SUBSTRATE THERMAL MANAGEMENT SYSTEM

BACKGROUND OF THE INVENTION

Field of the Invention:

This invention relates in general to the field of wafer processing and to rapid, uniform heating and cooling of semiconductor wafers during integrated circuit manufacturing in particular.

Discussion of Related Art:

Temperature uniformity across a wafer surface is an important factor in many integrated circuit fabrication steps since rate processes used in fabrication are generally temperature dependent. In particular processes, thermal non-uniformity can adversely effect a circuit element's critical dimension size by enlarging it relative to a design goal. Thus, as trends toward smaller integrated circuit critical dimensions continue, temperature uniformity requirements for wafer thermal management systems will become increasingly stringent.

For example, as compared to earlier standards, current temperature uniformity requirements of 0.1°C across a several hundred millimeters diameter wafer represent a 50% increase in temperature uniformity. Wafer heating and cooling units must be able to achieve such temperature uniformity figures of merit over a wide range of process operating temperatures, typically from about 20°C to several hundred degrees Celsius, and in a manner consistent from wafer-to-wafer. Rapid thermal management over the operating temperature range is also desirable for economy of process.

In the wafer processing art, stringent requirements for efficient, rapid, controllable and uniform thermal management over a wide temperature range are not fully met in an integrated device. In examples of closely related art, separate devices carry out heating and cooling functions, but as a mere combination of separate heating and cooling units positioned in opposition to each other. In these

devices, a wafer is interposed between the heating and cooling elements and is translated between the elements.

An example of such a device is shown in FIG. 1. In FIG. 1, semiconductor wafer 110, heating surface 120, and cooling surface 130 are shown. A hot thermal source and a cold thermal sink interacting with the wafer are not integrated. Rather, they are physically separated or otherwise thermally isolated from each other. To heat or cool the semiconductor wafer, the wafer is mechanically translated in a space between the heating and cooling surfaces according to the desired function. This is inefficient for the manufacturing process flow and clean-room floor space utilization, as compared to an integrated thermal management device that performs both heating and cooling functions.

Thus, due to the limitations of related art, there is a need for methods of efficient, rapid, controllable and uniform thermal management over a wide temperature range. Further, there is a need for an apparatus that provides the desired high performance during both steady state and transient conditions and that is very suitable for easy use within a manufacturing setting.

SUMMARY OF THE INVENTION

This invention relates to thermal management for efficient, rapid, controllable and uniform thermal management over a wide temperature range.

According to one aspect of the invention, there is provided a wafer thermal management device, comprising: a thermal diffuser positioned stationary relative to a wafer surface, the thermal diffuser having a diffuser thermal mass, M_d , and a temperature field T_d over a heating surface which heats the wafer surface; a thermal source positioned stationary relative to the wafer surface, having a source thermal mass, M_s, less than or equal to about 0.1 (M_d) and a temperature field over a surface proximal to the thermal diffuser, T_s , different from T_d ; a thermal sink, having a sink thermal mass, M_{sk} , positioned stationary relative to the wafer surface comprising a heat-carrying media with a controllable temperature, T_{sk} , the thermal sink thermally coupled to the thermal source and thermal diffuser by heat transfer across solid materials or across liquid and solid materials; and at least one controllable power

supply connected to the thermal source.

According to another aspect of the invention, there is provided a wafer thermal management device, comprising: a thermal reservoir having a reservoir thermal mass, M_r, positioned stationary relative to a wafer surface, the thermal reservoir internally containing media having heat-carrying capacities; a thermal diffuser positioned stationary relative to the thermal reservoir and a wafer surface, the thermal diffuser having a diffuser thermal mass, M_d, less than M_r and a temperature field T_d over a heating surface which heats the wafer surface; a thermal source interposed between the thermal diffuser and thermal reservoir, the thermal source having a source thermal mass, M_s, less than or equal to about 0.1 (M_d) and a temperature field over a surface proximal to the thermal diffuser, T_s, different from T_d; a thermal sink comprising a heat-carrying media with a controllable temperature, T_{sk}, the thermal sink substantially contained by the thermal reservoir and thermally coupled to the thermal source, thermal reservoir and thermal diffuser by heat transfer across solid materials or across liquid and solid materials; and at least one controllable power supply connected to the thermal source.

