Heating Plate with Planar Heater Zones for Semiconductor Processing

Background of the Disclosure

[0001] With each successive semiconductor technology generation, substrate diameters tend to increase and transistor sizes decrease, resulting in the need for an ever higher degree of accuracy and repeatability in substrate processing. Semiconductor substrate materials, such as silicon substrates, are processed by techniques which include the use of vacuum chambers. These techniques include non plasma applications such as electron beam deposition, as well as plasma applications, such as sputter deposition, plasma-enhanced chemical vapor deposition (PECVD), resist strip, and plasma etch.

[0002] Plasma processing systems available today are among those semiconductor fabrication tools which are subject to an increasing need for improved accuracy and repeatability. One metric for plasma processing systems is increased uniformity, which includes uniformity of process results on a semiconductor substrate surface as well as uniformity of process results of a succession of substrates processed with nominally the same input parameters. Continuous improvement of on-substrate uniformity is desirable. Among other things, this calls for plasma chambers with improved uniformity, consistency and self diagnostics.

Summary of the Invention

[0003] In accordance with one embodiment, a heating plate for a substrate support assembly used to support a semiconductor substrate in a semiconductor plasma processing apparatus, comprises at least a first electrically insulating layer, planar heater zones comprising at least first, second, third and fourth planar heater zones laterally distributed across the first electrically insulating layer, electrically conductive power supply lines comprising at least a first power supply line electrically connected to the first and second heater zones and a second power supply line electrically connected to the third and fourth heater zones, electrically conductive power return lines comprising at least a first power return line

electrically connected to the first and third heater zones, and a second power return line electrically connected to the second and fourth heater zones.

Brief Description of Drawings

[0004] **Fig. 1** is a schematic of the cross-sectional view of a substrate support assembly in which a heating plate with an array of heater zones is incorporated, the substrate support assembly also comprising an electrostatic chuck (ESC).

[0005] **Fig. 2** illustrates the topological connection between power supply and power return lines to an array of heater zones in one embodiment of a heating plate which can be incorporated in a substrate support assembly.

[0006] **Fig. 3A** shows an embodiment wherein the power supply lines and the heater zones are on the same plane.

[0007] **Fig. 3B** shows the power return lines on a plane separated from the plane in Fig. 3A by an electrically insulating layer and the power return lines are connected to the heater zones through vias extending through the electrically insulating layer.

[0008] **Fig. 3C** is a schematic of the cross-sectional view of a substrate support assembly in which the heating plate of Fig. 3A and 3B is incorporated.

[0009] **Fig. 4A** shows an embodiment wherein the power supply lines and the heater zones are on the same plane.

[0010] **Fig. 4B** shows a plane separated from the plane in Fig. 4A by an electrically insulating layer wherein the power supply lines are connected to leads in this plane through vias, and brought to a single hole in the cooling plate (not shown). The power return lines on this plane are connected to the heater zones through vias extending between this plane and the plane in Fig. 4A. The power return lines are also brought to a single hole in the cooling plate (not shown).

[0011] **Fig. 5A** shows an embodiment wherein the heater zones are on a plane without the power supply lines or power return lines on that plane. The heater zones are connected to power supply lines and power return lines on one or more different planes through vias.

[0012] **Fig. 5B** shows the power supply lines on a second plane separated from the plane in Fig. 5A by an electrically insulating layer. The power supply lines are

connected to the heater zones through vias extending between the two planes in Fig. 5A and 5B.

[0013] **Fig. 5C** shows the power return lines on a third plane separated from the planes in Fig. 5A and 5B by another electrically insulating layer. The power return lines are connected to the heater zones through vias extending between all three planes in Fig. 5A-C. The leads connected to the power supply lines in Fig. 5B are also routed through feedthroughs in this plane.

[0014] **Fig. 5D** is a schematic of the cross-sectional view of a substrate support assembly in which the heating plate in Fig. 5A-C is incorporated.

[0015] **Fig. 5E** is a schematic of the cross-sectional view of a substrate support assembly in which an alternative heating plate in Fig. 5A-C is incorporated.

[0016] **Fig. 6** is a schematic of the cross-sectional view of a substrate support assembly in which a heating plate is incorporated, the substrate support assembly further including a primary heater layer above the array of heater zones, the primary heater located on an additional plane separated from all the planes in the heating plate by an electrically insulating layer.

[0017] **Fig. 7A** is a schematic of an exemplary plasma processing chamber, which can include a substrate support assembly with the heating plate described herein.

[0018] **Fig. 7B** is a schematic of an RF isolation approach.

