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(54) **TEMPERATURE CONTROLLED SUBSTRATE SUPPORT ASSEMBLY**

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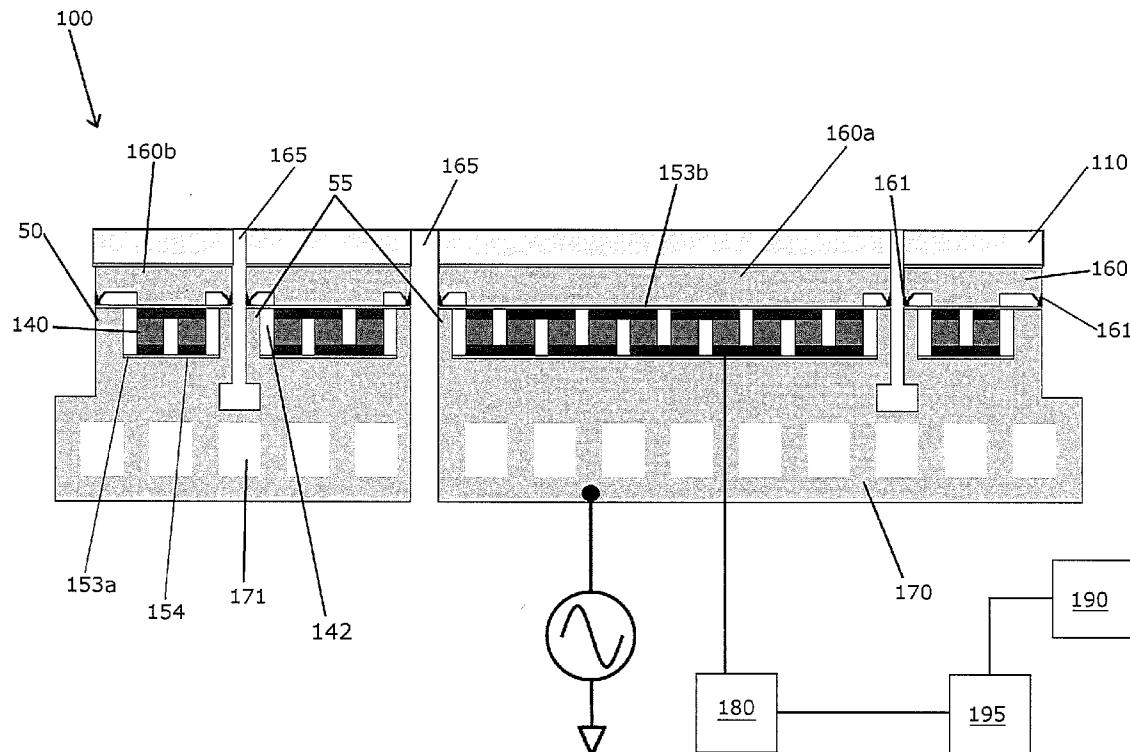
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ABSTRACT

A temperature controlled substrate support assembly used for processing a substrate in a vacuum chamber of a semiconductor processing apparatus. The substrate support assembly comprises a top plate for supporting the substrate. A base plate is disposed below the top plate wherein the base plate comprises a cavity in an upper surface of the base plate. A cover plate is disposed between the top plate and the base plate. At least one thermoelectric module is in the cavity in the upper surface of the base plate wherein the at least one thermoelectric module is in thermal contact with the top plate and the base plate, and the at least one thermoelectric module is maintained at atmospheric pressure.



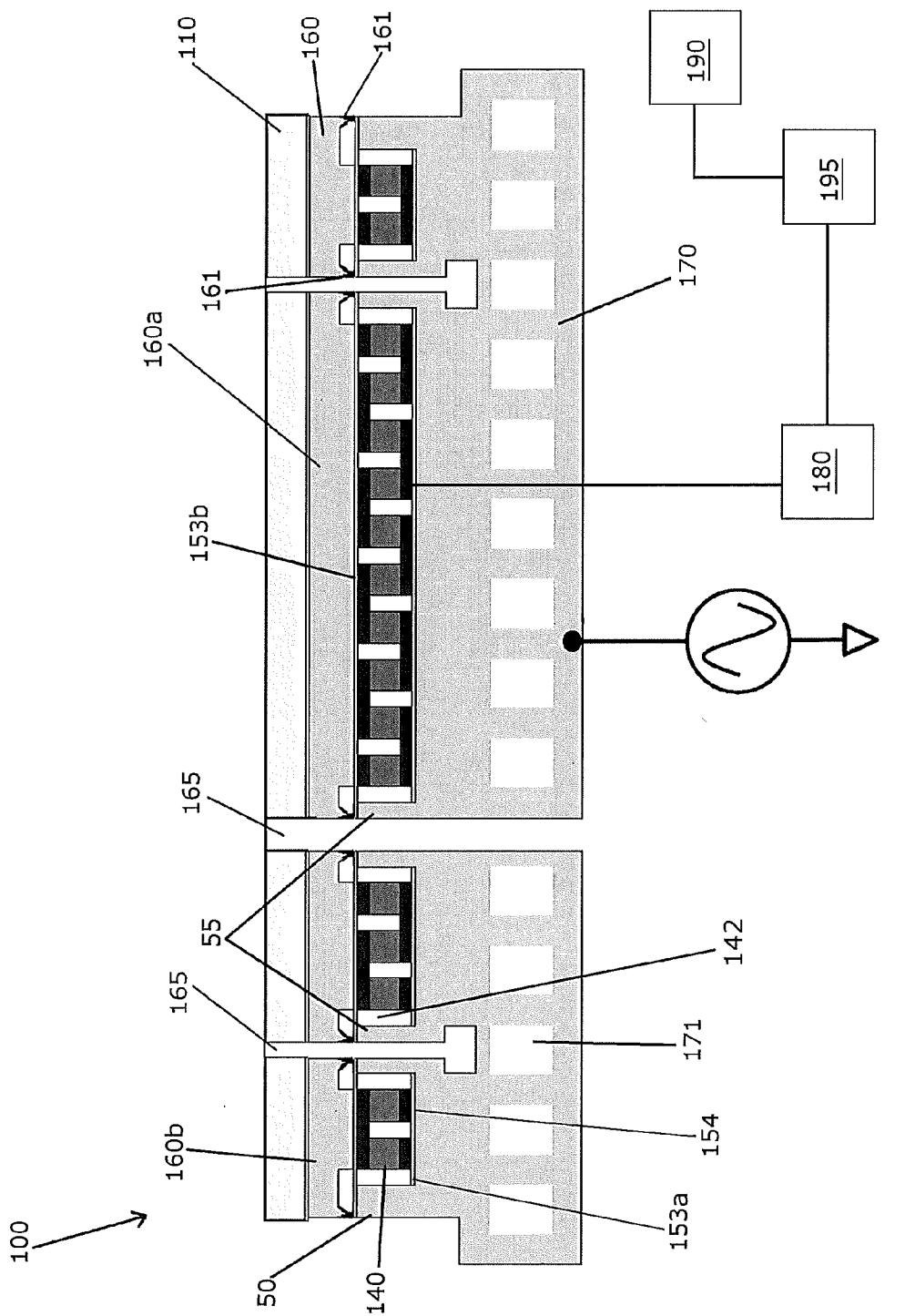
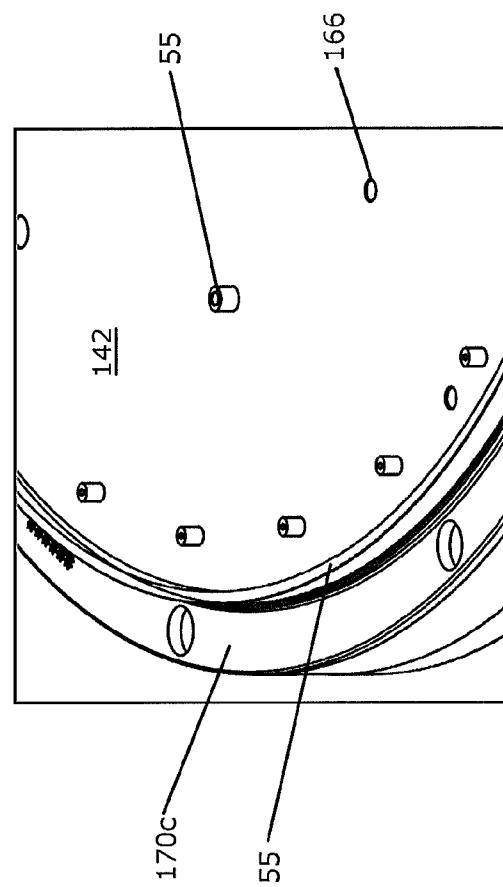
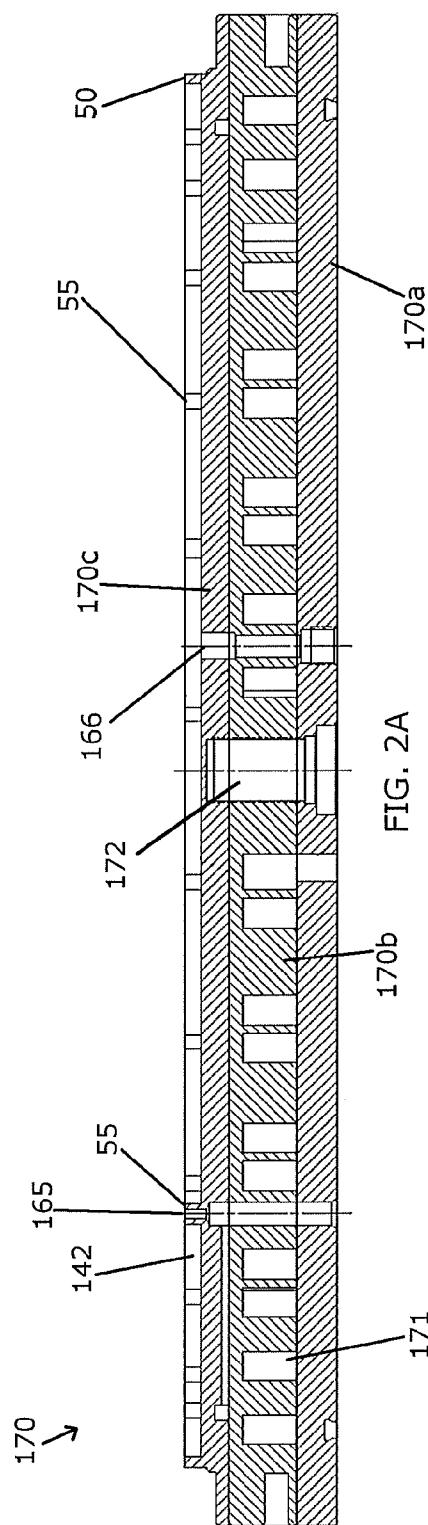


