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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ^{6} :
H01J 61/06

A1

(11) International Publication Number: **WO 99/41767**

(43) International Publication Date: 19 August 1999 (19.08.99)

(21) International Application Number: PCT/US99/02948

(22) International Filing Date: 10 February 1999 (10.02.99)

(30) Priority Data:
09/022,507 12 February 1998 (12.02.98) US

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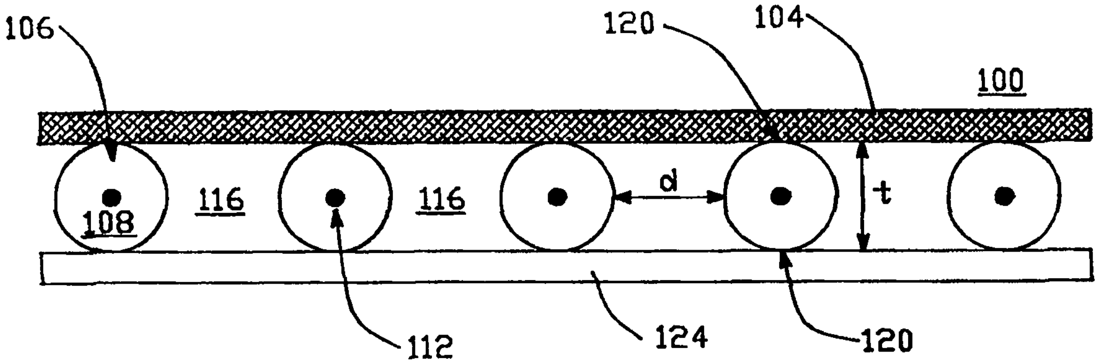
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.

(54) Title: LARGE AREA SILENT DISCHARGE EXCITATION RADIATOR



(57) Abstract

Ultraviolet and vacuum ultraviolet radiators (100) for use in the manufacture of semiconductors are provided which have improved lifetimes, improved distribution of radiation generation, improved distribution of emitted radiation, increased efficiency of radiation emission, and improved means for cooling. The radiators (100) have novel electrodes (106), novel electrode configurations, novel means for distributing plasmas between electrodes, and have novel cooling means. These features enable the miniaturization of the radiators permitting high intensity and uniform radiation exposure of planar surfaces. The radiators are used in the pre-treatment of semiconductor surfaces, the deposition of semiconductor thin films, and the post-deposition processing of semiconductor thin films.

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LARGE AREA SILENT DISCHARGE EXCITATION RADIATOR

BACKGROUND OF THE INVENTION

I. Field of the Invention

The present invention relates to the field of devices for the generation of electromagnetic radiation of the ultraviolet and vacuum ultraviolet wavelengths useful in the manufacture and processing of semiconductor devices.

II. Discussion of the Related Art

A. Semiconductor Manufacturing Problems

The manufacture of semiconductor devices relies on the deposition of thin, even films of desired chemical composition and structure. Deposition of thin, even films requires that the surface on which the film is to be deposited to be smooth and even. Otherwise, the deposited layer will not be smooth and even. One aspect of this property of film deposition is termed "surface sensitivity." {See Kwok et al., *J. Electrochem. Soc.*, 141(8):2172-2177 (1994); Matsuura et al., *Proceedings of the 22^{d} International Conference on Solid State Devices and Materials, Sendai*, pp:239-242 (1990); Fujino et al., *J. Electrochem. Soc.* 138(2):550-554 (1991); and Fujino et al., *J. Electrochem. Soc.* 139(6):1690-1692 (1992), each incorporated herein fully by reference.} Surface sensitivity is characterized by inconsistent and variable deposition rates and increased roughness of the resulting films as the process conditions are varied. The process conditions of interest are deposition temperature, deposition pressure, mole-fraction of the reactants (e.g., TEOS and ozone), and possibly some hardware conditions specific to the design of the reactor used to deposit these films.

An approach to decrease the surface sensitivity is to modify the surface of the underlying film. Maeda et al., U.S. Patent No. 5,387,546 taught the exposure of deposited semiconductor films to ultraviolet radiation during heating. The ultraviolet radiation was produced by a mercury lamp which generates electromagnetic radiation with wavelengths of 185 nanometers (nm) and 254 nm, as well as some longer wavelength radiation. However, because this process is carried out on layers of USG film which have already been deposited, it does not deal with the problem of surface sensitivity. Thus, there is a need for improved ways of reducing surface sensitivity.

Additionally, with increasing miniaturization of semiconductor devices, as the gaps between device features decreases, these gaps becomes increasingly more difficult to fill adequately with dielectric material. Moreover, as the surface films increase in thickness, the corresponding film does not completely fill the gap, resulting in the formation of a "void." This is especially the case if there is surface sensitivity of deposition of materials within the gap. Films which provide a conformal coating of device features, result in the formation of voids as the gaps becomes filled. These voids can trap contaminants which can degrade the integrated circuit device, and are not effective dielectrics. Thus, there is a need for improved gap filling in the manufacture of semiconductor devices.

Additionally, as circuit feature density increases, there is a need for developing new dielectric materials. Such materials include organic polymers. Deposition of these polymers can be accomplished by dissociating precursors with reactive intermediates and permitting these intermediates to polymerize on the semiconductor substrate. To improve the physical and chemical properties of these deposited materials, dissociation of precursors can be accomplished using electromagnetic radiation in the ultraviolet and vacuum ultraviolet wavelengths. However, the currently available devices for such irradiation are not well suited to optimizing the exposure of substrates and films to ultraviolet radiation. The problems and attempted solutions to these problems are discussed in more details below.

B. Ultraviolet and Vacuum Ultraviolet Lamps

Lamps for producing ultraviolet or vacuum ultraviolet radiation are known in the art, and are exemplified by the devices described in Kogelschatz, U.S. Patent No. 5,432,398; Kogelschatz, U.S. Patent No. 5,386,170; Eliasson et al., U.S. Patent No. 4,837,484; Eliasson et al., U.S. Patent No. 4,945,290; Eliasson et al., U.S. Patent No. 4,983,881; Gellert et al., U.S. Patent No. 5,006,758; Kogelschatz et al., U.S. Patent No. 5,198,717; and Kogelschatz, U.S. Patent No. 5,214,344. Each of the aforementioned references in herein incorporated fully by reference.

Dielectric barrier discharge devices consist of two conductive electrodes, at least one of which is covered with a dielectric layer and are separated from each other by an emitter moiety-containing gap. Emitter moieties are usually in the form of a gas, whose atoms, under normal temperatures and other pressures, do not form chemical bonds between them. For example, at usual temperatures and pressures, noble gases normally do not form interatomic bonds. However, under high energy conditions, such as those present in plasmas, the emitter moieties lose electrons, and therefore the moieties can form intra-atomic bonds, thereby forming “excited emitter moieties.” “Excited emitter moieties” as herein defined comprise at least two emitter moieties bonded to each other under conditions of radiator operation. These bonds have high energy and are unstable, and upon their breakdown, electromagnetic radiation of wavelengths characteristic of the excited emitter moiety is emitted.

The high energy plasma used to form the excited emitter moieties is generated by dielectric discharge, which is generated when an electrical field is created between electrodes with high resistance to electric current flow between them. Electrodes are coated with a dielectric material which provides the large resistance to the flow of electrical current between the electrodes and have a high capacitance. Thus, a high voltage is required to overcome the dielectric barrier, and when the voltage is sufficiently high, the barrier is overcome, and a plasma is generated in the gas between the electrodes. Because a higher voltage is needed to initiate plasma formation between dielectric barrier electrodes, the resulting current through the gas is substantially higher than between electrodes without the dielectric layer, and consequently, more power is delivered to the gas.

C. Problems in the Art

The prior art devices, however, suffer from several problems which make them less desirable for use for the exacting needs of semiconductor manufacture. These include uneven temperature distribution within the device, uneven radiation distribution over the surface to be treated, and short useful lifetime.

1. Generation of Uneven Plasmas

The first problem is that for each plasma microfilament generated between electrodes, the dielectric barrier is overcome at only a few sites along the electrode's surface. Once a site of plasma microfilament formation has been established, the dielectric material at that site can be degraded, thereby decreasing its resistance to electrical current. As the resistance decreases, that site becomes the focus for subsequent discharges. Repeated discharges further exacerbate the dielectric degradation and results in locally high temperatures within the dielectric material. This leads to further degradation of the properties of the dielectric. As the dielectric material becomes degraded, it loses the ability to store charge, the threshold voltage for dielectric discharge decreases, resulting in progressive loss of electrical power and weakening of the plasma field. Because the power output of the excimer device is related to the power of the electrical discharge, loss of electric power results in decreased radiation output from the device. Thus, the useful lifetime of the excimer device is limited.

2. Temperature Regulation

Another problem is that during use, the electrodes and emitter gas can be overheated. Overheating the electrodes alters the wavelength of the emitted radiation and can lead to degradation of the electrode dielectric material, reducing the useful lifetime of the lamp. Although the exact mechanism of this overheating is not known, it is known that plasma microfilaments are not evenly distributed in the discharge spaces of the prior art devices. This uneven distribution of plasma results in variations of gas temperature in different parts of the devices.

As a result of temperature differences within the discharge tube, there are differences in the wavelengths of the emitted radiation generated by the lamp. This results in a broader spectrum of emitted radiation, which can have undesired consequences on semiconductor processing. When working with precursor materials for film deposition, the energy required to dissociate a particular type of chemical bond is narrow. Controlled processing of these precursor molecules requires the precise control of the energy of the radiation used to dissociate the desired bonds.

However, broadening the spectrum of radiation can break bonds within the semiconductor material which are not intended to be broken, leading to a heterogeneous mixture of precursor molecules, some of which are not desired and actually contaminates the film to be deposited. Furthermore, exposing a surface to broadened spectrum of radiation can lead to degradation of the semiconductor surface or formation of undesired species of radicals. For example, in the case of Xe, when the temperature of the excimer gas exceeds about 300° C, the interatomic bonds between xenon atoms do not form. Thus, without interatomic bonds to breakdown, there is no excimer radiation emitted by the device.

Thus, a significant problem in the art is how to overcome these differences in temperatures locally within the devices, and how to keep the emitters cool enough to efficiently generate UV or VUV radiation. Prior art devices have incorporated water to both cool the devices and provide more even temperatures. However, because water has a very high dielectric constant ($K = 81$), water conducts electrical fields easily, thereby providing an alternative pathway for electrical energy to flow away from the excimer gas. This leakage of current to electrical ground requires a much higher power output from the AC source to generate the needed electrical power to the gas to initiate and maintain lamp operation.

3. Uneven Distribution of Radiation

Another problem specific to the manufacture of semiconductor devices is the desirability of providing even distribution of the radiation onto the surface of a semiconductor wafer. Several of the prior devices consist of tubes in which a central electrode is surrounded by an outer electrode. Examples of such devices are found in Kogelschatz, U.S. Patent No. 5,013,959, Kogelschatz, U.S. Patent No. 5,386,170, Kogelschatz, U.S. Patent No. 5,432,398, and Kogelschatz et al., U.S. Patent No. 5,198,717. Each of these patents is herein incorporated fully by reference. Because the discharge tubes of these devices emit radiation radially in all directions, they do not provide even emission of radiation in a particular desired direction. This is because the intensity of the radiation is altered by its passing through the elements of the device, such as quartz tubes, electrodes, and by passing through the emitter gas itself. The electromagnetic power not reaching the wafer is therefore wasted. Additionally, the geometry of cylindrical emitters with a central electrode surrounded by the electrode inherently produces uneven radiation. Uneven distribution of radiation results in uneven exposure of the flat wafer, thereby resulting in uneven treatment of the surface, thereby reducing the precision and consistency of the exposure of a semiconductor wafer to the radiation.