According to again another aspect of the invention, there is provided a wafer thermal management device, comprising: a thermal diffuser positioned stationary relative to a wafer surface, the thermal diffuser having a diffuser thermal mass, M_d, and a temperature field T_d over a heating surface which heats the wafer surface; a thermal source comprising a plurality of zones, the thermal source positioned stationary relative to the wafer surface and having a source thermal mass, M_s, less than or equal to M_d and a controllable temperature field over a surface proximal to the thermal diffuser, T_s, different from T_d; wherein the zones are adapted to provide differing amounts of heat; and a thermal sink positioned stationary relative to a wafer undergoing processing consisting of a heat-carrying media with a controllable temperature, T_{sk}, the thermal sink thermally coupled to the thermal source and thermal diffuser by heat transfer across solid materials or across liquid and solid materials; and at least one controllable power supply connected to the thermal source.

One object for the thermal management device is to integrate a thermal source, thermal sink and a thermal diffuser. According to an embodiment of the invention, a thermal diffuser is positioned stationary relative to the wafer surface and coupled to a

thermal source and a thermal sink, which are also stationary relative to the wafer surface. The thermal sink comprises a heat-carrying media with a controllable temperature.

Another object of the thermal management device is to minimize thermal non-uniformity across a wafer surface by non-uniform control of zones in a thermal source. According to an embodiment of the invention, a thermal diffuser is positioned stationary relative to the wafer surface and coupled to a thermal source and a

thermal sink, which are also stationary relative to the wafer surface. The thermal source includes a plurality of zones adapted to provide differing amounts of heat and a controllable temperature field over a surface proximal to the thermal diffuser. The thermal sink comprises a heat-carrying media with a controllable temperature.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a drawing showing an exemplary prior art device.

FIG. 2 is an exploded view showing one embodiment of the invention assembly.

FIG. 3 is a sketch illustrating one embodiment of a thermal source used with the apparatus shown in FIG. 2.

FIG. 4 is a graph illustrating thermal time response for a particular embodiment of the invention.

FIG. 5 is a graph illustrating the smoothing of temperature gradients by the thermal diffuser.

FIG. 6 is a graph illustrating the smoothing of temperature gradients by the thermal diffuser over a time interval during transient operation.

FIG. 7A-7F are sketches illustrating aspects of the invention suited to provide a uniform temperature field in the thermal reservoir by employing convection heat transfer.

DETAILED DESCRIPTION

In contrast to other teachings, this invention integrates a thermal source and a thermal sink in a substrate thermal management system. Integrating heating and cooling units interacting with a substrate has attendant advantages over a mere combination of a thermal source and a thermal sink, enabling efficient, rapid, controllable and uniform thermal management over a wide temperature range. This desired high performance is achieved during both steady state and transient conditions and the system apparatus is very suitable for easy use within a manufacturing setting.

FIG. 2 is an exploded view showing an assembly according to one embodiment of this invention. The assembly may be an element of a system further comprising a plurality of devices such as the one illustrated in FIG. 2 or a sub-atmospheric enclosure or a super-atmospheric enclosure. Typical embodiments, however, are adapted to operate at room conditions.

In FIG. 2, wafer 200, wafer surface 210, thermal reservoir 220, thermal diffuser 230, heating surface 235, thermal source 240, thermal sink 245, power supply 250, controller 260 and optional thermal insulators 270 and 275 are shown. A preferred embodiment includes a thermal diffuser made of a material with an isotropic thermal conductivity, such as Cu or Al, and a thermal insulator 270 substantially made of Kapton.™ Alternative embodiments include a thermal diffuser made of a material with a non-isotropic thermal conductivity. Typically, the thermal diffuser thickness perpendicular to the wafer surface is less than about 0.100 inch.