FIG. 1



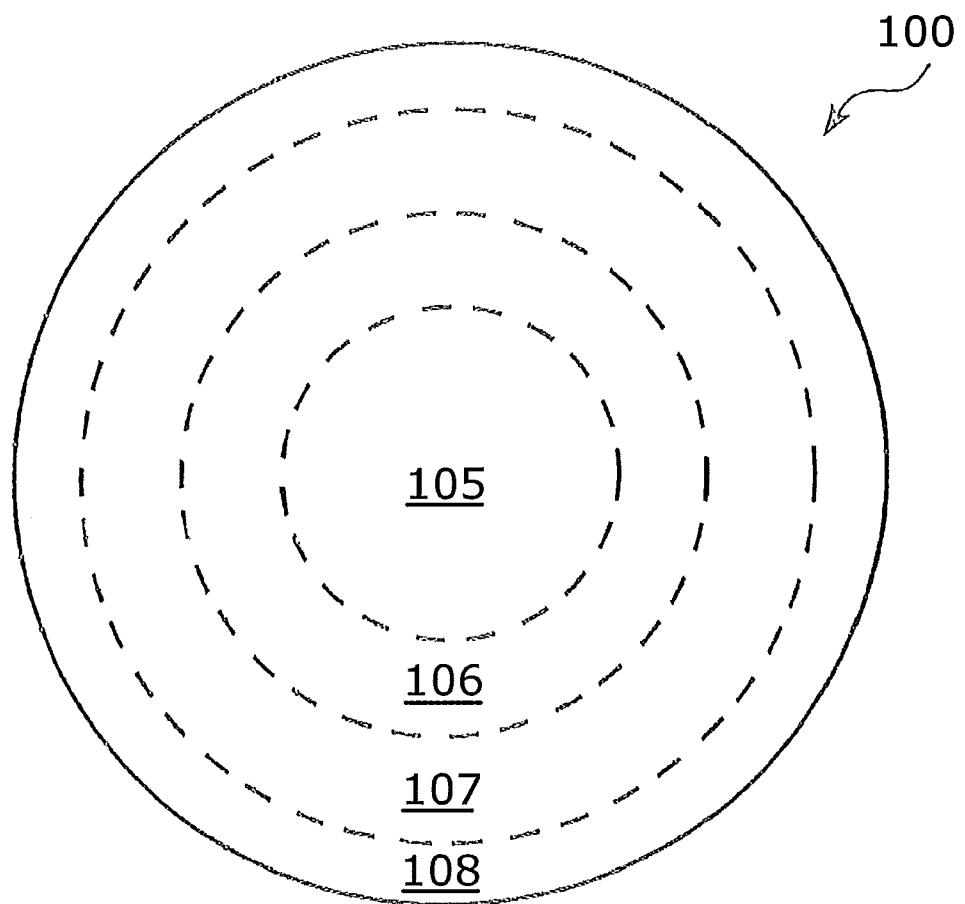


FIG. 3

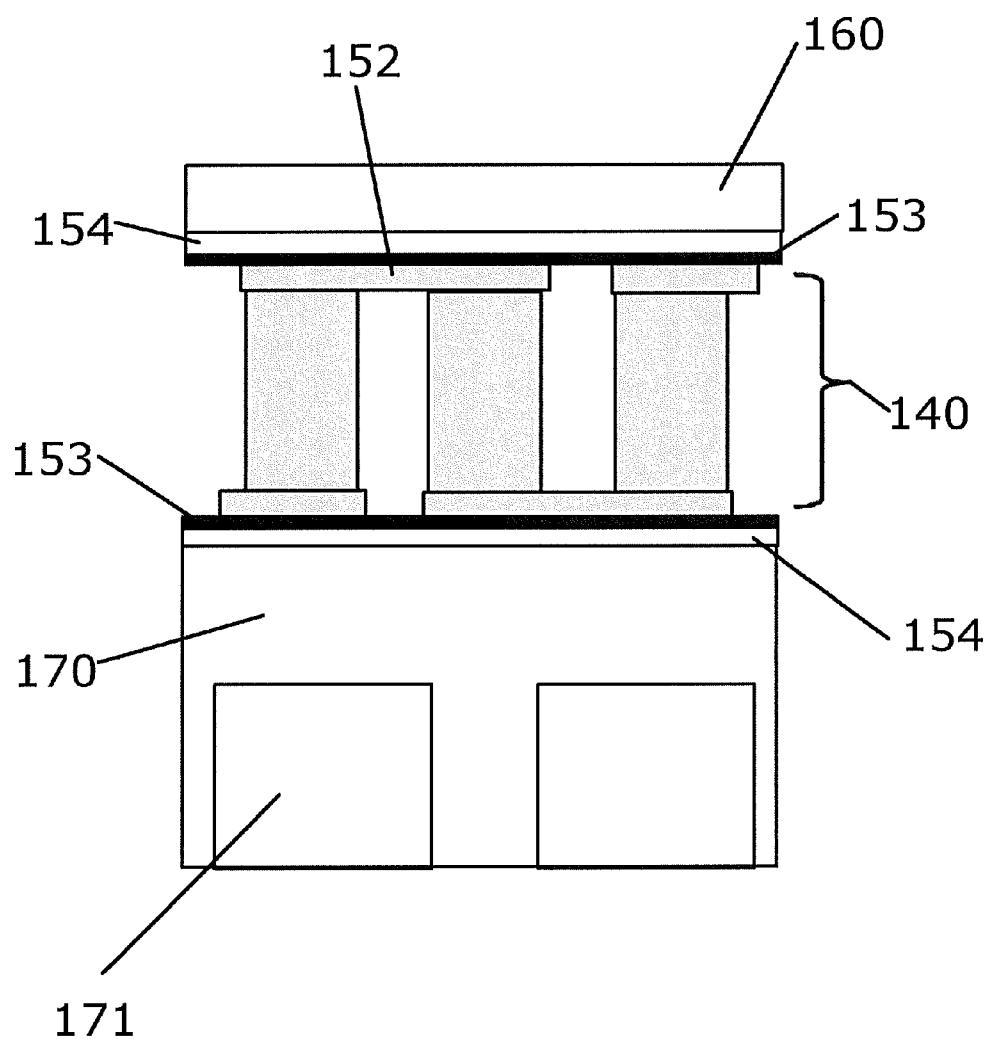


FIG. 4

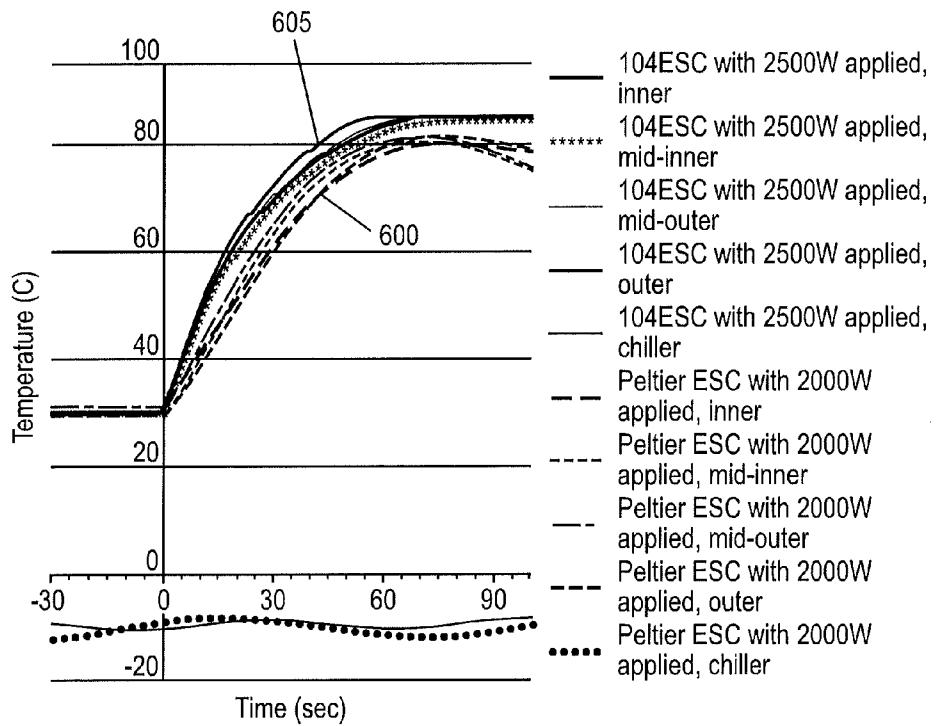


FIG. 5A