Attempts in the prior art to overcome uneven distribution include devices such as those exemplified by Gellert et al., U.S. Patent No. 5,006,758, Eliasson et al., U.S. Patent No. 4,983,881, Eliasson et al., 5,173,638, and Eliasson et al., U.S. Patent No. 4,945,290. Each of the above patents is herein incorporated fully be reference. These devices suffer from the same problem of localized loss of dielectric efficacy and uneven plasma generation. Additionally, with many of the prior art devices, there is no means for cooling the electrodes, and further degradation of the dielectric material and heating of the excimer gas results in inefficiency and short useful device lifetime.

4. Contamination of Radiators

An additional problem in the art is that with use, excimer lamps become contaminated with by-products of the impurities within the excimer gas, and from the dielectric material. These contaminants deposit on the window of the lamp, thereby decreasing its transparency to the UV or VUV radiation. This contamination reduces the useful lifetime of the device.

Thus, there are persistent problems in the art to design and manufacture excimer devices which remain cool during use, have long useful lifetimes, have narrow spectra in the desired wavelength ranges, have even distribution of intensity of the emitted radiation and are convenient and relatively inexpensive to manufacture.

SUMMARY OF THE INVENTION

Thus, one object of the invention is the design of excimer lamps which provide even distribution of emitted radiation, suitable for semiconductor manufacture and processing.

Another object of the invention is the design of excimer lamps which have long useful lifetimes.

A further object of the invention in the design of excimer lamps is miniaturization.

Another object of the invention is the design of excimer lamps which retain their efficiency under conditions of increased power output.

Yet another object of the invention is the design of excimer lamps which are easy to decontaminate during operation.

A further object of the invention is the design of excimer lamps wherein the contamination is confined to areas which will not affect the radiation intensity or wavelength.

To address these problems, this invention provides excimer lamps which comprise arrays of electrodes in a plane, the electrodes being individually cooled and having means to distribute the plasma discharges along the length of each electrode.

Therefore, one aspect of the invention comprises a design for a conductive electrode surrounded by a dielectric material with grooves in the dielectric material to distribute the plasma generating sites along the length of the electrode.

Another aspect of the invention comprises an array of electrodes imbedded within a dielectric layer, with depressions in the dielectric material to distribute the plasma generating sites over the dielectric layer.

Another aspect of the invention comprises an array of electrodes and radiator which are miniaturized to increase efficiency, decrease power consumption, and increase the evenness of distribution of emitted radiation.

A further aspect of the invention comprises an array of discharge tubes with electrodes between the tubes, wherein the radiation is easily transmitted through the walls of the tubes.

Yet another aspect of the invention comprises means for decontaminating the excimer gas while the gas is inside the radiator.

A further aspect of the invention comprises thin windows for transmission of radiation while maintaining sufficient mechanical strength to withstand high pressure gradients.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1a depicts an embodiment of an array of electrodes wherein the electrodes are in contact with a cooling block and a transparent window. Electrodes are viewed in cross-section.

Figure 1b depicts a top view of an electrode of Figure 1a with grooves for distributing plasma discharges along the length of the electrode.

Figure 1c is a side view of an electrode depicted in Figure 1b showing the orientation of grooves in the dielectric layer.

Figure 1d depicts an embodiment of a groove of Figure 1b with curved contours.

Figure 1e is a cross-sectional view of an electrode of Figure 1b depicting the orientation of a groove and its dimensions relative to the electrode

Figure 2 depicts an embodiment of the invention in which the flow of emitter gas is parallel to the electrodes, and in which a getter device is used to de-contaminate the gas.

Figure 3a depicts an embodiment of the invention in which electrodes are cooled by a cooling block and by a liquid medium. Electrodes are viewed in cross-section.

Figure 3b depicts a side view of an electrode shown in Figure 3a, depicting grooves for distributing plasma, channels for flow of emitter gas, and cooling means.

Figure 3c depicts a side view of the electrode body shown in Figure 3b, showing the orientation of gas channels and grooves.

Figure 4 depicts an embodiment of the invention in which the electrodes are in contact with a cooling block which is cooled by cooling fluid circulated within the block.

Figure 5a depicts an embodiment of the invention in which an array gas discharge tubes are interspersed with electrodes.

Figure 5b depicts details of the configuration comprising a cooling block, electrodes and gas discharge tubes of Figure 5a.

Figure 5c depicts the construction of one embodiment of a plate electrode of Figure 5a.

Figure 5d depicts an embodiment of the invention in which the discharge space is bounded by a transparent window.

Figure 6a depicts an alternative embodiment of the invention in which the electrodes are wire or spiral wire within an electrode cooling space.

Figure 6b depicts details of the construction of an electrode as shown in Figure 6a, having a spiral conductive element.

Figure 6c depicts an alternative embodiment in which the cooling of the electrodes is primarily by the interior electrode cooling space.

Figure 7a depicts an embodiment of the invention in which the discharge spaces are defined by a hemi-cylindrical element and a transparent window, with cooling fluid circulating around each electrode.

Figure 7b depicts an embodiment of the invention in which the electrodes are in contact with cooling fluid directly, and are imbedded in dielectric material and are outside the plane of the discharge space, and in which details of window construction are shown.

Figure 7c depicts an embodiment in which thin electrodes are imbedded in dielectric material and are outside the discharge space.

Figure 7d is a top view depicting an embodiment shown in Figures 7b or 7c, showing the relationship between spherical spacers and underlying electrodes.

Figure 8 depicts an array of electrodes arranged to provide a circular area of radiation emission.

The Figures are more fully explained in the Detailed Description of the Invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention comprises apparatus for treating semiconductor substrates with electromagnetic radiation of the ultraviolet (UV) and vacuum ultraviolet (VUV) wavelengths. This treatment can occur either before or after deposition of a semiconductor device layer, such as metal lines or dielectric layers.

I. Dielectric Barrier Discharge Lamps

Dielectric barrier discharge lamps (also known as silent discharge lamps) incorporating novel electrode design, novel discharge tubes, novel electrode configurations, and novel cooling means form the basis of the devices of this invention. These devices produce radiation by fluorescent emission mechanisms and by excimer processes, depending upon the type(s) of moieties present within the discharge tube. Depending on what the emitter gas is, the wavelength of the emitted radiation may be in the ultraviolet or vacuum ultraviolet range. VUV and UV radiation can be generated from noble gases and other atomic species (see Table 1).

Table 1

Emission Wavelengths For Selected Electromagnetic Radiation Emitters

Emitter Moiety	**Wavelength (nanometers)**
He_2	60 - 100
Ne_2	80 - 90
Ar_2	107 - 165
Kr_2	140 - 160
Xe_2	160 - 190
N_2	337 - 415
KrF	240 - 255
Hg/Ar	235
Deuterium	150 - 250
XeF	340 - 360, 400 - 550
XeCl	300 - 320
XeI	240 - 260
ArF	180 - 200
ArCl	165 - 190
ArCl/KrCl	165 - 190, 200 - 240
KrCl	200 - 240
Hg	185, 254, 320 - 370, 390 - 420
Se	196, 204, 206

Data from Eliasson et al., U.S. Patent No. 4,983,881 and Kogelschatz, U.S. Patent No. 5,432,398, incorporated herein fully by reference.

These ranges of wavelengths encompass the wavelengths equivalent to the energy of the chemical bonds of the precursors for film deposition, those present in the deposited films, or those present as undesired contaminants on the substrate surface. Some of the chemical bonds commonly associated with semiconductor manufacturing and processing are given in Table 2 below and correspond to energies in the UV and VUV ranges.

According to some theories, surface modification requires the breaking of undesirable bonds and/or the formation of desirable surface bonds or surface sites. These bonds include Si-OH, Si-C and Si-N, among others. The bond energies of some relevant bonds are shown in Table 2. These energies lie in the visible, ultraviolet (UV) and vacuum ultraviolet (VUV) range, and therefore electromagnetic radiation of these wavelengths will interact with these bonds. Therefore, it is possible to modify the bonding states of the thermal oxide or other underlying materials such as insulators, metal conductors, or barrier layers by exposing this surface to UV or VUV radiation.

Table 2

Bond Energies For Selected Bonds

Bond	Energy (eV)	Wavelength (nm)
H-H	4.52	274
C-C	3.60	344
Si-Si	1.83	678
N-N	1.67	745
O-O	1.44	861
C-H	4.28	289
Si-H	3.05	406
N-H	4.05	306
O-H	4.80	259
C-Si	3.01	413
C-N	3.02	410
C-O	3.64	340
Si-O	3.82	324
C=C	6.34	195
C≡C	9.22	134

Data from L. Pauling, *The Nature of the Chemical Bond and the Structure of Molecules and Crystals: An Introduction to Modern Structural Chemistry*, Third Edition, Cornell University Press, Ithaca, New York, 1960; and Atkins, *Physical Chemistry, 3d Edition*, Oxford University Press (1988), incorporated herein fully by reference.

As can be seen from Table 2, certain bonds can absorb electromagnetic radiation and thereby be disrupted. The electromagnetic radiation of the lamps of this invention have sufficient energy to break the bonds, thereby allowing removal of the moieties from the surface. {For example, Khan et al., Serial No. 08/986,916, titled *Processes for Surface Modification of Semiconductors Using Electromagnetic Radiation* discloses methods for reducing the surface sensitivity of semiconductor wafers to the subsequent deposition of tetraethylorthosilicate/ozone films, incorporated herein fully by reference.}

Although the wavelengths shown in Table 1 are those exhibiting the maximum power, there is a bandwidth of the wavelengths generated by each of the above emitter moieties. The bandwidths vary from about 1 to about 17 nm. {Newman et al., Aust. J. Phys. 48:543-556 (1995), incorporated herein fully by reference.} Thus, these emitters can be used to expose the surface of a semiconductor substrate to a spectrum of electromagnetic radiation, thereby increasing the number and types of chemical bonds which may be dissociated.

A. Electrode Design

The problem of uneven plasma formation with the device is minimized by the use of a novel round-contoured grooves or alternatively, dimples, ovals, cylinders or other shaped depressions in the surfaces of the dielectric-coated electrodes, and by minimizing the size of the electrodes (for cylindrical electrodes, for example, see Figure 1a). The electrodes can have a diameter of from about 20 μm to about 20 mm, preferably from about 20 μm to about 10 mm, and more preferably from about 100 μm to about 3 mm. The grooves or depressions are cut into the dielectric material to a depth of from about ¼ of the electrode radius to about ½ of the electrode radius and are oriented perpendicularly to the plane of the electrode array (for example, see Figure 3b and 3c). The depressions are sites of formation of plasma microfilaments. By providing many such sites of plasma microfilament formation, there is a decreased tendency for the plasma to be progressively formed at only a few sites in the discharge space. Consequently, the power will be more evenly distributed within the radiator and the emitted radiation will be more uniform.

The depressions provide areas of increased capacitance between adjacent electrodes. These areas then become the sites of formation of plasma filaments. The depressions can be spaced along the electrode at any convenient distance, by way of example only, of about 20 μm to about 10 mm with more depressions or grooves providing more sites of plasma formation. Thus, more closely spaced depressions are preferred, for example, about 20 μm to about 5 mm. In general, the spacing of depressions is preferably no smaller than the radius of curvature (r) of the electrode. Thus, for thinner electrodes, the depressions can be spaced closer together than for wider electrodes.