In FIG. 2, the wafer is heated across a gap between wafer surface 210 and heating surface 235. The gap is typically a few hundred micrometers wide and filled with a gas such as room air, or nitrogen, or helium, or other gasses with desirable physical properties. Alternate embodiments have different gap widths and gases with comparatively greater thermal conductivity than air. Thermal reservoir 220, thermal diffuser 230, thermal source 240, and thermal sink 245 have associated thermal masses, M_r, M_d, M_s, and M_{sk}, respectively. The heating surface and a surface of the thermal source proximal to the thermal diffuser have associated temperature fields, T_d and T_s, respectively. The thermal source, thermal reservoir and thermal diffuser are integrated and in inseparable communication by thermal conduction. Typically, thermal sink 245 is a volume of flowing fluid material with controllable temperature, which may be a constant temperature. Thus, the thermal sink and the thermal reservoir are typically in inseparable communication by conduction and convection heat transfer. Other embodiments of the thermal sink are not limited to a flowing fluid, such as a stationary fluid or a solid.

In FIG. 2, thermal sink 245 determines the lower temperature bound of the thermal management system. The thermal mass of the thermal sink, M_{sk}, may be

significantly greater than the thermal masses of the other elements. In different embodiments, M_{sk} is at least 10, or at least 10^2, or at least 10^3, or at least 10^4 times greater than M_d. In a preferred embodiment, the thermal sink is a constant temperature thermal sink provided by a chilled water supply in a factory. By virtue of continuous coupling of the comparatively large thermal mass of the thermal sink to thermal reservoir 220, the thermal reservoir may be a substantially constant and substantially uniform temperature thermal reservoir. Particular embodiments of the thermal reservoir may include features to further enhance temperature uniformity, *infra*.

FIG. 3 is a sketch illustrating a particular embodiment of thermal source 240. In FIG. 3, heating element 310, heating zone 320, temperature sensor 325, covering material 330, thermal source surface 340, power supply 350 and controller 360 are shown. As illustrated in FIG. 2, thermal source 240 is coupled to thermal reservoir 220 and thermal diffuser 230. Particular embodiments of the thermal source may require continuous thermal coupling to the thermal reservoir and thermal sink during operation to avoid overheating the thermal source. Covering material 330 is typically an electrical insulator. Particular embodiments include a thermally resistive covering material such as Kapton.™ In a preferred embodiment, the thermal coupling of the source and the thermal reservoir is inseparable.

Typically, thermal source 240 is an electrical resistance heater with a relatively small thermal mass, M_s, as compared to the thermal masses of other components shown in FIG. 2. In different embodiments, the ratio (M_s/ M_d) is less than about 10^{-1}, or less than about 10^{-2}, or less than about 10^{-3}, or less than about 10^{-4}. Particular embodiments of the thermal source are heaters with sub-millimeter sized metallic electrical resistance heating elements 310 contained in at least one heater zone 320 to produce a surface temperature field T_s on thermal source surface 340. An example of such a resistance heater is a Thermofoil™ heater from Minco Products, Inc., Minneapolis, MN. Typically, the thermal source is rated at less than 100 W/in^2 and may include a polymer covering material. The thickness of the thermal source in a direction perpendicular to wafer 200 (see FIG. 2) is generally

less than 0.05 in. The thermal mass of the thermal source is typically less than about one tenth of the thermal mass of the thermal diffuser.

The particular form and distribution of heating elements 310 within heater zones 320, and the number and placement of independently controllable heating zones, enables controller 360 to adjust the surface temperature field, T_s, on a surface of thermal source 240. Further, controlling amounts of power delivered to electrical resistance heating elements in the thermal source provides a controllable energy flux which may be smoothly variable over an interface between covering material 330 and another element to which the thermal source is coupled (see FIG. 2). Feedback control of T_s is accomplished by use of at least one temperature sensor 325 embedded in the thermal source. Particular embodiments may a equal numbers of sensors and zones. A typical embodiment can control T_s to be uniform to within less than 1°C. Alternate embodiments may have a controllably non-uniform T_s. Generally, there is a temperature difference of about 200-300°C between the thermal source and the thermal sink, although this figure is not a limitation.

As shown in FIG. 2, thermal source 240 is coupled to thermal diffuser 230, which faces wafer 200. In a preferred embodiment, the thermal source and diffuser are in direct contact. The thermal diffuser acts passively, reducing the magnitudes of gradients in T_s as heat passes through the diffuser to provide heating surface 235 with a substantially uniform temperature field. Gradients in T_s arise from the length scales inherent to the structure of the thermal source 240 and can lead to non-uniform heating of the wafer. The substantially uniform temperature field T_d over the heating surface then acts to heat wafer surface 210 across a very narrow gap of typically a few hundred micrometers.

