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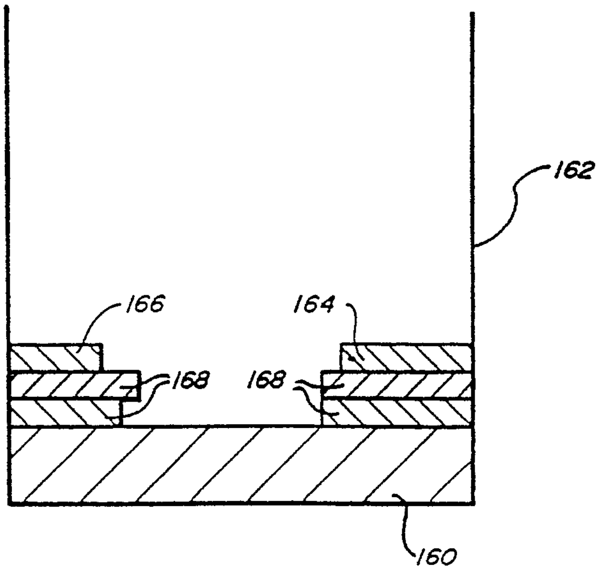
(54) **Method and apparatus for tuning microwave transmission windows.**

(57) A method and apparatus for tuning a microwave transmission window (160) to maximize and stabilize the power transmitted therethrough. The power transmitted through the window is tuned by adding a pair of tuning structures (164, 166) to the window, which are tuned to transmit the power required to achieve the required deposition conditions. The tuning structures are formed by stacking a plurality of segments (168) of dielectric material adjacent the outer edge of the window. The dimensions of the tuning structure, both width and height, are adjusted to achieve both a high transmission coefficient and a stable plasma excitation.



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# Method and Apparatus for Tuning Microwave Transmission Windows

## BACKGROUND OF THE INVENTION

This invention relates to a method and apparatus for tuning microwave transmission windows and more particularly for maximizing the power transmitted through the windows. The invention has application with any microwave power transmission into a plasma, but has particular applicability for plasma-type systems, such as those incorporating amorphous semiconductor alloys. The invention includes to a method and apparatus for making such devices by plasma deposition from reaction gases wherein the plasmas are excited by microwave energy. The invention has one of its most important applications in making commercial electrophotographic devices having a cyclindrical or drum configuration with the amorphous semiconductor alloys coated or deposited on the outer surfaces thereof. The present invention enhances the commercial mass production of electrophotographic drums incorporating amorphous semiconductor alloys.

Silicon is the basis of the huge crystalline semiconductor industry and is the material which has produced expensive high efficiency (18 percent) crystalline solar cells for space applications. When crystalline semiconductor technology reached a commercial state, it became the foundation of the present huge semiconductor device manufacturing industry. This was due to the ability of the scientists to grow substantially defect-free germanium and particularly silicon crystals, and then turn them into extrinsic materials with p-type and n-type conductivity regions therein. This was accomplished by diffusing into such crystalline material parts per million of donor (n) or acceptor (p) dopant materials introduced as substitutional impurities into the substantially pure crystalline materials, to increase their electrical conductivity and to control their being either of a p or n conduction type. The fabrication processes for making p-n junction crystals involve extremely complex, time consuming, and expensive procedures. Thus, these crystalline materials useful in solar cells and current control devices are produced under very carefully controlled conditions by growing individual single silicon or germanium crystals, and when p-n junctions are required, by doping such single crystals with extremely small and critical amounts of dopants.

In summary, crystal silicon devices have fixed parameters which are not variable as desired, require large amounts of material, are only producible in relatively small areas and are expensive and time consuming to produce. Devices based upon amorphous silicon can eliminate these crystal silicon disadvantages. Amorphous silicon has an optical absorption edge having properties similar to a direct gap semiconductor and only a material thickness of one micron or less is necessary to absorb the same amount of sunlight as the 50 micron thick crystalline silicon. Further, amorphous silicon can be made faster, easier and in larger areas than can crystalline silicon.

Accordingly, a considerable effort has been made to develop processes for readily depositing amorphous semiconductor alloys or films, each of which can encompass relatively large areas, if desired, limited only by the size of the deposition equipment, and which could be readily doped to form p-type and n-type materials where p-n junction devices are to be made therefrom equivalent to those produced by their crystalline counterparts. For many years such work was substantially unproductive. Amorphous silicon or germanium - (Group IV) films are normally four-fold coordinated and were found to have microvoids and dangling bonds and other defects which produce a high density of localized states in the energy gap thereof. The presence of a high density of localized states in the energy gap of amorphous silicon semiconductor films results in a low degree of photoconductivity and short carrier lifetime, making such films unsuitable for photoresponsive applications. Additionally, such films could not be successfully doped or otherwise modified to shift the Fermi level close to the conduction or valence bands, making them unsuitable for making p-n junctions for solar cell and current control device applications.

In an attempt to minimize the aforementioned problems involved with amorphous silicon and germanium, W.E. Spear and P.G. Le Comber of Carnegie Laboratory of Physics, University of Dundee, in Dundee, Scotland, did some work on "Substitutional Doping of Amorphous Silicon", as reported in a paper published in Solid State Communications, Vol. 17, pp. 1193-1196, 1975, toward the end of reducing the localized states in the energy gap in amorphous silicon or germanium to make the same approximate more closely intrinsic crystalline silicon or germanium and/or substitutionally doping the amorphous materials with suitable classic dopants, as in doping crystalline materials, to make them extrinsic and of p or n conduction types.

The reduction of the localized states was accomplished by glow discharge deposition of amorphous silicon films wherein a gas of silane ($SiH_4$) was passed through a reaction tube where the gas was decomposed by a radio frequency (RF) glow discharge and deposited on a substrate at a substrate temperature of about 500-600°K (227-327°). The material so deposited on the substrate was an intrinsic amorphous material consisting of silicon and hydrogen. To produce a doped amorphous material, a gas of phosphine ($PH_3$) for n-type conduction or a gas of diborane ($B_2H_6$) for p-type conduction was premixed with the silane gas and passed through the glow discharge reaction tube under the same operating conditions. The gaseous concentration of the dopants used was between about $5 \times 10^{-6}$ and $10^{-2}$ parts per volume. The material so deposited included supposedly substitutional phosphorous or boron dopant and was shown to be extrinsic and of n or p conduction type.

While it was not known by these researchers, it is now known by the owrk of others that the hydrogen in the silane combines at an optimum temperature with many of the dangling bonds of the silicon during the glow discharge deposition, to substantially reduce the density of the localized states in the energy gap toward the end of making the electronic properties of the amorphous material approximate more nearly those of the corresponding crystalline material.

The incorporation of hydrogen in the above RF deposition method not only has limitationns based upon the fixed ratio of hydrogen to silicon in silane, but, more importantly, various Si:H bonding configurations introduce new antibonding states which can have deleterious consequences in these materials. Therefore, there are basic limitations in reducing the density of localized states in these materials which are particularly harmful in terms of effective p as well as n doping. The resulting density of states of the RF silane deposited materials leads to a narrow depletion width, which in turn limits the efficiencies of solar cells and other devices whose operation depends on the drift of free carriers. The RF method of making these materials by the use of only silicon and hydrogen also results in a high density of surface states which affects all the above parameters.

After the development of the glow discharge deposition of silicon from silane gas was carried out, work was done on the sputter depositing of amorphous silicon films in the atmosphere of a mixture of argon (required by the sputtering deposition process) and molecular hydrogen, to determine the results of such molecular hydrogen on the characteristics of the deposited amorphous silicon film. This research indicated that the hydrogen acted as an altering agent which bonded in such a way as to reduce the localized states in the energy gap. However, the degree to which the localized states in the energy gap were reduced in the sputter deposition process was much less than that achieved by the silane deposition process described above. The above-described p and n dopant gases also were introduced in the sputtering process to produce p and n doped materials. These materials had a lower doping efficiency than the materials produced in the glow discharge process. Neither process produced efficient p-doped materials with sufficiently higher acceptor concentrations for producing commercial p-n or p-i-n junctions devices. The n-doping efficiency was below desirable acceptable commercial levels and the p-doping was particularly undesirable since it reduced the width of the band gap and increased the number of localized states in the band gap.