Moreover, deeper depressions increase capacitance more than shallower depressions. The depressions or grooves should be deep enough to initiate plasma discharge. However, deeper depressions have to be wider than shallower ones. The depth of the depression should be shallow enough to avoid direct electrical breakdown of the dielectric material. The preferred depths of the depressions are in the range of from about 0.1 to about 0.9 times the thickness of the dielectric material covering the conductive element of the electrode. The pitch of a depression is herein defined as the ratio of dimensions of the depression, approximated by the deepest depth of the depression divided by its width at the surface of the electrode. In general, the depressions are preferably not less than the cross section diameter of the micro-discharge channel (from about 10 μm to about 100 μm in diameter). Therefore, shallower depressions can be spaced more closely together.

The exact shapes and dimensions of the depressions can vary, but depressions are preferred which have no sharp corners or edges which would concentrate the charge and initiate plasma formation at undesired locations (Figures 1c - 1d). Depression features are preferred in which the radius of the feature is in the range of from about 0.1r to about 0.3r, where r is the radius of the electrode.

In alternative electrode design, including, by way of example, electrodes imbedded within a dielectric material (see Figures 7b and 7c), the depressions can be made in the overlying dielectric layer. Depressions can be as grooves, dimples, ovals, or cylindrical shaped structures as desired. For grooves, their orientation can be in a matrix array, perpendicular to the electrodes, or it can be parallel to the electrodes. For dimples, their location is preferably over the conductive elements. However, other orientations of depressions are contemplated and are within the scope of this invention.

B. Electrode Configuration and Lamp Design

In one embodiment of this invention, electrodes can be used which preferably comprise a thin conductive element such as, by way of example only, tantalum wire, surrounded by a layer of dielectric material, by way of example only, such as quartz or ceramic (Figure 1a). This type of construction provides long, thin electrodes which can be arranged preferably in parallel, thereby providing a planar electrode array which is thinner than devices currently available (Figure 2). When placed within a discharge space containing an emitter gas, the dimensions of the discharge space can be as narrow as the electrode (see Figure 1). Typical electrode diameters (t) are in the range of from about 20 μm to about 20 mm, preferably from about 100 μm to about 5 mm, and more preferably from about 1 mm to about 3 mm. In this electrode configuration, the emitter gas is between the electrodes and is contained within a discharge space bounded at one surface by a window that is transparent to the wavelengths of radiation generated.

In alternative embodiments, the discharge tubes are small (about 100 μm - 10 mm in diameter) are arranged in a planar array with electrodes between them. The cross-sectional shape of the discharge tubes can vary, being rectangular (Figures 5a - 5d, Figures 6a and 6c), circular, semi-circular (Figure 7a), or any other desired shape. In this type of configuration, the electrodes need not be encased in layers of separate dielectric material. The discharge tube itself can be a sufficient dielectric material with sufficient resistance to permit the high power plasmas to be generated within the discharge tubes.

In yet other embodiments, the electrodes are imbedded within a dielectric layer with a surface delimiting one side of the discharge space, with the discharge space being located above the plane of the electrodes (see, for example, Figures 7b and 7c). The thickness of the dielectric layer is chosen to provide sufficient dielectric breakdown voltage to initiate plasma microfilament formation and excitation of the emitter gas within the discharge space.

The overall shapes of the lamps can vary, depending on the length and shape of the space between electrodes. Circular, rectangular, ovate, triangular, or other desired shaped lamps can be made by adjusting the relative lengths and positions of the electrodes in the array.

The electrodes are connected to a source of alternating electrical current to generate the plasmas. Such electrical devices are well known in the art and will not be described further. The voltages necessary to initiate plasma discharge across the gap between electrodes are in the range of about 1 kV/cm to about 50 kV/cm, preferably between about 10 kV/cm and about 40 kV/cm, and for electrodes 1.2 mm in diameter, the working voltage across the gap will be less than about 10 kV. Further miniaturization of the electrodes and closer spacing can decrease the required voltage to below 5 kV, and can be as low as, by way of example only, to about 300 V for certain gases.

The window or discharge tubes must be transparent to the radiation emitted. For UV radiation, the windows may be made, by way of example only, of quartz, preferably single crystal quartz or ceramic, and for VUV radiation, the windows can be made, by way of example only, of LiF, MgF_2, CaF_2, synthetic quartz, or sapphire.

Moreover, the pressure within discharge space is usually below atmospheric pressure for VUV devices. This is because the VUV radiation can be absorbed by the gas, thereby decreasing the transmission of the VUV radiation to the exterior of the device. The pressure within the discharge space can also be below the pressure outside the discharge space, thus creating a pressure differential across the window, which can subject the window to large stress. The combination of reduced dimensions and reduced pressure requires the window of the devices to be strong enough to understand the differences in pressures between the interior of the discharge space and the exposure chamber in which the radiation is used. Therefore, this invention can incorporate means for supporting the window to maintain integrity in view of a relatively large pressure difference across the device.

Furthermore, the sides of the discharge spaces opposite the window can be coated with a suitable reflective material such as, by way of example only, MgF_2.

Additionally, novel shapes of the discharge tubs can be used, such as by way of example only, cylindrical or rectangular cross sections, thus eliminating the need for a separate window. By placing electrodes between discharge tubes, radiation generated within the tube can exit the tube and thereby expose the surface to be treated. For devices requiring larger discharge spaces, windows can be supported by the electrodes themselves or by ceramic supports.

C. Minimizing Lamp Contamination

Sealed lamps become contaminated with impurities from the gas or from the window materials. This contamination decreases transmission of radiation through the windows or discharge tubes. To solve this problem, the lamps of this invention use a flow-through system for continually exchanging the emitter gas within the discharge spaces and tubes.

It is known that plasmas can become unstable if the flow of gas is not parallel to the direction of the plasma. Unstable plasmas generate uneven discharge intensity. Therefore, in certain embodiments of this invention using a flow-through system, the flow of the emitter gas is oriented perpendicular to the electrodes, thus ensuring that the gas flow is parallel to the orientation of the plasma microfilaments. This orientation of gas flow parallel to the plasma microfilaments ensures that the intensity of the emitted radiation is even, thus permitting more accurate regulation of the surface treatment. In some embodiments incorporating a flow-through of emitter gas, wherein the flow of gas is parallel to the electrodes, and thus perpendicular to the plasma microfilaments, the plasma instability associated with this orientation of gas flow and plasma orientation can be minimized by using low gas flow rates.

In other embodiments, the emitter gas can be decontaminated while within the lamp by the use of getters. Getters can trap ionic or radical moieties, and thereby decontaminate the stream of emitter gas. The getters are preferably located at the periphery of the array of electrode. See Figure 2.

The problem of contamination can also be solved by exhausting the emitter gas from the lamp into an external filter, where the gas can be decontaminated and thereafter re-used. Alternatively, fresh, unused gas can be introduced into the lamps.

D. Cooling

Because of the high power requirements of dielectric discharge lamps, it is important to be able to carefully regulate the temperature of the devices. This is accomplished by miniaturizing the lamps to reduce power and by incorporating novel cooling means into the lamps.

Miniaturization promotes more even temperature distribution by permitting transfer of heat through thermally conductive elements over shorter distances. Moreover, miniaturization permits more efficient use of power to the device, thus reducing the total power dissipated within the device. Thus, less heat is produced, and along with the use of novel cooling means, the miniaturization permits operation of the lamps of this invention at lower temperatures.

Alternatively, the electrodes can be mounted on a thermally conductive material such as, by way of example only, beryllium oxide, aluminum nitride or Kerafoil ™, a trademark of the MHNW International Corporation's (Mahwah, N.J.) ceramic heat-conductive film. Other suitable thermally conductive materials known in the art can also be used in this invention. Suitable ceramic materials conduct heat rapidly, and can therefore draw away excess heat generated by the electrodes. For this to occur efficiently, the electrodes must be in close contact with the thermally conductive ceramic material. Moreover, electrodes, dielectric material, and the ceramic support preferentially have similar thermal conductivity and coefficients of thermal expansion. Tantalum wire and quartz have similar coefficients of thermal expansion, and thus are among preferred materials for electrode construction. This ensures that with use, the electrodes and support elements remain in close contact with each other, so that any increases in electrode temperature do not result in decreased heat loss through differential expansion creating gaps between electrode and the cooling block.

In addition to this conductive cooling means, this invention also can also rely on devices using the reverse Peltier effect for removing excess heat from the thermally conductive material. Devices incorporating the reverse Peltier effect are well known in the art and are available commercially. By way of example only, TechniCOOL ™, a trademark for Melcor's (Trenton, N.J.) solid state thermoelectric cooling device is suitable.

Alternatively, radiators can incorporate liquid cooling means to remove excess heat. See Figures 3-7. Such means include the formation of bores within the cooling blocks and a pump to circulate coolant to a radiator to remove excess heat. For certain applications, the cooling fluid may be water, but for other applications requiring electrical isolation of the cooling means from the electrodes, fluids with low dielectric constants can be used. These include glycol or Halon ™ based glycol.

The degree of cooling will depend on the power consumption and output of the radiator. Increasing the power output of the radiator requires more efficient cooling to maintain the radiator temperature within a desired operating range. The temperature of the excimer moieties should be sufficiently low to permit intra-atomic bonding during radiator operation. For example, when Xe is used an as excimer moiety, the maximum operating temperature should be below about 300° C.

All of these aspects of the invention permit careful control of the distribution of radiation intensity, decreases in the power requirements for the lamps, and thereby permit more exacting exposure of semiconductor materials to the radiation. These improvements are useful for the manufacture and processing of semiconductor materials.

II. Uses of UV and VUV Lamps

A. Pre-Treatment of Semiconductor Substrates

Pre-treatment of semiconductor substrates with UV or VUV radiation reduces contaminants on the semiconductor material, and thereby provides a more ideal surface upon which to deposit subsequent layers of semiconductor materials. For example, if the semiconductor surface is rough, subsequent layers of semiconductor materials may not deposit evenly on the surface, and can result in variations of film thickness or dielectric constant. This variation of film deposition depending on the underlying substrate is termed surface sensitivity. Surface roughness or voids in film deposition can result from the presence of contamination by organic materials, water, or other undesired materials. Treatment with UV or VUV radiation can decrease surface sensitivity by removing contaminants which are responsible for the phenomenon.

For example, a thermally oxidized semiconductor surface is expected to have Si-O-Si, Si-H, and Si-OH bonds on the surface along with some hydrocarbon or other organic contaminants. According to one theory, the presence of these types of bonds decreases the homogeneity of the resulting deposited film, thereby causing it to have a rough surface. According to this theory, these bonds may form when contaminants on the surface bind to the silicon or oxygen atoms in the SiO_2 film.

Another theory relates to the presence of organic contaminants on the substrate surface. Typical sources of organic contamination are clean room air and the photoresist residue from photolithography processes. The organic moieties found include silicon carbide, amides, silicones, organophosphorous compounds, C_6 - C_{28} aliphatic or aromatic hydrocarbons, phthalates, alcohols (e.g., isopropyl alcohol), N-methyl pyrrolidone, creosols and amines. Camenzind et al., *Balazs News,* Number 20: 1-3 (October 1997); and Camenzind et al., *MICRO* pp: 71-76 (October 1995), incorporated herein fully by reference.