FIG. 4 is a graph illustrating thermal time response curves for one embodiment of the invention. Both a wafer temperature 410 and a temperature of the heating surface 235 (see FIG. 2) are shown. The embodiment comprises a thermal sink at a constant temperature of 8°C; a thermal source providing an energy flux of 45 W/in^2, and a 0.060 inch thick aluminum thermal diffuser. An air gap of 0.006 inch is between the thermal diffuser and the wafer. In general, preferred embodiments span a design temperature range for heating or cooling the

wafer in a time interval no more than about 60s. Typically, thermal speeds are greater than 0.5°C/s. In FIG. 4, the wafer is heated from room temperature to 150°C in less than 60s and cooled from 150°C to room temperature in approximately 60s. In typical embodiments, a cooling time is comparable to a heating time over the same temperature range to within about 25%.

FIG. 5 is a graph illustrating the smoothing of temperature gradients by thermal diffuser 230 (see FIG. 2) for one embodiment of the invention. FIG. 5 contains a family of temperature profiles. The temperature profiles are along a radius of a circular thermal diffuser for various depths within the thermal diffuser material. Profiles proximal and distal to thermal source 240 are indicated as 510 and 520, respectively. In this embodiment, the thermal source comprised electrical resistance strips 0.040 inch wide and spaced apart by 0.030 inch-0.060 inch. The thermal diffuser was 0.040 inch thick Al. An air gap of 0.006 inch was between the thermal diffuser and the wafer. As shown in FIG. 5, the temperature profile at the heating surface 235 is uniform to within about 0.15°C.

FIG. 6 is a graph illustrating the smoothing of temperature gradients by thermal diffuser 230 (see FIG. 2) for one embodiment of the invention over a time interval during transient operation. FIG. 6 contains a family of temperature profiles. The temperature profiles are along a radius of a circular thermal diffuser for various depths within the thermal diffuser material over a 25 ms time interval. Profiles proximal and distal to thermal source 240 are indicated as 610 and 620, respectively. Thus, the profile distal to the thermal source in FIG. 6 is the temperature profile on heating surface 235 (see FIG. 2). In the embodiment for FIG. 6, the thermal source comprised electrical resistance strips 0.020 inch wide and spaced apart by 0.020 inch. The thermal diffuser was 0.040 inch thick Al. An air gap of 0.006 inch is between the thermal diffuser and the wafer. As shown in FIG. 6, the temperature profile 620 at heating surface 235 is highly uniform over the transient time interval.

FIG. 7A-7D are sketches illustrating particular aspects of the invention suited to providing a uniform temperature field at a thermal reservoir-heat source interface (see FIG. 2) by employing convection heat transfer. Typically, the thermal sink is a flowing single-phase fluid, such as liquid water. Alternate

embodiments may have a stationary solid thermal sink or gaseous thermal sink. Typically, the thermal sink is at a temperature greater than about –40 °C. FIG. 7A shows a top view schematic of a device from a field of related art. In FIG. 7A, thermal reservoir 700, fluid inlet 701 and fluid outlet 702 are shown. Fluid enters inlet 701 and exits at outlet 702 with different fluid elements experiencing differing residence times within the thermal reservoir. The differing residence times can lead to small temperature gradients in the fluid within the thermal reservoir due to the fluid's finite heat conductivity. Temperature gradients in the fluid may lead to undesirable temperature gradients on thermal reservoir surfaces.

According to this invention, the internal structure of the thermal reservoir equalizes residence times of fluid elements within it. Further, the thermal reservoir structure is designed to accelerate an internal fluid flow field or establish a non-uniform flow. This achieves a substantially uniform fluid temperature within the thermal reservoir and a corresponding substantially uniform temperature field on a thermal reservoir surface facing the rest of the thermal management apparatus (see FIG. 2).

