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(54) **NOZZLE DESIGN FOR GENERATING FLUID STREAMS USEFUL IN THE MANUFACTURE OF MICROELECTRONIC DEVICES**

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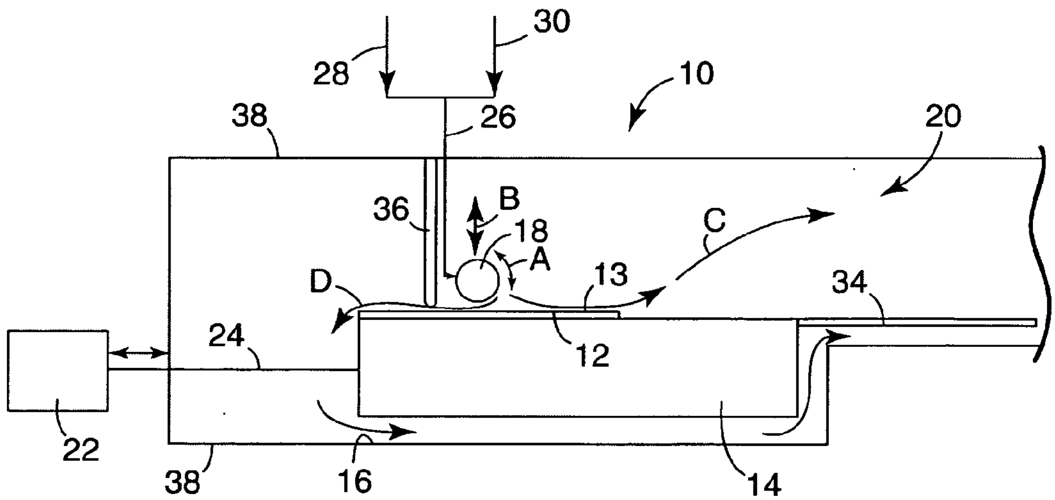
(57) **ABSTRACT**

Improved nozzle design that discharges fluid streams through a series of nozzle orifices distributed along a length of the nozzle. The present invention may be incorporated into a wide range of microelectronic device manufacturing processes and equipment types for which an array of process streams are desired for treating microelectronic workpieces. The present invention is particularly useful to cryogenically clean microelectronic workpieces.