These theories are included only for descriptive purposes, and the present invention does not rely upon any particular of these theories for its operability. Regardless of the molecular source or mechanism responsible for the modifications of semiconductor surfaces by UV and VUV radiation, the present invention discloses improved excimer devices for processing semiconductor surfaces.

III. Deposition of Dielectric Films and In-Film Processing of Substrate Materials

In addition to pre-treating semiconductor surfaces, UV and VUV radiation is useful for initiating chemical reactions involved in semiconductor manufacture. For example, Lee et al., U.S. Application Serial No.: 08/958,057, incorporated herein fully by reference, discloses the use of VUV and UV radiation for selectively breaking bonds within precursor molecules thereby generating reactive intermediates which can polymerize to form low dielectric films with improved thermal and mechanical stability on the semiconductor surface.

Moreover, treatment of deposited semiconductor films with electromagnetic radiation also can be used to break certain bonds within the film itself, thereby promoting cross-linking or other desired chemical reactions within the material. Such chemical reactions can increase the thermal and mechanical stability of the material, and also can result in altering dielectric properties of the material.

Examples

The following examples illustrate some of the features of this invention. Other embodiments are possible, and are all considered part of the invention.

Example 1

Example 1 shows a schematic diagram (Fig. 1a) of a device **100** according to the instant invention. Device **100** includes a planar layer of thermally conductive ceramic material **104** and a plurality of electrodes **106** comprising a central conductive element **112** made of any suitable material, including, by way of example only, tantalum, surrounded by a dielectric material **108** manufactured from, for example, quartz or other suitable material. The conductive elements **112** and the dielectric material **108** are chosen to have compatible coefficients of thermal expansion, so that during use, as the electrodes **106** warm, no gaps or undue stresses are created within the electrodes. This increases the useful lifetime of the electrodes. Tantalum and quartz have similar coefficients of thermal expansion, and are therefore preferred. However, other pairs of conductive elements and dielectric materially with high thermal conductivity and similar coefficients of thermal expansion are suitable. Thermally conductive ceramic **104** can be any suitable material, with preferred materials including beryllium oxide and aluminum nitride.

The electrodes **106** can be manufactured from conductive elements **112** and a dielectric tube **108** having a central bore of slightly smaller diameter than the conductive element **112**. Upon sufficient heating, the dielectric tube **108** expands, increasing the diameter of the central bore to accommodate the conductive element **112**. After inserting the conductive element **112**, the electrode is cooled, and the dielectric contracts to form a close contact with conductive element **112**. Care should be taken to prevent stresses upon the electrode which would weaken it or could form fractures which would degrade the dielectric properties of the material **108**.

The electrodes **106** should have an outside diameter of from about 20 μm to about 20 mm, preferably about 100 μm to about 5 mm and more preferably from about 1 mm to about 3 mm. The electrodes **106** are welded to the ceramic or quartz material **104** using any suitable, thermally conductive method so that heat generated within the electrodes can dissipate easily into the material **104** and thereafter further dissipated from the device. Such welding methods include, for example, glass frits, stitching, ceramic glues or thermal compression methods known in the art.

The electrodes **106** are spaced closely and evenly, thereby defining a plurality of discharge spaces **116** about 100 μm to about 1 mm wide, which contain any suitable gas or mixture of gases. The gases may be emitter gases or may be a combination of emitter gases and carrier gases such as nitrogen. It is important that the gases chosen not excessively absorb the desired wavelengths of emitted radiation. However, using certain gases to selectively absorb undesired wavelengths of radiation can increase the selectivity of output of the excimer lamp. The gases and their absorption spectra are well known in the art.

The gas pressures within the discharge spaces **116** can be sub-atmospheric, atmospheric, or greater than atmospheric pressure. By providing more emitter gas, the intensity of the radiation can be increased. However, the VUV path length through a gas decreases with increased pressure due to increased absorption by denser gas which exists at higher pressures. Therefore preferred pressures are in the range of about 10 milliTorr to about 100 Torr, and more preferably about 10 milliTorr, a pressure at which the path length of VUV radiation is about 1 cm.

The electrodes **106** are welded to a window **124** using similar methods as described above. The welds between electrodes **106** and window **124** are capable of dissipating generated heat, as well as is the conductive ceramic **104** subserves that purpose. The window **124** is made of any material transparent to the wavelength of radiation desired. In general, the intensity of transmitted radiation through a window is expressed by the following relationship:

$$I = I^{o} e^{-\alpha x}$$

where I is the measured intensity of radiation after the light passes through the window, I^o is the initial intensity of the radiation before passing through the window, e is the base of the Napierian logarithms, α is the coefficient of transmittance of the window, and x is the window thickness. In general, it is preferable if the ratio I/I^o is from about 80 % to about 90 % to maximize the efficiency of the emission of radiation.

For example, for UV wavelengths, quartz crystals are suitable, preferably those made of single crystals. For shorter wavelengths such as those of VUV, highly purified quartz crystals, LiF, MgF_2, or CaF_2 are used, preferably single crystals of those materials. LiF is preferred, as this material is about 80% - 90% transparent to wavelengths as short as about 110 nm. MgF_2 is also suitable for uses in which the wavelength is no shorter than about 120 nm, as MgF_2 transmits about 80% to about 90% of wavelengths longer than about 120 nm. For longer wavelengths, fused quartz or sapphire crystals are suitable. The window **124** should be as thin as possible while being sufficiently strong to maintain the pressure differential between the discharge space **116** and the outside of the emitter device.

The thickness (**t**) of the discharge space **116** and the electrodes **106** should be from about 20 μm to about 10 mm, preferably about 100 μm to about 5 mm, and more preferably about 1 mm to about 3 mm. However, the dimensions of the electrodes and discharge space can be chosen to optimize the emission of radiation. With larger diameter electrodes **106**, there can be more gas molecules, which can therefore emit more radiation for a given gas pressure. Alternatively, with a thinner discharge space **116** in the **t** dimension, and a higher gas pressure, the same amount of radiation can be generated.

Alternating electrical power is applied to the electrodes in pairs, with adjacent electrodes being subjected to one pole of the AC source, and the adjacent member being exposed to the other pole. Alternating current frequencies can vary from about 5 Hz to about 1000 kHz, preferably from about 10 kHz to about 200 kHz, and more preferably about 20 kHz. The voltage across the electrodes can be in the range of about 300 V to about 20 kV, with preferred voltages of about 3 kV to about 8 kV, and more preferred voltages of about 5 kV. These lower voltages are possible if the distances between the electrodes are kept low and the gas pressure in the discharge space are in the range of about 10 milliTorr.

The power and exposure times are selected to provide the desired effect. For minimizing surface sensitivity to the deposition of undoped silicate glass (USG), the power output of the excimer lamps is in the range of from about 15 milliWatts/cm^2 to about 100 W/cm^2. Preferably, the power output is in the range of from about 15 milliWatts/cm^2 to about 50 Watts/cm^2, and more preferably about 1 Watt/cm^2

Exposure times can vary inversely with the power output of the generator. However, these exposure guidelines can be altered depending upon the pre-existing state of the surface. For some surfaces, less power and/or shorter exposure durations are necessary.

To distribute the sites of generation of plasma microfilaments within the excimer device, the electrodes **106** are made with grooves **118** (Figure 1b - Figure 1e) in the dielectric **108**. The grooves **118** can be triangular in cross section (Figure 1b) or can have a rounded inner portion (Figure 1d). Preferably, the grooves will have no sharp edges or corners. Generally, the axes of the grooves **118** are perpendicular to the axis of the conductive element **112** (Figure 2c). The grooves are also arranged with their axes perpendicular to the axis of the electrode array. Thus, the grooves will have their interior surfaces facing the adjacent electrodes. Generally, the grooves are of sufficient depth to result in a subtended angle between the ends of the groove and the center of conductive element **112** of about 90°. However, variations in the groove depth and length can be made without departing from the invention.

The grooves distribute the sites of plasma microfilament formation and thereby increase the useful lifetime of the electrode. They also distribute the radiation more evenly. By creating areas of increased capacitance within them, the grooves promote formation of plasma discharges in the grooves and thereby prevent a more localized discharge pattern restricted to only a few sites along the electrode, as is the case with prior art devices. By distributing the discharge to more locations along the electrode, the flux of electrical current at each discharge site is decreased, resulting in more evenly distributed local heating of the electrode, and thereby minimizing the heat-induced degradation of the ceramic **108**. This in only one possible theory of the beneficial role of the grooves **118**. Other theories may account for the beneficial effect, and they all are included within the scope of this invention.

Alternatively, grooves **118** can be replaced by other shapes, including by not limited to dimples, ovals, cylinders and be within the spirit of the invention.

Figure 2 shows an embodiment of the invention incorporating the grooved electrodes as shown and described above in Figure 1. In this array, an array of electrodes is part of an excimer device **200** with adjacent electrodes **206** being connected alternatively to the opposite sides of the device **200**. One set of leads **210** is connected to one side of an AC source (not shown), and the leads **211** are connected to the other side of the AC source. The device **200** has an inlet port **204** for the introduction of gas mixtures, and has an outlet port **220** for the exhaustion of gases. Getters **217** are incorporated into the walls of the lamp to permit decontamination of the emitter gas as it passes through the device. The getters are made of titanium or any other suitable material known in the art. The getters **217** can be in the form of flat sheets or of mesh. The getters **217** are activated by the application of an electrical field to enhance attraction of contaminant ions. The electrical fields can be generated using any suitable electrical source known in the art. Direct current voltages are in the range of from about 50 V to about 1000 V, and are preferably about 300V.

In this configuration, the flow of gas is parallel to the electrodes (arrows), and is therefore perpendicular to the plasma microfilaments generated between adjacent electrodes. This configuration is easy to manufacture, because the electrodes are relatively simple in design. The dimensions of the device **200** are chosen to accommodate the size of the semiconductor wafer to be exposed to the radiation. Multiple electrodes can be incorporated into this configuration as required for the particular application.

Example 2

Another embodiment of the invention **300**, depicted in Figure 3a includes additional cooling means and a alternative pattern of emitter gas flow through the device **300**. Figure 3a shows a typical arrangement of elements in this embodiment. Electrodes **306** comprise an electrically conductive element **312** surrounded by a dielectric material **308**, are arrayed as in Figures 1 and

2, and are welded to thermally conductive element **304** and window **324**. To cool the thermally conductive element **304**, a cooling medium **328** is transported across the surface of element **304**. The cooling medium **328** is enclosed by coolant containment element **332**, which can be made of any substance compatible with the coolant chosen. Thermally conductive element **304** and coolant containment element **332** define a coolant containment space. By way of example only, the coolant containment space can be sheet like, with relatively unrestricted flow patterns of coolant medium **328** between conductive element **304** and containment element **332**. The coolant medium **328** is chosen to provide good thermal conductivity and high heat capacity. Preferred media also have low dielectric constant and high dielectric strength to minimize leakage of electrical current to ground during lamp operation. Examples of preferred media include glycol and Halon ™ based glycol. The flow rate of the coolant should be sufficient to maintain electrode temperature of below about 300° C, when used with Xe as the emitter gas. The coolant is circulated by means of a pump (not shown).

Additionally, in this embodiment, the excimer gas flow in the discharge space **316** is perpendicular to the axis of the electrodes (arrows). This means that the flow of gas is parallel to the electrical field discharges between the electrodes. This configuration permits the formation of a more stable plasma than is possible with the configuration shown in Figure 2. The increased stability of the plasma permits the output of the lamp to be regulated more closely and within narrower tolerance limits than lamps using other configurations. However, the embodiment shown in Figures 3a - 3c is more complex and requires more manufacturing steps than the embodiment shown in Figures 1 and 2.