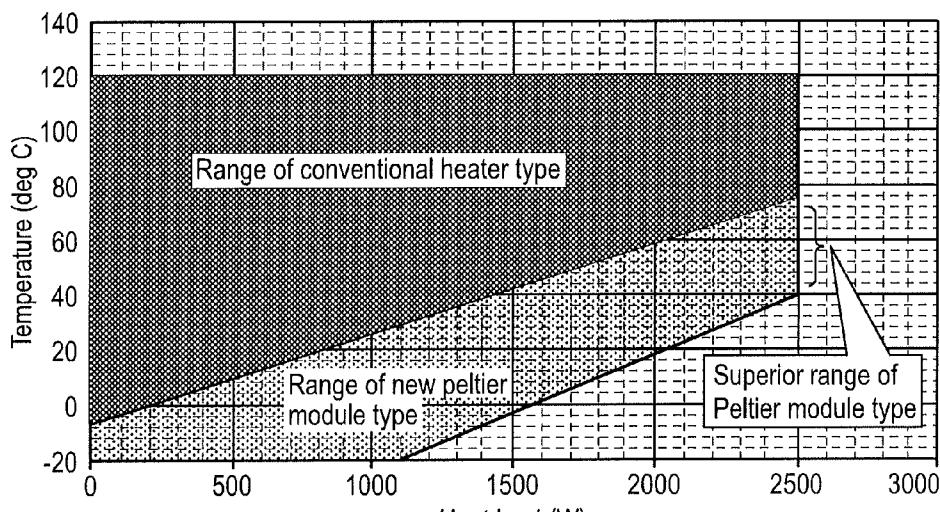
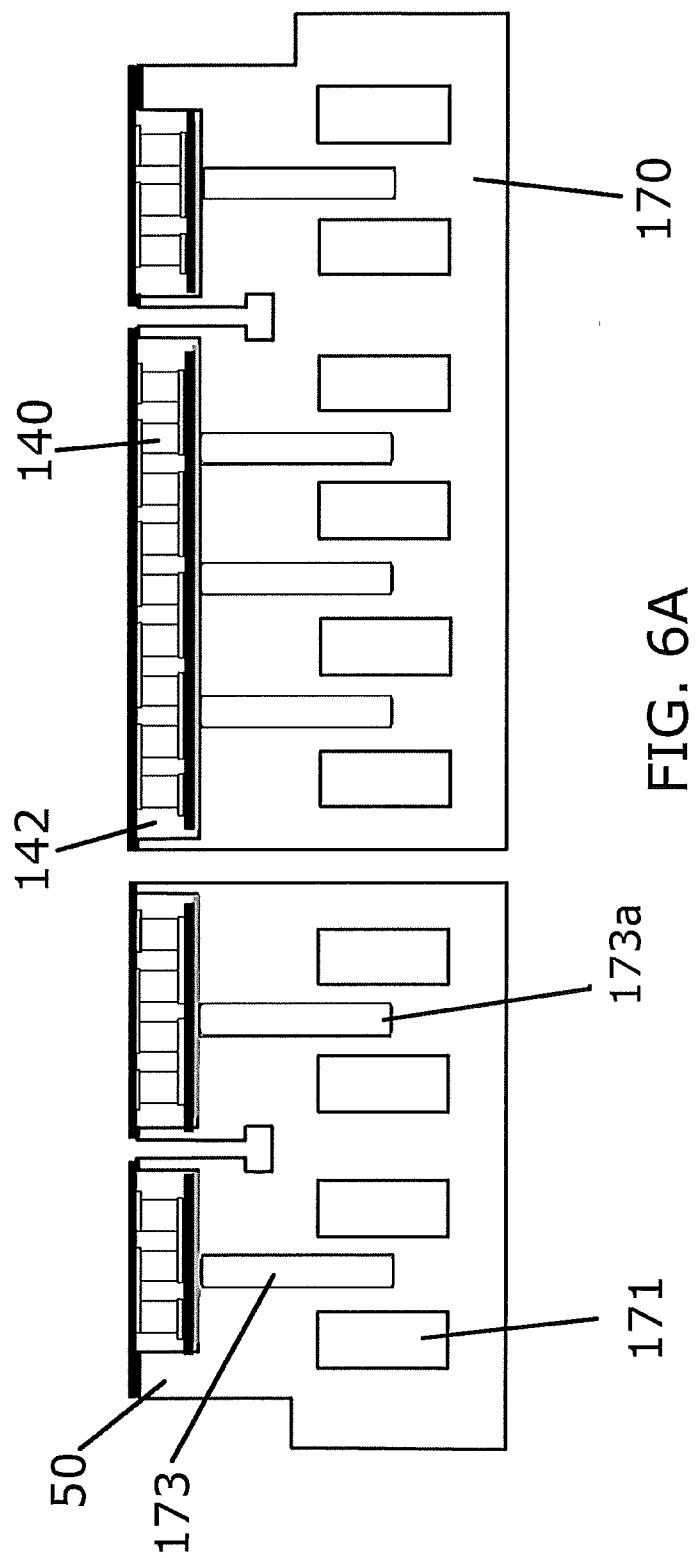
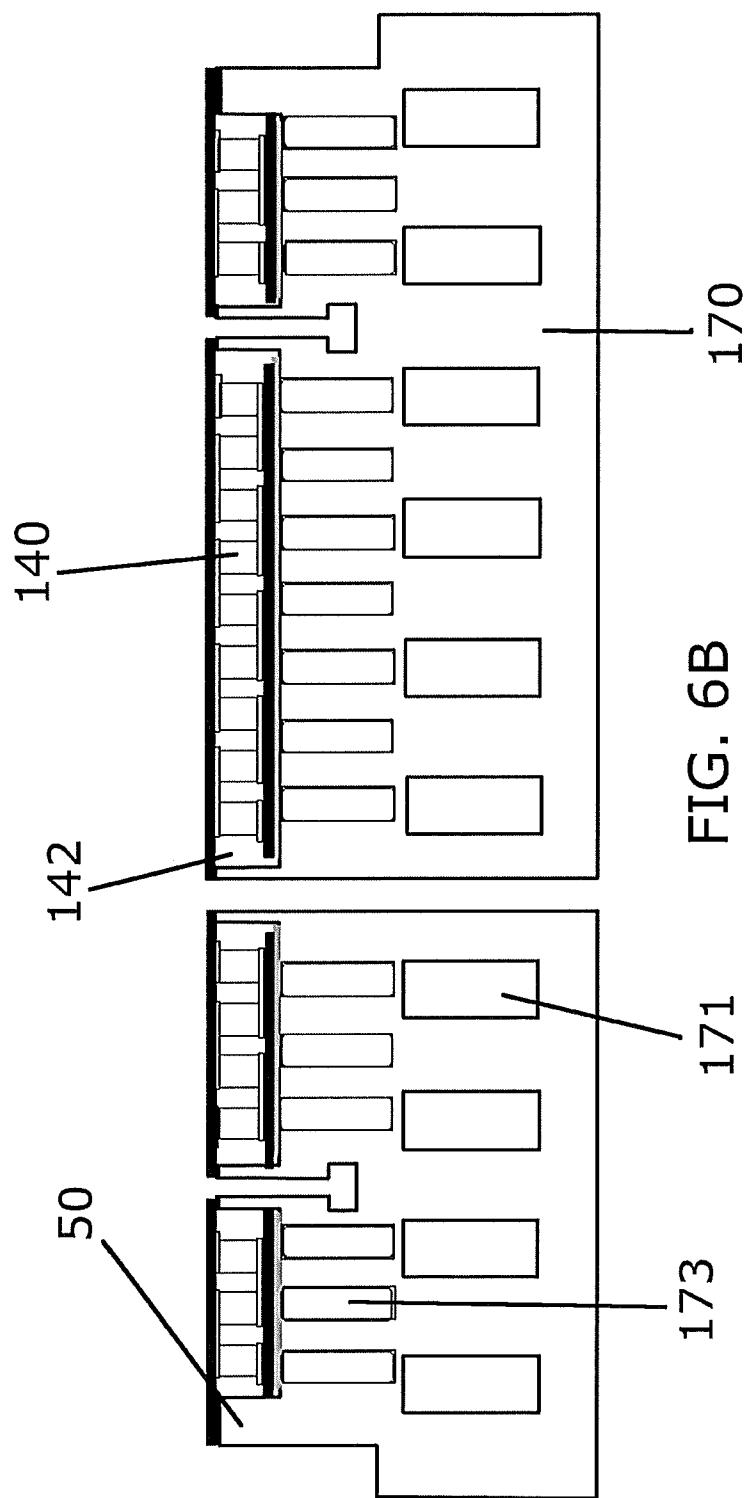
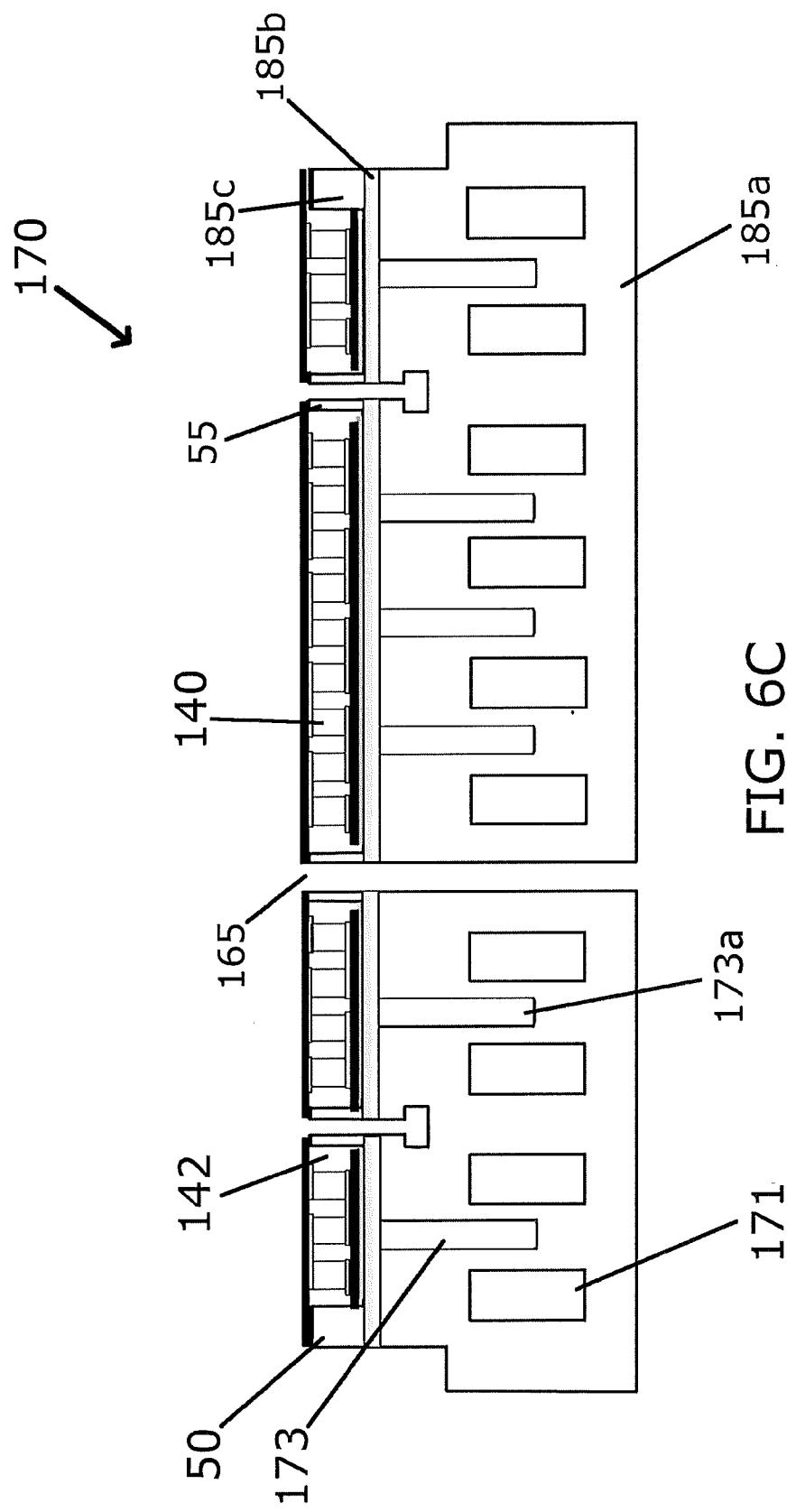