Greatly improved amorphous silicon alloys having significantly reduced concentrations of localized states in the energy gaps thereof and high quality electronic properties have been prepared by glow discharge as fully described in U.S. Patent No. 4,226,898, Amorphous Semiconductors Equivalent to Crystalline Semiconductors, Stanford R. Ovshinsky and Arun Madan which issued October 7, 1980, and by vapor deposition as fully described in U.S. Patent No. 4,217,374, Stanford R. Ovshinsky and Masatsugu Izu, which issued on August 12, 1980, under the same title. As disclosed in these patents, which are incorporated herein by reference, fluorine is introduced into the amorphous silicon semiconductor to substantially reduce the density of localized states therein. Activated fluorine especially readily diffuses into and bonds to the amorphous silicon in the amorphous body to substantially decrease the density of localized defect states therein, because the small size of the fluorine atoms enables them to be readily introduced into the amorphous body. The fluorine bonds to the dangling bonds of the silicon and forms what is believed to be a partially ionic stable bond with flexible bonding angles, which results in a more stable and more efficient compensation or alteration than is formed by hydrogen and other compensating or altering agents. Fluorine is considered to be a more efficient compensating or altering element than hydrogen when employed alone or with hydrogen because of its exceedingly small size, high reactivity, specificity in chemical bonding, and highest electronegativity. Hence, fluorine is qualitatively different from other halogens and so is considered a super-halogen.

As an example, compensation may be achieved with fluorine alone or in combination with hydrogen with the addition of these elements(s) in very small quantities (e.g., fractions of one atomic percent). However, the amounts of fluorine and hydrogen most desirably used are much greater than such small percentages so as to form a silicon-hydrogen-fluorine alloy. Such alloying amounts of fluorine and hydrogen may, for example, be in the range of 1 to 5 percent or greater. It is believed that the new alloy so formed has a lower density of defect states in the energy gap than that achieved by the mere neutralization of dangling bonds and similar defect states. Such larger amount of fluorine, in particular, is believed to participate substantially in a new structural configuration of an amorphous silicon-containing material and facilitates the addition of other alloying materials, such as germanium. Fluorine, in addition to its other characteristics mentioned herein, is believed to be an organizer of local structure inthe silicon-containing alloy through inductive and ionic effects. It is believed that fluorine also influences the bondign of hydrogen by acting in a beneficial way to decrease the density of defect states which hydrogen contributes while acting as a density of states reducing element. The ionic role that fluorine plays in such an alloy is believed to be an important factor in terms of the nearest neighbor relationships.

About forty-five years ago, C. Carlson developed the first electrophotographic process based on a sulfur material. Other chalcogenides such as selenium and selenium alloys were thereafter suggested for such applications together with organic substances such as polyvinyl carbazole (PVK). These materials, however, exhibited certain deficiencies. They were toxic, and therefore difficulty to handle, soft, and therefore subject to wear, and had poor infrared light photoresponse.

In view of the above noted deficiencies of these materials, silicon based amorphous semiconductor alloys were investigated for possible applications in electrophotographic processes. These materials were considered likely to be useful because of the hardness of amorphous silicon alloys, because of their nontoxic nature, and because of their improved photoresponse to infrarred light. Also, as previously mentioned, these materials could be made with a density of states reduced to a point where charging of the materials to the potentials required for electrophotographic replication was considered possible. Thus, amorphous semiconductor alloys made by the processes hereinabove described have demonstrated photoresponsive and structural characteristics which are suited for electrophotographic applications. These prior art processes, however, have suffered from relatively slow deposition rates and low conversion efficiency of the reaction gas feed stock which are important considerations from the standpoint of using amorphous semiconductor materials on a commercial basis.

A new and improved process for making electrophotographic devices incorporating amorphous semiconductor alloys is disclosed in U.S. application Serial No. 580,081, filed February 14, 1984 for "An Improved Method Of Making A Photoconductive Member And Improved Photoconductive Members Thereby", filed in the names of Annette G. Johncock and Stephen J. Hudgens, which is incorporated herein by reference. The process described therein is a microwave glow discharge deposition process which provides substantially increased deposition rates and reaction gas feed stock utilization. Among the many applications for amorphous semiconductor alloys, high deposition rates and reaction gas feed stock conversion efficiency and utilization are most essential for the commercial viability of electrophotographic devices utilizing such materials. High deposition rates and reed stock conversion efficiency and utilization are necessary because layer thicknesses of about 15 microns or more of amorphous semiconductor alloy are required in such devices to enable sufficient surface potential, about 350 volts, to be applied thereto. As a result, amorphous semiconductor alloys can be deposited at sufficient rates and have desired photoresponsive characteristics to enable the commercial utilization of such materials in electrophotographic devices.

The electrophotographic devices used in commercial practice usually take the form of cylindrical or dum members. An apparatus and method which facilitates the deposition of amorphous semiconductor alloys uniformly over the entire outer surface of such drums to form electrophotographic devices thereon is disclosed in U.S. Application Serial No. 580,086, also filed February 14, 1984, for "Method and Apparatus For Making Electrophotographic Devices", filed in the names of the current inventors, Eugene W. Fournier, Erik J. Bjornard, Annette G. Johncock and Joachim Doehler, which is incorporated herein by reference. At the same time, all of the advantages of microwave glow discharge processes including high reaction gas feed stock utilization can be realized. The present invention provides a method and apparatus to maximize and stabilize the power transmitted through the microwave window into the deposition chamber to enhance the microwave glow discharge process which can be utilized in making the above electrophotographic devices.

## SUMMARY OF THE INVENTION

The invention provides a method and apparatus for turning a microwave transmission window to maximize and stabilize the power transmitted through the window into a microwave plasma. The window is tuned to transmit the power required to achieve the plasma conditions desired. The power transmission through the window is tuned by adding a pair of tuning structures to the window. The tuning structures can be formed by stacking a plurality of small disks or other shaped pieces of dielectric material, such as alumina, adjacent the outer edge of the window. The width or diameter and the height of the tuning structures are adjusted to achieve both a high transmission coefficient as well as a consistent plasma excitation to provide stability in the plasma, for example, in a glow discharge deposition process. One particular utilization of the invention is with making electrophotographic devices incorporating amorphous semiconductor alloys as described in the above-referenced, copending applications.

Copending application Serial No. 580,086 provides a method and apparatus for depositing a layer of material onto the outer surface of at least a pair of cylindrical members. The method includes the steps of forming an inner chamber including the pair of cylindrical members by aligning the members with the longitudinal axes thereof disposed substantially parallel and the outer surfaces of the members closely spaced apart to form the inner chamber and a narrow passage communicating with the inner chamber between the members. The method further includes the steps of introducing at least one reaction gas into the inner chamber through the narrow passage, wherein, the at least one reaction gas includes at least one element to be deposited, and forming a plasma from the at least one reaction gas within the inner chamber to deposit the layer of material containing the at least one element onto the outer surface of the cylindrical members.

The inner chamber can be formed by forming a substantially closed loop of a plurality of the cylindrical members by aligning the members with the longitudinal axes thereof disposed substantially parallel and the outer surfaces of adjacent members closely spaced apart to form the inner chamber substantially closed and a narrow passage between adjacent members communicating with the inner chamber. The at least one reaction gas is then introduced into the inner chamber through at least one of the narrow passages.

The reaction gases can include silane ($SiH_4$), silicon tetrafluoride ($SiF_4$), germane ($GeH_4$), germanium tetrafluoride ($GeF_4$), diborane ($B_2H_6$), boron trifluoride ($BF_3$), phosphine ($PH_3$), phosphorus pentafluoride ($PF_3$), ammonia ($NH_3$), nitrogen ($N_2$), oxygen ($O_2$) and methane ($CH_4$) or combinations thereof. The plasma within the inner chamber can be formed by coupling microwave energy or radio frequency energy into the inner chamber through a microwave transmission window.

Serial No. 580,086 provides an apparatus for depositing a layer of material onto the outer surfaces of at least a pair of cylindrical members. The apparatus includes a substantially closed deposition chamber, means for aligning the members with the longitudinal axes thereof disposed substantially parallel with the outer surfaces of the members closely spaced apart to form a substantially closed inner chamber within the deposition chamber and a narrow passage communicating with the inner chamber between the members. The apparatus further includes means for introducing at least one reaction gas into the inner chamber through the narrow passage wherein the at least one reaction gas includes at least one element to be deposited onto the outer surfaces of the members. The apparatus further includes means for forming a plasma from the at least one reaction gas within the inner chamber to deposit the layer of material containing the at least one element onto the outer surface of the cylindrical members.

The apparatus can include means for aligning a plurality of the cylindrical members in a substantially closed loop with the longitudinal axes thereof disposed substantially parallel and the outer surfaces of adjacent members closely spaced apart to form the substantially closed inner chamber and a narrow passage between each pair of members communicating with the inner chamber. The reaction gas introducing means are arranged to introduce the reaction gas into the inner chamber through at least one of the narrow passages.