Figure 3b shows an embodiment **301** in which the electrodes enable the perpendicular excimer gas flow and also shows a configuration of cooling elements different from Figure 3a. The electrode **306** is shown in a side view of a longitudinal section, with ovate grooves **318**, and gas channels **336**. Gas channels **336** provide passageways through which gas can flow from one discharge space **316** to the adjacent discharge space. These gas channels may be of rounded contours as shown, or may be of any other convenient shape. The gas channels **336** should be sufficiently numerous and of sufficient size to provide little impediment to the flow of gas within the device. If the gas channels **336** are too narrow or too few, the pressure drops from one discharge space to the adjacent spaces may be so large as to significantly alter the pressures in the discharge spaces, resulting in inefficient lamp operation. As in the previous examples, the electrodes **306** are welded to a thermally conductive material **304** and to the window **324**.

Additionally, Figure 3b shows a cooling block **342** is adjacent and in thermal contact with thermally conductive material **304**. Coolant channels

344 for coolant fluid **328** are within the cooling block **342**, are oriented perpendicularly to the electrodes, and serve to carry excess heat away from the electrodes. The coolant channels are connected to a coolant pump and reservoir (not shown).

Figure 3c shows more details of construction of the embodiment shown in Figure 3b, including the electrode **306**. The orientations of conductive elements **312**, dielectric elements **308**, grooves **318**, Window **324**, thermally conductive element **304**, and ovate gas channels **336** are shown.

Example 3

In another embodiment **400** of the invention, shown in Figure 4, the cooling block **442** has cooling channels **430** to accommodate flow of coolant **428** in one direction, and alternate cooling channels **430** accommodate flow of coolant **428** in another direction. In this embodiment, the cooling channels are oriented parallel to the electrodes. This configuration will tend to even out the temperature throughout the device, resulting in more consistent radiation from all parts of the lamp. As in previous figures, electrodes **406** comprise a conductive element **412** within a dielectric element **408**. The electrodes **406** are welded to thermally conductive material **404**, which is welded to adjacent layer **410**, which may be the same or of different composition as material **404**. Electrodes **406** are also welded to window **424** using glass cement, glass frits, thermocompression or other welding means **420**.

Example 4

Example 4 demonstrates another embodiment of lamp **500** (Figure 5a - Figure 5c). In this device, as shown in Figure 5a, the thermally conductive material **504** is attached to gas discharge tubes **508**, which are of rectangular cross section. These tubes are made of any suitable UV or VUV-transparent material as described above. The discharge tubes define discharge spaces **516** which contain the emitter gas as described above. The thermally conductive material **504** is cooled by coolant **528** which is circulated over the material **504** by a pump (not shown). The thermally conductive material **504** can be of beryllium oxide, aluminum nitride, or other material with high thermal conductivity. Figures 5b and 5c depict the electrodes **512** of this embodiment. Electrodes **512** comprise an attachment portion **520** which is inserted into mating grooves **511** in material **504**. This configuration provides mechanical, electrical and thermal contact between the electrode and the surrounding elements. Electrode plate **522** is thin, being between 10 μm and 1000 μm in thickness, and extends from about 1/4 of the distance to about the entire distance along the side of discharge tube **508**. The electrodes can be made by thin film deposition or other techniques.

Electrodes are arrayed in pairs, one of each pair being connected to one pole of the AC source (not shown) and the other of each pair being connected to the other pole of the AC source. Discharge tube **508** is made of a material with sufficient dielectric properties to provide the necessary capacitance and resistance to electrical flow to initiate and maintain dielectric discharge conditions. Additionally, discharge tube **508** is made of a material which is transparent to the wavelengths of the radiation desired.

This configuration provides good heat transfer from the electrodes and discharge tubes, and serves as the electrical connection to the power supply. Additionally, this configuration does not require the manufacture of combined conductive element /dielectric electrodes as in Examples 1 - 3.

In another embodiment **501** of this type of lamp, shown in Figure 5d, the discharge tube is replaced by a U-shaped discharge element **509**. The window **524** in this embodiment is not necessarily made of the same material as the U-shaped element **509**. For example, element **509** can be of quartz or ceramic, with window **524** being transparent to the generated radiation. Window **524** is welded using glass cement, glass frits, or thermocompression to the U-shaped element **509** to provide a pressure-tight seal. As in previous embodiments, the electrodes **512** are in thermal contact with a thermally conductive material **504**.

Example 5

A different type of electrode configuration **600** is shown in Figure 6a - Figure 6b. In one configuration of this embodiment (Figure 6a), gas discharge tubes **608** define gas discharge spaces **616**, and are spaced apart to permit insertion of electrodes **612** between tubes **608**. Electrodes **612** are supported by supports **620** enabling the electrodes to be situated near the mid-portion of the gas discharge tubes **608** Gas discharge tubes **608** are mounted on thermally conductive material **604**, made of suitable material with high thermal conductivity such as beryllium oxide or aluminum nitride. The electrode array is cooled by coolant fluid **628** which is circulated by a pump (not shown).

Electrodes **612** can be made of tantalum wire encased tightly in dielectric material as described above in previous examples, or may be in the form of a thin coiled wire **614** inside an inner electrode space **615** which may optionally be cooled internally by a flow of coolant (arrows) (Figure 6b). The use of deionized water as coolant provides both cooling and electrical contact between the wire electrode element **614** and the wall of the electrode **613**. Additional cooling of the electrode and the discharge tube **608** can be by another cooling space **629** containing a fluid of high thermal conductivity, circulated by a pump separate from that used to circulate coolant **628**. The discharge tubes are welded to window **624** using methods described for previous embodiments of the invention.

Another embodiment **601** of the invention is shown in Figure 6c. In this embodiment, U-shaped discharge elements **609** are welded to window **624** with the electrodes **612** of Figure 6b held in place with supports **620** thereby defining gas discharge spaces **616**. In this embodiment, cooling is primarily via the internal electrode cooling means **614** described in Figure 6b.

Example 6

An alternative embodiment **700** is shown in Figure 7a. Device **700** comprises a series of discharge tubes **709** abutting each other, in a planar array, with the edges of the discharge tubes **709** defining cusps **710** between them. Each tube **709** is hemi-cylindrical in cross section, and is made of a suitable dielectric material. The edges of discharge tubes **709** are welded to window **724** which permits the transmission of radiation. The discharge tubes **709** and window **724** define gas discharge spaces **716**. Electrodes **712** are spaced between the discharge tubes **709**, for example only, in the cusps **710** such that activation of electric discharge elicits excimer radiation in discharge space **716**. Electrodes **712** are located within a coolant space defined by the discharge tubes **709** and the thermally conductive material **704**. The coolant space is filled with coolant fluid **728**, which is circulated by a pump (not shown), thereby cooling the electrodes and the discharge space. Coolant **728** should have a sufficiently low dielectric constant and sufficiently high dielectric strength to minimize the likelihood that the coolant would be a pathway for electrical current flow between electrodes **712**.

Another embodiment **701** (Figure 7b) provides for direct cooling of the electrodes. In this embodiment, electrodes **712** are partially imbedded within dielectric material **705** and are partially exposed to coolant **728**, held in a coolant space defined by the dielectric material **705** and a coolant wall **732**. In this type of electrode configuration, the dielectric discharge is not immediately between electrodes **712**, but rather is in the discharge space **716** which is above the dielectric material **705**. Electric fields generated by the electrodes **712** is induced at the surface of dielectric layer **705** directly over electrodes **712**. When a sufficient voltage threshold is reached, electrical current flows from one part of the dielectric surface **705** to a nearby part, thereby generating the plasma within discharge space **716**. Plasma dispersion depressions **718** are shown in the dielectric material **705**. The dispersions depressions **718** can be in, for example, grooves, dimples, cylinders, ovals, or other convenient shapes. Spherical ceramic or quartz spacers **726** are welded to the dielectric layer **705** and to the window **724** to maintain the proper thickness of the discharge space **716**. Spacers need not be spherical, but need only be of sufficiently similar size to provide support for window **724** without causing undue mechanical stress on the parts. These spacers can be spread throughout the discharge space **716** in a variety of patterns and matrices (see Figure 7d). In this embodiment, coolant **728** must have a sufficiently low dielectric constant and sufficiently high dielectric strength so as to not provide a pathway for electrical current between electrodes **712**.

Figure 7c depicts another embodiment **702** of the invention. In this case, electrodes **714** are placed in recesses within the dielectric layer **705**. Other elements of this embodiment are labeled as in Figure 7b. In this way, the electrodes may be thin, in the range of about 100 nm to about 1000 μm, preferably in the range of about 100 nm to about 500 μm, and even more preferably about 200 μm.

By making the electrodes thin, the lateral capacitance between the electrodes in the dielectric layer is higher than the sum of the capacitances of the dielectric layers above the electrodes and the discharge gas in the discharge space. Thus, the preferred current flow is from one electrode through the dielectric layer, through the gas, and through the other part of the dielectric layer to the second electrode, rather than between the electrodes directly.

The coolant **728** preferably has sufficient thermal conductivity and heat capacity to maintain electrode temperature below about 300° C, and preferably has sufficiently low dielectric constant and sufficiently high dielectric strength to prevent current flow to electrical ground through the cooling system. Suitable coolants include glycol and Halon ™ based glycol.

Figure 7d shows a top view of embodiments **701** or **702** showing the array of spacer elements **726**. The array may be, by way of example only, in the form of a matrix as shown, being over the underlying electrodes **712** or **714**. Alternatively, the spacers **726** can be arrayed in any other convenient way that provides sufficient support for window **724** shown in Figures 7b - 7c to provide sufficient strength to withstand the pressure difference between discharge space **716** and the exterior of the device. Spacers **726** can be approximately spherical as shown, or can be rod-like. However, spherical spacers can be arrayed close together and still maintain sufficient spaces between them to permit unrestricted flow of emitter gas in the discharge space **716**. If rods are used for spacers, they preferably are segments short enough to permit unrestricted emitter gas flow.

Example 7

Figure 8 shows an alternative embodiment **800** providing a circular radiation source. The radiation pattern of the device is determined by the lengths of the electrodes **812** and **813**. Electrodes **812** are connected to one pole of an AC source **815**, and electrodes **813** are connected to the other pole of AC source **815**.

While the present invention has been described with reference to the alternative embodiments described above, those embodiments are offered by way of example, not by way of limitation. Those of ordinary skill in the art will be enabled by this disclosure to add to or modify the embodiments of the present invention in various obvious ways. Accordingly, such modifications and additions are deemed to lie within the spirit and scope of the invention as set out in the appended claims.

WHAT IS CLAIMED IS:

1. A silent discharge radiator comprising:

a plurality of electrodes, each electrode having an electrode axis;

walls delimiting a discharge space containing said electrodes, wherein said discharge space is adapted to be filled with a gas capable of emitting radiation under dielectric discharge conditions, wherein at least one wall of said discharge space is substantially transparent to a wavelength of the emitted radiation;

wherein at least one of said electrodes comprises a conducting element imbedded within a dielectric material; and

means for distributing sites of dielectric discharge associated with at least an electrode.

2. The radiator of claim 1 wherein the distributing means includes a plurality of sites along the length of at least one of said electrodes.

3. The radiator of claim 1 wherein the means for distributing the sites of discharge comprises a plurality of depressions in the dielectric material of at least one electrode.