FIG. 5B







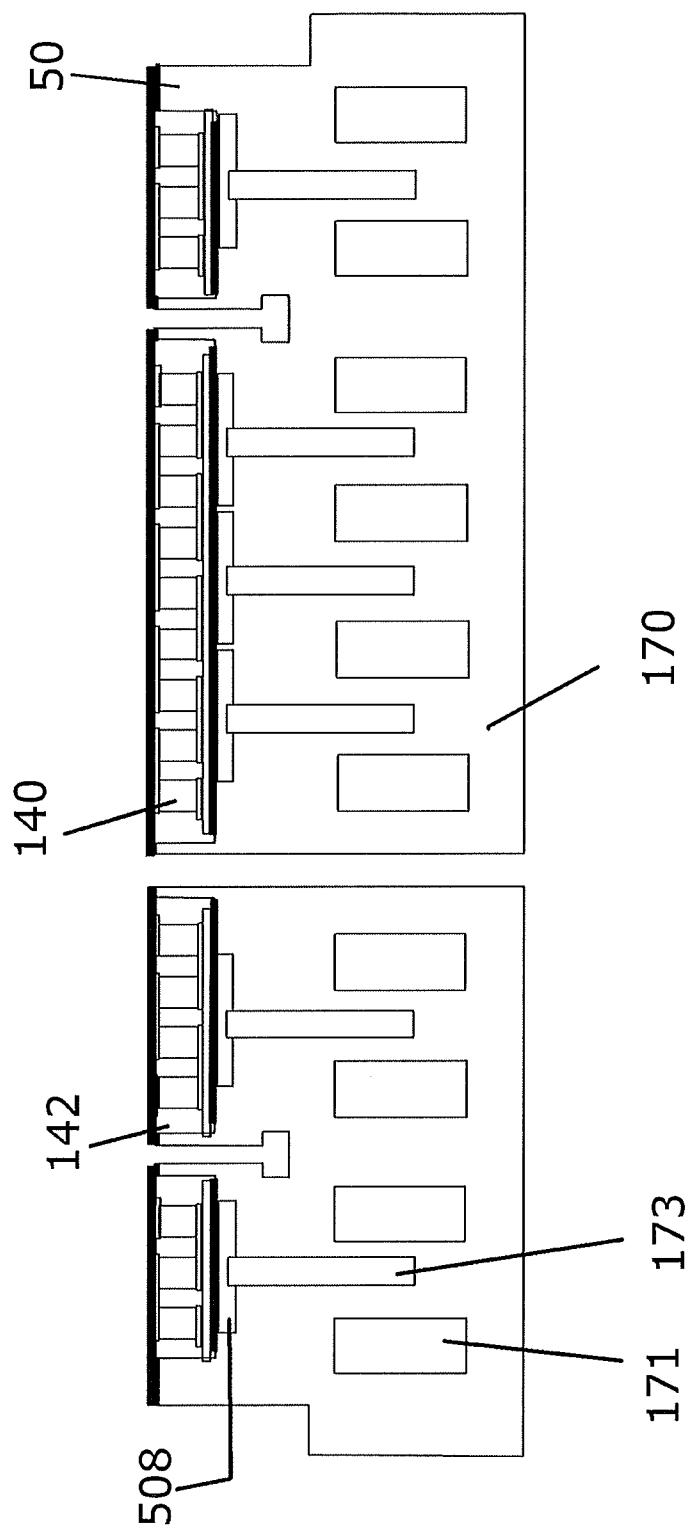


FIG. 6D

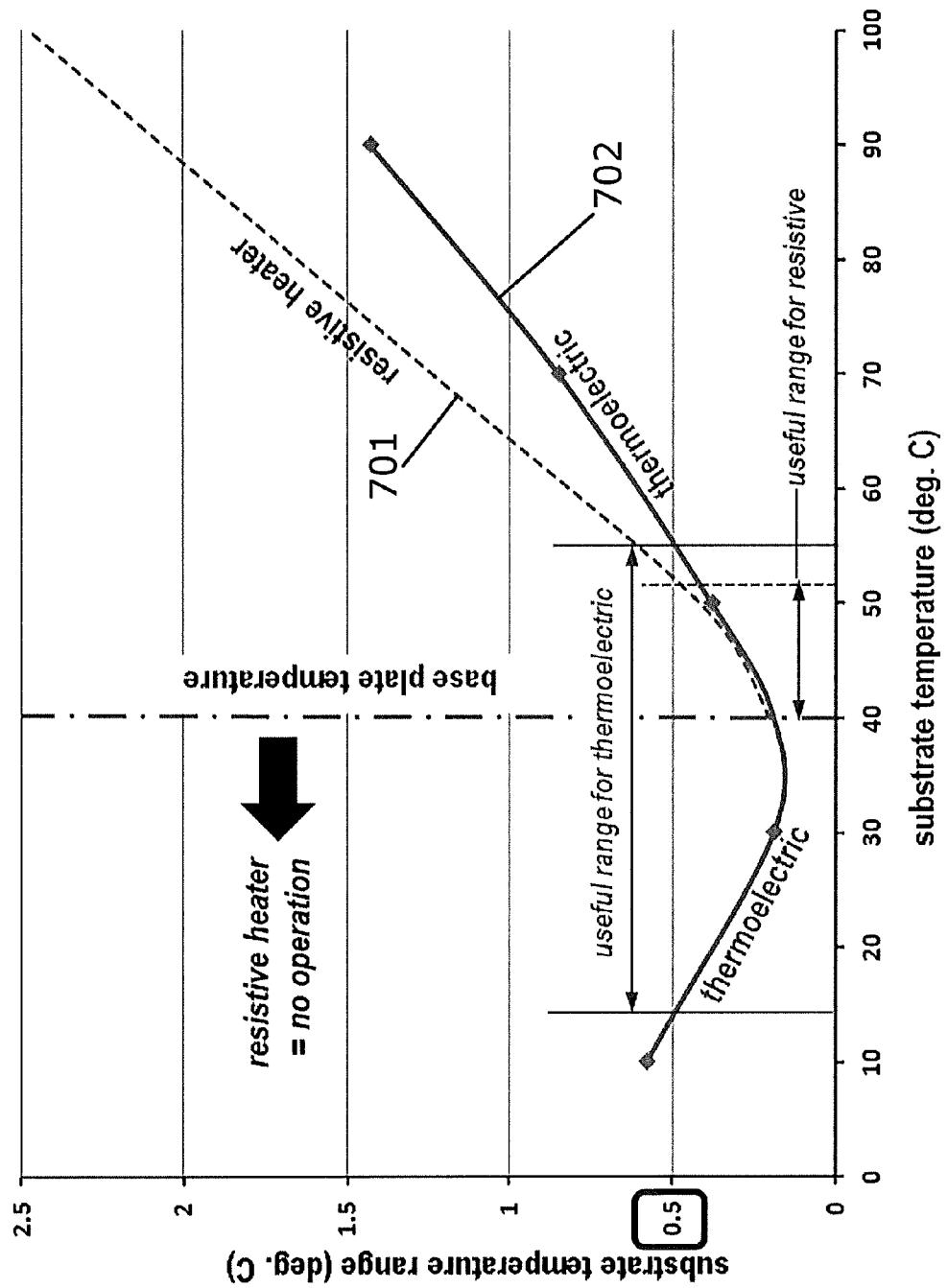


FIG. 7

TEMPERATURE CONTROLLED SUBSTRATE SUPPORT ASSEMBLY

FIELD OF THE INVENTION

[0001] The present invention relates to plasma processing apparatuses, and more specifically to temperature control of a substrate support assembly.

BACKGROUND

[0002] Integrated circuits are formed from a wafer or semiconductor substrate over which are formed patterned microelectronics layers. In the processing of the substrate, plasma is often employed to deposit films on the substrate or to etch intended portions of the films. Shrinking feature sizes and implementation of new materials in next generation microelectronics layers have put new requirements on plasma processing equipment. The smaller features, larger substrate size and new processing techniques require improvement in plasma processing apparatuses to control the conditions of the plasma processing.

[0003] During plasma etching, etch rates and etch rate selectivities can vary across the semiconductor substrate. Because etch rates and etch rate selectivities are influenced by temperature, there is a need for improved spatial temperature control across the substrate. In addition to improved spatial temperature control, expanding temperature ranges used to process the semiconductor substrate can allow for semiconductor substrates comprising complex material stacks to be utilized during processing.

SUMMARY

[0004] Disclosed herein is a temperature controlled substrate support assembly for processing a substrate in a vacuum chamber of a semiconductor processing apparatus. The substrate support assembly comprises a top plate for supporting the substrate. A base plate is disposed below the top plate wherein the base plate comprises a cavity in an upper surface of the base plate. A cover plate is disposed between the top plate and the base plate. At least one thermoelectric module is in the cavity in the upper surface of the base plate wherein the at least one thermoelectric module is in thermal contact with the top plate and the base plate, and the at least one thermoelectric module is maintained at atmospheric pressure.

[0005] Also disclosed herein is a method of manufacturing a substrate support assembly for controlling a temperature of a substrate during plasma processing. The method comprises bonding a lower surface of at least one thermoelectric module to a surface within a cavity in an upper surface of a base plate, bonding a lower surface of an upper electrically insulating layer included on an upper surface of the at least one thermoelectric module to a cylindrical wall defining the cavity in the upper surface of the base plate and to upwardly extending bosses within the cavity, wherein the bonded lower surface of the upper electrically insulating layer forms a vacuum seal with the cylindrical wall and the upwardly extending bosses and the cavity is open to the atmosphere through a surface of the cavity within the upper surface of the base plate, and bonding an upper surface of the upper electrically insulating layer to a cover plate.