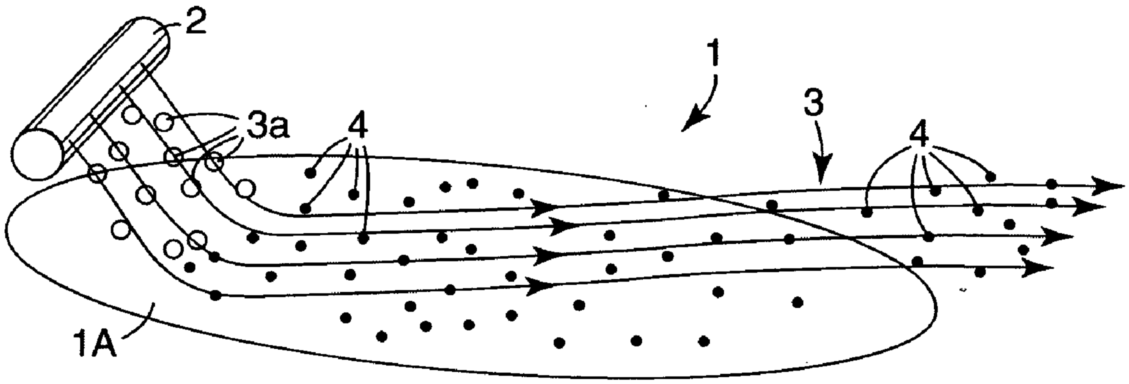


Fig. 1

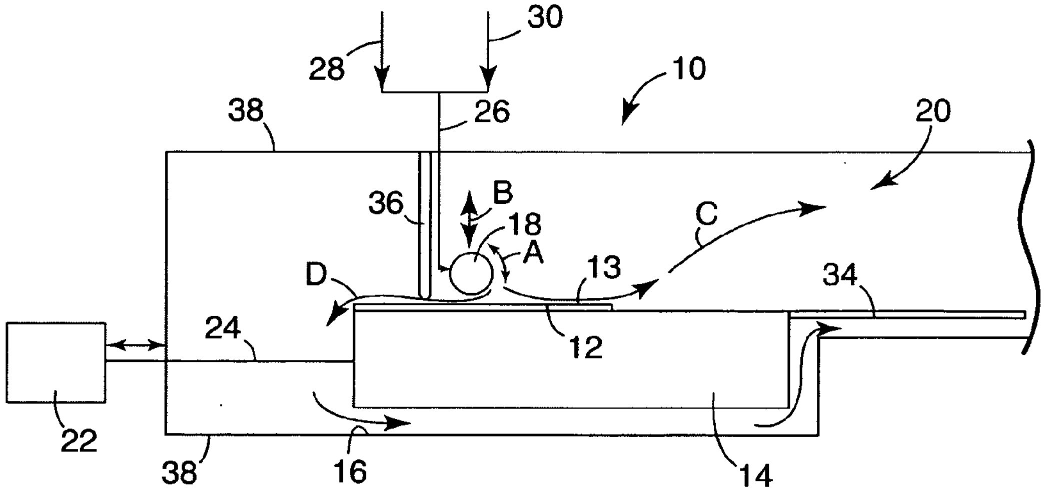


Fig. 2

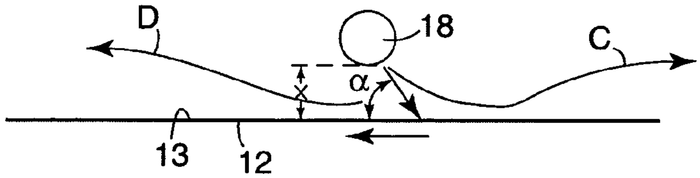


Fig. 3

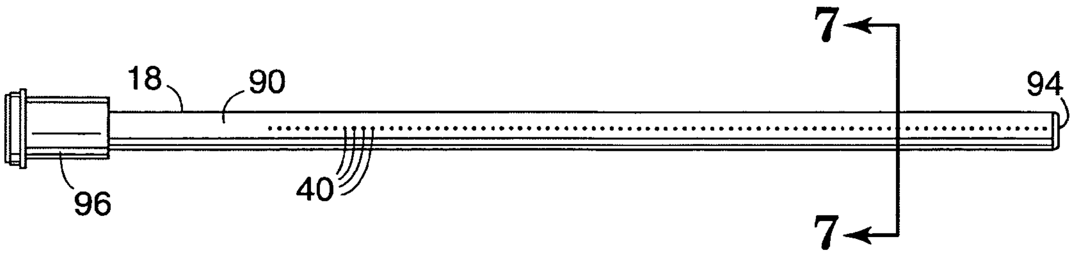


Fig. 4

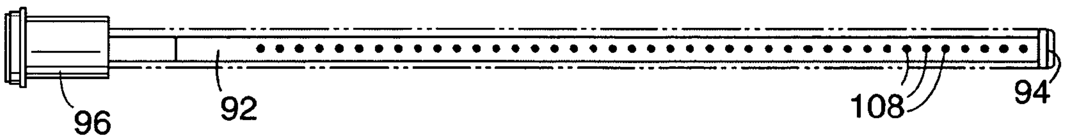
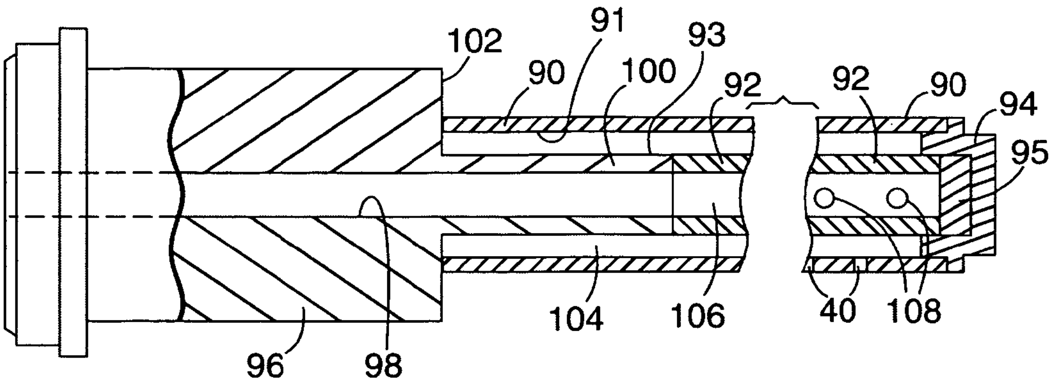


Fig. 5


102
91
93
90
100
92
92
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98
104
106
40
108