[0019] **Fig. 8** shows a block diagram of signal flow in one embodiment of the control electronics for the substrate support assembly.

Detailed Description

[0020] Radial and azimuthal substrate temperature control in a semiconductor processing apparatus to achieve desired critical dimension (CD) uniformity on the substrate is becoming more demanding. Even a small variation of temperature may affect CD to an unacceptable degree, especially as CD approaches sub-100nm in semiconductor fabrication processes.

[0021] A substrate support assembly may be configured for a variety of functions during processing, such as supporting the substrate, tuning the substrate temperature, and power supplying radio frequency power. The substrate support assembly can comprise an electrostatic chuck (ESC) useful for electrostatically clamping a

substrate onto the substrate support assembly during processing. The ESC may be a tunable ESC (T-ESC). A T-ESC is described in commonly assigned U.S. Patent Nos. 6,847,014 and 6,921,724, which are hereby incorporated by reference. The substrate support assembly may comprise a ceramic substrate holder, a fluid-cooled heat sink (hereafter referred to as cooling plate) and a plurality of concentric heater zones to realize step by step and radial temperature control. Typically, the cooling plate is maintained between 0 °C and 30 °C. The heaters are located on the cooling plate with a layer of thermal insulator in between. The heaters can maintain the support surface of the substrate support assembly at temperatures about 0 °C to 80 °C above the cooling plate temperature. By changing the heater power within the plurality of heater zones, the substrate support temperature profile can be changed between center hot, center cold, and uniform. Further, the mean substrate support temperature can be changed step by step within the operating range of 0 to 80 °C above the cooling plate temperature. A small azimuthal temperature variation poses increasingly greater challenges as CD decreases with the advance of semiconductor technology.

[0022] Controlling temperature is not an easy task for several reasons. First, many factors can affect heat transfer, such as the locations of heat sources and heat sinks, the movement, materials and shapes of the media. Second, heat transfer is a dynamic process. 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 plasma, which of course is always present in plasma processing, make theoretical prediction of the heat transfer behavior of any practical plasma processing apparatus very difficult if not impossible.

[0023] The substrate temperature profile in a plasma processing apparatus is affected by many factors, such as the plasma density profile, the RF power profile and the detailed structure of the various heating the cooling elements in the chuck, hence the substrate temperature profile is often not uniform and difficult to control with a small number of heating or cooling elements. This deficiency translates 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.

[0024] In light of the complex nature of temperature control, it would be advantageous to incorporate multiple independently controllable heater zones in the substrate support assembly to enable the apparatus to actively create and maintain the desired spatial and temporal temperature profile, and to compensate for other adverse factors that affect CD uniformity.

[0025] Described herein is a heating plate for a substrate support assembly in a semiconductor processing apparatus with multiple independently controllable heater zones. This heating plate comprises a scalable multiplexing layout scheme of the heater zones and the power supply and power return lines. By tuning the power of the heater zones, the temperature profile during processing can be shaped both radially and azimuthally. Although this heating plate is primarily described for a plasma processing apparatus, this heating plate can also be used in other semiconductor processing apparatuses that do not use plasma.

[0026] Also described are methods for manufacturing this heating plate, a substrate support assembly comprising such a heating plate, and methods for powering and controlling a substrate support assembly comprising such a heating plate.

[0027] The heater zones in this heating plate are preferably arranged in a defined pattern, for example, a rectangular grid, a hexagonal grid, a polar array, concentric rings or any desired pattern. Each heater zone may be of any suitable size and may have one or more heater elements. All heater elements in a heater zone are turned on or off together. To minimize the number of electrical connections, power supply and power return lines are arranged such that each power supply line is connected to a different group of heater zones and each power return line is connected to a different group of heater zones with each heater zone being in one of the groups connected to a particular power supply line and one of the groups connected to a particular power return line. No two heater zones are connected to the same pair of power supply and power return lines. Thus, a heater zone can be activated by directing electrical current through a pair of power supply and power return lines to which this particular heater zone is connected. The power of the heater elements is preferably smaller than 20W, more preferably 5 to 10 W. The heater elements may be resistive heaters, such as polyimide heaters, silicone rubber heaters, mica heaters, metal heaters (e.g. W, Ni/Cr alloy, Mo or Ta), ceramic heaters (e.g. WC),