[0006] Also disclosed herein is a method of processing a substrate in a semiconductor processing apparatus wherein the substrate is supported on a top plate of a temperature

controlled substrate support assembly in a vacuum processing chamber. The method comprises a step of supplying current to at least one respective thermoelectric module in heat transfer contact with the top plate so as to control temperatures of one or more zones across the top plate. The method also comprises controlling the current to set the temperature of the top plate surface and to provide a desired temperature distribution across the substrate during processing.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

[0007] FIG. 1 illustrates an embodiment of a temperature controlled substrate support assembly comprising a plurality of thermoelectric modules.

[0008] FIGS. 2A, B illustrate an embodiment of a base plate which may be used in accordance with embodiments of temperature controlled substrate support assemblies disclosed herein.

[0009] FIG. 3 illustrates an embodiment of temperature control zones which may be formed in a temperature controlled substrate support assembly disclosed herein.

[0010] FIG. 4 illustrates a cross section of an exemplary bonding arrangement for thermoelectric modules between a base plate and a cover plate.

[0011] FIGS. 5A, B each illustrate a graph of temperature control exhibited by an embodiment disclosed herein of a temperature controlled substrate support assembly comprising a plurality of thermoelectric modules.

[0012] FIG. 6A-D illustrate further embodiments of a base plate which may be used in accordance with embodiments of temperature controlled substrate support assemblies disclosed herein.

[0013] FIG. 7 illustrates a graph of the relationship between substrate temperature and substrate temperature uniformity of a substrate supported on a temperature controlled substrate support assembly in accordance with embodiments disclosed herein.

DETAILED DESCRIPTION

[0014] Disclosed herein is a temperature controlled substrate support assembly ("substrate support assembly" herein), wherein the substrate support assembly comprises at least one thermoelectric module to heat and/or cool a substrate supported on a top plate (i.e. substrate support) of the substrate support assembly. In the following description, numerous specific details are set forth in order to provide a thorough understanding of present embodiments disclosed herein. It will be apparent, however, to one skilled in the art that the present embodiments may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the present embodiments. Additionally, as used herein, the term "about" refers to $\pm 10\%$.

[0015] Controlling the temperature of a substrate supported on a top plate comprises many variables. First, many factors can affect heat transfer, such as the locations of heat sinks in the substrate support assembly as well as the detailed structure of the various heating and cooling elements in the substrate support assembly. Second, heat transfer is a dynamic process. Therefore, unless the system in question is in heat equilibrium, heat transfer will occur and the temperature profile and heat transfer will change with time. Third, non-equilibrium phenomena, such as the plasma density profile, and

the RF power profile, which are present during plasma processing, make theoretical prediction of the heat transfer behavior of any practical plasma processing apparatus difficult, hence the substrate temperature profile is often not uniform and difficult to control. These deficiencies may translate to non-uniformity in the processing rate across the whole substrate and non-uniformity in the critical dimension of the device dies on the substrate.

[0016] Further, top plates which include resistive heating elements rely on the inherent thermal resistance of the entire assembly to define the achievable range of operating temperatures. For example, substrate support assemblies which have high thermal resistance enable higher achievable temperatures because less heat is transferred to a coolant which flows through the base plate. However, substrate support assemblies which have high thermal resistance limit the minimum achievable temperatures for a given process heat load. Conversely, substrate support assemblies which have a low thermal resistance enable lower achievable temperatures for a given process heat load, but also limit the maximum achievable temperatures. To expand the operating range of the substrate support assembly, the coolant temperature can be lowered and the heating power can be increased, however, this introduces a larger thermal difference between top plate and the coolant, which exaggerates thermal non-uniformity.

[0017] To control substrate temperature, a plasma etching system can have at least one thermoelectric module arranged in the substrate support assembly, and a controller unit that controls DC current which flows through each of the thermoelectric modules arranged in the substrate support assembly. One or more thermoelectric modules can be used to expand the operating temperature range of the substrate support assembly wherein each thermoelectric module can be set to a temperature above or below the temperature of the coolant flowing through the base plate thereof. Each thermoelectric module is formed from alternating p-doped and n-doped semiconductor elements (as used herein "thermoelectric pairs"), wherein the p-doped semiconductor element and the n-doped semiconductor element are connected electrically in series and thermally in parallel by a junction. Thus, when an electrical current passes through the junction of the two semiconductor elements, it either cools or heats the junction depending on the direction of the current, thereby forming a hot side and a cool side of each thermoelectric module such that each thermoelectric module can heat or cool a respective portion of the substrate support assembly. Each thermoelectric module is preferably formed in a defined pattern, wherein each of thermoelectric modules may be arranged to so as to form a respective temperature control zone within the substrate support assembly. By tuning the power of each of thermoelectric modules under control of the controller unit, and by having an appropriate arrangement of each thermoelectric module in the substrate support assembly, a substrate may be heated or cooled and the temperature profile of a substrate during processing can be shaped concentrically, radially, and azimuthally. Additionally, the temperature gradient across the substrate support assembly can be controlled in order to maintain a desired temperature distribution across the substrate during processing by arranging each of the thermoelectric modules in the substrate support assembly. For example, a rectangular grid, a hexagonal grid, concentric circles, one or more radial arrays, or other pattern of the thermoelectric modules may be formed thereby forming temperature control zones. The substrate support assembly is

operable to control the substrate temperature and consequently the plasma etching process at each device die location to maximize the yield of devices from the substrate.

[0018] During plasma processing, the vacuum chamber containing the substrate support assembly is maintained at a desired pressure such as 0 to 20 mTorr, 20 to 50 mTorr, or 50 to 300 mTorr. To prevent exposure to chemical reagents and/or undesirable glow discharge, each thermoelectric module is located in the substrate support assembly and maintained at atmospheric pressure (about 1 atm). The thermoelectric modules assembled in the substrate support assembly can provide active substrate cooling, increase temperature operating windows of the substrate support assembly, and aid in low temperature processing of substrates. The thermoelectric modules can provide greater temperature control of substrates, such as non-uniform thermal arrays or uniform thermal arrays. For example, the independently controllable thermoelectric modules assembled in the substrate support assembly can achieve about 0.1° C. uniformity across an upper surface of the substrate support assembly.

[0019] FIG. 1 illustrates a substrate support assembly 100 for a semiconductor processing system in which the substrate support assembly 100 is temperature controlled and may be used in accordance with methods and structures disclosed herein. The substrate support assembly 100 may be used for plasma processing a substrate (not shown) within a vacuum chamber in which the substrate support assembly 100 is located. The substrate is preferably supported by a top plate 110 of the substrate support assembly 100. The substrate may be, for example, a semiconductor substrate or a flat panel display. The top plate 110 may comprise an electrostatic chuck ("ESC"). The substrate support assembly 100 may also comprise an interface to a radio frequency ("RF") power source and a thermoelectric temperature control system ("thermoelectric system") formed from at least one thermoelectric module 140. The substrate may be clamped to the top plate 110 either mechanically or preferably by an ESC structure incorporated in the top plate 110. Although not illustrated, the substrate support assembly may also comprise other features such as a substrate handling system, such as lift pins and associated actuating equipment, disposed therein, conducts to deliver heat transfer gas to the backside of a substrate, temperature sensors, power lines, or the like.

[0020] The substrate support assembly 100 further includes a base plate 170 which is RF driven to provide RF bias on a substrate undergoing processing and act as a lower electrode in the plasma chamber. The base plate 170 may be formed from aluminum, copper, or other high thermal conductivity material. The base plate 170 may contain an upper surface formed from aluminum, copper, silver, pyrolytic graphite encased in aluminum, or other high thermal conductivity material upon which the thermoelectric modules are attached. The use of aluminum or pyrolytic graphite encased in aluminum permits the base plate 170 to be formed with brazing. The base plate 170 is disposed below the top plate 110 and comprises a cavity 142 in an upper surface of the base plate 170 to house the at least one thermoelectric module 140. Preferably the cavity 142 is defined by a cylindrical wall 50 which is located near an outer periphery of the base plate 170. The base plate 170 acts as a heat sink by circulating a heat transfer medium (e.g. coolant) at a constant temperature through fluid channels 171 in the base plate 170 and localized temperatures of the substrate are controlled by the at least one thermoelectric module 140. The fluid channels 171 are pref-

erably configured for supplying a coolant or a temperature controlled gas such that the base plate **170** may act as a heat sink. For example, the base plate **170** may be cooled with a gas such as air, He, N₂ or the like or liquid cooled with deionized water (DI), dielectric liquid such as Fluorinert or the like. Preferably the base plate **170** helps cut down on the power requirement to control the heat load on the upper side of the thermoelectric control system.

[0021] In a preferred embodiment more than one thermoelectric module **140** may be arranged in a single cavity **142** in the upper surface of the base plate **170** such that each thermoelectric module may form a temperature control zone within the substrate support assembly **100**. The temperature control zones formed by each of thermoelectric modules **140** may be arranged into any desired configuration such as a center temperature control zone with one or more surrounding annular formations, a grid formation, a radial formation, an azimuthal formation, a polar formation, or a nonpolar formation. Preferably upwardly extending bosses **55** are located within the cavity **142** in the upper surface of the base plate **170**. Thin upper and lower electrically insulating layers **153a,b** are further included on an lower and upper surface of the at least one thermoelectric module **140** wherein the thermoelectric module **140** is adhered to the insulating layers **153a,b** with an adhesive. The insulating layers **153a,b** are preferably ceramic or flexible polyimide layers and can have a thickness of about 0.004 to 0.02 inch. The insulating layer **153a** on the lower surface of the at least one thermoelectric module **140** is bonded to the upper surface of the base plate **170** within the cavity **142** with an adhesive **154**, wherein the adhesive is preferably an epoxy. Alternatively, the lower surface of the at least one thermoelectric module may be bonded directly to the upper surface of the base plate **170** within the cavity **142** with solder or a low melting point alloy provided that the upper surface of the base plate **170** includes a coating of an electrically insulating material such as anodization, spray-coated aluminum oxide, Teflon®, or the like. The insulating layer **153b** on the upper surface of the at least one thermoelectric module **140** is preferably bonded to a cover plate **160** with an adhesive **154**, wherein the adhesive is preferably silicone. The cover plate **160** is disposed between the top plate **110** and the base plate **170**. The insulating layer **153b** on the upper surface of the at least one thermoelectric module **140** is also bonded to the cylindrical wall **50** defining the cavity **142** in the upper surface of the base plate **170** and the upwardly extending bosses **55** located within the cavity **142** of the base plate **170**. The insulating layer **153b** forms a vacuum seal with the cylindrical wall **50** and the bosses **55** of the base plate **170** such that the at least one thermoelectric module **140** is not exposed to the vacuum environment in the vacuum chamber and instead can be maintained at atmospheric pressure in the cavity **142** of the base plate **170**.