4. The radiator of claim 3, wherein the depressions comprise grooves in the dielectric which define a groove axis, said groove axis being substantially perpendicular to the axis of the electrode.

5. The radiator of claim 1, wherein the means for distributing the discharge sites comprises decreasing the resistance of the between selected portions of adjacent electrodes relative to the resistance between other areas of the adjacent electrodes.

6. The radiator of claim 1 wherein:

each site of discharge is created by an area of higher capacitance.

7. The radiator of claim 3, wherein said grooves have ends and the ends of the grooves subtend about 90° of angle relative to the centers of said electrodes.

8. The radiator of claim 1, wherein a wall of said discharge space has an inlet port whereby said gas is introduced into said discharge space, and wherein a wall of said discharge space has an outlet port, whereby said gas is exhausted from said discharge space.

9. The radiator of claim 1, wherein a getter is placed within the gas discharge space to decontaminate said gas.

10. The radiator of claim 1, wherein the flow of gas is substantially perpendicular to the electrode axis.

11. The radiator of claim 1, wherein the flow of gas is substantially parallel to the electrode axis.

12. A silent discharge radiator comprising:

a plurality of electrodes wherein each of said electrodes comprises a conducting element imbedded within a dielectric material, each electrode having an electrode axis;

walls delimiting a discharge space, said discharge space containing the electrodes, said discharge space being adapted to be filled with a gas capable of emitting radiation under dielectric discharge conditions, and wherein at least one wall delimiting said discharge space is substantially transparent to a wavelength of the emitted radiation; and

a plurality of distributed sites of dielectric discharge associated with at least an electrode.

13. The radiator of claim 12 including: means for cooling each electrode.

14. The radiator of claim 13, wherein said means for cooling comprises providing thermal contact between each electrode and a cooling fluid which flows past each of said electrodes.

15. The radiator of claim 14, wherein the flow of cooling fluid is substantially perpendicular to the electrode axis.

16. The radiator of claim 14, wherein the flow of cooling fluid is substantially parallel to the electrode axis.

17. The radiator of claim 13, wherein each electrode is attached to a thermally conductive base.

18. The radiator of claim 17, wherein said thermally conductive base comprises one of the group consisting of beryllium oxide and aluminum nitride.

19. The radiator of claim 17, wherein said thermally conductive base is cooled by a thermoconductive cooling device.

20. The radiator of claim 17, wherein a cooling fluid cools said thermally conductive base.

21. The radiator of claim 20, wherein said cooling fluid comprises at least one of glycol and Halon ™-based glycol.

22. The radiator of claim 14 wherein:

the fluid of the cooling means is sufficient to maintain electrode temperature below about 300°C.

23. The radiator of claim 17 wherein:

the thermally conductive base has sufficient thermal conductivity to maintain electrode temperature below about 300°C.

24. A silent discharge radiator comprising:

a plurality of discharge tubes having at least one wall, said discharge tube adapted to contain a filler gas capable of emitting radiation under dielectric discharge conditions, wherein at least one wall of each of said discharge tubes are substantially transparent to a wavelength emitted by said filler gas; and

electrodes being disposed between the discharge tubes.

25. The radiator of claim 24 including:

means for cooling said electrodes.

26. The radiator of claim 24, wherein said discharge tubes have rectangular cross section.

27. The radiator of claim 24, wherein said discharge tubes and electrodes are in contact with a cooling material sufficient to maintain the temperature of the electrodes below about 300° C.

28. The radiator of claim 27, wherein said cooling material is selected from the group consisting of beryllium oxide and aluminum nitride.

29. The radiator of claim 27, wherein said cooling material comprises at least one of glycol and Halon ™-based glycol.

30. The radiator of claim 24, wherein said discharge tubes have an approximately semi-circular cross sectional shape having a curved side and a planar side, and wherein the planar sides of adjacent discharge tubes are coplanar.

31. The radiator of claim 30, wherein the discharge tubes have an inner wall and an outer wall, and wherein adjacent discharge tubes meet to form a cusp between the outer walls of said discharge tubes, and wherein said cusp contains an electrode.

32. The radiator of claim 24, wherein said electrodes are disposed individually between and closely applied to each of said adjacent tubes, and wherein each electrode is cooled by a cooling fluid which flows past each of said electrodes sufficiently to maintain electrode temperature below about 300° C.

33. The radiator of claim 27, wherein said cooling fluid is at least one of glycol and Halon ™-based glycol.

34. The radiator of claim 24 wherein said discharge tubes are substantially semi-circular in cross-sectioned shape.

35. A silent discharge radiator comprising:

means for providing a plurality of electrodes, each electrode including a conducting element embedded in a dielectric material;

means for defining on said electrodes, a matrix of defined discharge sites; and

means for providing a gas capable of emitting radiation under dielectric discharge conditions to said site.

36. A silent discharge radiator comprising:

an array of electrodes with each electrode having a conductor associated with dielectric material;

said array of electrodes having a multiplicity of predefined sites for dielectric discharge; and

a emitter gas distribution device associated with the discharge sites.

37. The silent discharge radiator of claim 35, wherein the matrix is 2 dimensional.

38. A silent discharge radiator further comprising:

a thin window, and

a plurality of spacers to support the window in the presence of a pressure differential.

39. The silent discharge radiator of claim 38, wherein the plurality of spacers is selected from the group consisting of spheres and rods.

40. The silent discharge radiator of claim 39, wherein the spacers have cross-sectional dimensions substantially similar to the cross-sectional dimensions of the electrodes.

41. An electrode for a silent discharge radiator comprising a conductive element imbedded within a dielectric material, and further comprising a plurality of gas channels in said electrode.

42. The electrode of claim 41, wherein said gas channels have a gas channel axis substantially perpendicular to said electrode.

43. The silent discharge radiator of claim 24, wherein said electrodes have a thickness of between about 10 µm and about 1000 µm.

44. The silent discharge radiator of claim 24, wherein said electrodes extend between said discharge tubes.

45. The silent discharge radiator of claim 24, wherein said electrodes extend between said discharge tubes having a height, to between about ¼ to about ⅞ of the height of said discharge tube.

46. An electrode for a silent discharge radiator comprising a conductive element imbedded within a dielectric material, and further comprising a multiplicity of predefined discharge sites provided in said dielectric material.

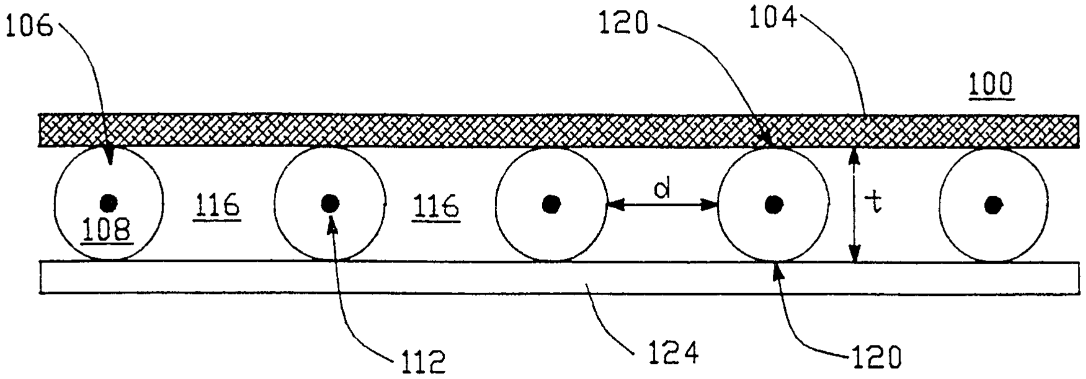

FIG.—1a

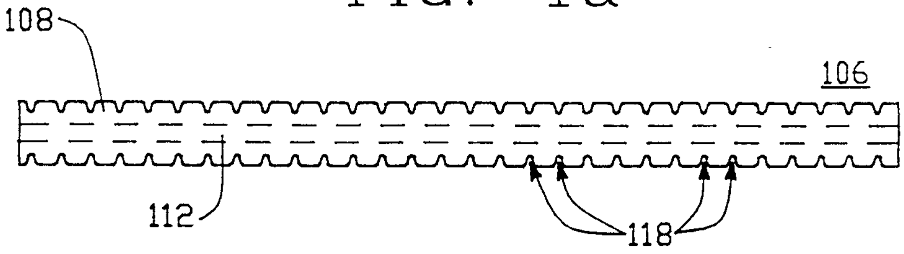

FIG.—1b

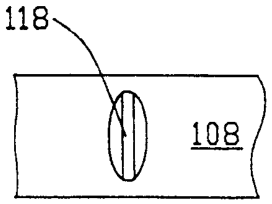

FIG.—1c

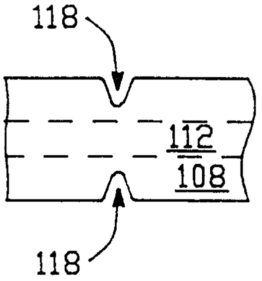

FIG.—1d

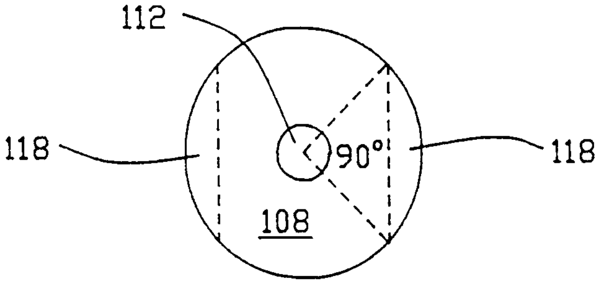

FIG.—1e

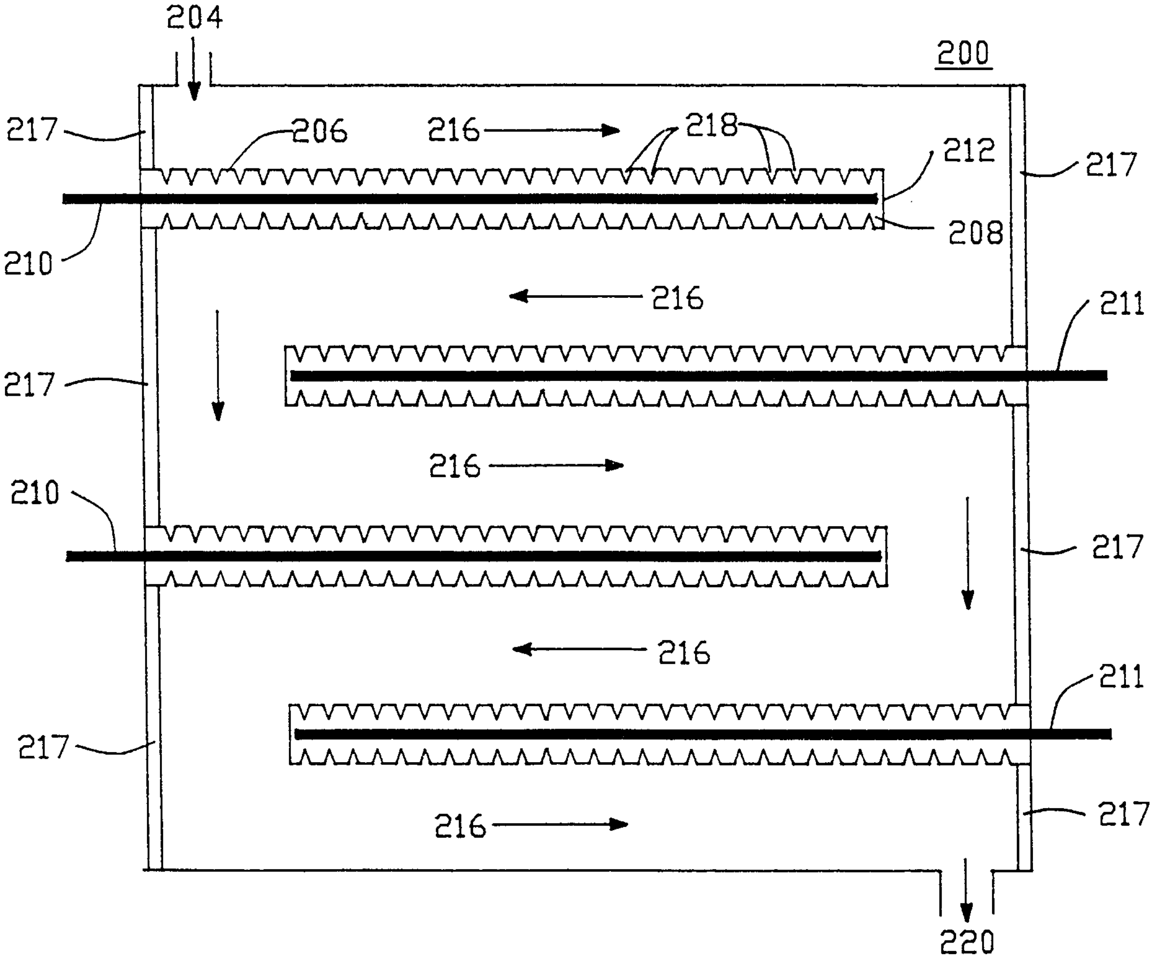
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FIG.-2