semiconductor heaters or carbon heaters. The heater elements may be screen printed, wire wound or etched foil heaters. In one embodiment, each heater zone is not larger than four device dies being manufactured on a semiconductor substrate, or not larger than two device dies being manufactured on a semiconductor substrate, or not larger than one device die being manufactured on a semiconductor substrate, or between 2 and 3 cm^2 in area to correspond to the device dies on the substrate. The thickness of the heater elements may range from 2 micrometers to 1 millimeter, preferably 5-80 micrometers. To allow space between heater zones and/or power supply and power return lines, the total area of the heater zones may be up to 90% of the area of the upper surface of the substrate support assembly, e.g. 50-90% of the area. The power supply lines or the power return lines (power lines, collectively) may be arranged in gaps ranging from 1 to 10 mm between the heater zones, or in separate planes separated from the heater zones plane by electrically insulating layers. The power supply lines and the power return lines are preferably made as wide as the space allows, in order to carry large current and reduce Joule heating. In one embodiment, in which the power lines are in the same plane as the heater zones, the width of the power lines is preferably between 0.3 mm and 2 mm. In another embodiment, in which the power lines are on different planes than the heater zones, the width of the power lines can be as large as the heater zones, e.g. for a 300 mm chuck, the width can be 1 to 2 inches. The materials of the power supply and power return lines may be the same as or different from the materials of the heater elements. Preferably, the materials of the power supply and power return lines are materials with low resistivity, such as Cu, Al, W, Inconel® or Mo.

[0028] Figs. 1-2 show a substrate support assembly comprising one embodiment of the heating plate having an array of heater zones **101** incorporated in two electrically insulating layers **104A** and **104B**. The electrically insulating layers may be a polymer material, an inorganic material, a ceramic such as silicon oxide, alumina, yttria, aluminum nitride or other suitable material. The substrate support assembly further comprises (a) an ESC having a ceramic layer **103** (electrostatic clamping layer) in which an electrode **102** (e.g. monopolar or bipolar) is embedded to electrostatically clamp a substrate to the surface of the ceramic layer **103** with a DC

voltage, (b) a thermal barrier layer **107**, (c) a cooling plate **105** containing channels **106** for coolant flow.

[0029] As shown in Fig. 2, each of the heater zones **101** is connected to one of the power supply lines **201** and one of the power return lines **202**. No two heater zones **101** share the same pair of power supply **201** and power return **202** lines. By suitable electrical switching arrangements, it is possible to connect a pair of power supply **201** and power return **202** lines to a power supply (not shown), whereby only the heater zone connected to this pair of lines is turned on. The time-averaged heating power of each heater zone can be individually tuned by time-domain multiplexing. In order to prevent crosstalk between different heater zones, a rectifier **250** (e.g. a diode) may be serially connected between each heater zone and the power supply lines connected thereto (as shown in Fig. 2), or between each heater zone and the power return lines connected thereto (not shown). The rectifier can be physically located in the heating plate or any suitable location. Alternatively, any current blocking arrangement such as solid state switches can be used to prevent crosstalk.

[0030] Figs. 3A, 3B and 3C show a substrate support assembly comprising an ESC, a cooling plate, and one embodiment of the heating plate wherein the heater zones **101** and power supply lines **201** are arranged in a first plane **302**, and the power return lines **202** are arranged in a second plane **303** separated from the first plane **302** by an electrically insulating layer **304**. The power return lines **202** are connected to the heater zones **101** by conductive vias **301** in the electrically insulating layer **304**, extending between the first plane **302** and the second plane **303**.

[0031] In use, the power supply lines **201** and power return lines **202** are connected to circuitry external to the heating plate through holes or conduits in the cooling plate. It should be appreciated that the presence of holes or conduits in the cooling plate can affect the temperature uniformity of substrate support assembly adversely, therefore reducing the number of holes or conduits in the cooling plate can enhance temperature uniformity. In addition, a small number of holes makes placing them around the edge of the substrate support assembly possible. For example, a single power supply conduit in the cooling plate can be used to feed

electrical leads to the power supply lines **201**. In one embodiment (Fig. 4A and 4B), the heater zones **101** and power supply lines **201** are arranged in a first plane **402**. The power supply lines **201** are connected to leads **404** in a second plane **403** through conductive vias **301** extending between the first plane **402** and the second plane **403**. The second plane **403** is separated from the first plane **402** by an electrically insulating layer (not shown). The power return lines **202** are arranged in the second plane **403** and are connected to the heater zones **101** through conductive vias **301** extending between the first plane **402** and the second plane **403**. In the second plane **403**, the leads **404** are brought through a hole or conduit **401** in the cooling plate while maintaining electrical insulation between the leads. Similarly, the power return lines **202** are connected to leads **405** brought through a hole or conduit **406** in the cooling plate while maintaining electrical insulation between the leads **405**.