Fig. 6

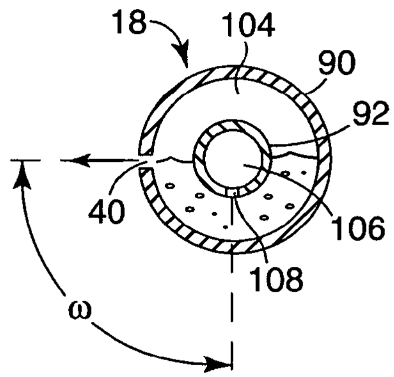
18
104
90
92
40
106
108
ω

Fig. 7

NOZZLE DESIGN FOR GENERATING FLUID STREAMS USEFUL IN THE MANUFACTURE OF MICROELECTRONIC DEVICES

REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application having Ser. No. 60/627310, filed on Nov. 12, 2004, entitled "Nozzle Design for Generating Fluid Streams Useful in the Manufacture of Microelectronic Devices," the entire disclosure of which is incorporated herein by reference for all purposes.

TECHNICAL FIELD

[0002] The present invention relates to equipment and methods for generating streams of cryogenic material that may be used in the manufacture of microelectronic devices. More specifically, the present invention relates to equipment and methods in which cryogenic material is dispensed through a nozzle including a plurality of orifices. The present invention is particularly useful for efficiently generating a cryogenic aerosol to clean particles from a microelectronic device with good particle removal efficiency and reduced damage of sensitive microelectronic structures.

BACKGROUND

[0003] The manufacture of microelectronic devices is complex and involves several process steps. Many of these steps involve applying one or more streams of fluid and/or particles (e.g., cryogenic cleaning fluids, particles, crystals, etc.) onto a workpiece surface in order to carry out one or more of etching, cleaning, stripping, rinsing, and the like. Often, it may be important to ensure that the fluid is directed onto the workpiece surface as efficiently as possible to help optimize process performance without damaging microelectronic structures. Cryogenic-aerosol cleaning of microelectronic workpieces is one illustrative area of concern.

[0004] Cryogenic-aerosol cleaning of wafers generally is a "dry" cleaning alternative to more conventional wet chemical cleans for particle and film residue removal. This technique is of particular interest in back-end-of-line applications in which wet chemicals might potentially corrode device features such as metal lines. Cryogenic-aerosol cleaning is able to use non-corrosive, inert substances such as argon, nitrogen, carbon dioxide, and/or the like, as the cleaning medium. Conventionally, the cleaning mechanisms are mechanical rather than chemical. The process is therefore environmentally friendly and device-safe.

[0005] A schematic drawing of an illustrative cryogenic cleaning process is shown in **FIG. 1**. A cryogenic apparatus **1** includes a chuck (not shown) that supports a microelectronic workpiece **1***a*. A nozzle **2** extends across workpiece **1***a*. An array of cryogenic aerosol streams **3** issue from a plurality of nozzle orifices (not shown) of nozzle **2**. The streams **3** include aerosol crystals **3***a*. These streams **3** of particles **3***a* impinge upon the surface of workpiece **1***a*, dislodging contaminants **4** adhering to the workpiece surface. The surface may be flat or patterned. Typical contaminants **4** might include one or more of film or particle residue generated as a result of etching and ashing processes. Nozzle **2** and the chuck move relative to each other to ensure that the streams **3** clean the entirety of surface of workpiece **1***a*. In the particular approach of **FIG. 1**, nozzle **2** is stationary, while the chuck, and hence workpiece **1***a*, move so that the entire surface of workpiece **1***a* is cleaned by movement underneath nozzle **2**. Of course, in other embodiments, the chuck could be stationary while nozzle **2** moves. In other embodiments, suitable relative movement may be obtained if both the chuck and nozzle **2** move relative to each other. For example, U.S. Pat. No. 5,942,037 describes a system that has a movable chuck and a rotatable and translatable nozzle.

[0006] The formation of cryogenic aerosol is an interesting process. The cryogenic aerosol is formed by the rapid cryogenic expansion of a suitable fluid discharged through the array of nozzle orifices. The fluid is generally a liquid, gas, or mixture of one or more materials. Exemplary materials include nitrogen, argon, carbon dioxide, water, or mixtures of these. The fluid enters the nozzle orifices at one pressure (e.g., 80 psia) and exits into a chamber maintained at a considerably lower pressure (typically below 1 psia). The resultant expansion of the fluid results in the formation of cryogenic, solid, or solid-liquid particle clusters due to expansive cooling. Further discussion of aerosol formation mechanisms can be found in U.S. Pat. No. 5,942,037; N. Narayanswami, "A Theoretical Analysis of Wafer Cleaning Using a Cryogenic Aerosol," J. of the Electrochemical Society, 146-2:767-774 (1999); N. Narayanswami et al., "Development and Optimization of a Cryogenic Aerosol Based Wafer Cleaning System," 28th Annual Meeting of the Fine Particle Society Proceedings (1998); and N. Narayanswami et al., "Particle Removal Mechanisms in Cryogenic-Aerosol-Based Wafer Cleaning," FSI International Document No. 1133-TRS-0499 (1999).

