6i software, which provided real-time temperature monitoring and microwave power control. Noise was reduced by using shift registers to generate sliding averages of suitable number of data points. Also, the number of stored data points in the array were limited to improve speed and computational efficiency. The pyrometer measured the temperature of a sensitive area of about 1 cm^2 , which was used to calculate an average temperature. The pyrometer sensed radiant intensities at two wavelengths and fit those intensities using Planck's law to determine the temperature. It will be appreciated, however, that other devices and methods for monitoring and controlling temperature are also available and can be used consistent with this invention. Control software that can be used consistent with this invention is described, for example, in concurrently filed U.S. Patent Application No. 10/____,____ (Attorney Docket No. 01837.0033), which is hereby incorporated by reference in its entirety.

[043] Chamber 14 had several glass-covered viewing ports with radiation shields and one quartz window for pyrometer access. Several ports for connection to a vacuum pump and a gas source were also provided, although not necessarily used.

[044] System 10 also included a closed-loop deionized water cooling system (not shown) with an external heat exchanger cooled by tap water. During operation, the deionized water first cooled the magnetron, then the load-dump in the circulator (used to protect the magnetron), and finally the radiation chamber through water channels welded on the outer surface of the chamber.

[045] Plasma Catalysts

[046] A plasma catalyst consistent with this invention can include one or more different materials and may be either passive or active. A plasma catalyst can be used, among other things, to ignite, modulate, and/or sustain a plasma at a gas pressure that is less than, equal to, or greater than atmospheric pressure.

[047] One method of forming a plasma consistent with this invention can include subjecting a gas in a cavity to electromagnetic radiation having a frequency less than about 333 GHz in the presence of a passive plasma catalyst. A passive plasma catalyst consistent with this invention can include any object capable of

inducing a plasma by deforming a local electric field (e.g., an electromagnetic field) consistent with this invention, without necessarily adding additional energy through the catalyst, such as by applying an electric voltage to create a spark.

[048] A passive plasma catalyst consistent with this invention can be, for example, a nano-particle or a nano-tube. As used herein, the term "nano-particle" can include any particle having a maximum physical dimension less than about 100 nm that is at least electrically semi-conductive. Also, both single-walled and multi-walled carbon nano-tubes, doped and undoped, can be particularly effective for igniting plasmas consistent with this invention because of their exceptional electrical conductivity and elongated shape. The nano-tubes can have any convenient length and can be a powder fixed to a substrate. If fixed, the nano-tubes can be oriented randomly on the surface of the substrate or fixed to the substrate (e.g., at some predetermined orientation) while the plasma is ignited or sustained.

[049] A passive plasma catalyst can also be a powder consistent with this invention, and need not comprise nano-particles or nano-tubes. It can be formed, for example, from fibers, dust particles, flakes, sheets, etc. When in powder form, the catalyst can be suspended, at least temporarily, in a gas. By suspending the powder in the gas, the powder can be quickly dispersed throughout the cavity and more easily consumed, if desired.

[050] In one embodiment, the powder catalyst can be carried into the cavity and at least temporarily suspended with a carrier gas. The carrier gas can be the same or different from the gas that forms the plasma. Also, the powder can be added to the gas prior to being introduced to the cavity. For example, as shown in FIG. 2, radiation source 52 can supply radiation to radiation chamber 55, in which plasma cavity 60 is placed. Powder source 65 provides catalytic powder 70 into gas stream 75. In an alternative embodiment, powder 70 can be first added to cavity 60 in bulk (e.g., in a pile) and then distributed in cavity 60 in any number of ways, including flowing a gas through or over the bulk powder. In addition, the powder can be added to the gas for igniting, modulating, or sustaining a plasma by moving, conveying, drizzling, sprinkling, blowing, or otherwise, feeding the powder into or within the cavity.

[051] In one experiment, a plasma was ignited in a cavity by placing a pile of carbon fiber powder in a copper pipe that extended into the cavity. Although sufficient radiation was directed into the cavity, the copper pipe shielded the powder from the radiation and no plasma ignition took place. However, once a carrier gas began flowing through the pipe, forcing the powder out of the pipe and into the cavity, and thereby subjecting the powder to the radiation, a plasma was nearly instantaneously ignited in the cavity.

[052] A powder plasma catalyst consistent with this invention can be substantially non-combustible, thus it need not contain oxygen or burn in the presence of oxygen. Thus, as mentioned above, the catalyst can include a metal, carbon, a carbon-based alloy, a carbon-based composite, an electrically conductive polymer, a conductive silicone elastomer, a polymer nano-composite, an organic-inorganic composite, and any combination thereof.

[053] Also, powder catalysts can be substantially uniformly distributed in the plasma cavity (e.g., when suspended in a gas), and plasma ignition can be precisely controlled within the cavity consistent with this invention. Uniform ignition can be important in certain applications, including those applications requiring brief plasma exposures, such as in the form of one or more bursts. Still, a certain amount of time can be required for a powder catalyst to distribute itself throughout a cavity, especially in complicated, multi-chamber cavities. Therefore, consistent with another aspect of this invention, a powder catalyst can be introduced into the cavity through a plurality of ignition ports to more rapidly obtain a more uniform catalyst distribution therein (see below).

[054] In addition to powder, a passive plasma catalyst consistent with this invention can include, for example, one or more microscopic or macroscopic fibers, sheets, needles, threads, strands, filaments, yarns, twines, shavings, slivers, chips, woven fabrics, tape, whiskers, or any combination thereof. In these cases, the plasma catalyst can have at least one portion with one physical dimension substantially larger than another physical dimension. For example, the ratio between at least two orthogonal dimensions should be at least about 1:2, but could be greater than about 1:5, or even greater than about 1:10.

[055] Thus, a passive plasma catalyst can include at least one portion of material that is relatively thin compared to its length. A bundle of catalysts (e.g., fibers) may also be used and can include, for example, a section of graphite tape. In one experiment, a section of tape having approximately thirty thousand strands of graphite fiber, each about 2-3 microns in diameter, was successfully used. The number of fibers in and the length of a bundle are not critical to igniting, modulating, or sustaining the plasma. For example, satisfactory results have been obtained using a section of graphite tape about one-quarter inch long. One type of carbon fiber that has been successfully used consistent with this invention is sold under the trademark Magnamite®, Model No. AS4C-GP3K, by the Hexcel Corporation, of Anderson, South Carolina. Also, silicon-carbide fibers have been successfully used.

[056] A passive plasma catalyst consistent with another aspect of this invention can include one or more portions that are, for example, substantially spherical, annular, pyramidal, cubic, planar, cylindrical, rectangular or elongated.

[057] The passive plasma catalysts discussed above include at least one material that is at least electrically semi-conductive. In one embodiment, the material can be highly conductive. For example, a passive plasma catalyst consistent with this invention can include a metal, an inorganic material, carbon, a carbon-based alloy, a carbon-based composite, an electrically conductive polymer, a conductive silicone elastomer, a polymer nano-composite, an organic-inorganic composite, or any combination thereof. Some of the possible inorganic materials that can be included in the plasma catalyst include carbon, silicon carbide, molybdenum, platinum, tantalum, tungsten, carbon nitride, and aluminum, although other electrically conductive inorganic materials are believed to work just as well.

[058] In addition to one or more electrically conductive materials, a passive plasma catalyst consistent with this invention can include one or more additives (which need not be electrically conductive). As used herein, the additive can include any material that a user wishes to add to the plasma. For example, in doping semiconductors and other materials, one or more dopants can be added to the plasma through the catalyst. See, e.g., commonly owned, concurrently filed U.S. Patent Application No. 10/____,____ (Attorney Docket No. 1837.0026), which is

hereby incorporated by reference in its entirety. The catalyst can include the dopant itself, or it can include a precursor material that, upon decomposition, can form the dopant. Thus, the plasma catalyst can include one or more additives and one or more electrically conductive materials in any desirable ratio, depending on the ultimate desired composition of the plasma and the process using the plasma.