[0022] The cover plate **160** is preferably formed from the same material as the base plate **170** such as aluminum, copper, pyrolytic graphite, or aluminum coated pyrolytic graphite. The cover plate **160** preferably includes downwardly extending bosses **161** wherein the bosses **161** are arranged to correspond to the upwardly extending bosses **55** located within the cavity **142**. The upwardly extending bosses **55** and the downwardly extending bosses **161** have aligned openings **165** with the top plate **110** wherein the aligned openings **165** are configured to receive lift pins and/or deliver backside helium to the upper surface of the substrate support assembly **100**. The upwardly extending bosses **55** and the correspond-

ing downwardly extending bosses **161** can be arranged so as to provide RF current paths within the substrate support assembly **100** to reduce RF transmission through the thermoelectric modules **140**. The downwardly extending bosses **161** are preferably chamfered such that they may minimize heat conduction between the base plate **170** and the cover plate **160** while still providing an RF current path. Additionally, the cover plate **160** may optionally act as an RF decoupling plate to electrically shield the thermoelectric modules **140** from RF voltage gradients while providing good thermal conduction between each of the thermoelectric modules **140** and the top plate **110**.

[0023] During processing of a substrate, the substrate is transferred into the vacuum chamber and loaded onto the top plate. The vacuum chamber provides the process environment to perform processing such as plasma etching, deposition, or other process involved in the production of integrated chips or the like. A substrate handling system which is part of the overall substrate processing system is used to load and unload the substrate to and from the vacuum chamber. The steps of inserting, processing, and removing the substrate may be repeated sequentially for a plurality of substrates.

[0024] The thermoelectric temperature control system for controlling temperature across the top plate **110** during processing is disposed below the top plate **110** and each thermoelectric module is located in the cavity **142** within the substrate support assembly **100** wherein the cavity **142** is maintained at atmospheric pressure. The thermoelectric system preferably comprises more than one thermoelectric module **140**. Each of the thermoelectric modules **140** controls temperatures across the top plate **110**, thereby controlling temperatures across the substrate during processing, in response to electrical current driven by a power supply **180** through a power feedthrough in the substrate support assembly **100**.

[0025] The current supply **180** may be formed of any conventional power supply. The power supply may, for example, comprise a single power source, a plurality of individual power sources, i.e. one for each thermoelectric module, or a plurality of power sources. Preferably, the power source(s) provide a direct current ("DC") wherein the DC current is electrically connected to the thermoelectric module(s) **140** via terminal(s) (not shown) which can be supported in holes **166** in the base plate **170** of the substrate support assembly **100** (see FIG. 2A). The range of current supplied by the current supply may be controlled, for example, between 0-25 amperes, depending on the heat load of the semiconductor processing system. An exemplary circuit arrangement for a thermoelectric system can be found in commonly-assigned U.S. Pat. No. 7,206,184, which is hereby incorporated in its entirety herein.

[0026] The solid state thermoelectric modules **140** control local temperatures of the substrate support assembly **100**, thereby controlling the temperature distribution across the substrate during processing. For example, by controlling the power, and direction of the current to the thermoelectric modules **140**, a desired temperature distribution can be established across the top plate **110** in order to provide desired processing conditions across the substrate during processing. Thus, a uniform or non-uniform temperature distribution may be maintained across the substrate during processing.

[0027] The power supply can be controlled to supply current at a sufficient level and for a period of time to achieve a desired temperature in a temperature control zone beneath the

substrate. For example, the power supply can supply currents having the same value to all the thermoelectric modules in one or more temperature control zones beneath the substrate. Alternatively, the currents supplied to each of thermoelectric modules may have different values, permitting dynamic temperature control of temperature control zones beneath the substrate wherein each temperature control zone is formed by a respective thermoelectric module. For example, the current supplied to a thermoelectric module arranged under the center of the top plate 110 may be different than the current supplied to a thermoelectric module arranged in an annular zone under an outer (edge) region of the top plate 110, so that the substrate surface is heated or cooled by different amounts in the center and edge regions. This dynamic temperature control compensates for differences in temperatures of the substrate surface at the center and the edge regions due to the semiconductor processing (e.g., plasma uniformity and RF uniformity), so that a desired temperature distribution across the substrate surface may be maintained during processing. The ability of the thermoelectric modules to cool the substrate, which thereby cools the substrate surface, expands the range of processing temperatures across the substrate which can be uniformly maintained (i.e., a temperature range of 0.5° C. or less) during processing of the substrate. As the difference in temperature between the baseplate 170 and top plate 110 increases, the thermal non-uniformity across the substrate also increases. This is because heat flux, even when completely uniform, passes through layers of material included in the substrate support assembly 100 which have non-uniform thicknesses. For example, as illustrated in FIG. 7, controlling the temperature of the substrate with resistive heating elements demonstrates a linear increase in temperature non-uniformity of the substrate as the temperature of the substrate is increased, and further the resistive heating elements cannot operate at temperatures below the temperature of the base plate (line 701). Whereas, controlling the temperature with thermoelectric modules, enables operation at temperatures above and below the base plate temperature wherein temperatures across the substrate can be uniformly maintained, thereby expanding the useful temperature range of the top plate (line 702).

[0028] In this manner, the localized temperature of the top plate 110 in the vicinity of each thermoelectric module 140 can be controlled, thereby permitting the temperature on the substrate surface to be kept uniform. Because electrons may move quickly through the p-type and n-type semiconductor elements, the heating and cooling operations can be rapidly performed, providing faster response times and more uniform temperature control than substrate support assemblies utilizing gas pressure, large mass heat sinks, resistance heating plates, or the like. Additionally, due to the Peltier effect, substrates may be cooled to temperatures below the temperature of the base plate 170.

[0029] By dynamically controlling the temperature of each thermoelectric module, the substrate support assembly may be divided into multiple zones of temperature control (i.e. a multizone substrate support assembly). Such temperature control zones may be arranged such that they form concentric zones, radial zones, annular zones and/or azimuthally aligned zones.

[0030] Preferably the substrate support assembly 100 comprises four temperature control zones wherein three temperature control zones are concentrically arranged around a central temperature control zone. For example as illustrated in

FIG. 3, a substrate support assembly 100 may be formed with four temperature control zones wherein a first center zone 105 is surrounded by three outer annular temperature zones 106, 107, 108. Alternatively it may be preferred that the substrate support assembly comprises 8 temperature control zones wherein 4 inner zones arranged in quadrants are surrounded by 4 outer zones arranged in quadrants. Examples of exemplary temperature control zone formations may be found in commonly-assigned U.S. Pat. Nos. 8,216,486, 7,718,932, and 7,161,121, which are hereby incorporated in their entirety herein.

[0031] FIGS. 2A, 2B illustrate an embodiment of the base plate 170 of the substrate support assembly 100 wherein FIG. 2A illustrates a cross section of the base plate 170 and FIG. 2B illustrates a top down view of a portion the base plate 170. The base plate 170 is preferably formed from aluminum and has a central bore 172. The central bore 172 receives an RF power supply connection such that the base plate 170 can provide an RF bias on a substrate supported on the top plate 110 of the substrate support assembly 100 during processing of the substrate. Alternatively, RF power can be supplied to the cover plate 160, or to a conductive layer embedded within the top plate 110 via electrical feedthroughs suitable for carrying the necessary RF current. The base plate 170 preferably can comprise an electrically conductive support plate 170a, an electrically conductive cooling plate 170b comprising fluid channels 171 disposed above the conductive support plate 170a, and an electrically conductive thermoelectric plate 170c disposed above the cooling plate 170b. The thermoelectric plate 170c comprises a single cavity 142 wherein the cavity 142 is maintained at atmospheric pressure. The cavity 142 is preferably defined by a cylindrical wall 50 which is located near an outer periphery of the thermoelectric plate 170c. Preferably upwardly extending bosses 55 are located within the cavity 142 wherein an upper insulating layer may be supported by the upwardly extending bosses 55 and the cylindrical wall 50 forming a vacuum seal thereon. Preferably the upwardly extending bosses 55 have openings 165 configured to support lift pins and/or backside helium gas supplies. The at least one thermoelectric module 140 is arranged within the cavity 142 formed in the upper surface of the thermoelectric plate 170c wherein the cavity 142 is open to the atmosphere. Holes 166 formed in the thermoelectric plate 170c may be configured to house temperature probes or electrical feedthroughs wherein the holes 166 can expose the cavity 142 to the atmosphere such that the cavity 142 may be maintained at atmospheric pressure.

[0032] In an embodiment, the substrate support assembly 100 has a thickness of about 1.5 inches. The base plate components 170a, 170b, 170c can have a combined thickness of about 1.2 to 1.3 inches. Preferably the thermoelectric plate 170c forms a step around the outer periphery wherein the step has a height of about 0.3 inch. For processing 300 mm diameter substrates, the base plate 170 preferably has an outer diameter of about 12 to 13 inches below the step formed in the thermoelectric plate 170c and an outer diameter above the step of the thermoelectric plate 170c is less than 12 inches, preferably of about 11.7 inches. The at least one thermoelectric module (not shown) are arranged in the cavity 142 of the thermoelectric plate 170c, wherein the thermoelectric plate 170c has a thickness of about 0.3 to 0.4 inch and the cavity 142 in the upper surface of the thermoelectric plate 170c has a depth of about 0.15 inch. The cooling plate 170b preferably has a thickness of about 0.5 to 0.6 inch and the support plate

170a preferably has a thickness of about 0.3 to 0.4 inch. Preferably the cooling plate **170b** and the support plate **170a** each have an outer diameter of about 12.6 inches.