The plasma-forming means includes means for coupling microwave energy into the inner chamber through a microwave transmission window. To facilitate the uniform deposition onto the outer surfaces of the cylindrical members, the apparatus can further include means for rotating the cylindrical members about their own longitudinal axes and means for rotating the microwave energy polarity. The reaction gas introducing means preferably include means for introducing the reaction gas into the inner chamber through at least one of the narrow passages and means for pumping unused reaction gases from the inner chamber through at least one narrow passage other than the narrow passage through which the reaction gas is introduced into the inner chamber.

## BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a partial cross-sectional view of a cylindrical member having materials deposited thereon in accordance with Serial No. 580,086 wherein the deposited materials adapt the cylindrical member for used as an electrophotographic device which can embody the present invention;

Fig. 2 is a side view partly in cross section of an apparatus in accordance with Serial No. 580,086 which can embody the present invention;

Fig. 3 is a cross-sectional view taken along lines 3-3 of Fig. 2;

Fig. 4 is a side view, partly in cross section, of another apparatus in accordance with Serial No. 580,086 which can embody the present invention;

Fig. 5 is an explanatory sketch of the microwave power reflected by one transmission window;

Fig. 6 is an explanatory sketch of the microwave power transmitted by the window of Fig. 5;

Fig. 7 is a graph illustrating the reflected power versus plasma intensity relationship;

Fig. 8 is a side diagrammatic view of an embodiment of the present invention; and

Fig. 9 is a top plan diagrammatic view of the embodiment of Fig. 8.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figs. 1 through 4 describe the method and apparatus claimed in copending application, U.S. Serial No. 580,086 with one radio frequency embodiment, Fig. 5 deleted. The applicability of Serial No. 580,086 to the present invention is described with respect to Figs. 1 through 4 and the additional new disclosure and structures of the present invention are more particularly described with respec to Fig. 5 and the figures and specification thereafter.

Referring now to Fig. 1, it illustrates, in partial cross-sectional side view, an electrophotographic device 10 of the type which can be formed utilizing the present inventin by depositing various materials onto the outer surface of a cylindrical member 12. The cyclindrical member 12 forms the substrate of the electrophotographic device 10. The device 10 includes a first blocking layer 14 deposited onto the substrate 12, a photoconductive layer 16 deposited onto the first blocking layer 14, and a second blocking layer 18 deposited onto the photoconductive layer 16. The photoconductive layer 16 preferably is formed from an amorphous semiconductor alloy and more particularly, an amorphous silicon alloy containing silicon and hydrogen and/or fluorine. Depending upon the type of blocking layers 14 and 18 selected, and the type of charge utilized in charging the device 10, the photoconductive region 16 can also include small amounts of a dopant such as boron to provide the region 16 with substantially intrinsic properties. Similarly, the photoconductive region 16 can be rendered slightly n-type without any dopant included.

The bottom blocking layer 14 is provided to preclude charge injection from the substrate 12 into the photoconductive region 16. To that end, the bottom blocking layer 14 can be made insulative when formed from an amorphous alloy including silicon and carbon, silicon and oxygen, or silicon and nitrogen. In forming such bottom blocking layers, reaction gas mixtures of silane ($SiH_4$) and/or silicon tetrafluoride ($SiF_4$) with methane ($CH_4$), ammonia ($NH_3$), nitrogen ($N_2$) or oxygen can be used. Such blocking layers are suitable for both positive and negative charging of the electrophotographic device 10.

If positive charging of the electrophotographic device 10 is desired, the bottom electron blocking layer 14 can be, for example, a p-type amorphous silicon alloy formed from reaction gas mixtures including silane and/or silicon tetrafluoride with a p-type dopant-containing compound such as diborane ($B_2H_6$) or boron trifluoride ($BF_3$). In this case, it is also preferred that the photoconductive region 16 be formed from an amorphous silicon alloy which includes a small amount of p-type dopant achieving substantially intrinsic properties.

If negative charging is desired, the bottom hole blocking layer can be, for example, an amorphous silicon alloy which is n-type. To form such a blocking layer, reaction gas mixtures of silane and/or silicon tetrafluoride with an n-type dopant-containing compound, such as phosphine ($PH_3$) or phosphorus pentafluoride ($PF_5$) can be used. In this case, the photoconductive layer 16 is preferably formed from an amorphous silicon alloy which is slightly n-type.

The top blocking layer 18 can be formed from any of the materials mentioned with respect to the bottom blocking layer 14. Hence, the top blocking layer can be formed from an insulative material or a p-type or n-type amorphous semiconductor alloy as previously described above. For further details with respect to specific examples of some of the configurations and materials of electrophotographic devices of the type which can be made by utilizing the present invention, reference can be had to the aforementioned copending U.S. patent application Serial No. 580,081.

As disclosed in the above-mentioned copending application the photoconductive region 16 preferably is thick in dimension, being on the order of 10 to 25 microns thick to facilitate a sufficient surface potential characteristic of the device. As also disclosed in that application, in order to make such devices on a commercial basis, it is necessary to deposit the materials forming the photoconductive region 16 by a method which exhibits high deposition rates. Conventional radio frequency glow discharge deposition techniques are not suitable for forming the entire 10 to 25 microns thick photoconductive region 16. However, as disclosed in the aforementioned copending application, microwave energy excited glow discharge plasmas facilitate the deposition of the photoconductive region 16 at deposition rates which render such devices commercially viable. The apparatus and method of the present invention contemplate an improved utilization of microwave energy for forming a plasma from which the materials of the electrophotographic device can be deposited at such commercially viable rates and with gas feed stock utilization no heretofore possible.

The photoconductive region 16 can be formed from both microwave and radio frequency glow discharge plasmas or radio frequency energy could be utilized to ignite the plasma. In the case of utilizing radio frequency to deposit a portion of the region 16, the major portion of the photoconductive region 16 can be formed from the microwave energy glow discharge plasma and the remaining or top portion of the photoconductive region 16 can then be formed from the radio frequency glow discharge plasma. The apparatus and method accommodates both modes of operation in order to facilitate the making of electrophotographic copier drums having desired photoresponsive and charge retention characterisitics to render the devices especially useful for electrophotographic copying.

Referring now to Figs. 2 and 3, they illustrate an apparatus 20, which can embody the present invention adapted for depositing a layer or layers of material, preferably amorphous semiconductor alloys, onto a plurality of drums or cylindrical members 12. The apparatus 20 includes a deposition chamber 22. The chamber 22 includes a pump-out port 24 adapted for suitable connection to a pump for pumping out reaction products from the chamber and to maintain the interior of the chamber at an appropriate pressure to facilitate the deposition process therein. The chamber 22 further includes a plurality of reaction gas input ports 26, 28, and 30 through which reactin gases are introduced into the depositon environment in a manner to be described hereinafter.

Within the chamber 22, there are supported a plurality of cylindrical members or drums 12. The drums 12 are arranged to form a substantially closed loop with the longitudinal axes of the drums being disposed substantially parallel and the outer surfaces of adjacent drums being closely spaced apart to form an inner chamber 32. For disposing the drums 12 in this manner, the chambe 22 includes a pair of upstanding walls 34 and 36 which support thereacross a plurality of stationary shafts 38. Each of the drums 12 is mounted for rotation on a respective one of the shafts 38 by a pair of disc-shaped spacers 40 and 42. The spacers 40 and 42 have an outer dimension corresponding to the inner dimension of the drums 12 to thereby make frictional engagement with the inner surfaces of the drums 12 for accurately positioning the drums with respect to one another. The spacers 40 include a sprocket 44 arranged to engate a drive chain 46. The drive chain 46 makes a continuous loop around the sprockets 44 and a drive sprocket 48 of a motor 50. Although the drums 12 are illustrated as having the support and drive mechanisms within the chamber 22, this structure can be external to the chamber 22 with appropriate vacuum feedthrough seals where desired. As a result, and as will be further explained hereinafter, during the deposition process the motor 50 is energized to cause each of the drums 12 to be rotated about its onw longitudinal axis. This facilitates a uniform deposition of the material being deposited over the entire outer surface of each of the drums 12.

As previously mentioned, the drums 12 are disposed so that the outer surfaces thereof are closely spaced apart to form the inner chamber 32. As can be noted in Fig. 3, the reaction gases from which the deposition plasma is formed are introduced into the inner chamber 32 through at least one of a plurality of narrow passages 52 formed between one pair of adjacent drums 12. Preferably, the reaction gases are introduced into the inner chamber 32 through every other one of the narrow passages 52.

Referring to Fig. 3, it can be seen that the plasma is confined within the inner chamber 32. The plasma changes in intensity as the surfaces of the drums 12 are rotated into and then out of the chamber 32. This can result in defects being formed in the weaker plasma regions in or adjacent the narrow passages 52. To avoid the possibility of a large plurality of defect regions or defect layers being formed as the material is deposited on the surface of the rotating drums 12, the drums 12 can be rotated a single or several revolutions to achieve a deposited high quality material of the thickness desired. For example, the drums 12 can only be rotated a single revolution to deposit the required material thickness to form the bottom blocking layer 14.