A uniform temperature fluid is provided by variation of a fluid mass flow rate and fluid velocity through the thermal reservoir. The interior structure of the thermal reservoir varies the fluid velocity in a manner that establishes a uniform net heat flux into a fluid element, resulting in a uniform fluid temperature. In the above, the net heat flux consists of contributions due to conduction and convention. With a uniform temperature fluid within the thermal reservoir, a substantially uniform temperature field results on a thermal reservoir surface facing the rest of the thermal management apparatus.

FIG. 7B is a sketch of a top view of one embodiment. Thermal reservoir 220, orifices 715, inlet 701, outlet 702 and plenum 710 are shown. Fluid enters the inlet to the plenum. A fluid flow from the plenum to the outlet is driven by a pressure gradient between the plenum and the outlet. The symmetry of the flow allows each fluid element to reside in the flow field for substantially the same time.

FIG. 7C is a sketch showing a cross-sectional view of the embodiment in FIG. 7B. FIG. 7C illustrates aspects of the thermal reservoir's structure that enable an acceleration of the internal fluid flow field to achieve a substantially uniform

fluid temperature within the thermal reservoir. In FIG. 7C, inlet 701, outlet 702 plenum 710, orifice 715, exemplary streamlines 750 and 760, cross sectional area 765, interface surface 790, and optional second thermal diffuser 780 are shown. In FIG. 7C, fluid enters the inlet to the plenum, where it resides until passing through an orifice and to flow along exemplary streamlines to the outlet.

If a fluid acting as thermal sink 245 within thermal reservoir 220 is at rest, the temperature of the fluid will tend to rise under the action of heat flux across interface surface 790 since a temperature gradient driving the conduction is reduced. Likewise, when a fluid element moves through the thermal reservoir as in FIG. 7A, any rise in the temperature of the fluid element during its residence time in the thermal reservoir will tend to decrease the flux of heat to it from the surroundings due to conduction. Thus, for a uniform heat flux input to the thermal reservoir, a non-uniform conduction heat flux to the fluid arises.

The magnitude of convection heat transfer depends on flow velocity as well as a temperature gradient. If the velocity of a fluid flow in the thermal reservoir is uniform, heat flux due to convection will scale in a manner similar to heat flux due to conduction. However, if the flow velocity is varied within the thermal reservoir, heat flux due to convection can be non-uniform. Acting in combination, then, a non-uniform conduction heat flux and a non-uniform convection heat flux may result in a uniform temperature fluid.

According to this invention, a variation in cross-section area 765 causes a variation in fluid velocity in the thermal reservoir. Variation of flow channel cross-section area is well understood to accelerate or decelerate fluid flows. Since the fluid velocity in non-uniform within the thermal reservoir, the net heat flux to the fluid may result in a uniform fluid temperature. With the fluid within the thermal reservoir having a uniform temperature, the temperature field at an interface surface 790 may also be substantially uniform. An optional second thermal diffuser 780 with characteristics similar to thermal diffuser 230 (see FIG. 2) may also be coupled in proximity to the thermal reservoir, acting to further reduce any residual temperature non-uniformity.

FIG. 7D-7F are drawings of components of a thermal reservoir sub-assembly for one embodiment. In this embodiment, ring 770, containing a plurality

- 2 SEP 2004

of orifices 715 lays in body 792, which has at least one inlet 701 and outlet 702. Cover 791 is bolted to the body, sealing the subassembly and forming plenum 710. In this embodiment, the form of body surface 793 substantially determines the change in flow channel cross-section area.

It will be readily apparent to those skilled in the art that this invention is not limited to the embodiments described above. Different configurations and embodiments can be developed without departing from the scope of the invention and are intended to be included within the scope of the claims set forth below.

CLAIMS

What is claimed is:

1. A wafer thermal management device, comprising:

a thermal diffuser positioned stationary relative to a wafer surface, the thermal diffuser having a diffuser thermal mass, M_d , and a temperature field T_d over a heating surface which heats the wafer surface;

a thermal source positioned stationary relative to the wafer surface, having a source thermal mass, M_s, less than or equal to about 0.1 (M_d) and a temperature field over a surface proximal to the thermal diffuser, T_s , different from T_d ;

a thermal sink, having a sink thermal mass, M_{sk} , positioned stationary relative to the wafer surface comprising a heat-carrying media with a controllable temperature, T_{sk} , the thermal sink thermally coupled to the thermal source and thermal diffuser by heat transfer across solid materials or across liquid and solid materials; and

at least one controllable power supply connected to the thermal source.