[059] The ratio of the electrically conductive components to the additives in a passive plasma catalyst can vary over time while being consumed. For example, during ignition, the plasma catalyst could desirably include a relatively large percentage of electrically conductive components to improve the ignition conditions. On the other hand, if used while sustaining the plasma, the catalyst could include a relatively large percentage of additives. It will be appreciated by those of ordinary skill in the art that the component ratio of the plasma catalyst used to ignite and sustain the plasma could be the same.

[060] A predetermined ratio profile can be used to simplify many plasma processes. In many conventional plasma processes, the components within the plasma are added as necessary, but such addition normally requires programmable equipment to add the components according to a predetermined schedule. However, consistent with this invention, the ratio of components in the catalyst can be varied, and thus the ratio of components in the plasma itself can be automatically varied. That is, the ratio of components in the plasma at any particular time can depend on which of the catalyst portions is currently being consumed by the plasma. Thus, the catalyst component ratio can be different at different locations within the catalyst. And, the current ratio of components in a plasma can depend on the portions of the catalyst currently and/or previously consumed, especially when the flow rate of a gas passing through the plasma chamber is relatively slow.

[061] A passive plasma catalyst consistent with this invention can be homogeneous, inhomogeneous, or graded. Also, the plasma catalyst component ratio can vary continuously or discontinuously throughout the catalyst. For example, in FIG. 3, the ratio can vary smoothly forming a gradient along a length of catalyst 100. Catalyst 100 can include a strand of material that includes a

relatively low concentration of a component at section 105 and a continuously increasing concentration toward section 110.

[062] Alternatively, as shown in FIG. 4, the ratio can vary discontinuously in each portion of catalyst 120, which includes, for example, alternating sections 125 and 130 having different concentrations. It will be appreciated that catalyst 120 can have more than two section types. Thus, the catalytic component ratio being consumed by the plasma can vary in any predetermined fashion. In one embodiment, when the plasma is monitored and a particular additive is detected, further processing can be automatically commenced or terminated.

[063] Another way to vary the ratio of components in a sustained plasma is by introducing multiple catalysts having different component ratios at different times or different rates. For example, multiple catalysts can be introduced at approximately the same location or at different locations within the cavity. When introduced at different locations, the plasma formed in the cavity can have a component concentration gradient determined by the locations of the various catalysts. Thus, an automated system can include a device by which a consumable plasma catalyst is mechanically inserted before and/or during plasma igniting, modulating, and/or sustaining.

[064] A passive plasma catalyst consistent with this invention can also be coated. In one embodiment, a catalyst can include a substantially non-electrically conductive coating deposited on the surface of a substantially electrically conductive material. Alternatively, the catalyst can include a substantially electrically conductive coating deposited on the surface of a substantially electrically non-conductive material. FIGS. 5 and 6, for example, show fiber 140, which includes under layer 145 and coating 150. In one embodiment, a plasma catalyst including a carbon core is coated with nickel to prevent oxidation of the carbon.

[065] A single plasma catalyst can also include multiple coatings. If the coatings are consumed during contact with the plasma, the coatings could be introduced into the plasma sequentially, from the outer coating to the innermost coating, thereby creating a time-release mechanism. Thus, a coated plasma

catalyst can include any number of materials, as long as a portion of the catalyst is at least electrically semi-conductive.

[066] Consistent with another embodiment of this invention, a plasma catalyst can be located entirely within a radiation cavity to substantially reduce or prevent radiation energy leakage. In this way, the plasma catalyst does not electrically or magnetically couple with the vessel containing the cavity or to any electrically conductive object outside the cavity. This prevents sparking at the ignition port and prevents radiation from leaking outside the cavity during the ignition and possibly later if the plasma is sustained. In one embodiment, the catalyst can be located at a tip of a substantially electrically non-conductive extender that extends through an ignition port.

[067] FIG. 7, for example, shows radiation chamber 160 in which plasma cavity 165 is placed. Plasma catalyst 170 is elongated and extends through ignition port 175. As shown in FIG. 8, and consistent with this invention, catalyst 170 can include electrically conductive distal portion 180 (which is placed in chamber 160) and electrically non-conductive portion 185 (which is placed substantially outside chamber 160). This configuration can prevent an electrical connection (e.g., sparking) between distal portion 180 and chamber 160.

[068] In another embodiment, shown in FIG. 9, the catalyst can be formed from a plurality of electrically conductive segments 190 separated by and mechanically connected to a plurality of electrically non-conductive segments 195. In this embodiment, the catalyst can extend through the ignition port between a point inside the cavity and another point outside the cavity, but the electrically discontinuous profile significantly can prevent sparking and energy leakage.

[069] Another method of forming a plasma consistent with this invention includes subjecting a gas in a cavity to electromagnetic radiation having a frequency less than about 333 GHz in the presence of an active plasma catalyst, which generates or includes at least one ionizing particle.

[070] An active plasma catalyst consistent with this invention can be any particle or high energy wave packet capable of transferring a sufficient amount of energy to a gaseous atom or molecule to remove at least one electron from the gaseous atom or molecule in the presence of electromagnetic radiation.

Depending on the source, the ionizing particles can be directed into the cavity in the form of a focused or collimated beam, or they may be sprayed, spewed, sputtered, or otherwise introduced.

[071] For example, FIG. 10 shows radiation source 200 directing radiation into radiation chamber 205. Plasma cavity 210 is positioned inside of chamber 205 and may permit a gas to flow there through via ports 215 and 216. Source 220 directs ionizing particles 225 into cavity 210. Source 220 can be protected, for example, by a metallic screen, which allows the ionizing particles to pass through but shields source 220 from radiation. If necessary, source 220 can be water-cooled.

[072] Examples of ionizing particles consistent with this invention can include x-ray particles, gamma ray particles, alpha particles, beta particles, neutrons, protons, and any combination thereof. Thus, an ionizing particle catalyst can be charged (e.g., an ion from an ion source) or uncharged and can be the product of a radioactive fission process. In one embodiment, the vessel in which the plasma cavity is formed could be entirely or partially transmissive to the ionizing particle catalyst. Thus, when a radioactive fission source is located outside the cavity, the source can direct the fission products through the vessel to ignite the plasma. The radioactive fission source can be located inside the radiation chamber to substantially prevent the fission products (i.e., the ionizing particle catalyst) from creating a safety hazard.

[073] In another embodiment, the ionizing particle can be a free electron, but it need not be emitted in a radioactive decay process. For example, the electron can be introduced into the cavity by energizing the electron source (such as a metal), such that the electrons have sufficient energy to escape from the source. The electron source can be located inside the cavity, adjacent the cavity, or even in the cavity wall. It will be appreciated by those of ordinary skill in the art that the any combination of electron sources is possible. A common way to produce electrons is to heat a metal, and these electrons can be further accelerated by applying an electric field.

[074] In addition to electrons, free energetic protons can also be used to catalyze a plasma. In one embodiment, a free proton can be generated by ionizing hydrogen and, optionally, accelerated with an electric field.

[075] Multi-mode Radiation Cavities

[076] A radiation waveguide, cavity, or chamber can be designed to support or facilitate propagation of at least one electromagnetic radiation mode. As used herein, the term "mode" refers to a particular pattern of any standing or propagating electromagnetic wave that satisfies Maxwell's equations and the applicable boundary conditions (e.g., of the cavity). In a waveguide or cavity, the mode can be any one of the various possible patterns of propagating or standing electromagnetic fields. Each mode is characterized by its frequency and polarization of the electric field and/or the magnetic field vectors. The electromagnetic field pattern of a mode depends on the frequency, refractive indices or dielectric constants, and waveguide or cavity geometry.