In Fig. 3, it can be noted that each pair of adjacent drums 12 is provided with a gas shroud 54. Each shroud 54 is connected to one of the reaction gas inlets 26, 28, and 30 by a conduit 56. Each shroud 54 defines a reaction gas reservoir 58 adjacent the narrow passage through which the reaction gas is introduced. The shrouds 54 further include lateral extensions 60 which extend from opposite sides of the reservoirs 58 and along the circumference of the drums 12 to form narrow channels 62 between the shroud extensions 60 and the outer surfaces of the drums 12.

The shrouds 54 are configured as described above so that the gas reservoirs 58 permit relatively high reaction gas conduction while the narrow channels 62 provide a high resistance or low conduction of the reaction gases. Preferably, the vertical conductance of the reaction gas reservoirs 58 is much greater than the conductance of the narrow passage 52 between the drums. Further, the conductance of the narrow passages 52 is much greate than the conductance of the narrow channel 62. This assures that a large percentage of the reaction gas will flow into the inner chamber 32 and uniform gas flow along the entire lateral extent of the drums 12.

The shrouds 54 further include side portions 64 which overlap end portions of the drums 12 and spacers 42 and 44. The side portions 64 are closely spaced from the end portions of the drums 12 and spacers 42 and 44 to continue the narrow channels 62 across the ends of the drums. The side portions 64 thereby impede reaction gas flow around the ends of the drums. It has been discovered by Applicants that the apparatus 20 can be utilized withoug the shrouds 54.

As can also be noted Fig. 3, in accordance with this embodiment, the narrow passages 66 which are not utilized for reaction gas introduction into the inner chamber 32 are utilized for conducting reaction products from the inner chamber 32 and the chamber 22. When the pump which is coupled to the pump-out port 24 is energized, the interior of the chamber 22 and the inner chamber 32 is pumped out, with the inner chamber being pumped out through the narrow passages 66. In this manner, reaction products can be extracted from the chamber 22 and the interior of the inner chamber 32 can be maintained at a suitable pressure for deposition.

To facilitate the formation of the deposition plasma identified by reference character 68 in Fig. 2, the apparatus 20, in accordance with this preferred embodiment, further includes a first microwave energy source 70 and a second microwave energy source 72. Each of the microwave energy sources 70 and 72 includes an antenna stub 74 and 76, respectively. The microwave energy sources 70 and 72 can be, for example, microwave frequency magnetrons having an output frequency of, for example, 2.45 $GH_z$. The magnetrons 70 and 72 are mounted to a cylindrical waveguide structure 78 and 80, respectively. The stubs 74 and 76 are spaced from back walls 79 and 81 of the waveguides 78 and 80 by a distance of about one-quarter of the waveguide wavelength. This spacing maximizes the coupling of the microwave energy from the stubs to the waveguides. The waveguide structures 78 and 80 are mounted for rotation onto another waveguide 82 and 84, respectively. The waveguides 82 and 84 project into the chamber 22 and terminate in close proximity to the edge portions of the drums 12. The end portions of the waveguides 82 and 84 include a lip portion 86 and 88. Against each of the lip portions 86 and 88 is disposed a sealing O-ring 90 and 92 each of which, together with the lip portions 86 and 88, supports a respective microwave transmission window 94 and 96. The transmission windows 94 and 96 together with the drums 12 define the substantially closed inner chamber 32. The present invention can be utilized to maximize and stabilize the microwave power transmitted through the windows 94 and 96.

The waveguides 78 and 82 form a coupling means for coupling the microwave energy generated by the magnetron 70 into the inner chamber 32. Similarly, the waveguides 80 and 84 define a coupling means for coupling the microwave energy generated by magnetron 72 into the inner chamber 32. The microwave energy generated by the magnetrons 70 and 72 is radiated by the antenna stubs 74 and 76, which determine the polarization of the radiated microwave energy. In order to avoid interaction between the stubs 74 and 76, the antenna stubs preferably are displaced from each other by an angle. In accordance with this preferred embodiment, the angle between the stubs is about 60°. However, for systems incorporating a greater number of drums than the six drums illustrated herein, the angle of displacement between the antenna stubs 74 and 76 will vary. The reason for this is that it is preferred that the antenna stubs be disposed with respect to the drums 12, so that each stub forms an identical and uniform microwave energy field within the inner chamber 32.

The windows 94 and 96, in addition to enclosing the inner chamber 32, protect the magnetrons 70 and 72 from the reaction gases. They further serve to preclude the formation of a plasma at the magnetron probes 74 and 76 and they also provide a low loss coupling of the microwave energy into the inner chamber 32. To that end, the windows 94 and 96 can be formed from a material such as alumina, and have a thickness which provides low reflected power into the waveguides 82 and 84.

To further diminish the interaction between the magnetrons 70 and 72, each magnetron can be energized sequentially. For example, if alternating current is being utilized to energize the magnetrons, the magnetrons can be energized during alternate half cycles of the alternating current. In this manner, the interaction between the magnetrons can be further diminished.

As previously mentioned, the waveguides 78 and 80 are mounted for rotation on their respective waveguides 82 and 84. As a result, each of the magnetron sources 70 and 72 can be rotated about the longitudinal axis of the waveguides 82 and 84 to rotate the polarity of the microwave energy to even out the microwave field. Such rotation assures that the time average density of depositing species is radially uniform. The polarization could also be circular to even out the field.

In utilizing the apparatus 20 of Figs. 2 and 3 for depositing a material onto the outer surfaces of the drums 12, and more particularly for depositing layers of materials to form electrophotographic copier drums, the drums 12 are first mounted as illustrated and as described above. Thereafter, reaction gases are introduced through the inlet ports 26, 28, and 30 while the chamber 22 is pumped out by the pump coupled to the outlet 24. With the reaction gases introduced into the inner chamber 32, the magnetrons 70 and 72 are then energized to couple microwave frequency energy into the inner chamber 32 to form a glow discharge plasma therein. The microwave energy is readily coupled into the inner chamber 32, because the inner chamber itself defines a waveguide structure at microwave frequencies.

The motor 50 is then energized to cause the drums 12 to be rotated about their own longitudinal axes. The magnetrons 70 and 72 can then also be rotated about the waveguides 82 and 84 as previously described. As a result of the foregoing, a uniform deposition of material will ensue upon the entire outer surfaces of the drums 12.

During the deposition process, it may be desirable to heat the drums 12. To that end, the apparatus 20 further includes a plurality of heating elements 100 which are mounted to the stationary shafts 38 by spacers 102. Since the shafts 38 are stationary, the heating elements 100 will also be stationary within the drums 12. The heaters 100 can take the form of resistance heating elements or incandescent lamps. for the deposition of amorphous semiconductor alloys, the drums are preferably heated to a temperature between 20°C and 400°C, and preferably, about 300°C. It can also be desirable to preheat the reaction gases prior to introduction thereof into the inner chamber 32. This can be accomplished, for example, by heating the shrouds 54 to about 300°C by slug heaters incorporated therein or lamps disposed adjacent the shrouds 54 external to the deposition region.

For making an electrophotographic drum as illustrated in Fig. 1, the first blocking layer 14 as previously described can be formed from an insulative material, a p-type amorphous silicon alloy, or an n-type amorphous silicon alloy. When the blocking layer 14 is formed from an insulative material such as silicon nitride, silicon carbide, or silicon dioxide, the reaction gases introduced into the inner chamber during the deposition process can be silane ($SiH_4$) and /or silicon tetrafluoride ($SiF_4$) with methane, nitrogen, ammonia, or oxygen. Such a blocking layer can be utilized for both positive and negative charging of the electrophotographic drum.

When the blocking layer 14 is a p-type amorphous silicon alloy, the reaction gases introduced into the inner chamber 32 can be silane and/or silicon tetrafluoride with diborane or boron trifluoride. Such a blocking layer is suitable for an electrophotographic drum to be positively charged.

When the blocking layer 14 is to be formed from an n-type amorphous silicon alloy, the reaction gases introduced into the iner chamber can be silane and/or silicon tetrafluoride and phosphine or phosphorus pentafluoride gas. Such a blocking layer is suitable for an electrophotographic device to be negatively charged.

For making the photoconductive region 16, the photoconductive region 16 can be an amorphous silicon alloy incorporating silicon, hydrogen, and/or fluorine. Such a material can be deposited from reaction gases of silane, and/or silicon tetrafluoride, and hydrogen. If the photoconductive region is to be rendered substantially intrinsic, boron trifluoride or diborane gas can also be utilized. If it is to be slightly n-type, no dopant is utilized.