2. A wafer thermal management device, comprising:

a thermal reservoir having a reservoir thermal mass, M_r , positioned stationary relative to a wafer surface, the thermal reservoir internally containing media having heat-carrying capacities;

a thermal diffuser positioned stationary relative to the thermal reservoir and a wafer surface, the thermal diffuser having a diffuser thermal mass, M_d , less than M_r and a temperature field T_d over a heating surface which heats the wafer surface;

a thermal source interposed between the thermal diffuser and thermal reservoir, the thermal source having a source thermal mass, M_s, less than or equal to about 0.1 (M_d) and a temperature field over a surface proximal to the thermal diffuser, T_s , different from T_d ;

a thermal sink comprising a heat-carrying media with a controllable temperature, T_{sk}, the thermal sink substantially contained by the thermal reservoir and thermally coupled to the thermal source, thermal reservoir and thermal diffuser by heat transfer across solid materials or across liquid and solid materials; and

at least one controllable power supply connected to the thermal source.

3. A wafer thermal management device, comprising:

a thermal diffuser positioned stationary relative to a wafer surface, the thermal diffuser having a diffuser thermal mass, M_d, and a temperature field T_d over a heating surface which heats the wafer surface;

a thermal source comprising a plurality of zones, the thermal source positioned stationary relative to the wafer surface and having a source thermal mass, M_s, less than or equal to M_d and a controllable temperature field over a surface proximal to the thermal diffuser, T_s, different from T_d; wherein the zones are adapted to provide differing amounts of heat; and

a thermal sink positioned stationary relative to a wafer undergoing processing consisting of a heat-carrying media with a controllable temperature, T_{sk}, the thermal sink thermally coupled to the thermal source and thermal diffuser by heat transfer across solid materials or across liquid and solid materials; and

at least one controllable power supply connected to the thermal source.

4. The wafer thermal management device of claim 1, further comprising at least one thermal insulator interposed between the thermal source and the thermal sink.

5. The wafer thermal management device of claim 1, further comprising at least one thermal insulator interposed between the thermal source and the wafer.

6. The wafer thermal management device of claim 1, further comprising at least one thermal insulator interposed between the thermal source and the wafer and at least one thermal insulator interposed between the thermal source and the thermal sink.

7. The wafer thermal management device of claim 4 or 5, wherein the thermal insulator is substantially made of Kapton™ material.

8. The wafer thermal management device of claim 1, wherein $M_d/M_{sk}<0.1$.

9. The wafer thermal management device of claim 1, wherein $M_d/M_{sk}<0.01$.

10. The wafer thermal management device of claim 1, wherein $M_d/M_{sk}<0.001$.

11. The wafer thermal management device of claim 1, wherein the thermal diffuser is made of material with an isotropic thermal conductivity.

12. The wafer thermal management device of claim 1, wherein the thermal diffuser is made substantially from Al or Cu.

13. The wafer thermal management device of claim 1, wherein the thermal diffuser is made of material with a non-isotropic thermal conductivity.

14. The wafer thermal management device of claim 1, wherein a thickness of the thermal diffuser perpendicular to the wafer surface is less than 0.100 inch (2.5 mm).

15. The wafer thermal management device of claim 1, wherein a thickness of the thermal diffuser perpendicular to the wafer surface is less than 0.050 inch (1.3 mm).

16. The wafer thermal management device of claim 1, wherein a thickness of the thermal diffuser perpendicular to the wafer surface is less than 0.025 inch (0.64 mm).

17. The wafer thermal management device of claim 1, wherein a thickness of the thermal diffuser is less than 0.100 inch (2.5mm).

18. The wafer thermal management device of claim 1, wherein the thermal source comprises at least one temperature sensor embedded within the thermal source.

19. The wafer thermal management device of claim 1, wherein the thermal source comprises metallic electrical resistance elements.

20. The wafer thermal management device of claim 1, wherein the thermal source is a thermal source rated at less than 50 W/in^2 (7.8 W/cm^2).