[077] A transverse electric (TE) mode is one whose electric field vector is normal to the direction of propagation. Similarly, a transverse magnetic (TM) mode is one whose magnetic field vector is normal to the direction of propagation. A transverse electric and magnetic (TEM) mode is one whose electric and magnetic field vectors are both normal to the direction of propagation. A hollow metallic waveguide does not typically support a normal TEM mode of radiation propagation. Even though radiation appears to travel along the length of a waveguide, it may do so only by reflecting off the inner walls of the waveguide at some angle. Hence, depending upon the propagation mode, the radiation (e.g., microwave) may have either some electric field component or some magnetic field component along the axis of the waveguide (often referred to as the z-axis).

[078] The actual field distribution inside a cavity or waveguide is a superposition of the modes therein. Each of the modes can be identified with one or more subscripts (e.g., TE₁₀ ("tee ee one zero")). The subscripts normally specify how many "half waves" at the guide wavelength are contained in the x and y directions. It will be appreciated by those skilled in the art that the guide wavelength can be different from the free space wavelength because radiation propagates inside the waveguide by reflecting at some angle from the inner walls of the

waveguide. In some cases, a third subscript can be added to define the number of half waves in the standing wave pattern along the z-axis.

[079] For a given radiation frequency, the size of the waveguide can be selected to be small enough so that it can support a single propagation mode. In such a case, the system is called a single-mode system (i.e., a single-mode applicator). The TE₁₀ mode is usually dominant in a rectangular single-mode waveguide.

[080] As the size of the waveguide (or the cavity to which the waveguide is connected) increases, the waveguide or applicator can sometimes support additional higher order modes forming a multi-mode system. When many modes are capable of being supported simultaneously, the system is often referred to as highly moded.

[081] A simple, single-mode system has a field distribution that includes at least one maximum and/or minimum. The magnitude of a maximum largely depends on the amount of radiation supplied to the system. Thus, the field distribution of a single mode system is strongly varying and substantially non-uniform.

[082] Unlike a single-mode cavity, a multi-mode cavity can support several propagation modes simultaneously, which, when superimposed, results in a complex field distribution pattern. In such a pattern, the fields tend to spatially smear and, thus, the field distribution usually does not show the same types of strong minima and maxima field values within the cavity. In addition, as explained more fully below, a mode-mixer can be used to "stir" or "redistribute" modes (e.g., by mechanical movement of a radiation reflector). This redistribution desirably provides a more uniform time-averaged field distribution within the cavity.

[083] A multi-mode cavity consistent with this invention can support at least two modes, and may support many more than two modes. Each mode has a maximum electric field vector. Although there may be two or more modes, one mode may be dominant and has a maximum electric field vector magnitude that is larger than the other modes. As used herein, a multi-mode cavity may be any cavity in which the ratio between the first and second mode magnitudes is less than about 1:10, or less than about 1:5, or even less than about 1:2. It will be

appreciated by those of ordinary skill in the art that the smaller the ratio, the more distributed the electric field energy between the modes, and hence the more distributed the radiation energy is in the cavity.

[084] The distribution of plasma within a processing cavity may strongly depend on the distribution of the applied radiation. For example, in a pure single mode system, there may only be a single location at which the electric field is a maximum. Therefore, a strong plasma may only form at that single location. In many applications, such a strongly localized plasma could undesirably lead to non-uniform plasma treatment or heating (i.e., localized overheating and underheating).

[085] Whether or not a single or multi-mode cavity is used consistent with this invention, it will be appreciated by those of ordinary skill in the art that the cavity in which the plasma is formed can be completely closed or partially open. For example, in certain applications, such as in plasma-assisted furnaces, the cavity could be entirely closed. See, for example, commonly owned, concurrently filed U.S. Patent Application No. 10/____,____ (Attorney Docket No. 1837.0020), which is fully incorporated herein by reference. In other applications, however, it may be desirable to flow a gas through the cavity, and therefore the cavity must be open to some degree. In this way, the flow, type, and pressure of the flowing gas can be varied over time. This may be desirable because certain gases, such as argon, which facilitate formation of the plasma, are easier to ignite but may not be needed during subsequent plasma processing.

[086] Mode-mixing

[087] For many applications, a cavity containing a uniform plasma is desirable. However, because radiation can have a relatively long wavelength (e.g., several tens of centimeters), obtaining a substantially uniform plasma distribution can be difficult to achieve. As a result, consistent with one aspect of this invention, the radiation modes in a multi-mode cavity can be mixed, or redistributed, over a period of time. Because the field distribution within the cavity must satisfy all of the boundary conditions set by the inner surface of the cavity, those field distributions can be changed by changing the position of any portion of that inner surface.

[088] In one embodiment consistent with this invention, a movable reflective surface can be located inside the radiation cavity. The shape and motion of the reflective surface should, when combined, change the inner surface of the cavity during motion. For example, an "L" shaped metallic object (i.e., "mode-mixer") when rotated about any axis will change the location or the orientation of the reflective surfaces in the cavity and therefore change the radiation distribution therein. Any other asymmetrically shaped object can also be used (when rotated), but symmetrically shaped objects can also work, as long as the relative motion (e.g., rotation, translation, or a combination of both) causes some change in location or orientation of the reflective surfaces. In one embodiment, a mode-mixer can be a cylinder that is rotatable about an axis that is not the cylinder's longitudinal axis.

[089] Each mode of a multi-mode cavity may have at least one maximum electric field vector, but each of these vectors could occur periodically across the inner dimension of the cavity. Normally, these maxima are fixed, assuming that the frequency of the radiation does not change. However, by moving a mode-mixer such that it interacts with the radiation, it is possible to move the positions of the maxima. For example, mode-mixer 38 of FIG. 1 can be used to optimize the field distribution within cavity 12 such that the plasma ignition conditions and/or the plasma sustaining conditions are optimized. Thus, once a plasma is excited, the position of the mode-mixer can be changed to move the position of the maxima for a uniform time-averaged plasma process (e.g., heating).

[090] Thus, consistent with this invention, mode-mixing can be useful during plasma ignition. For example, when an electrically conductive fiber is used as a plasma catalyst, it is known that the fiber's orientation can strongly affect the minimum plasma-ignition conditions. It has been reported, for example, that when such a fiber is oriented at an angle that is greater than 60° to the electric field, the catalyst does little to improve, or relax, these conditions. By moving a reflective surface either in or near the cavity, however, the electric field distribution can be significantly changed.

[091] Mode-mixing can also be achieved by launching the radiation into the applicator chamber through, for example, a rotating waveguide joint that can be

mounted inside the applicator chamber. The rotary joint can be mechanically moved (e.g., rotated) to effectively launch the radiation in different directions in the radiation chamber. As a result, a changing field pattern can be generated inside the applicator chamber.

[092] Mode-mixing can also be achieved by launching radiation in the radiation chamber through a flexible waveguide. In one embodiment, the waveguide can be mounted inside the chamber. In another embodiment, the waveguide can extend into the chamber. The position of the end portion of the flexible waveguide can be continually or periodically moved (e.g., bent) in any suitable manner to launch the radiation (e.g., microwave radiation) into the chamber at different directions and/or locations. This movement can also result in mode-mixing and facilitate more uniform plasma processing (e.g., heating) on a time-averaged basis. Alternatively, this movement can be used to optimize the location of a plasma for ignition or other plasma-assisted process.

[093] If the flexible waveguide is rectangular, a simple twisting of the open end of the waveguide will rotate the orientation of the electric and the magnetic field vectors in the radiation inside the applicator chamber. Then, a periodic twisting of the waveguide can result in mode-mixing as well as rotating the electric field, which can be used to assist ignition, modulation, or sustaining of a plasma.