In some instances, as fully described in cross-reference Serial No. 580,081, it may also be desirable to incorporate a layer of material in the photoconductive region 16 towards the top thereof which has a more narrow band gap than the bulk of the photoconductive region. To deposit such a material, germane ($GeH_4$) or germanium tetrafluoride - ($GeF_4$) gas can also be introduced into the inner chamber 32. The germane or garmanium tetrafluoride together with the silane and/or silicon tetrafluoride will form an amorphous silicon germanium alloy having a reduced band gap for infrared photoresponsive applications. Also, as fully described in cross-referenced Serial No. 580,081, a top blocking enhancement layer can be deposited before the top blocking layer 18 by RF deposition.

Lastly, for forming the top blocking layer 18, any of the materials and gas mixtures previously referred to form the bottom blocking layer 14 can be utilized. During the deposition of any one of the layers 14, 16, or 18, it may be desirable to introduce a plasma-sustaining gas such as argon. Also, the pressure within the inner chamber should be about .05 Torr or less.

Referring now to Fig. 4, it illustrates another apparatus 110 which can embody the present invention. The apparatus 110 in the major respects thereof is essentially identical to the apparatus 20 of Fig. 2. Therefore, the apparatus 110 will be described only to the extent of the difference between the apparatus 110 and the apparatus 20 of Fig. 2.

As can be notd from Fig. 4, the apparatus 110 includes a single source of microwave energy, magnetron 70. The other magnetron has been removed and a plate 112 is substituted therefor. The plate 112 makes contact with a cylindrical tube 114 which supports the window 96 at its end opposite the plate 112 and a wall 116 intermediate its ends. As a result, a single magnetron 70 can be utilized for coupling microwave energy into the inner chamber 31. Again, during the deposition, the magnetron 70 can be rotated about the waveguide 82 to rotate the polarization of the microwave field.

As will also be noted in Fig. 4, the apparatus 110 includes a cylindrical waveguide structure 120 formed from a wire mesh or screen. The waveguide structure 120 is disposed within the inner chamber 32 and preferably is closely spaced with respect to the drums 12. The waveguide structure 120 can be utilized to provide a more uniform and continuous waveguide structure and thereby provide more efficient propogation of the microwave energy within the inner chamber 32. However, the waveguide structure 120 will decrease the gas utilization efficiency of the system by a small amount inasmuch as deposition will take place on the waveguide structure 120.

Referring now to present invention, Applicants have discovered that the tuning of the power transmitted through a transmission window is not as simple as might first be assumed. Applicants have discovered that there are a number of important conditions which must be taken into account.

1. The frequency of the microwave power generator or magnetron is not fixed. The frequency depends on the magnetron output power and therefore oscillates in a band (about 50MHz) in synchronism with the power supply output ripple. The frequency also varies in accordance with the magnetron temperature and fluctuates as the magnetron cooling water temperatures and pressure varies.

2. There are unavoidable dimensional changes in the deposition chamber as the glow discharge process proceeds due to the changes in temperature of the transmission window structure which cause the window to expand.

3. A separate conventional tuner can, in principle, compensate for any dielectric discontinuity introduced in the waveguide by the transmission window. Applicants, however, have determined that such a separate tuner (such as a 4-stub unit) absorbs more power as the mismatch increases. In some cases, the separate conventional tuner has resulted in power absorption of greater than ninety percent.

4. The microwave power or radiation transmitted through the window into the process gas must both ignite the glow discharge plasma and maintain the plasma. A single, high-Q, tuner configuration cannot tune the deposition system for both the plasma off and plasma on conditions, since the complex dielectric constant of the ignited plasma is not the same as the complex dielectric constant of the gas in the deposition system with the plasma off. A compromise must be made.

5. The tuning for the plasma on condition is not necessarily stable when various process gases are utilized, since the complex dielectric constant of the plasma and the microwave power absorbed by the plasma couple to each other through changes in the microwave transmission. The plasma conditions, such as the species existing from the various reaction gases, are in part dependent upon the amount of power transmitted into the plasma and in turn the reflected power is related to the plasma conditions which the microwave energy sees.

Applicants have discovered that item 3, above, requires that the window structure must have low-loss tuning elements, close to the window to reduce the standing wave current in the tuner. Items 4 and 5, above, do not require further changes in the tuning configuration once an acceptable compromise has been found.

Applicants originally assumed that the window only needed to be matched for one parameter, that being a suitable transmission over an acceptable broad band. After further investigation, a second parameter was formed which must be dealt with. Referring now to the power reflected by a window illustrated in Fig. 5 and the power transmitted by the window illustrated in Fig. 6, there are two major reflection peaks 150 and 152. (It should be noted that a difference in measuring instrumentation resulted in a reversal of the X and Y axis directions between Fig.5 and Fig.6). The peaks 150 and 152 have the following characteristics:

(1) The peaks are extremely narrow, on the order of 2MHz. In order even to be found, the instrumentation must be precisely adjusted. Because of their narrow width, the peaks at first were not even discovered.

(2) The frequency at which the peaks occur depends upon the diameter of the transmission window. The peaks hence can drift into the magnetron frequency band as windows are changed or as the various fluctuations described above occur.

(3) The peaks introduce a large discontinuity in the matching of the window to the plasma.

Applications have interpreted the peaks 150 and 152 as mode shifts in the transmission window. Because of the high dielectric constant of the window material, such a alumina, the optical size of the window (in this example, four inches in diameter) is large enough to sustain four propagation modes. The magnetron operating frequency is, in the examples illustrated, 2.45 GHz. Other frequencies can be utilized in accordance with the invention. The cut-off frequency of the fifth propagation mode was determined to be substantially at the operating frequency. The deposition or other plasma system can be operated satisfactorily with whatever number of modes are propagated through the window, however, it appears that the system does not operate properly if the microwave propagation energy switches randomly from one mode to another. This can cause an unstable plasma condition which can vary the deposition parameters and can result in the plasma going into the off condition.

A further operating condition which must be taken into account is illustrated in the graph of Fig. 7. The plasma intensity (1) is related to the reflected power (R) by an operating curve 154. A point of minimum R 156 would appear to be the optimum operating condition, since the point 156 is the lowest lost R point. However, if the plasma conditions move toward a lesser intensity, i.e. the plasma becomes weaker for any reason, the R increases in a runaway or unstable type of condition and hence the plasma will go off. Therefore, a compromise operating region 158 is chosen in which to operate the system, which is a slightly higher R loss region, but which is a stable plasma operating region.

To compensate for the above discovered conditions, Applicants have invented the following tuning method and apparatus. Referring to Figs. 8 and 9, a microwave transmission window 160 is mounted in one end of a microwave transmission system 162. A plasma (not shown) will exist on the free side of the window 160. A pair of tuning structures 164 and 166 embody the present invention. As illustrated, each of the structures 164 and 166 are formed from a plurality of separate segments 168, which preferably are formed from the same dielectric material as the window 160 to provide the required low loss tuning structures. The segments can be disks 168 or can be any other shape such as a rectangle 168′. The size of the segments 168 and the heights of the tuning structures 164 and 166 are adjusted to achieve both high transmission through the window and a stable plasma mode excitation. The structures 164 and 166 then are fixed such as by tape or other adhesive and the window 160 is then tuned for the desired system operation.

The segments 168 and tape or adhesive are selected to have minimum microwave absorption properties and can be formed from the same materials as the window 160 or from other suitable dielectric material. The system is tuned for a compromise between the plasma off and on conditions, but at a level which will still allow for the plasma to be ignited, although a separate RF or other signal could be utilized to ignite the plasma. The tuning structures 164 and 166 provide substantially the lowest possible power loss, because the structures are placed onto the surface of the window 160 itself. Any tuning structure, such as the conventional stub which is placed close to, but separate from the window 160, will result in power being reflected between the stub and the window resulting in heating of the system and hence a power loss. Referring to Figs. 5A, 5B, 6A and 6B, the widths of the segments 168 are chosen to move the magnetron operating frequency to a midpoint between the peaks 150 and 152 to provide a stable operating region between the peaks. Further, the height of the tuning structures 164 and 166 is selected to move the operating R point towards a minimum amount (Figs. 5A and 5B).

In addition, although the present invention has been particularly described with respect to the formation of electrophotographic drums, it can be appreciated by those skilled in the art that the method and apparatus of the present invention can be utilized with any type of microwave transmission window and any type of plasma. Although alumina is a preferably window material when depositing silicon, other types of plasma which do not contain silicon, such as a plasma etching system could use other dielectric materials, such as quartz. Applicants have discovered that quartz is not a preferable material when utilizing silicon, since the window 160 must be cooled to prevent the silicon deposited on the window surface from crystallizing, which can cause thermal runaway and hence require a shut down of the system operation. Alumina or another dielectric material with high thermal conductivity is thus preferred for utilization with a silicon depositing plasma. As a result of the foregoing, it can be seen that the present invention can be practiced in a manner otherwise than as specifically described herein.