[0007] U.S. Pat. Nos. 4,747,421 and 4,806,171 describe an apparatus for cleaning substrates using CO_2 aerosol particles. U.S. Pat. Nos. 4,974,375 and 5,009,240 describe sandblasting devices that use ice particles generated using water. U.S. Pat. Nos. 5,062,898, and 5,209,028, and 5,294,261 describe the use of cryogenic aerosols for surface cleaning. Borden et. al., in a paper presented at the Ultraclean Manufacturing Conference, pp. 55-60, October 1994, describes the use of CO_2 snow jet spray in silicon wafer cleaning.

[0008] Contaminant particle removal efficiency is an important criterion for assessing the performance of a cryogenic cleaning process. Contaminant particle removal efficiency refers to the percentage of particles that are removed as a result of cryogenic aerosol cleaning. Particle removal efficiency characteristics are often viewed separately for particles within different size ranges, because it is important that particle removal efficiency independently satisfy desired performance specifications for both large and small particles.

[0009] Because cryogenic cleaning directs aerosol crystals upon a workpiece surface to dislodge contaminant particles, device structures on the workpiece surface can be sometimes physically damaged by the particles. This is more of a concern with regard to smaller, more sensitive features. Increasing miniaturization of device features has caused cryogenic damage to become more of a concern. Such damage may include, for example, broken polysilicon lines, and the like. In any case, such damage generally affects further processing of the device structure or some performance aspect of the device itself. Given the increasing miniaturization of microelectronic structures, even the presence of very small particles or damaged regions can significantly impair or ruin the performance of the resultant microelectronic device. Thus, it is desirable to have a cryogenic cleaning process that has a high particle removal efficiency with minimal or substantially no damage to device structures.

SUMMARY

[0010] The present invention provides an improved cryogenic cleaning nozzle design and cryogenic cleaning processes that can provide a high particle removal efficiency with minimal or substantially no damage to device structures being cleaned. Nozzles and methods in accordance with the present invention are particularly useful for removing small particles that often require greater energy or force to remove without damaging sensitive structures. A nozzle in accordance with the present invention may be incorporated into a wide range of microelectronic device manufacturing processes and equipment types for which high particle removal efficiency with minimal or substantial, no damage in treating microelectronic workpieces is desired.

[0011] Generally, a nozzle in accordance with the present invention includes plural nozzle orifices distributed along a length of the nozzle. The nozzle orifices are preferably formed by an electrical discharge machining (EDM) process and are smaller in size, have smoother walls and edges, and have less variation in diameter than previously known nozzle orifice designs. Smaller nozzle orifices produce smaller droplets with greater size uniformity. Smoother orifices reduce turbulence in the aerosol as it leaves the orifice resulting in more uniform droplet formation. As such, smaller aerosol crystals having a more uniform particle size distribution can be formed. Moreover, smaller aerosol crystals generally cause less damage to device structure than larger aerosol crystals. A nozzle having nozzle orifices with such characteristics in accordance with the present invention provides high particle removal efficiency with little or no damage to device structures. Also, a nozzle having nozzle orifices formed by EDM are generally cleaner in that such orifices have less contamination or residual particulate matter resulting from the manufacturing process. One advantage of this is that nozzles in accordance with the present invention generally need less operating time to clean up the nozzles and eliminate particles that may come off of the nozzles during operation.

[0012] In one aspect of the present invention, a nozzle for use in an apparatus for treating a surface of a microelectronic workpiece is provided. The nozzle comprises a body portion having an outside wall that defines an inside cavity of the body portion. The nozzle also includes a plurality of nozzle orifices distributed along a length of the body portion. The nozzle orifices provide a path through the outside wall of the body portion. In accordance with the present invention at least two of the plurality of nozzle orifices have a diameter less than 0.0045 inches. Preferably the plurality of nozzle orifices are formed by electrical discharging machining a plurality of openings through the outside wall of the body portion.