[0032] Figs. 5A, 5B, 5C and 5D show a substrate support assembly comprising yet another embodiment of the heating plate, the heater zones **101** are arranged in a first plane **501**; the power supply lines **201** are arranged in a second plane **502**; and the power return lines **202** are arranged in a third plane **503**. The first plane **501**, second plane **502** and third plane **503** are separated from each other by electrically insulating layers **504** and **304**. The power supply lines **201** and power return lines **202** are connected to the heater zones **101** through conductive vias **301** in the electrically insulating layers **304** and **504**, extending between the planes **501**, **502** and **503**. Leads (not shown) connected to the power supply lines **201** are routed through holes or conduits **505** in the layer **504**. It should be appreciated that the planes **501**, **502** and **503** may be arranged in any order in the vertical direction, provided that the vias and conduits are suitably arranged. Preferably, the heaters are arranged closest to the substrate support assembly upper surface. Fig. 5E shows an embodiment wherein each heater zone **101** is connected to the power return line **202** through a rectifier **506** (e.g. a diode). The rectifier **506** only allows electric current flowing from the power supply line **201** through the heater zone **101** to the power return line **202**, and thus prevents crosstalk between heater zones.

[0033] The substrate support assembly can comprise an additional electrically insulating layer **604** in which one or more additional heaters (hereafter referred to as

primary heaters **601**) are incorporated (Fig. 6). Preferably, the primary heaters **601** are individually controlled high-power heaters. The power of the primary heaters is between 100 and 10000W, preferably, between 1000 and 5000W. The primary heaters may be arranged as a rectangular grid, concentric annular zones, radial zone or combination of annular zones and radial zones. The primary heaters may be used for changing the mean temperature, tuning the radial temperature profile, or step-by-step temperature control on the substrate. The primary heaters may be located above or below the heater zones of the heating plate.

[0034] In one embodiment, at least one of the insulating layers in the heating plate is a sheet of polymer material.

[0035] In another embodiment, at least one of the insulating layers in the heating plate is a sheet of inorganic material such as ceramic or silicon oxide. Examples of suitable insulating and conductive material for use in manufacture of ceramic chucks are disclosed in commonly assigned U.S. Patent No. 6483690, the disclosure of which is hereby incorporated by reference.

[0036] A substrate support assembly can comprise an embodiment of the heating plate, wherein each heater zone of the heating plate is of similar size to or smaller than a single device die or group of device dies on the substrate so that the substrate temperature, and consequently the plasma etching process, can be controlled for each device die position to maximize the yield of devices from the substrate. The scalable architecture of the heating plate can readily accommodate the number of heater zones required for die-by-die substrate temperature control (typically more than 100 dies on a substrate of 300-mm diameter) with minimal number of power supply lines, power return lines, and feedthroughs in the cooling plate, thus reduces disturbance to the substrate temperature, the cost of manufacturing and complexity of the substrate support assembly. Although not shown, the substrate support assembly can comprise features such as lift pins for lifting the substrate, helium back cooling, temperature sensors for providing temperature feedback signals, voltage and current sensors for providing heating power feedback signals, power feed for heaters and/or clamp electrode, and/or RF filters.

[0037] In one embodiment of the method for manufacturing the heating plate, where the insulating layers are ceramic, the insulating layers may be formed by

depositing the ceramic on a suitable substrate using techniques such as plasma spraying, chemical vapor deposition or sputtering. This layer can be an initial starting layer or one of the insulating layers of the heating plate.

[0038] In one embodiment of the method for manufacturing the heating plate, where the insulating layers are ceramic, the insulating layers may be formed by pressing a mixture of ceramic powder, binder and liquid into sheets and drying the sheets (hereafter referred as green sheets). The green sheets can be about 0.3 mm in thickness. The vias may be formed in the green sheets by punching holes in the green sheets. The holes are filled with a slurry of conducting powder. The heater elements, power supply and power return lines may be formed by: screen printing a slurry of conducting powder (e.g. W, WC, doped SiC or $MoSi_2$), pressing a precut metal foil, spraying a slurry of conducting powder, or any other suitable technique. Recesses for accommodating any rectifiers such as diodes may be pressed during the forming process of the green sheets or cut in the green sheets after the forming process. Discrete component rectifiers may be mounted into these recesses. Multiple green sheets with a variety of components (power lines, vias, rectifiers and heater elements) are then aligned, pressed and sintered to form an entire heating plate.