## Claims

1. A method of tuning a microwave transmission window (160), comprising:
providing microwave generating means (74, 76);
providing a plasma chamber (22);
coupling said chamber to said generating means through a dielectric microwave transmission window; and
tuning said window to maximize the power generated by said generating means and transmitted through said window into said chamber by providing at least two tuning structures (164, 166) and placing said structures adjacent the outer edges of said window.

2. The method as defined in claim 1 wherein said tuning includes forming each of said tuning structures from a plurality of dielectric segments - (168) placed on top of one another.

3. The method as defined in claim 2 wherein said tuning includes sizing said segments as to width and adjusting the height of said structures to maximize said transmitted power.

4. The method as defined in claim 3 further including tuning said segments to stabilize the modes transmitted into said chamber.

5. The method as defined in claim 1 including introducing a least one reaction gas into said chamber and forming a plasma from said reaction gas prior to tuning said window.

6. The method as defined in claim 5 wherein said at least one reaction gas is a semiconductor containing compound.

7. The method as defined in claim 6 wherein said at least one reaction gas includes silicon.

8. The method as defined in claim 1 further including the step of maintaining the pressure within said inner chamber at about .05 Torr or less.

9. The method as defined in claim 1 further including the step of adjusting the power density of said microwave energy between about .1 to 1 watt per cubic centimeter.

10. The method as defined in claim 1 wherein the frequency of said microwave energy is 2.45 Gigahertz.

11. An apparatus for tuning a microwave transmission window (160), comprising:
generating means (74, 76);
a plasma deposition chamber (22);
said chamber coupled to said generating means through a dielectric microwave transmission window; and
means for tuning said window to maximize the power generated by said generating means and transmitted through said window into said chamber, said tuning means including at least two tuning structures (164, 166) located adjacent the outer edges of said window.

12. The apparatus as defined in claim 11 wherein each of said tuning structures is formed from a plurality of dielectric segments (168) placed on top of one another.

13. The apparatus as defined in claim 12 wherein said segments are sized as to width and the height of said structures is adjusted to maximize said transmitted power.

14. The apparatus as defined in claim 12 wherein said segments are utilized to stabilize the modes transmitted into said chamber.

15. The apparatus as defined in claim 12 wherein said window and said segments are formed from alumina.

16. A tuned microwave transmission window - (160) for a plasma deposition system, said system including microwave generating means (74, 76) coupled to a plasma deposition chamber (22) through the transmission window, said tuned window comprising:
a dielectric window member coupling and separating the microwave generating means from the deposition chamber, means for tuning said dielectric window member to maximize the power generated by said generating means and transmitted through said dielectric window member into said chamber, said tuning means including at least two tuning structures (164, 166) located adjacent the outer edges of said dielectric window member.

17. The apparatus as defined in claim 16 wherein each of said tuning structures is formed from a plurality of dielectric segments (168) placed on top of one another.

18. The apparatus as defined in claim 17 wherein said segments are sized as to width and the height of said structures is adjusted to maximize said transmitted power.

19. The apparatus as defined in claim 18 wherein said segments are utilized to stabilize the modes transmitted into said chamber.

20. The apparatus as defined in claim 17 wherein said dielectric window member and said segments are formed from alumina.

FIG I

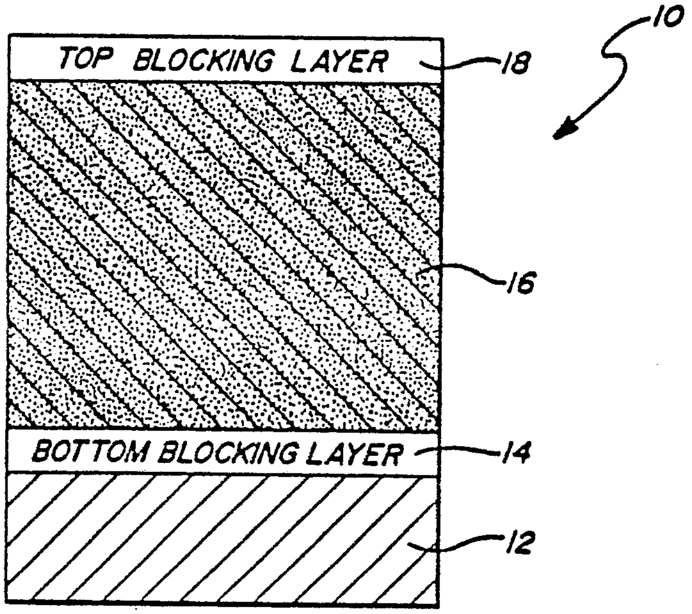
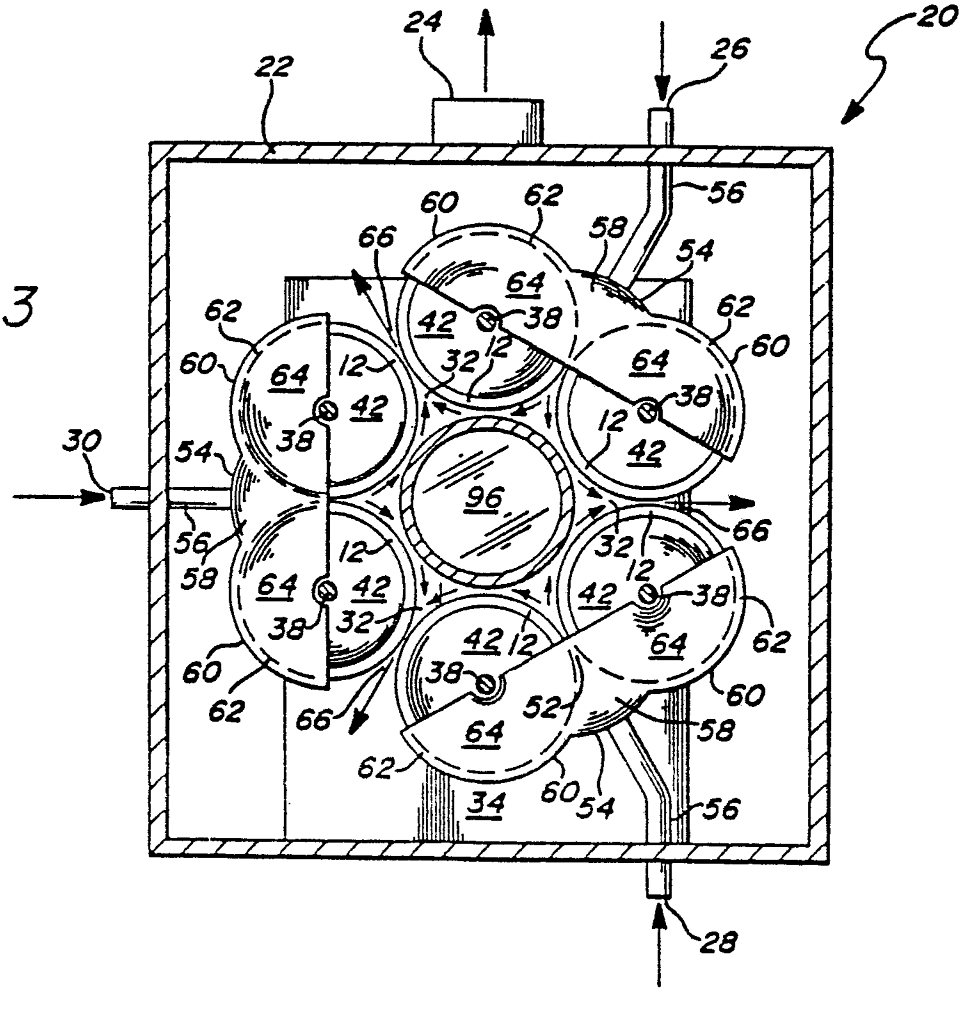