[094] Thus, even if the initial orientation of the catalyst is perpendicular to the electric field, the redirection of the electric field vectors can change the ineffective orientation to a more effective one. Those skilled in the art will appreciate that mode-mixing can be continuous, periodic, or preprogrammed.

[095] In addition to plasma ignition, mode-mixing can be useful during subsequent plasma processing to reduce or create (e.g., tune) "hot spots" in the chamber. When a processing cavity only supports a small number of modes (e.g., less than 5), one or more localized electric field maxima can lead to "hot spots" (e.g., within cavity 12). In one embodiment, these hot spots could be configured to coincide with one or more separate, but simultaneous, plasma ignitions or processing events. Thus, the plasma catalyst can be located at one or more of those ignition or subsequent processing positions.

[096] Multi-location Ignition

[097] A plasma can be ignited using multiple plasma catalysts at different locations. In one embodiment, multiple fibers can be used to ignite the plasma at different points within the cavity. Such multi-point ignition can be especially beneficial when a uniform plasma ignition is desired. For example, when a plasma is modulated at a high frequency (i.e., tens of Hertz and higher), or ignited in a relatively large volume, or both, substantially uniform instantaneous striking and restriking of the plasma can be improved. Alternatively, when plasma catalysts are used at multiple points, they can be used to sequentially ignite a plasma at different locations within a plasma chamber by selectively introducing the catalyst at those different locations. In this way, a plasma ignition gradient can be controllably formed within the cavity, if desired.

[098] Also, in a multi-mode cavity, random distribution of the catalyst throughout multiple locations in the cavity increases the likelihood that at least one of the fibers, or any other passive plasma catalyst consistent with this invention, is optimally oriented with the electric field lines. Still, even where the catalyst is not optimally oriented (not substantially aligned with the electric field lines), the ignition conditions are improved.

[099] Furthermore, because a catalytic powder can be suspended in a gas, it is believed that each powder particle may have the effect of being placed at a different physical location within the cavity, thereby improving ignition uniformity within the cavity.

[0100] Dual-Cavity Plasma Igniting/Sustaining

[0101] A dual-cavity arrangement can be used to ignite and sustain a plasma consistent with this invention. In one embodiment, a system includes at least a first ignition cavity and a second cavity in fluid communication with the first cavity. To ignite a plasma, a gas in the first ignition cavity can be subjected to electromagnetic radiation having a frequency less than about 333 GHz, optionally in the presence of a plasma catalyst. In this way, the proximity of the first and second cavities may permit a plasma formed in the first cavity to ignite a plasma in the second cavity, which may be sustained with additional electromagnetic radiation.

[0102] In one embodiment of this invention, the first cavity can be very small and designed primarily, or solely for plasma ignition. In this way, very little radiation energy may be required to ignite the plasma, permitting easier ignition, especially when a plasma catalyst is used consistent with this invention.

[0103] In one embodiment, the first cavity may be a substantially single mode cavity and the second cavity is a multi-mode cavity. When the first ignition cavity only supports a single mode, the electric field distribution may strongly vary within the cavity, forming one or more precisely located electric field maxima. Such maxima are normally the first locations at which plasmas ignite, making them ideal points for placing plasma catalysts. It will be appreciated, however, that when a plasma catalyst is used, it need not be placed in the electric field maximum and, many cases, need not be oriented in any particular direction.

[0104] Illustrative Cavity Shapes

[0105] As used herein, the term “plasma-assisted processing”, or simply “plasma-processing,” refers to any operation, or combination of operations, that involves the use of a plasma. Thus, a plasma process can include, for example, heat-treating, synthesizing and depositing carbides, nitrides, borides, oxides, and other materials, doping, carburizing, nitriding, and carbo-nitriding, sintering, multi-part processing, joining, sintering, decrystallizing, making and operating furnaces, gas exhaust-treating, waste-treating, incinerating, scrubbing, ashing, growing carbon structures, generating hydrogen and other gases, forming electrodeless radiation jets, plasma processing in assembly lines, sterilizing, etc.

[0106] When processing is intended for only some locations on the surface of an object within a cavity, it may be desirable to form plasma at the locations on the surface of the object intended for processing and prevent plasma forming at other locations on the surface of the object not intended for processing. Locations on the surface of the object within the cavity intended for processing may be the locations on the surface of the object intended for greater processing (e.g., heating) and locations on the surface of the object within the cavity not intended for processing may be the locations on the surface of the object intended for reduced processing (e.g., heating).

[0107] As described more fully above, the distribution of plasma within a processing cavity can depend on the distribution of the applied radiation. For example, a strong plasma may only form at locations at which the electric field (e.g., the radiation density) is large. Because the strength of electric field can be reduced, or even made to be zero near the inner surface of the cavity, a plasma can be substantially prevented at that surface. Therefore, the inner surface of a cavity can be contoured to selectively form and/or prevent plasmas at any different location on the surface of an object being processed.

[0108] Therefore, a cavity consistent with this invention can selectively generate plasma at any portion of an object's surface inside the cavity by designing an appropriate part surface/cavity inner surface distance. It will be appreciated that when processing is intended for only some portions of a surface of the object, the

cavity can be designed that protects only other portions of the object by preventing those other portions from being exposed to the plasma.

[0109] The electric field in a cavity may not be strong enough to form plasma at locations spaced from the surface of a metallic or conducting object by a distance of less than about $\lambda/4$. Therefore, a location on the surface of the object intended for reduced heating, for example, may be spaced from the inner surface of the cavity by a distance of less than about $\lambda/4$. Another location on the surface of the object intended for processing may be spaced from the inner surface of the cavity by a distance greater than about $\lambda/4$.

[0110] In one successful experiment, the distance between the object and the inner surface of the cavity was less than a fraction of an inch, which prevented plasma from being generated there. For example, when 2.45 GHz radiation energy was used to form a plasma, a distance of about 0.5 inches was sufficient to prevent plasma from forming. However, a shorter distance may also be used, including the case when the two surface make contact. It will also be appreciated that the shaping of a inner surface of a cavity can be contoured to selectively cause and prevent plasma forming at any particular location on the surface of the object.

[0111] FIG. 11 shows a side cross-sectional view of plasma processing cavity 360 formed in vessel 313 and object 300 to be processed consistent with this invention. In this example, processing is intended for surface portion 310 and not intended for surface portion 320. Cavity 360 can be custom-configured to conform, in at least some areas, to the contour of surface portion 310 or surface portion 320. For example, cavity 360 can have at least one inner surface, for example inner surface 365, and can be shaped to hold object 300 in a manner such that surface portion 320 of object 300 can be spaced from inner surface 365 of cavity 360 by distance 325 of less than about $\lambda/4$. Also, surface portion 310 of object 300 can be spaced from inner surface 365 of cavity 12 by distance 315 by at least about $\lambda/4$, wherein λ is the wavelength of the applied radiation. Distance 305 between surface 330 of object 300 and surface 370 of cavity 360 at aperture 380 can be less than $\lambda/4$ to substantially confine the plasma within cavity 360.

[0112] Thus, it will be appreciated that object 300 can act as a partial seal by at least partially blocking aperture 380. Also, surface 370 of cavity 360 can be custom-configured to conform, in at least some areas, to the contour of surface portion 330 at aperture 380. Moreover, although one gas port is shown, aperture 380 can act as another port, or vessel 313 can have more than one gas port. It will also be appreciated that object 300 can act as a partial seal at aperture 380 and can be supported there.

[0113] FIG. 12 shows a side cross-sectional view of another illustrative cavity 460 in which portion 410 of object 400 can be processed consistent with this invention. Thus, cavity 460 can be shaped such that cavity 460 includes an aperture or port for supporting and/or selectively processing desired portion 410 of object 400. Cavity 460 is formed in vessel 413 having wall 465 in which aperture 480 can be formed. Portion 420 is not intended for processing and may extend at through aperture 480 and be external to cavity 460 during processing. It will be appreciated, then, that object 400 can act as a seal where object 400 at least partially blocks aperture 480. Thus, surface 470 of cavity 460 can be custom-configured to conform, in at least some areas, to the contour of surface portion 430 of object 400 at aperture 480 although a gap may exist between surface 470 and portion 430.