[0039] In another embodiment of the method for manufacturing the heating plate, where the insulating layers are ceramic, the insulating layers may be formed by pressing a mixture of ceramic powder, binder and liquid into green sheets and drying the green sheets. The green sheets can be about 0.3 mm in thickness. Holes are punched in the green sheets for accommodating vias. Recesses for accommodating any rectifiers such as diodes may be pressed during the forming process of the green sheets or cut in the green sheets after the forming process. Then, individual green sheets are sintered. The holes in the sintered sheets for accommodating vias are filled with a slurry of conducting power. The heater elements, power supply and power return lines may be screen printed with a slurry of conducting powder (e.g. W, WC, doped SiC or $MoSi_2$), or be formed using any other suitable technique, on the sintered sheets. Discrete component rectifiers may be mounted into the recesses in the sintered sheets. Multiple sintered sheets with a variety of components (lines,

vias, rectifiers and heater elements) are then aligned and bonded with an adhesive to form an entire heating plate.

[0040] In one embodiment where the insulating layers are silicon oxide sheets, the insulating layers may be formed by depositing a thin film silicon oxide onto a suitable substrate using techniques such as evaporation, sputtering, PVD, CVD, PECVD.

[0041] In one preferred embodiment of the method for manufacturing the heating plate, a thin metal sheet (component layer) such as Al, Inconel® or Cu foil, is bonded (e.g. heat pressed, adhered with adhesive) to a first polymer film such as polyimide. A patterned resist film is applied to the surface of the component layer wherein the patterns define the shapes and positions of the electrical components such as heater elements, power supply lines or power return lines. The exposed metal is chemically etched and the resist pattern is retained in the remaining metal sheet. The resist is then removed by dissolution in a suitable solvent or dry stripping. A second polymer film with holes for accommodating vias (via layer) is aligned and bonded to the first polymer film. The sidewalls of the holes may be coated by plating metal therein. Any suitable number of component layers and via layers may be incorporated serially. Finally, exposed metal components are covered by a continuous polymer film for electrical insulation.

[0042] In another embodiment, the heater elements, power supply and power return lines are made of metal films deposited (e.g. plasma sprayed, electroplated, chemical vapor deposition, or sputtered) on an insulating layer or substrate (e.g. a green sheet).

[0043] In another embodiment, the heater elements, power supply and power return lines are made of a thin layer of amorphous conductive inorganic film such as indium tin oxide deposited (e.g. electroplated, chemical vapor deposition, or sputtered) on an insulating layer or substrate (e.g. a green sheet).

[0044] In yet another embodiment, the heater elements, power supply and power return lines are made of a thin layer of conductive ceramic film deposited (e.g. chemical vapor deposition, or sputtered) on an insulating layer or substrate (e.g. a green sheet).

[0045] In one embodiment, the power supply and power return lines in the heating plate may be connected to the external circuitry by terminal connectors such as spring tipped passthroughs embedded in but electrically insulated from the cooling plate.

[0046] In another embodiment, the power supply and power return lines in the heating plate may be connected to the external circuitry by attaching (soldered, bonded with conductive adhesive or spot welded) lead wires to the power supply and power return lines and threading these lead wires through holes or conduits in the cooling plate.

[0047] In a plasma processing system, the RF power applied in the plasma processing chamber is usually above 100W, sometimes above 1000W. The amplitude of RF voltages can exceed a kilovolt. Such strong RF power can easily affect the operation of the control and power circuit of the heater zones without proper filtration or isolation. An RF filter can be used to shunt the RF power away from the control and power circuit. An RF filter may be a simple broad-band filter or a tuned-filter for the specific RF frequencies used in the plasma processing system. An RF isolator, in contrast, eliminates direct electrical connection between any RF-coupled components and the control and power circuit. An RF isolator may be an optical coupler or a transformer.

[0048] As an overview of how a plasma processing chamber operates, Fig. 7A shows a schematic of a plasma processing chamber comprising a chamber **713** in which an upper showerhead electrode **703** and a substrate support assembly **704** are disposed. A substrate **712** is loaded through a loading port **711** onto the substrate support assembly **704**. A gas line **709** supplies process gas to the upper showerhead electrode **703** which delivers the process gas into the chamber. A gas source **708** (e.g. a mass flow controller power supplying a suitable gas mixture) is connected to the gas line **709**. A RF power source **702** is connected to the upper showerhead electrode **703**. In operation, the chamber is evacuated by a vacuum pump **710** and the RF power is capacitively coupled between the upper showerhead electrode **703** and a lower electrode in the substrate support assembly **704** to energize the process gas into a plasma in the space between the substrate **712** and the upper showerhead electrode **703**. The plasma can be used to etch device die features into layers on the

substrate **712**. The substrate support assembly **704** may have heaters incorporated therein. It should be appreciated that while the detailed design of the plasma processing chamber may vary, RF power is coupled through the substrate support assembly **704**.