10
TOP BLOCKING LAYER
18
16
BOTTOM BLOCKING LAYER
14
12

FIG 3


20
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12
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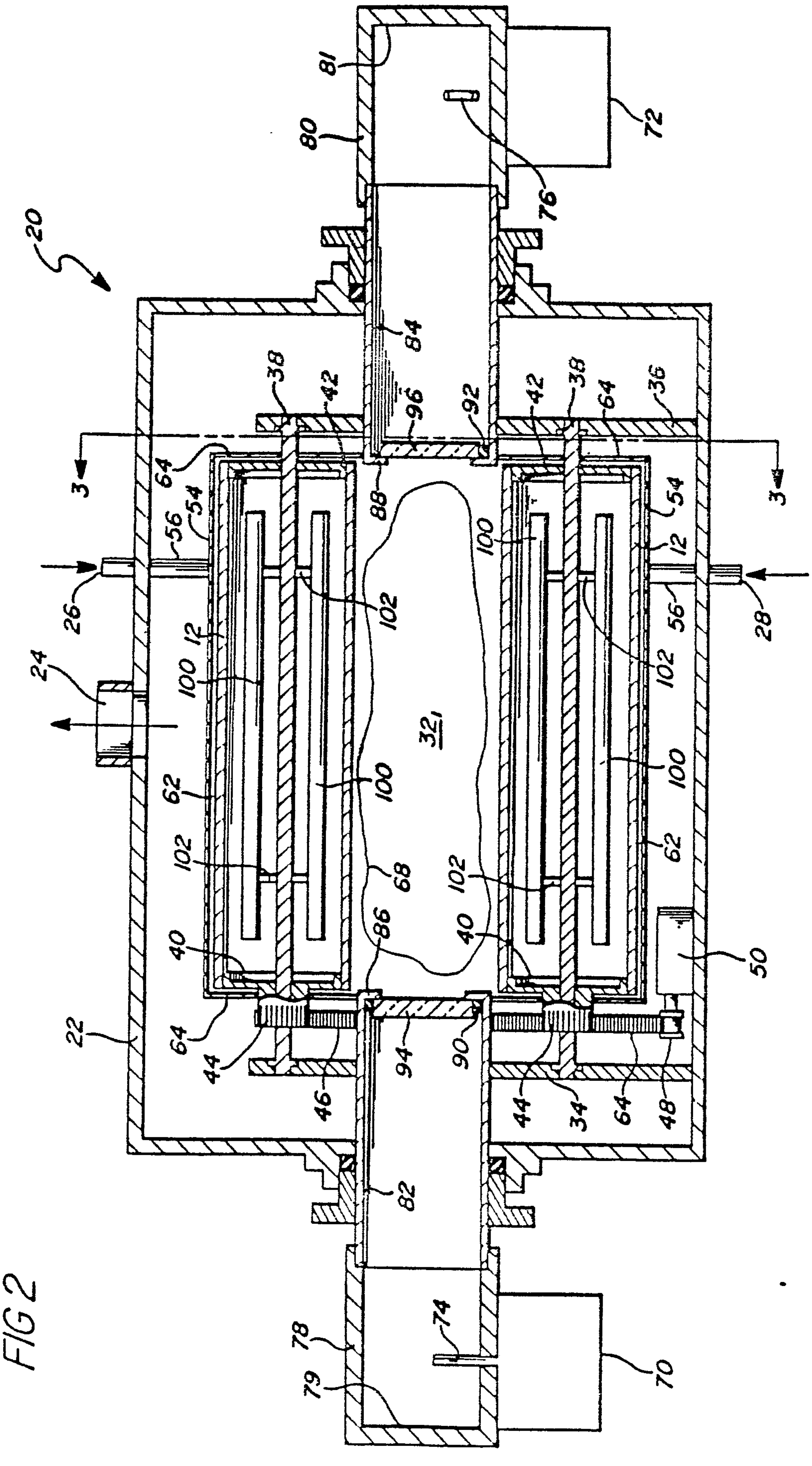
34
28


20
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54
12
26
24
12
100
102
102
28
56
102
32
100
100
62
62
102
68
102
40
86
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94
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44
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64
48
82
78
79
74
70