[0114] FIG. 13 shows another side cross-sectional view of illustrative radiation chamber 540 consistent with this invention. In this case, chamber 540 forms a plasma cavity and a radiation chamber. In this embodiment, chamber 540 can include at least two inner surfaces 515 and 516 to form cavity 560. Inner surfaces 515 and 516 can consist of at least one substantially radiation-transmissive material. The substantially radiation-transmissive material may be at least one of quartz, Al_2O_3 , and ceramic components. At least one of the surfaces, for example inner surface 515, can be custom-configured to closely conform, in at least some areas, object 500 to prevent a plasma from forming at those areas.

[0115] In this embodiment, cavity 560 can be shaped to hold object 500 in a manner such that surface portion 520 of object 500 is spaced from adjacent inner surface 515 by distance 525, which can be less than about $\lambda/4$, and portion 510 of

the surface of object 500 is spaced from adjacent inner surface 516 by distance 526, which can be greater than about $\lambda/4$. In one embodiment, surface 515 or surface 570 can at least partially support object 500. Those locations can be well suited as support surfaces because plasma processing may not be used there.

[0116] Distance 535 between surface 530 of object 500 and surface 570 of cavity 560 at aperture 580 can be less than about $\lambda/4$ to assist in substantially confining a plasma within cavity 560. As mentioned above, object 500 itself can act as a seal where object 500 at least partially blocks aperture 580.

[0117] In the foregoing described embodiments, various features are grouped together in a single embodiment for purposes of streamlining the disclosure. This method of disclosure is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the following claims are hereby incorporated into this Detailed Description of Embodiments, with each claim standing on its own as a separate preferred embodiment of the invention.

WE CLAIM:

1. A method of selectively processing an object with plasma formed with electromagnetic radiation having a wavelength of λ , the method comprising:
 - placing the object in a cavity having at least one inner surface;
 - arranging the object so that a location on the object intended for reduced heating is spaced from the inner surface by a distance of less than about $\lambda/4$;
 - introducing gas into the cavity; and
 - irradiating the cavity with the radiation to form a plasma in the cavity in an area other than the location on the object intended for reduced heating.
2. The method of claim 1, further comprising placing a plasma catalyst at a position such that it is in the radiation when the plasma forms in the cavity.
3. The method of claim 2, wherein the catalyst is at least one of an active catalyst and a passive catalyst.
4. The method of claim 3, wherein the catalyst comprises at least one of metal, inorganic material, carbon, carbon-based alloy, carbon-based composite, electrically conductive polymer, conductive silicone elastomer, polymer nanocomposite, and an organic-inorganic composite.
5. The method of claim 4, wherein the catalyst is in the form of at least one of a nano-particle, a nano-tube, a powder, a dust, a flake, a fiber, a sheet, a needle, a thread, a strand, a filament, a yarn, a twine, a shaving, a sliver, a chip, a woven fabric, a tape, and a whisker.
6. The method of claim 3, wherein the catalyst comprises carbon fiber.
7. The method of claim 3, wherein the catalyst is in the form of at least one of a nano-particle, a nano-tube, a powder, a dust, a flake, a fiber, a sheet, a needle, a thread, a strand, a filament, a yarn, a twine, a shaving, a sliver, a chip, a woven fabric, a tape, and a whisker.

8. The method of claim 3, wherein the plasma catalyst comprises an active plasma catalyst including at least one ionizing particle.

9. The method of claim 8, wherein the at least one ionizing particle comprises a beam of particles.

10. The method of claim 8, wherein the particle is at least one of an x-ray particle, a gamma ray particle, an alpha particle, a beta particle, a neutron, and a proton.

11. The method of claim 8, wherein the at least one ionizing particle is a charged particle.

12. The method of claim 8, wherein the ionizing particle comprises a radioactive fission product.

13. The method of claim 1, wherein the cavity is formed in a vessel comprising a radiation-transmissive material.

14. The method of claim 13, wherein the substantially radiation-transmissive material is at least one of quartz, Al_2O_3 , and ceramic components.

15. The method of claim 1, wherein the gas has a pressure that is about equal to or greater than atmospheric pressure.

16. The method of claim 1, wherein the cavity has a radiation density during the irradiating, and wherein the method further comprises distributing the radiation such that the time-average of the density is substantially uniform over most of the cavity.

17. The method of claim 1, wherein the irradiating comprises directing the radiation through a wall of the cavity.

18. The method of claim 1, wherein the irradiating comprises directing the radiation into the cavity through at least one of a waveguide, coaxial cable, and a radiation transmissive material.

19. The method of claim 1, further comprising sustaining the plasma in the cavity until a predetermined temperature profile is reached.

20. The method of claim 1, wherein the cavity is formed in a vessel having a wall in which an aperture is formed, and wherein during the irradiation, a portion of the object extends through the aperture and is external to the cavity.

21. An apparatus for plasma-processing an electrically conducting object using a plasma, the apparatus comprising:

a source for generating radiation having a wavelength of λ ;

a vessel in which a cavity is formed, the cavity being arranged to be irradiated by the source, the cavity having at least one inner surface and being shaped to hold the object in a manner such that a portion of the object is spaced from the inner surface by a distance of less than about $\lambda/4$, and a portion of the object is spaced from another portion of the surface by a distance of at least $\lambda/4$; and

a conduit for introducing gas into the cavity, such that in the presence of the radiation, at least a portion of the gas becomes a plasma and the plasma is formed in regions other than those where the spacing between the inner surface and the object is less than about $\lambda/4$.

22. The apparatus of claim 21, wherein the cavity is custom-configured to conform, in at least some areas, to a contour of the object.

23. The apparatus of claim 21, wherein the cavity is formed of a substantially radiation-transmissive material.

24. The apparatus of claim 23, wherein the substantially radiation-transmissive material is at least one of quartz, Al_2O_3 , and ceramic components.

25. The apparatus of claim 21, further comprising a mode-mixer for increasing uniformity of the radiation throughout the cavity over a period of time.

26. The apparatus of claim 21, further comprising a plasma catalyst in the cavity.

27. A chamber for use in process for selectively processing an object using a plasma induced by radiation having a wavelength of λ , the chamber comprising:

a first cavity surface portion contoured to a shape of at least a portion of the object; and

a second cavity surface portion, wherein a distance between the first surface portion and an adjacent surface of the object is less than about $\lambda/4$, and wherein a distance between the second cavity portion and an adjacent surface of the object is greater than about $\lambda/4$.

28. The chamber of claim 27, wherein the cavity is formed of a substantially radiation-transmissive material.

29. The chamber of claim 28, wherein the substantially radiation-transmissive material comprises at least one of a quartz, Al_2O_3 , and ceramic components.

30. The chamber of claim 27, wherein the second cavity surface portion is shaped to follow a contour of the object.

31. The chamber of claim 27, wherein the chamber is custom-configured to the contour of the object such that portions of the object intended for reduced heating are located closer to the surface portion of the chamber than portions of the object intended for greater heating.

32. The chamber of claim 27, wherein the first cavity surface portion and the adjacent surface are not in contact.

33. A method of selectively processing an object with a plasma formed in a cavity with electromagnetic radiation having a wavelength of λ and a frequency less than about 333 GHz, wherein the cavity has an inner surface, and wherein the object has a first surface region and a second surface region, the method comprising:

placing the object in the cavity such that: (a) a first gap is formed between the first surface region and the inner surface, wherein the gap has a thickness less than about $\lambda/4$ and (b) a second gap is formed between the second surface region and the inner surface, wherein the gap has a thickness at least about $\lambda/4$;

introducing gas into the cavity; and

irradiating the cavity with the radiation to form a plasma in the second gap but substantially not in the first gap.