[0049] Fig. 7B shows a schematic of an embodiment of RF filtration or isolation, wherein no filters or isolators are connected on the heater zone power supply and power return lines and the control and power circuit **705** is connected to a filter or isolator **706B**, which is connected to the electric ground **701**. The primary heaters (not shown), if present in the substrate support assembly, preferably have separate filters or isolators due to their high power. In this approach, the control and power circuit **705** floats at the RF potential or "high side". This approach allows multiple heater zones to share only one filter or isolator.

[0050] All the high side circuitry can be housed inside a local floating Faraday cage immediately under the substrate support assembly base structure.

[0051] Alternatively, an isolation transformer is used as the single filter or isolator **706B** to isolate the power and control circuitry **705** from the RF. The control and power circuitry **705** of the heater zones should be capable of operating at relatively high frequency (25 to 250KHz) because the transformer strongly attenuates DC and low frequency transmission. The control and power circuitry is referenced to a single floating potential (floating ground). This requires that the control and power circuitry connected to this isolation transformer must be subject to very similar RF exposure. If the RF potentials differ substantially between two groups of control and power circuits, significant RF current flows between these groups. In this scenario, each group must have its own filter or isolator, or there must be a filter or isolator between these groups.

[0052] The filter or isolator **706B** may be physically located in the plasma processing chamber or any other suitable location.

[0053] One embodiment of the heater control electronics is depicted in Fig. 8. A low side controller **809** may be a microcontroller unit (MCU) or a higher level device such as a computer (PC). Through an optical coupler **807**, the low side controller communicates digitally to the high side MCU **805** which interacts with the heater zones **801**, sensors **803**, and any auxiliary circuits **802**. If the high side MCU

805 has sufficient capability and local memory, any set-point and program may be preloaded into the high side MCU **805** before each run, thus eliminating the need of a real-time link to the low side controller **809**. **804** represents one-way communication links between modules. **806** represents two-way communication links between modules.

[0054] In one embodiment of time-domain multiplexing schemes, the high side MCU supplies power to each heater zone power supply line sequentially. Only one power supply line is connected to a power supply at the same time. During the time when one power supply line is powered, the high side MCU may keep any or all power return lines connected to the floating reference for a portion of this duration. A heater zone is turned on when at least one of the power supply lines connected to this heater zone is connected to the power supply, and at least one of the power return lines connected to this heater zone is connected to the floating reference. The average power of a heater zone is directly proportional to the average duration it is turned on. Alternatively, during the time when one power supply line is powered, the high side MCU may keep any or all power return lines connected to the floating reference for this entire duration and regulate the power transmitted to each heater zone that is turned on.

[0055] For example, with a 10-by-10 grid of heater zones, heater zones in row number N are connected to a power supply line number N; heater zones in column number M are connected to a power return line number M. The high side MCU may control heating such that each of the power supply lines is connected to the power supply for 100 ms, sequentially. For example, during the 100 ms of time when power supply line number 3 is connected to the power supply, the MCU is operable to connect power return lines number 7, 8, and 9 to the floating reference for 10, 50 and 100 ms, respectively, as directed by the particular heating requirement during this 100 ms. Thus, the heater zone in row number 3 and column number 7 has a duty cycle of 1%; the heater zone in row number 3 and column number 8 has a duty cycle of 5%; the heater zone in row number 3 and column number 9 has a duty cycle of 10%. In this particular example, the maximum peak power for each heater zone would be set to ten times the average maximum power desired.

[0056] In order to prevent detectable temperature modulation, the switching frequencies and the entire multiplexing scheme are preferably sufficiently rapid that each heater zone gets addressed frequently (at least 1Hz). Additional loop control may be implemented using feedback data from one of more temperature sensors. Voltage and current sensors can also be implemented if desired. These sensors can be configured to measure parameters such as temperatures on different locations on the substrate and power of heater zones. These measured parameters are sent to the control and power circuit to be compared with set targets of these parameters so that the control and power circuit can adjust the power delivered to the heater zones accordingly in order to minimize the difference between the measured parameters and their set targets.