[0033] Referring back to FIG. 1, in a preferred embodiment, the cover plate **160** can preferably be formed from an inner cover **160a** and an outer cover **160b**. Preferably the cover plate **160** has a thickness of about 0.12 inch and the inner cover **160a** has an outer diameter of about 9.8 inches while the outer cover **160b** has an outer diameter of about 11.7 inches. The top plate **110** preferably includes at least one electrostatic clamping electrode in a layer of dielectric material and has a thickness of about 0.1 inch and a diameter of about 11.7 inches. The insulating layers **153a,b** preferably have a thickness of about 0.004 to 0.02 inch, e.g., flexible polyimide layers can have a thickness of about 0.004 inch whereas ceramic layers can have a thickness of about 0.02 inch.

[0034] FIG. 4 illustrates an exemplary embodiment of a cross section of a thermoelectric module **140** (Peltier device) disposed between the base plate **170** and the cover plate **160**. Preferably, the junctions **152** connecting the alternating p-type and n-type semiconductor devices of the thermoelectric module **140** are attached to an insulating layer **153a,b** with an adhesive. Preferably the junctions **152** are formed from an electrically conductive material such as aluminum or copper. Preferably the insulating layers **153a,b** are of a flexible polyimide material possessing characteristics such as good thermal conductivity, strength and impact resistance, creep resistance, dimensional stability, radiation resistance, and chemical resistance on upper and lower surfaces of the thermoelectric modules **140**. Preferably the insulating layers **153a,b** are formed from polyimide material, but alternatively the insulating layers **153a,b** may be formed from a flexible polyamide material or are ceramic. Preferably the polyimide layers **153a,b** provide electrical isolation and a flexible supporting surface to absorb strain on the thermoelectric modules **140** induced by temperature changes. The thermoelectric modules **140** including the insulating layers **153a,b** are adhered to the base plate **170** and the cover plate **160** with adhesive layers **154**. Preferably the adhesive adhering the insulating layer **153a** to the base plate **170** is an epoxy, and the adhesive adhering the insulating layer **153b** to the cover plate **160** is silicone. An exemplary thermoelectric module with upper and lower polyimide films is manufactured by KELK Ltd., a wholly owned subsidiary of Komatsu Ltd and can be found in U.S. Published Application No. 2013/0098068, incorporated herein by reference.

[0035] FIG. 5A illustrates a graph of temperature vs. time for a comparative multizone substrate support assembly having multizone resistance heaters over a base plate maintained at a constant temperature, represented by straight lines **605**, and a multizone substrate support assembly comprising thermoelectric modules, represented by the dotted lines **600**. The multizone substrate support assembly comprising thermoelectric modules can achieve similar results with a power of 2000 W in each temperature zone as the comparative multizone substrate support assembly with a power of 2500 W. For example, the multizone substrate support assembly comprising thermoelectric modules can increase the temperature of the support surface and in turn the substrate from about 30° C. to about 80° C. in about 60 seconds. Furthermore, the substrate support assembly comprising the thermoelectric modules can have a temperature transition rate of about 1.3° C. per second and can reach a maximum temperature of about 90° C.

Additionally the substrate support assembly comprising the thermoelectric modules can achieve greater cooling temperature ranges. For example, as illustrated in FIG. 5B the cooling function of the substrate support assembly comprising the thermoelectric modules can maintain temperatures of about -20° C. with about a 1000 W heat load (the base plate maintained at about -10° C.) and can maintain temperatures of about 40° C. with a 2500 W heat load. In contrast, the comparative substrate support assembly operates at about 20° C. with 1000 W heat load and about 70° C. with a 2500 W heat load.

[0036] Referring back to FIG. 1, the at least one thermoelectric module **140** is arranged in the cavity **142** in the upper surface of the base plate **170**, and is enclosed within the cavity **142** of the base plate **170** by the cover plate **160** wherein an insulating layer **153b** bonded to the cover plate **160** forms a vacuum seal with the base plate **170**. Preferably at least four thermoelectric modules are in the cavity **142** of the base plate **170** wherein the at least four thermoelectric modules are arranged so as to form four temperature control zones in the substrate support assembly **100**. For example, a first thermoelectric module can be arranged to form a respective first circular zone, a second thermoelectric module can be arranged to form a respective second annular zone, a third thermoelectric module can be arranged to form a respective third annular zone, and a fourth thermoelectric module can be arranged to form a respective fourth annular zone.

[0037] Maintaining the at least one thermoelectric module in the internal space between the base plate **170** and the cover plate **160** of the substrate support assembly **100** at atmospheric pressure may reduce the risk for parasitic plasma discharge and arcing since the vertical and horizontal dimensions of the physical gaps between thermoelectric pairs are ideal for glow discharge at the operating pressures of plasma processing. In addition maintaining the cavity containing the thermoelectric modules at atmospheric pressure may reduce operating costs due to additional pumping facilities required to evacuate the chamber pressure during operation of the plasma processing apparatus. However, maintaining the thermoelectric module cavities at atmospheric pressure while the vacuum chamber of the plasma processing chamber is operating may lead to bowing of the cover plate **160**, thereby bowing the top plate **110**. Therefore, the cover plate **160** is preferably thick enough to account for the pressure differentials found in the vacuum chamber atmosphere and the internal space of the substrate support assembly **100**. Preferably the cover plate **160** has a thickness of about 0.5 to 4 mm. In some embodiments it is preferred that the cover plate **160** be separated into two pieces, an inner cover plate **160a** and an outer annular cover ring **160b**, such that strain due to thermal expansion and contraction may be reduced on the underlying substrate support assembly **100** elements such as the at least one thermoelectric module **140**.

[0038] The orientation of the thermoelectric modules and the number of thermoelectric modules in the substrate support assembly **100** can be selected to achieve the desired temperature distribution across the substrate. For example, for processing a substrate from which a large number of small device dies are desired, a greater number of thermoelectric modules can be used to achieve a highly uniform temperature across the temperature control zones created by the thermoelectric modules. The number of thermoelectric modules may, for example, be in the range of from 1 to 1000, or even greater as substrate sizes increase. Preferably the semicon-

ductor elements which make up the at least one thermoelectric module **140** have a height of about 2.5 to 4.5 mm, more preferably about 3.0 to 3.5 mm, and the spacing between the p-type and n-type semiconductor elements are in the range of about 1.0 to 2.0 millimeters, more preferably about 1.5 mm.

[0039] FIG. 6A, B illustrate further embodiments of a base plate **170** of a temperature controlled substrate support assembly **100**. The base plate **170** may be formed from aluminum, copper, pyrolytic graphite encased in aluminum, or other high thermal conductivity material, and comprises a single cavity **142** in an upper surface of the base plate **170** to house the at least one thermoelectric module **140**. Preferably the cavity **142** is defined by a cylindrical wall **50** which is located near an outer periphery of the base plate **170**. The base plate **170** acts as a heat sink by circulating a heat transfer medium at a constant temperature through fluid channels **171** in the base plate **170** and localized temperatures of the substrate are controlled by the at least one thermoelectric module **140**. The fluid channels **171** are preferably configured for supplying a coolant or a temperature controlled gas such that the base plate **170** may act as a heat sink. For example, the base plate **170** may be cooled with a gas such as air, He, N₂ or the like or liquid cooled with deionized water (DI), dielectric liquid such as FLUORINERT® or the like.

[0040] In an embodiment, the base plate **170** includes heat transfer pipes **173**, wherein vertical holes may be drilled into the lower surface of the cavity **142** and heat transfer pipes **173** may be inserted such that an upper surface of each heat transfer pipe **173** is flush with the upper surface of the base plate **170** within the cavity **142**. An exemplary heat transfer pipe that can be used is a tubular heat-pipe, which is commercially available from CRS Engineering Limited of Hadston, United Kingdom. The heat transfer pipes **173** can be used to increase thermal conduction between the at least one thermoelectric module in the cavity **142** and the fluid channels **171** of the base plate **170**, thereby improving the cooling capacity of the substrate support assembly **100**. The heat transfer pipes **173** are preferably formed from a metal such as stainless steel or high purity copper with or without a plain copper surface finish or plating of tin, nickel, brass, silver, chromium or gold, and have an outer diameter of about 1 to 12 mm, and preferably an outer diameter of about 1 to 3 mm. The heat transfer pipes **173** have a length of about 7 to 20 mm and more preferably a length of about 10 to 15 mm. Each heat transfer pipe **173** operates with an anti-gravity wicking system wherein a liquid is evaporated at a first end of the tube, condenses back to a liquid at the second end of the tube, and returns to the first end via capillary action in a porous lining. Each heat transfer pipe **173** is mounted in the base plate with a condensation side at a lower end thereof and an evaporation side at an upper end thereof. The evaporation and condensation of the fluid within the heat transfer pipes **173** operates via capillary action to overcome the gravitational tendency of the fluid which increases the thermal conduction between the at least one thermoelectric module in the upper surface of the base plate **170** and the fluid channels **171**. The fluid can be water or the like when the base plate **170** is operating at ambient temperatures, or the fluid can be ammonia, ethanol, or the like when the base plate **170** is operating at temperatures at less than about 0°C. Details of a heat transfer pipe can be found in U.S. Published Application No. 2006/0207750, which is incorporated by reference herein. Preferably the base plate **170** includes an array of the heat transfer pipes **173** wherein the number and arrangement of heat transfer pipes

are based upon the individual cooling capacity of each heat transfer pipe **173**. As illustrated in FIG. 6A, the heat transfer pipes **173** are disposed between fluid channels **171** wherein each condensation side **173a** of the heat transfer pipes **173** is located at about the midpoint of each fluid channel **171**. In an alternate embodiment as illustrated in FIG. 6B, the heat transfer pipes **173** are disposed above the fluid channels **171**. Preferably the base plate **170** helps cut down on the power requirement to control the heat load on the upper side of the thermoelectric control system.