34. The method of claim 33, wherein the irradiating comprises irradiating in the presence of a plasma catalyst.

35. The method of claim 34, wherein the plasma catalyst is at least one of a passive plasma catalyst and an active plasma catalyst.

36. The method of claim 35, wherein the active catalyst comprises at least one ionizing particle.

37. The method of claim 36, wherein the at least one ionizing particle comprises a beam of particles.

38. The method of claim 36, wherein the ionizing particle consists of at least one of an electron and an ion.

39. The method of claim 36, wherein the particle is at least one of an x-ray particle, a gamma ray particle, an alpha particle, a beta particle, a neutron, and a proton.

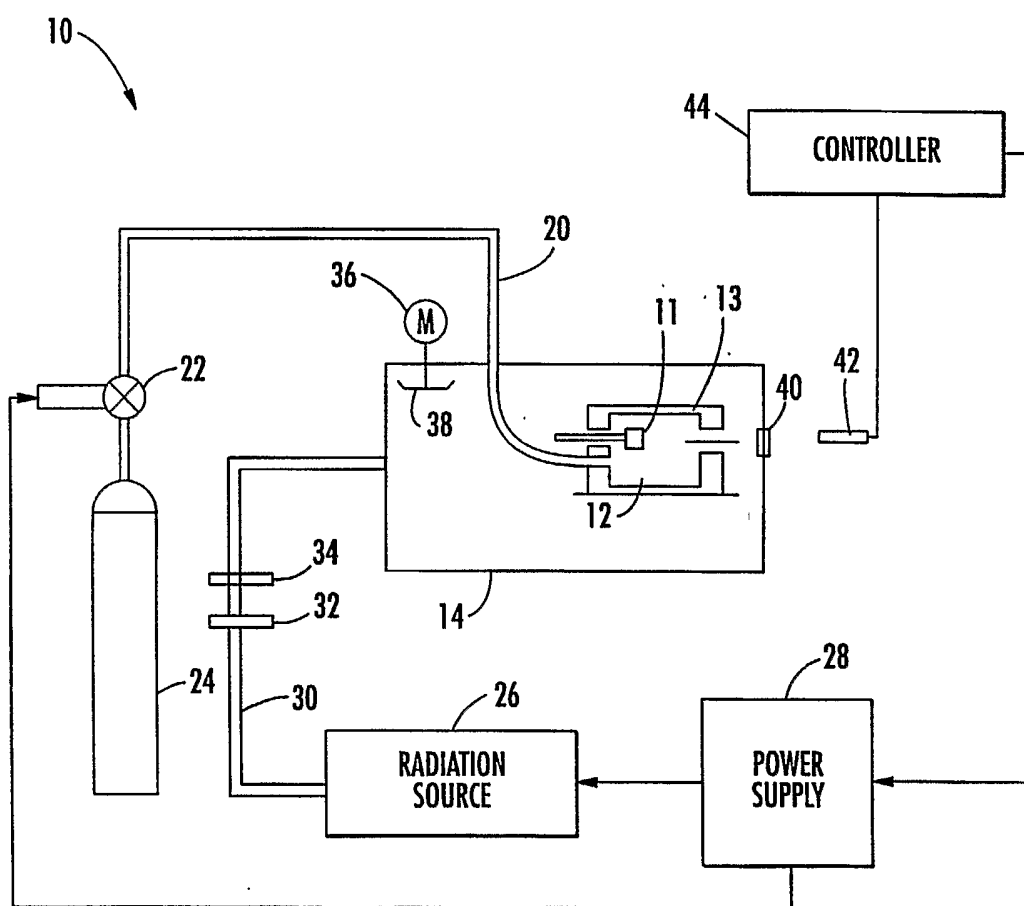
40. The method of claim 35, wherein the passive catalyst comprises a material that is at least electrically semi-conductive.

41. The method of claim 40, wherein the material comprises at least one of metal, inorganic material, carbon, carbon-based alloy, carbon-based composite, electrically conductive polymer, conductive silicone elastomer, polymer nanocomposite, organic-inorganic composite, and any combination thereof.

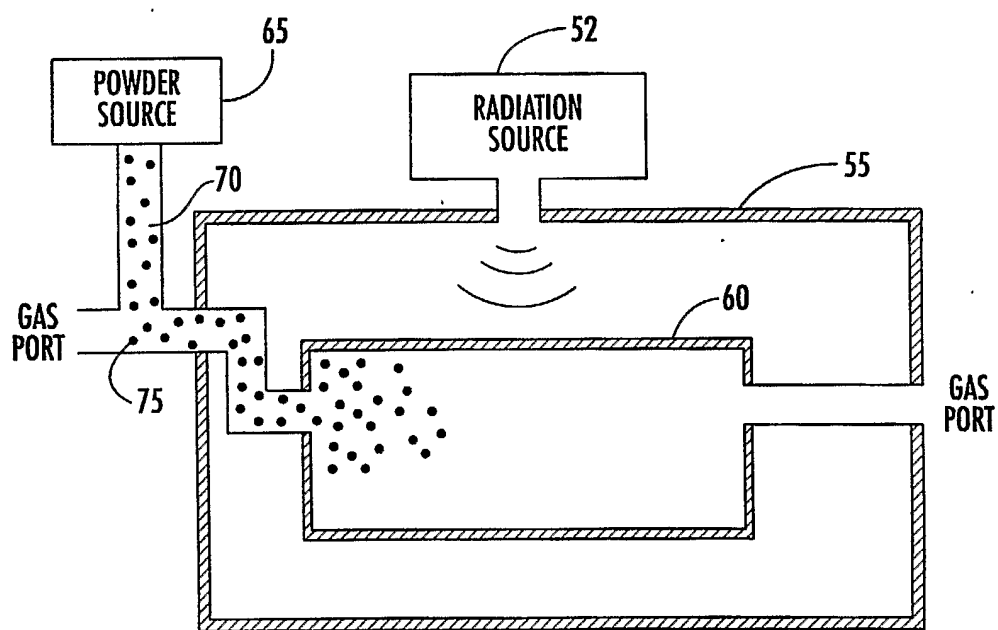
42. The system of claim 41, wherein the material is in the form of at least one of a nano-particle, a nano-tube, a powder, a dust, a flake, a fiber, a sheet, a needle, a thread, a strand, a filament, a yarn, a twine, a shaving, a sliver, a chip, a woven fabric, a tape, a whisker, and any combination thereof.