[0057] While a heating plate, methods of manufacturing the heating plate, a substrate support assembly comprising the heating plate, and a method of using a plasma processing chamber containing the substrate support assembly have been described in detail with reference to specific embodiments thereof, it will be apparent to those skilled in the art that various changes and modifications can be made, and equivalents employed, without departing from the scope of the appended claims. For instance, the substrate support assembly can include temperature sensors for monitoring substrate temperature, a power feed arrangement to power the ESC with desired clamping voltage, a lifting pin arrangement for raising and lowering a substrate, a heat transfer gas feed arrangement for supplying gas such as helium to the underside of the substrate, a temperature controlled liquid feed arrangement to supply heat transfer liquid to the cooling plate, a power feed arrangement to individually power primary heaters above or below the planar heater zones, a power feed arrangement to supply RF power at one or more frequencies to a lower electrode incorporated in the substrate support assembly, and the like.

We Claim:

1. A heating plate for a substrate support assembly used to support a semiconductor substrate in a semiconductor processing apparatus, the heating plate comprising:

a first electrically insulating layer;

planar heater zones comprising at least first, second, third and fourth planar heater zones, each comprising one or more heater elements, the planar heater zones laterally distributed across the first electrically insulating layer and operable to tune a spatial temperature profile on the substrate;

power supply lines comprising at least a first electrically conductive power supply line electrically connected to the first and second planar heater zones and a second electrically conductive power supply line electrically connected to the third and fourth planar heater zones;

power return lines comprising at least a first electrically conductive power return line electrically connected to the first and third planar heater zones and a second electrically conductive power return line electrically connected to the second and fourth planar heater zones.

2. The heating plate of claim 1, wherein

(a) the planar heater zones and the power supply lines are in a first plane; the power return lines are in a second plane parallel to the first plane; the first and second planes are separated from one another by the first electrically insulating layer; the power return lines are electrically connected to the planar heater zones by vias extending vertically in the first electrically insulating layer;

(b) the planar heater zones and the power return lines are in a first plane; the power supply lines are in a second plane parallel to the first plane; the first and second planes are separated from one another by the first electrically insulating layer; the power supply lines are electrically connected to the planar heater zones by vias extending vertically in the first electrically insulating layer; or

(c) the planar heater zones are in a first plane; the power supply lines are in a second plane parallel to the first plane; the power return lines are in a third plane parallel to the first plane; the first and second planes are separated by the first

electrically insulating layer; the second and third planes are separated by a second electrically insulating layer; the power supply lines and power return lines are electrically connected to the planar heater zones by vias extending through the electrically insulating layers.

3. The heating plate of claim 1, wherein the planar heater zones are sized such that:

(a) each planar heater zone is not larger than four device dies being manufactured on the semiconductor substrate, or

(b) each planar heater zone is not larger than two device dies being manufactured on the semiconductor substrate, or

(c) each planar heater zone is not larger than one device die being manufactured on the semiconductor substrate, or

(d) the area of each planar heater zone is between 2 and 3 square centimeters, or

(e) the heating plate includes 100 to 400 planar heater zones, or

(f) each planar heater zone is 1 to 15 cm^2, or

(g) each planar heater zone is 16 to 100 cm^2, or

(h) each planar heater zone is scaled with sizes of device dies on the semiconductor substrate and the overall size of the semiconductor substrate.

4. The heating plate of claim 1, wherein the first electrically insulating layer comprises a polymer material, a ceramic material, or a combination thereof.

5. The heating plate of claim 1, wherein the total number of the power supply lines and the power return lines is equal to or less than the total number of the planar heater zones.

6. The heating plate of claim 1, wherein a total area of the planar heater zones is from 50% to 90% of an upper surface of the heating plate.

7. The heating plate of claim 1, wherein the planar heater zones are arranged in a rectangular grid, hexagonal grid or concentric rings; and the planar heater zones are separated from each other by gaps at least 1 millimeter in width and at most 10 millimeters in width.

8. The heating plate of claim 1, wherein a rectifier is serially connected between each heater zone and the power supply line connected thereto, or a rectifier is serially connected between each heater zone and the power return line connected thereto.

9. The heating plate of claim 8, wherein the rectifier is a semiconductor diode.

10. A substrate support assembly comprising:

an electrostatic chuck (ESC) including an electrostatic clamping layer having at least one clamping electrode configured to electrostatically clamp a semiconductor substrate on the substrate support assembly;

the heating plate of claim 1 arranged below the electrostatic clamping layer;

a cooling plate attached to a lower side of the heating plate by a thermal barrier layer.