[0041] FIG. 6C illustrates a further embodiment of a base plate **170** of a temperature controlled substrate support assembly **100**. The base plate **170** preferably can comprise an electrically conductive cooling plate **185a** comprising fluid channels **171** and heat transfer pipes **173** wherein an upper surface of each heat transfer pipe **173** is flush with an upper surface of the cooling plate **185a**. An electrically conductive heat transfer plate **185b** is disposed above the electrically conductive cooling plate **185a**, and an electrically conductive thermoelectric plate **185c** is disposed above the heat transfer plate **185b**. The electrically conductive heat transfer plate **185b** is preferably formed of aluminum or a like material and configured to uniformly distribute heat between the cooling plate **185a** and the thermoelectric plate **185c**. The thermoelectric plate **185c** comprises a single cavity **142** wherein the cavity **142** is maintained at atmospheric pressure. The cavity **142** is preferably defined by a cylindrical wall **50** which is located near an outer periphery of the thermoelectric plate **185c**. Preferably upwardly extending bosses **55** are located within the cavity **142** wherein an upper insulating layer may be supported by the upwardly extending bosses **55** and the cylindrical wall **50** forming a vacuum seal thereon. Preferably the upwardly extending bosses **55** have openings **165** configured to support lift pins and/or backside helium gas supplies. The at least one thermoelectric module **140** is arranged within the cavity **142** formed in the upper surface of the thermoelectric plate **185c** wherein the cavity **142** is open to the atmosphere via openings in a bottom of the plate **185c**.

[0042] FIG. 6D illustrates a further embodiment of a base plate **170** of a temperature controlled substrate support assembly **100** wherein the base plate **170** includes heat transfer pipes **173**. The base plate **170** comprises a single cavity **142** in an upper surface thereof to house the thermoelectric modules **140** wherein the cavity **142** is defined by a cylindrical wall **50** which is located near an outer periphery of the base plate **170**. A heat transfer sheet **508** is located on a lower surface of the cavity **142**. Each evaporation side of each heat transfer pipe **173** is attached to the heat transfer sheet **508** wherein the heat transfer sheet **508** expands the effective surface area of each heat transfer pipe **173** thereby increasing heat transfer between the thermoelectric modules **140** and the fluid channels **171**. The heat transfer sheet **508** has high thermal conductivity and is preferably formed from aluminum, copper, pyrolytic graphite, or aluminum coated pyrolytic graphite. In an embodiment, the heat transfer sheet **508** may be segmented, such that each segment of the heat transfer sheet **508** is attached to a respective heat transfer pipe **173**, or alternatively, each segment of the heat transfer sheet **508** is attached to a group of respective heat transfer pipes **173**.

[0043] A controller **195** may be used to control the currents supplied by the current supply **180**. The controller may control the currents based on statistical data concerning the temperature distribution of a substrate. In this case, the controller controls the current supply to supply constant currents that

are set in advance. Alternatively, the controller may control the currents in response to sensed temperature information obtained during processing of a substrate. The sensed temperature information may be obtained, from a sensor **190** such as one or more thermocouples or an infrared (IR) camera. The sensors **190** sense the temperature across the substrate surface during processing. Based on the sensed temperature information, the controller **195** adjusts the direction and power of currents supplied to the thermoelectric modules **140** by the current supply, thus providing real time substrate temperature control.

[0044] Further disclosed herein is a method of processing a substrate in a semiconductor processing apparatus wherein the substrate is supported on a top plate of a temperature controlled substrate support assembly in a vacuum processing chamber. The method comprises controlling temperatures of respective portions of the top plate by supplying current to at least one thermoelectric module in heat transfer contact with the top plate while processing the substrate. Preferably, the process comprises plasma etching the substrate. The method also comprises controlling the current to control the temperature of the top plate surface and to provide a desired temperature distribution across the substrate.

[0045] It will be appreciated by those of ordinary skill in the art that the present invention can be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The presently disclosed embodiments are therefore considered in all respects to be illustrative, and not restrictive. The scope of the invention is indicated by the appended claims, rather than the foregoing description, and all changes that come within the meaning and range of equivalence thereof are intended to be embraced therein.

What is claimed is:

1. A temperature controlled substrate support assembly for processing a substrate in a vacuum chamber of a semiconductor processing apparatus comprising:

a top plate configured to support the substrate;
a base plate disposed below the top plate wherein the base plate comprises a cavity in an upper surface of the base plate;
a cover plate enclosing the cavity and disposed between the top plate and the base plate; and
at least one thermoelectric module in the cavity in the upper surface of the base plate wherein the at least one thermoelectric module is in thermal contact with the top plate and the base plate, and the at least one thermoelectric module is maintained at atmospheric pressure.

2. The temperature controlled substrate support assembly of claim **1**, wherein (a) the at least one thermoelectric module comprises alternating p-type and n-type semiconductor elements which are in electrical contact and which operate according to the Peltier effect; (b) upwardly extending bosses are located in the cavity in the upper surface of the base plate; and/or (c) electrically insulating layers cover respective upper and lower surfaces of the at least one thermoelectric module.

3. The temperature controlled substrate support assembly of claim **2**, wherein (a) the electrically insulating layers on the upper and lower surface of the at least one thermoelectric module are bonded to the cover plate and the base plate with an adhesive; (b) the electrically insulating layer on the upper surface of the at least one thermoelectric module forms a vacuum seal with the upwardly extending bosses and an outer wall on the upper surface of the base plate; and/or (c) each upwardly extending boss of the base plate includes a verti-

cally extending hole configured to receive a lift pin and/or deliver backside helium gas to the top plate surface.

4. The temperature controlled substrate support assembly of claim **1**, wherein (a) the top plate comprises an electrostatic chuck having at least one electrostatic electrode embedded in a layer of dielectric material; and/or (b) the base plate comprises fluid channels through which a temperature controlled fluid circulates.

5. The temperature controlled substrate support assembly of claim **1**, wherein the lower surface of the at least one thermoelectric module is bonded to an upper surface of the cavity in the base plate with solder or a low melting point alloy.

6. The temperature controlled substrate support assembly of claim **1**, wherein at least two thermoelectric modules are arranged in the cavity such that each thermoelectric module in the cavity forms a respective temperature control zone on the top plate.

7. The temperature controlled substrate support assembly of claim **6**, wherein each thermoelectric module forms a respective temperature control zone on the top plate wherein the temperature control zones include a center temperature control zone with one or more surrounding temperature control zones forming an annular formation, a grid formation, a radial formation, an azimuthal formation, a polar formation, or a nonpolar formation.

8. The temperature controlled substrate support assembly of claim **1**, further comprising a plurality of sensors corresponding with temperature control zones across the top plate, each sensor operable to output a signal representative of the temperature of each respective temperature control zone.

9. The temperature controlled substrate support assembly of claim **8**, further comprising a controller for receiving a signal from each sensor and for adjusting the power delivered to each thermoelectric module of each temperature control zone based on a set point or a feedback control loop for each temperature control zone.

10. The temperature controlled substrate support assembly of claim **1**, wherein (a) the cover plate comprises an inner cover plate and an outer annular cover plate; and/or (b) the cover plate is formed from aluminum, copper, pyrolytic graphite, a ceramic material, or aluminum coated pyrolytic graphite.

11. The temperature controlled substrate support assembly of claim **10**, wherein the cover plate has a thickness of about 0.5 to 4 millimeters.

12. The temperature controlled substrate support assembly of claim **2**, wherein the cover plate comprises downwardly extending bosses corresponding to the upwardly extending bosses of the base plate wherein the downwardly extending bosses and the upwardly extending bosses have aligned holes configured to receive lift pins and/or deliver backside helium gas and the upwardly extending bosses and corresponding downwardly extended bosses are configured to provide an RF current path within the temperature controlled substrate support assembly.

13. The temperature controlled substrate support assembly of claim **1**, wherein the base plate includes heat transfer pipes configured to increase the thermal conductance between the at least one thermoelectric module in the cavity and fluid channels included in the base plate through which a temperature controlled fluid circulates; and wherein (a) the base plate includes a heat transfer plate disposed above the heat transfer pipes and below the at least one thermoelectric module; or (b)

the base plate includes a heat transfer sheet disposed in the cavity wherein each heat transfer pipe is attached to the heat transfer sheet.

14. The temperature controlled substrate support assembly of claim **13**, wherein the heat transfer pipes include a fluid selected from the group consisting of water, ammonia, and ethanol.

15. The temperature controlled substrate support assembly of claim **13**, wherein (a) the heat transfer plate is formed of copper; or (b) the heat transfer sheet is formed of copper, aluminum, pyrolytic graphite, or aluminum coated pyrolytic graphite.

16. A method of manufacturing a substrate support assembly for controlling a temperature of a substrate during plasma processing comprising:

bonding a lower surface of at least one thermoelectric module to a surface within a cavity in an upper surface of a base plate;

bonding a lower surface of an upper electrically insulating layer included on an upper surface of the at least one thermoelectric module to a cylindrical wall defining the cavity in the upper surface of the base plate and to upwardly extending bosses within the cavity, wherein the bonded lower surface of the upper electrically insulating layer forms a vacuum seal with the cylindrical wall and the upwardly extending bosses and the cavity is open to the atmosphere through a surface of the cavity within the upper surface of the base plate; and

bonding an upper surface of the upper electrically insulating layer to a cover plate.

17. The method of claim **16**, wherein (a) the lower surface of the at least one thermoelectric module is bonded to the surface within the cavity in the upper surface of the base plate with soldering or a low melting point alloy; or (b) the lower

surface of the at least one thermoelectric module is bonded to a lower electrically insulating layer, and a lower surface of the lower electrically insulating layer is bonded to the surface within the cavity in the upper surface of the base plate.

18. The method of claim **16**, further comprising (a) drilling vertical holes in a surface of the base plate and inserting a heat transfer pipe in each drilled hole in the base plate, wherein an upper surface of each heat transfer pipe is flush with the surface of the base plate wherein each hole is drilled; and/or (b) installing a heat transfer plate in the substrate support assembly wherein the heat transfer plate is disposed above the heat transfer pipes and below the at least one thermoelectric module, the heat transfer plate configured to uniformly distribute heat among the plurality of thermoelectric devices and the heat transfer pipes.

19. A method of processing a substrate in a semiconductor processing system comprising the temperature controlled substrate support assembly of claim **1** and a vacuum processing chamber enclosing the substrate support assembly, the method comprising the steps of:

supplying current to the at least one thermoelectric module in heat transfer contact with the top plate to control the temperature of one or more zones across the top plate surface; and

controlling the current supplied to the at least one thermoelectric module so as to control the temperature across the top plate surface and to provide a desired temperature distribution across the substrate during processing of the substrate.

20. The method of claim **19**, wherein the top plate further comprises at least one electrostatic electrode embedded therein and the substrate comprises a wafer, the processing comprising plasma etching or chemical vapor deposition.

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