21. The wafer thermal management device of claim 1, wherein the thermal source is a thermal source rated at less than 40 W/in^2 (6.2 W/cm^2).

22. The wafer thermal management device of claim 1, wherein the thermal source is a thermal source rated at less than 20 W/in^2 (3.1 W/cm^2).

23. The wafer thermal management device of claim 1, wherein the thermal source is a thermal source rated at less than 10 W/in^2 (1.6 W/cm^2).

24. The wafer thermal management device of claim 1, wherein the thermal source comprises a plurality of independently controllable electrical resistance heating elements distributed in zones.

25. The wafer thermal management device of claim 24, wherein the zones have unequal temperature fields.

26. The wafer thermal management device of claim 1, wherein the thermal source comprises polymer material.

27. The wafer thermal management device of claim 1, wherein the thermal source has a thickness perpendicular to the wafer of less than 0.040 inch (1.0 mm).

28. The wafer thermal management device of claim 1, wherein the thermal source has a thickness perpendicular to the wafer of less than 0.030 inch (0.8 mm).

29. The wafer thermal management device of claim 1, wherein the thermal source has a thickness perpendicular to the wafer of less than 0.020 inch (0.5 mm).

30. The wafer thermal management device of claim 1, wherein M_s/M_d is no more than about 0.01.

31. The wafer thermal management device of claim 1, wherein M_s/M_d is no more than about 0.001.

32. The wafer thermal management device of claim 1, wherein the thermal sink is a solid state thermal sink.

33. The wafer thermal management device of claim 32, wherein the solid state thermal sink is a thermoelectric chip.

34. The wafer thermal management device of claim 1, wherein the thermal sink is a liquid thermal sink.

35. The wafer thermal management device of claim 34, wherein the thermal sink is water.

36. The wafer thermal management device of claim 1, wherein the thermal sink is a gaseous thermal sink.

37. The wafer thermal management device of claim 1, wherein the thermal sink has a temperature greater than about 0° C.

38. The wafer thermal management device of claim 1, wherein the thermal sink has a temperature greater than about -30° C.

39. The wafer thermal management device of claim 1, wherein a gap between the thermal diffuser and the wafer contains air.

40. The wafer thermal management device of claim 1, wherein a gap between the thermal diffuser and the wafer contains a gas with a thermal conductivity greater than that of air at comparable thermodynamic conditions.

41. The wafer thermal management device of claim 1, further comprising a super-atmospheric pressure chamber surrounding the wafer.

42. The wafer thermal management device of claim 1, further comprising a sub-atmospheric chamber surrounding the wafer.

43. A wafer processing system, comprising at least one wafer thermal management device of claim 1.

44. A wafer processing system, comprising at least one wafer thermal management device of claim 1, adapted to operate in an open environment at room conditions.

45. The wafer thermal management device of claim 2, wherein the thermal sink comprises a fluid medium, and the fluid medium flows through at least one passage in the thermal reservoir.

46. The wafer thermal management device of claim 45, wherein the thermal reservoir includes a plenum and a plurality of inlet orifices for the fluid medium.

47. The wafer thermal management device of claim 45, wherein a cross-sectional area of a fluid passageway varies along the passageway.

48. The wafer thermal management device of claim 2 further comprising a second thermal diffuser interposed between the thermal source and the thermal reservoir.

49. The wafer thermal management device of claim 1, wherein a temperature of the thermal sink is a controllable and substantially constant temperature.

50. The wafer thermal management device of claim 1, wherein the thermal source is a spatially uniform thermal source to within less than 1° C.

51. The wafer thermal management device of claim 1, wherein the thermal source temperature field, T_s, is non-uniform.

52. The wafer thermal management device of claim 1, wherein the difference between thermal source and thermal sink temperatures is about 200° C.

53. The wafer thermal management device of claim 52, wherein a wafer temperature in a range bounded by the thermal sink temperature and a thermal source temperature is achieved in a time interval of no more than about 60s.

54. The wafer thermal management device of claim 52, wherein a wafer temperature varies from about 21° C to about 25° C in a time interval no greater than about 5s.

55. The wafer thermal management device of claim 8, wherein a wafer temperature varies at a rate of about 1° C/s.