43. The system of claim 42, wherein the material comprises at least one nano-tube.

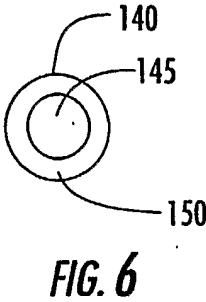
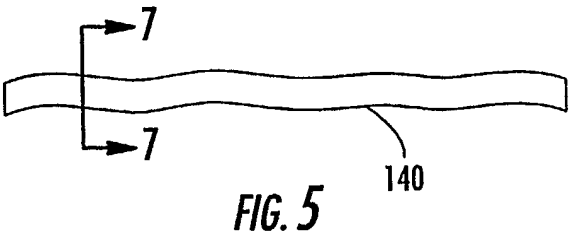
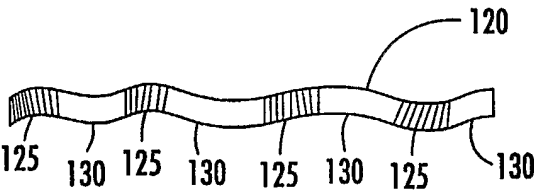
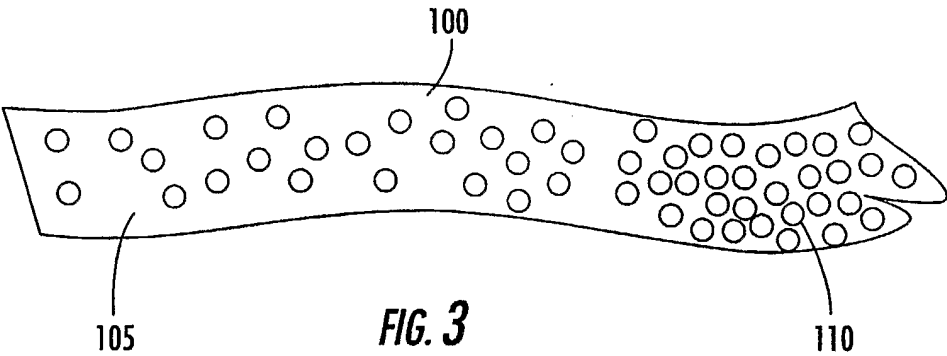
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*FIG. 1*

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**FIG. 2**

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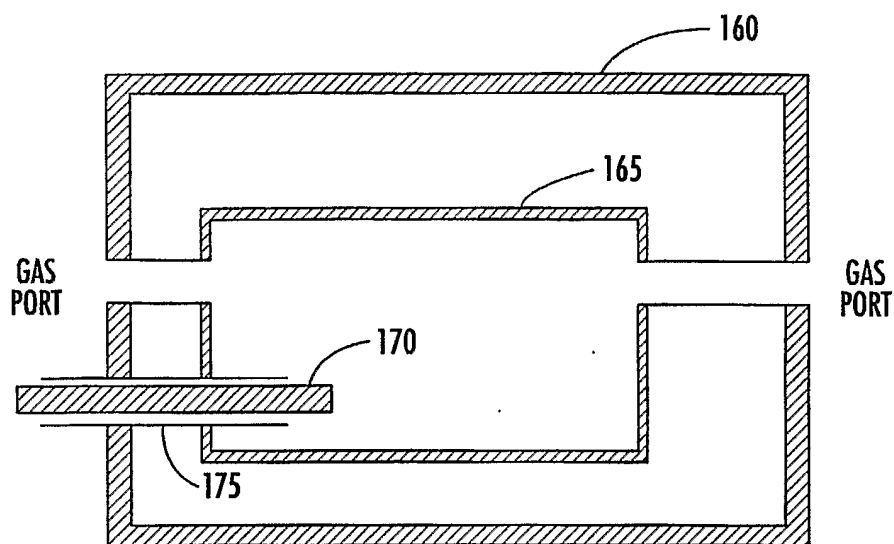


FIG. 7

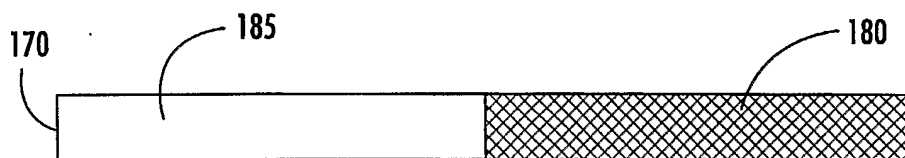


FIG. 8

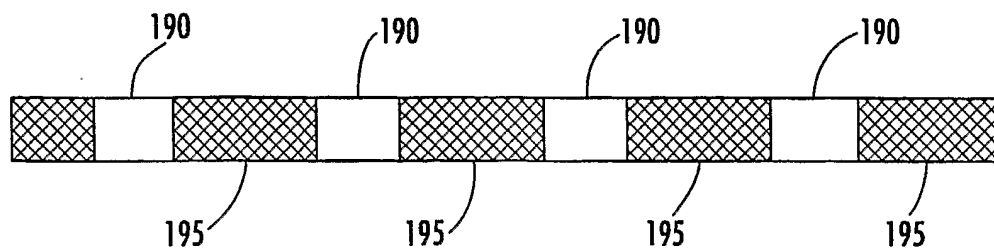
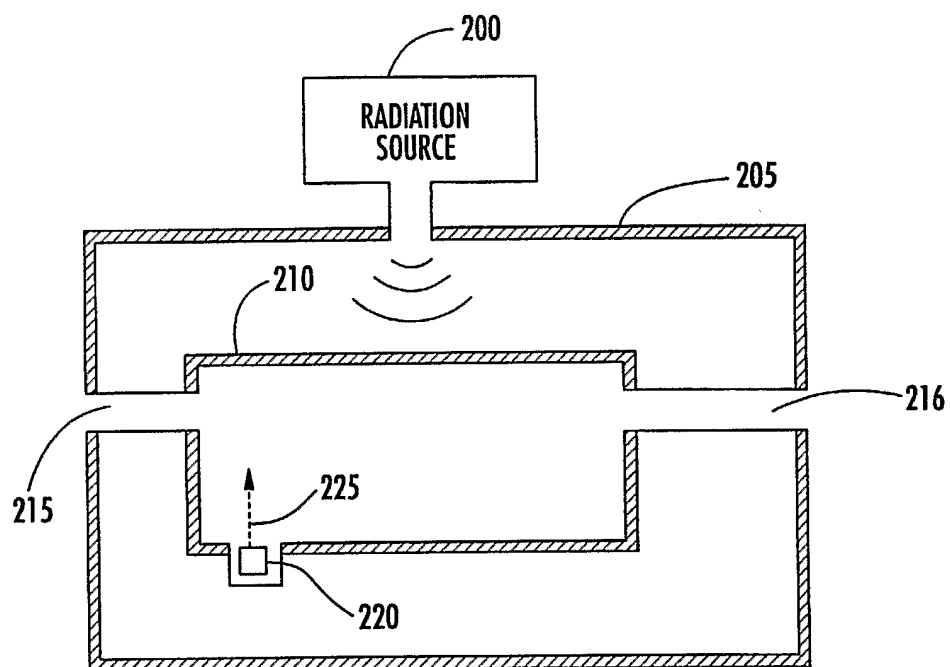