11. The substrate support assembly of claim 10, wherein:

(a) the power supply lines are connected to leads electrically insulated from each other and extended through at least one power supply conduit in the cooling plate and the power return lines are connected to leads electrically insulated from each other and extended through at least one power return conduit in the cooling plate; or

(b) the power supply lines and power return lines are connected to terminal connectors embedded in the cooling plate.

12. The substrate support assembly of claim 10, further comprising a control and power circuit operable to selectively supply power at any given time to (a) only the first heater zone, (b) only the second heater zone, (c) only the third heater zone, (d)

only the fourth heater zone, (e) only the first and second planar heater zones, (f) only the first and third planar heater zones, (g) only the second and fourth planar heater zones, (h) only the third and fourth planar heater zones, and (i) all of the planar heater zones.

13. The substrate support assembly of claim 12, further comprising at least one filter or isolator serially connected between the control and power circuit and electric ground.

14. The substrate support assembly of claim 13, wherein the at least one filter or isolator is a transformer.

15. The substrate support assembly of claim 10, further comprising at least one primary heater layer arranged above or below the first electrically insulating layer of the heating plate, wherein the primary heater layer is electrically insulated from the planar heater zones, the power supply lines, and the power return lines of the heating plate; the primary heater layer includes at least one heater which provides mean temperature control of the semiconductor substrate; the planar heater zones provide radial and azimuthal temperature profile control of the semiconductor substrate, during processing thereof.

16. A method for manufacturing the heating plate of claim 1, comprising:

(a) forming holes in ceramic sheets;

(b) screen-printing a slurry of conductor powder, or pressing a precut metal foil, or spraying a slurry of conductor powder, on the ceramic sheets to form the planar heater zones, the power supply lines, and power return lines;

(c) filling the holes in the ceramic sheets with a slurry of conductor powder to form power supply and power return vias;

(d) aligning, pressing and bonding the ceramic sheets to form the heating plate.

17. The method of claim 16 for manufacturing the heating plate, wherein:

(a) the planar heater zones and power supply lines are formed on the upper side of a first ceramic sheet, the power return lines are formed on the lower side of the first ceramic sheet, a second ceramic sheet is placed over the upper surface of the first ceramic sheet and a third ceramic sheet is placed below the first ceramic sheet, and the first, second and third ceramic sheets are pressed together and sintered to form a joint-free heating plate; or

(b) the planar heater zones are formed on the upper side of a first ceramic sheet, the power supply lines are formed on the upper side of a second ceramic sheet placed below the first ceramic sheet, the power return lines are formed on the upper side of a third ceramic sheet placed below the second ceramic sheet, a fourth ceramic sheet is placed over the upper surface of the first ceramic sheet, and the first, second, third and fourth ceramic sheets are pressed together and sintered to form a joint-free heating plate.

18. A method for manufacturing the heating plate of claim 1, comprising:

manufacturing a component layer including steps:

(a) bonding a metal sheet onto a polymer film;

(b) applying a patterned resist film onto the metal sheet wherein openings in the patterned resist film correspond to locations where metal is to be removed;

(c) etching the metal sheet to remove metal exposed through openings of the resist film, the etching forming an electrically conductive metal pattern of the planar heater zones, power supply lines and/or power return lines;

(d) removing the resist film;

manufacturing a via layer including steps:

(a) punching or cutting holes in a polymer film;

(b) forming conductive vias in the holes;

building a laminate by bonding one or more component layers and one or more via layers;

insulating the laminate by bonding a continuous polymer film onto upper and/or lower surfaces of the laminate.

19. A method for manufacturing the heating plate of claim 1, comprising: depositing metal, amorphous conductive inorganic material, or conductive ceramic on the first insulating layer to form the planar heater zones, power supply lines and/or power return lines.

20. A method for plasma processing semiconductor substrates in a plasma processing chamber containing the substrate support assembly of claim 10, comprising:

(a) loading a semiconductor substrate into the processing chamber and positioning the semiconductor substrate on the substrate support assembly;

(b) determining a temperature profile that compensates for processing conditions affecting critical dimension (CD) uniformity;

(c) heating the semiconductor substrate to conform to the temperature profile using the substrate support assembly;

(d) igniting plasma and processing the semiconductor substrate while controlling the temperature profile by independently controlled heating of the planar heater zones;

(e) unloading the semiconductor substrate from the processing chamber and repeating steps (a)-(e) with a different semiconductor substrate.

21. The substrate support assembly of claim 11, wherein the terminal connectors are spring-tipped passthroughs.

22. The substrate support assembly of claim 15, wherein the primary heater layer includes two or more heaters.