FIG 2

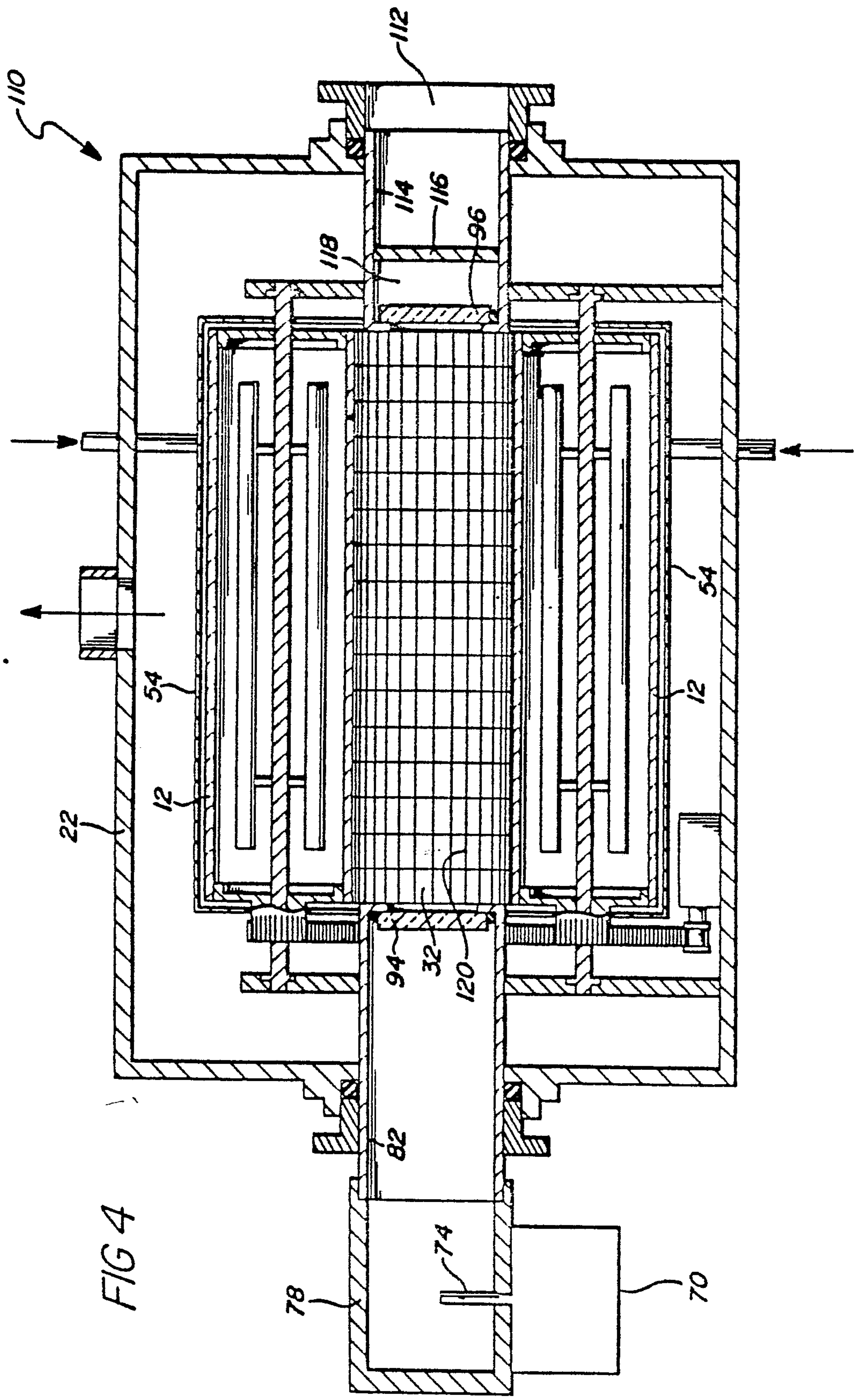

FIG 4

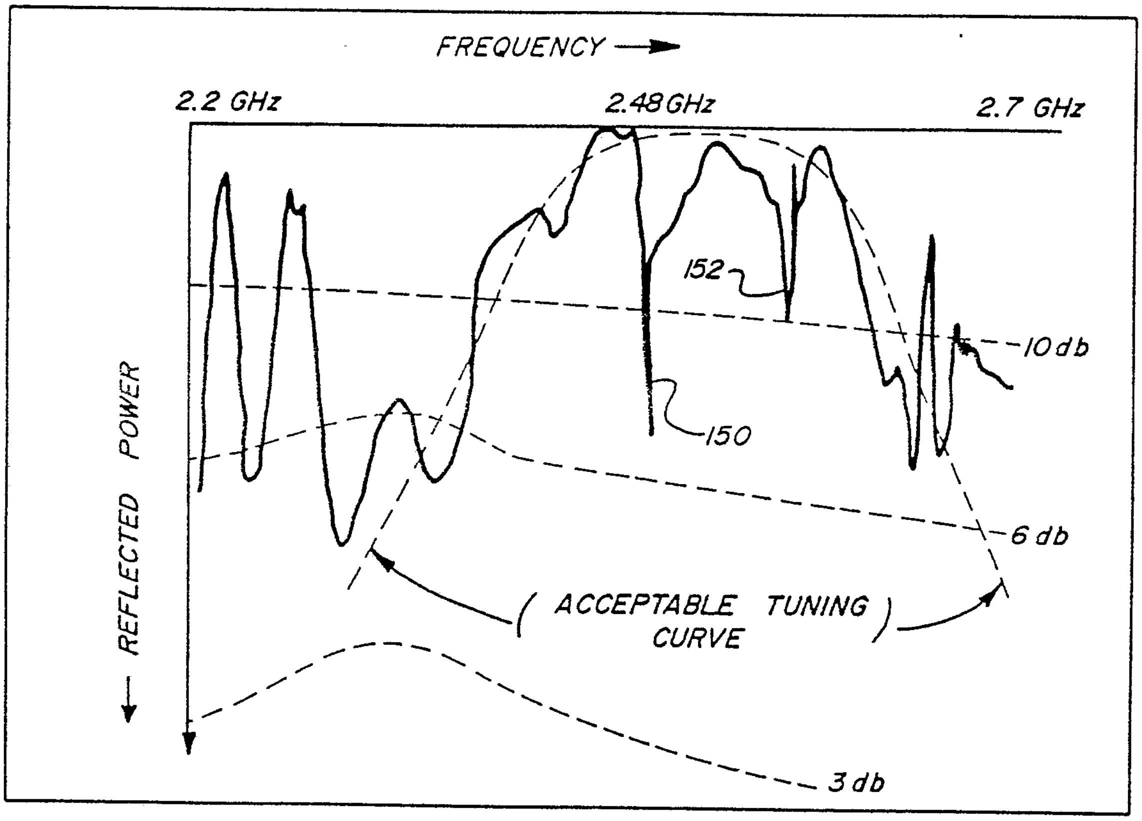
FREQUENCY →
2.2 GHz
2.48 GHz
2.7 GHz
152
10 db
150
6 db
← REFLECTED POWER
( ACCEPTABLE TUNING CURVE )
3 db

FIG. 5

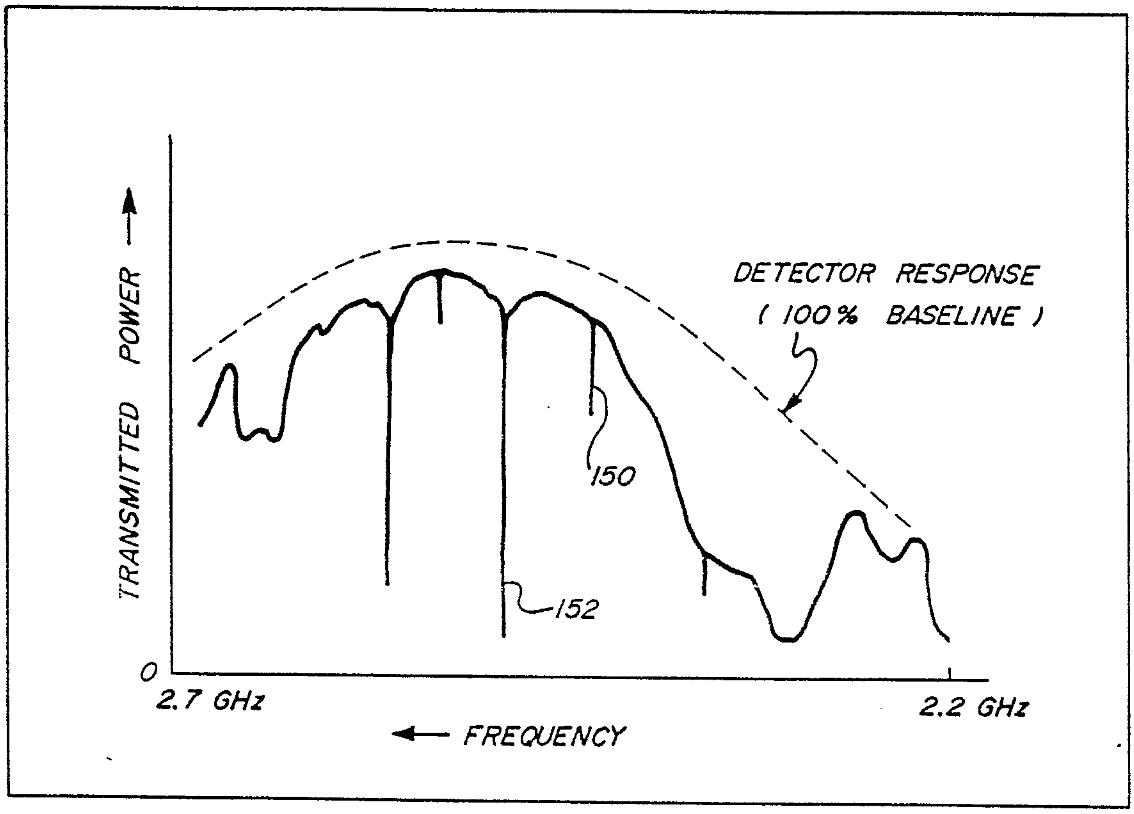
TRANSMITTED POWER →
DETECTOR RESPONSE ( 100% BASELINE )
150
152
0
2.7 GHz
2.2 GHz
← FREQUENCY

FIG. 6

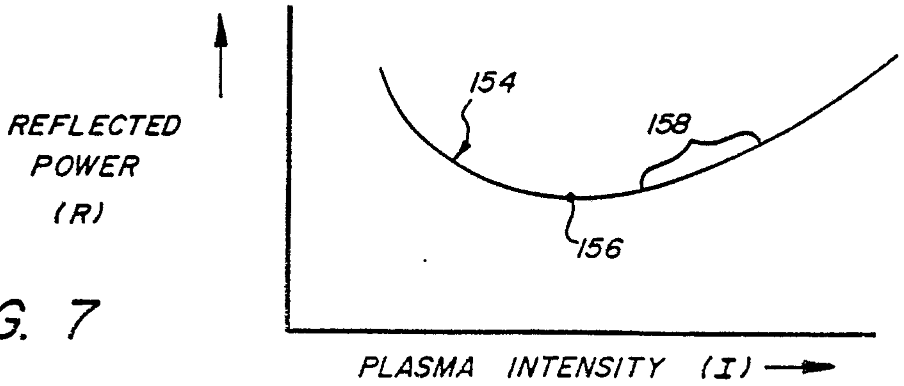

FIG. 7

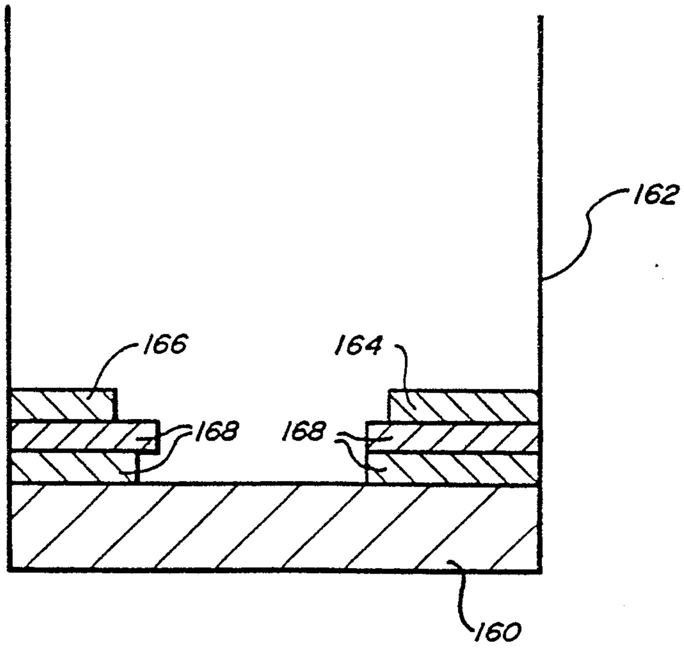

FIG. 8

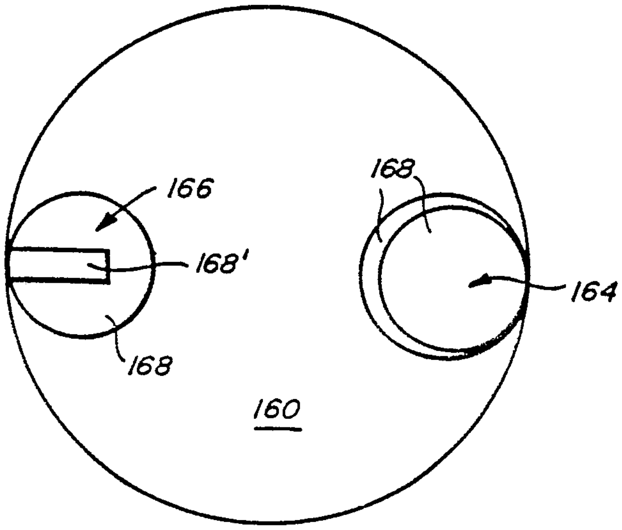

FIG. 9