FIG. 9

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**FIG. 10**

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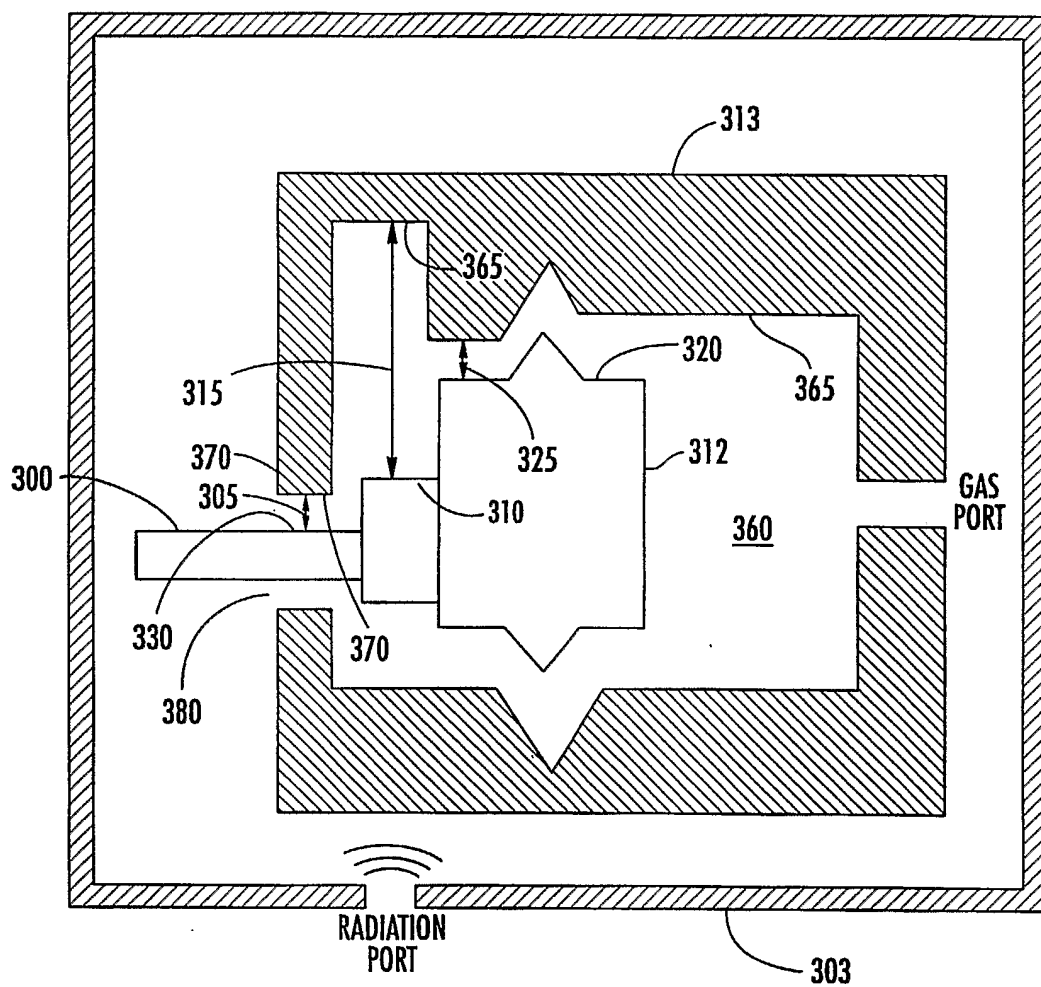


FIG. 11

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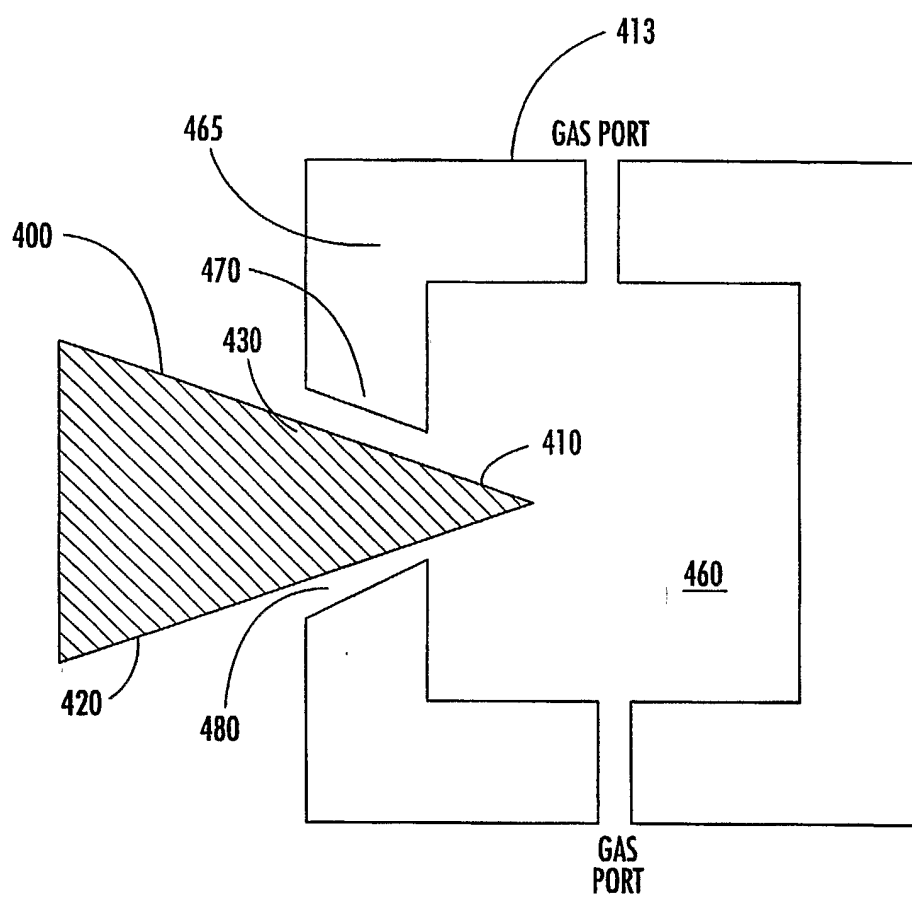
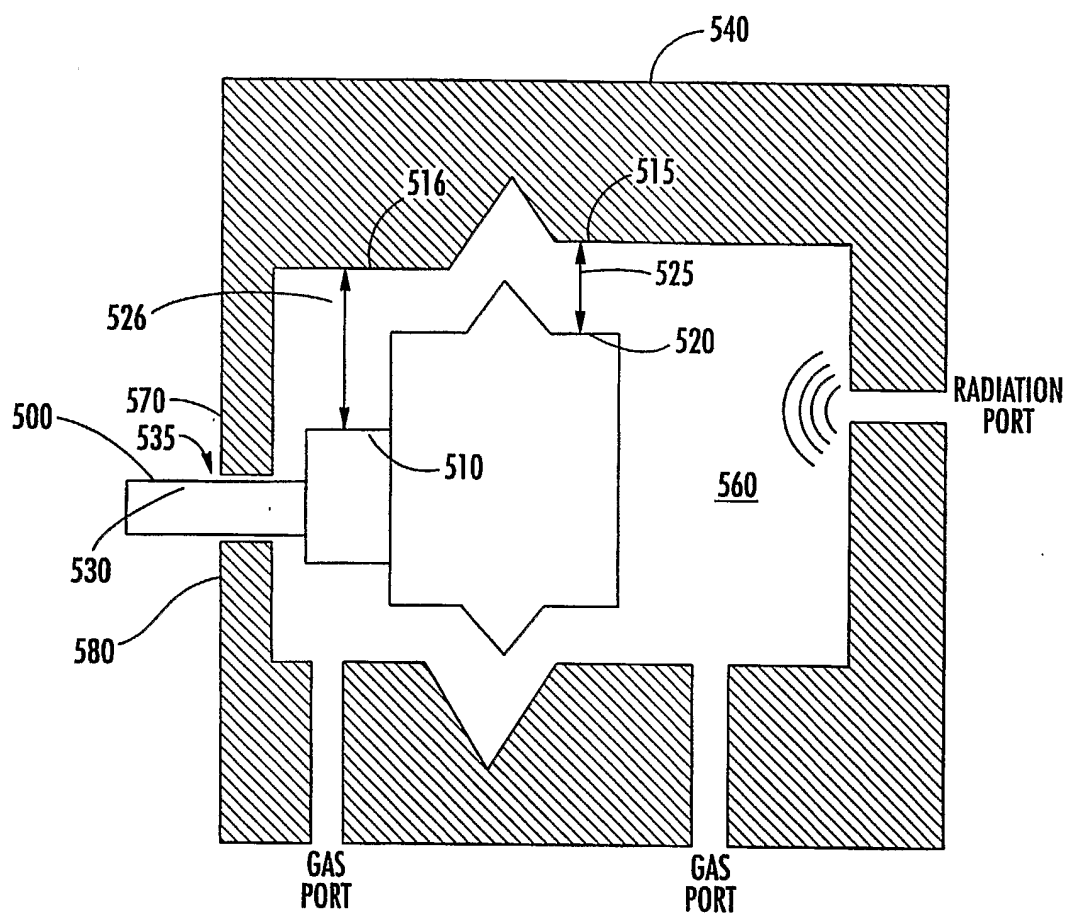


FIG. 12

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**FIG. 13**