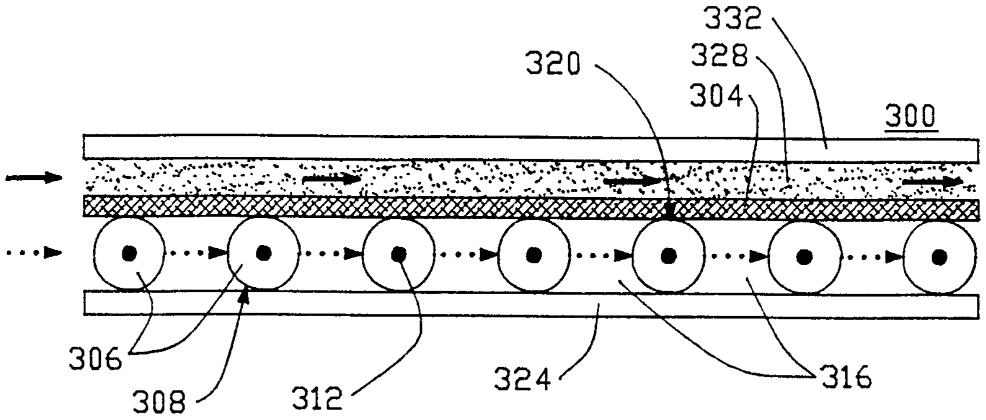

FIG.—3a

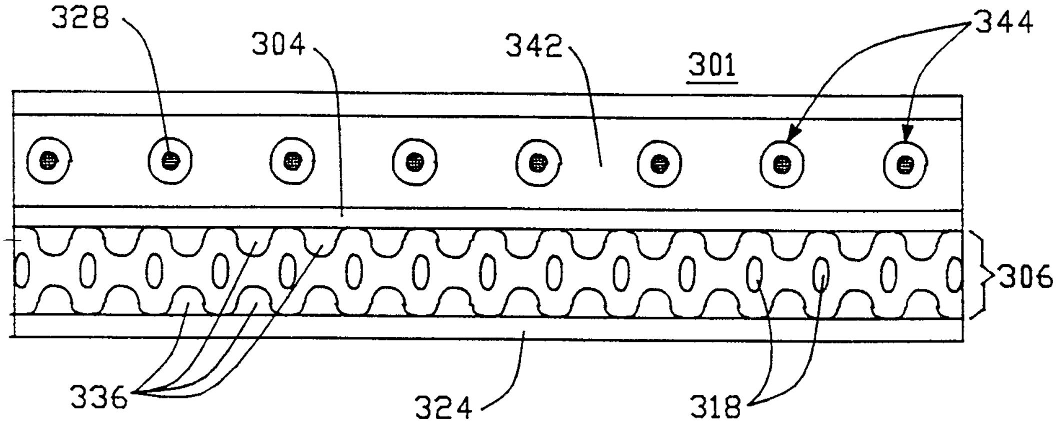

FIG.—3b

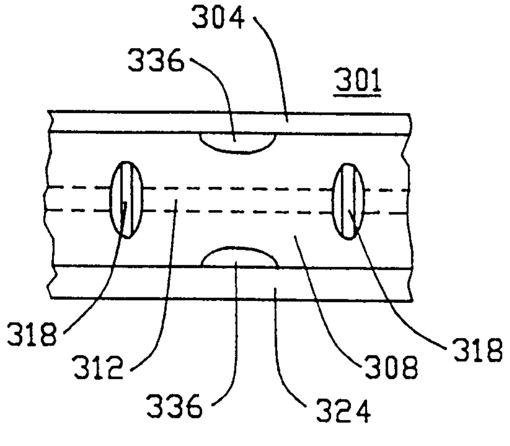

FIG.—3c

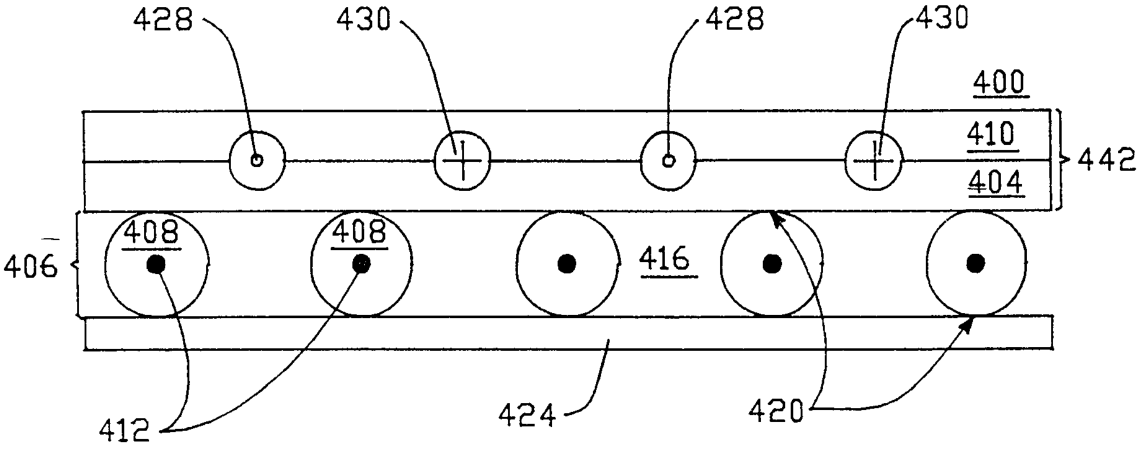

FIG.-4

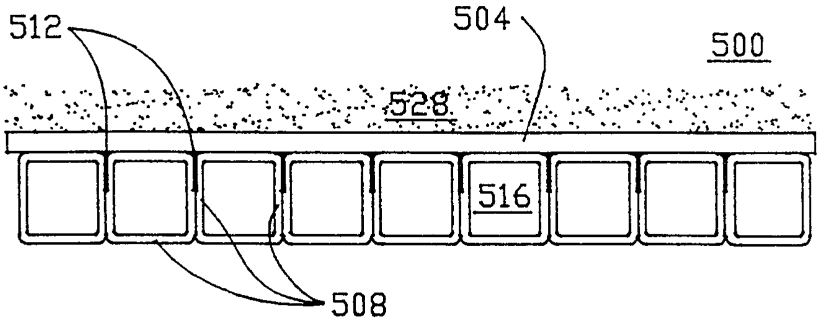

FIG.—5a

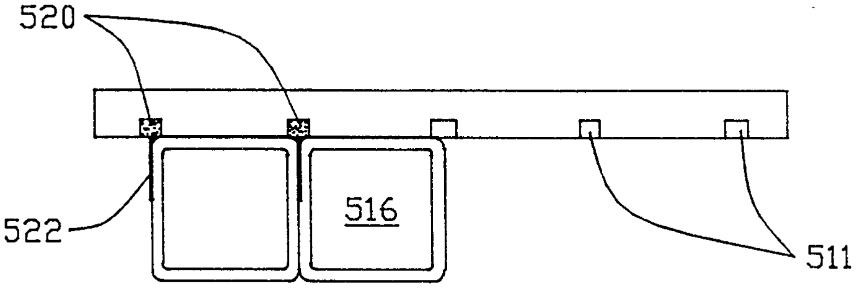

FIG.—5b

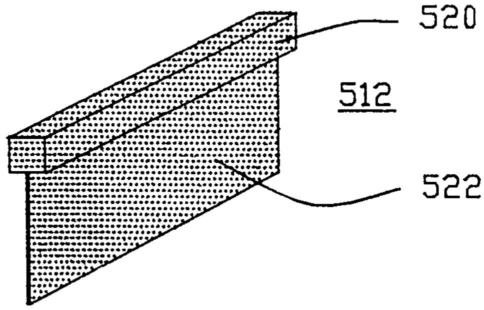

FIG.—5c

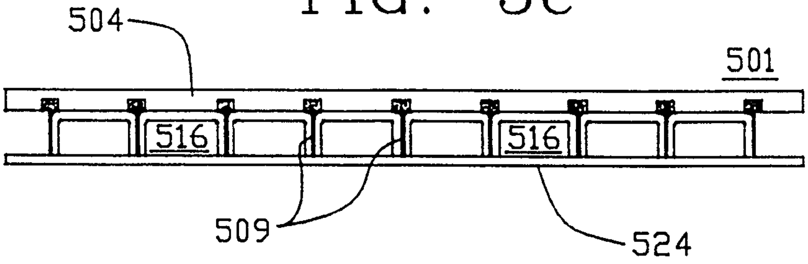

FIG.—5d

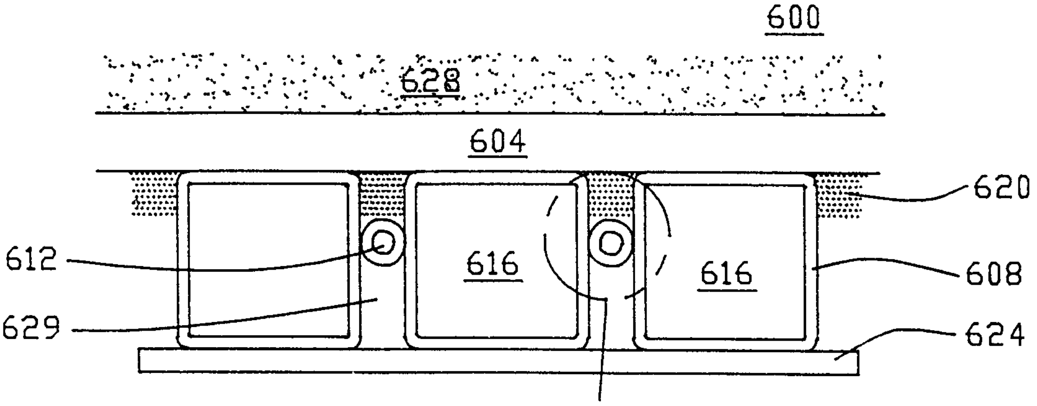

FIG.—6a

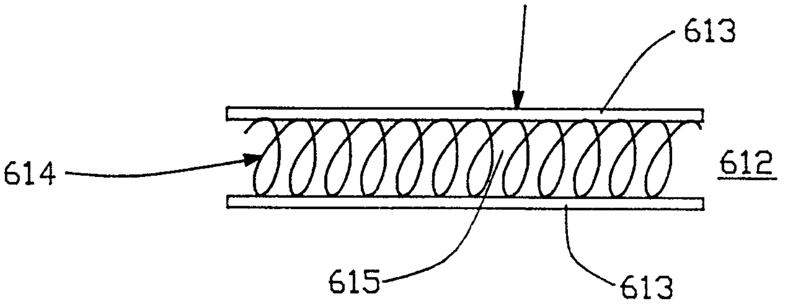

FIG.—6b

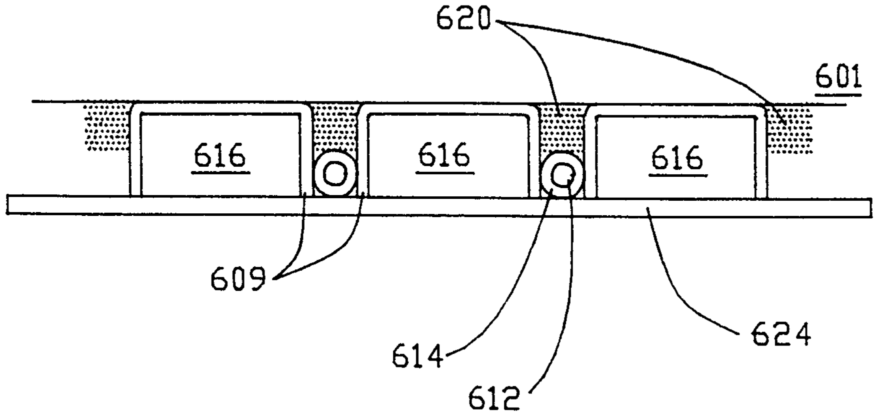

FIG.—6c

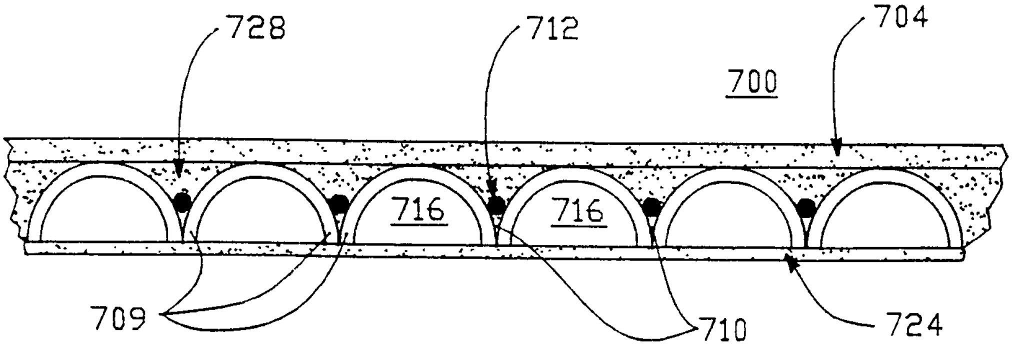

FIG.—7a

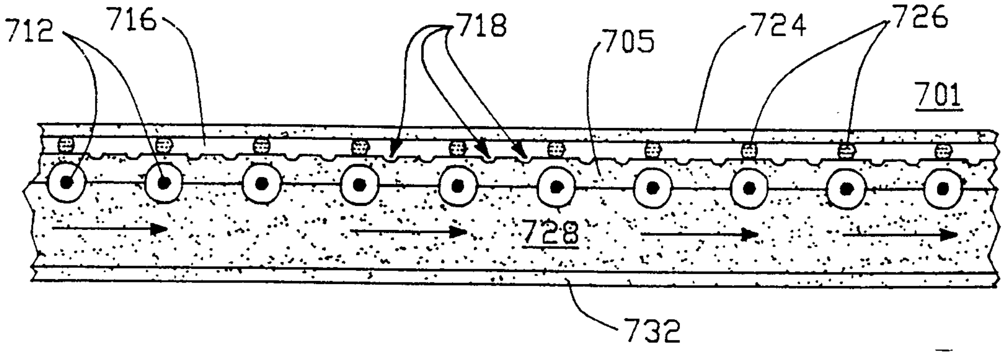

FIG.—7b

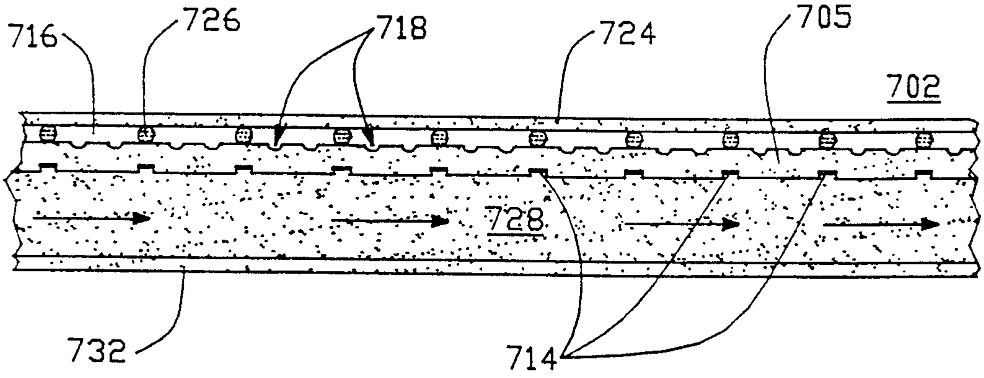

FIG.—7c

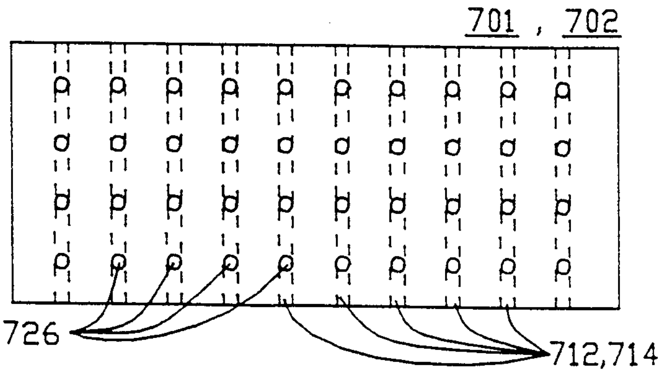

FIG.—7d

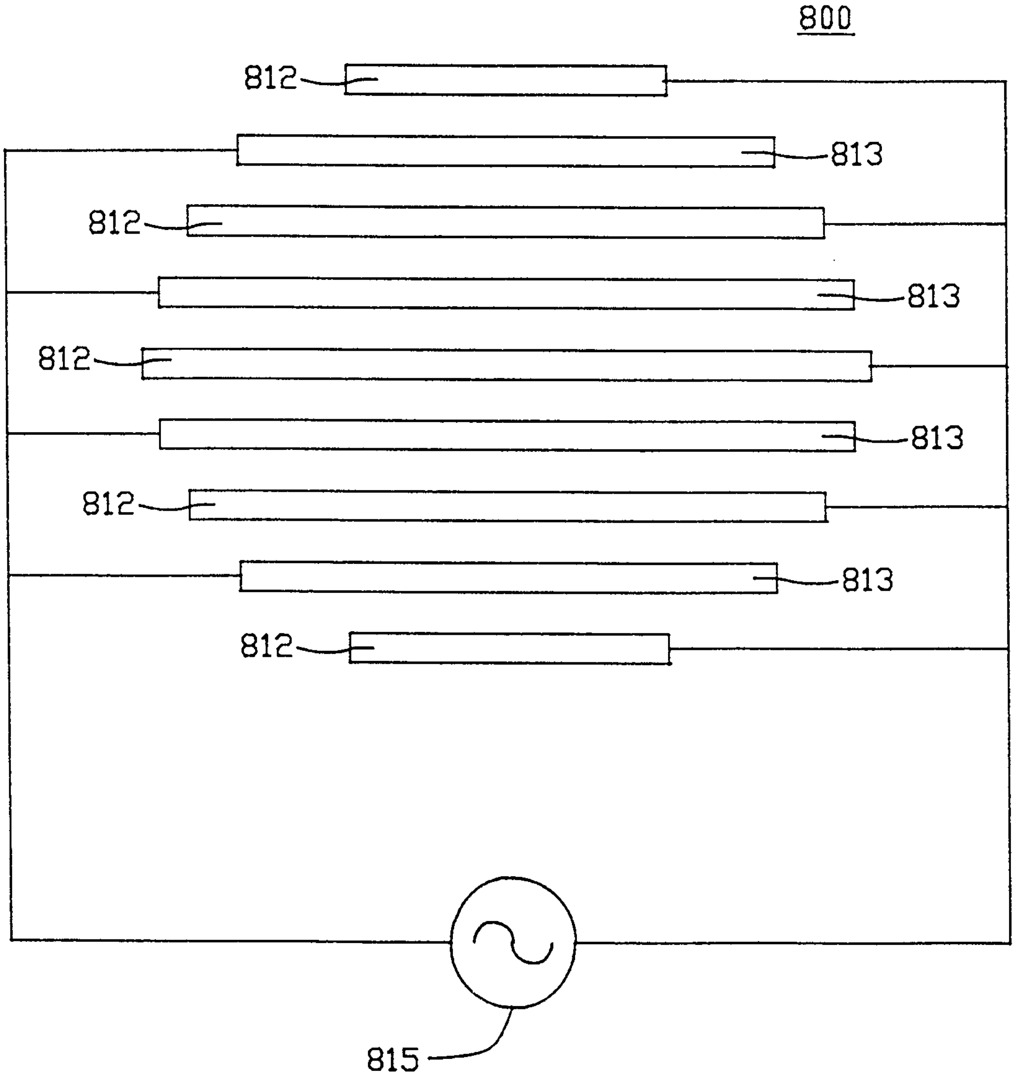

FIG.-8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/02948

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : H01J 61/06
US CL : 250/504R; 313/609, 612, 631, 634
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 250/504R; 313/609, 612, 631, 634

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X -- Y	US 4,843,281 A (MENDELSOHN) 27 June 1989, whole document.	1, 2, 5, 6, 12, 35-37, and 46 -------------- 8-11 and 13-23
Y	US 5,118,989 A (EGERMEIER et al) 02 June 1992, col. 5, lines 6-10, Figure 4.	8, 10, and 11
Y	US 5,581,152 A (MATSUNO et al) 03 December 1996, col. 8, lines 2-4.	9

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

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

Date of the actual completion of the international search

03 MAY 1999

Date of mailing of the international search report

20 MAY 1999

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/02948

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X -- Y	US 5,049,777 A (MECHTERSHEIMER) 17 September 1991, whole document.	24-27, 29-34, and 41-45 --------- 13-23 and 28
Y	US 5,214,344 A (KOGELSCHATZ) 25 May 1993, col. 2, lines 56-61.	17-21, 23, and 28
X	US 5,006,758 A (GELLERT et al) 09 April 1991, col. 3, lines 37-40.	38-40