[0013] In another aspect of the present invention, an apparatus for treating a surface of a microelectronic workpiece is provided. The apparatus comprises at least one nozzle. The nozzle comprises a body portion having an outside wall that defines an inside cavity of the body portion. The nozzle also includes a plurality of nozzle orifices distributed along a length of the body portion. The nozzle orifices provide a path through the outside wall of the body portion. In accordance with the present invention at least two of the plurality of nozzle orifices have a diameter less than 0.0045 inches. Preferably the plurality of nozzle orifices are formed by electrical discharging machining a plurality of openings through the outside wall of the body portion.

[0014] In another aspect of the present invention, an apparatus for treating a surface of a microelectronic workpiece is provided. The apparatus comprises a treatment chamber in which a microelectronic workpiece is positioned for treatment. The apparatus also comprises a nozzle at least partially positioned in the treatment chamber. The nozzle is operatively positioned relative to the microelectronic workpiece. The nozzle comprises a plurality of nozzle orifices distributed along a length of the nozzle in a manner effective to aim the plurality of nozzle orifices toward the microelectronic workpiece. In accordance with the present invention at least two of the plurality of nozzle orifices have a diameter less than 0.0045 inches. Preferably the plurality of nozzle orifices are formed by electrical discharging machining a plurality of openings through the outside wall of the body portion.

[0015] In another aspect of the present invention, a method of treating a surface of a microelectronic workpiece is provided. The method comprises the steps of providing an apparatus having a nozzle for treating a surface of a microelectronic workpiece and causing a process fluid to be cryogenically discharged from the nozzle onto the workpiece surface. The apparatus comprises a treatment chamber in which a microelectronic workpiece is positioned for treatment and a nozzle at least partially positioned in the treatment chamber and operatively positioned relative to the microelectronic workpiece. The nozzle comprises a plurality of nozzle orifices distributed along a length of the nozzle in a manner effective to aim the plurality of nozzle orifices toward the microelectronic workpiece wherein at least two of the nozzle orifices have a diameter less than 0.0045 inches.

[0016] In yet another aspect of the present invention a method of making a nozzle for use in an apparatus for treating a surface of a microelectronic workpiece is provided. The method comprises the steps of providing a body portion comprising a wall that defines an inside cavity of the body portion and forming a plurality of nozzle orifices distributed along a length of the body portion that provide a path through the outside wall of the body portion wherein at least two of the plurality of nozzle orifices have a diameter less than 0.0045 inches.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] The above mentioned and other advantages of the present invention, and the manner of attaining them, will become more apparent and the invention itself will be better understood by reference to the following description of the embodiments of the invention taken in conjunction with the accompanying drawings, wherein:

[0018] **FIG. 1** is a schematic view of a conventional cryogenic aerosol system for cleaning the surface of a silicon wafer;

[0019] **FIG. 2** is a side schematic view of a cryogenic cleaning system of the present invention;

[0020] **FIG. 3** is a schematic side view of a substrate moving to the left relative to a nozzle of the present invention and showing the angle of impingement of a stream and the spray distance between the nozzle and the substrate surface;

[0021] **FIG. 4** is a side view of a nozzle of the present invention showing a linear array of nozzle orifices distributed along the length of the nozzle;

[0022] **FIG. 5** is a side view of the nozzle of **FIG. 4** that is rotated by 90 degrees radially from the view of **FIG. 4**, wherein the outer tube (shown by the dashed lines) is removed and the inner tube is shown as having a linear array of orifices distributed along its length;

[0023] **FIG. 6** is a partial cross-section view of the nozzle of **FIG. 4**; and

[0024] **FIG. 7** is a partial cross-section view of the nozzle of **FIG. 4** taken along line **7-7**.

DETAILED DESCRIPTION

[0025] The embodiments of the present invention described below are not intended to be exhaustive or to limit the invention to the precise forms disclosed in the following detailed description. Rather the embodiments are chosen and described so that others skilled in the art may appreciate and understand the principles and practices of the present invention.

[0026] The principles of the present invention are advantageously incorporated into cryogenic cleaning processes and, in fact, offer improved cleaning processes having high particle removal efficiency with reduced or substantially eliminated damage to device structures in this context. Using unconventionally fine nozzle orifices, preferably made using EDM techniques, is an important aspect of this improvement. In a conventional cryogenic cleaning apparatus, cleaning fluid is cryogenically discharged onto a workpiece surface through an array of orifices. Conventionally, the resultant jets of cryogenically discharged material tend to form aerosol crystals that are relatively large with respect to the device structures being cleaned. Such large aerosol particles can provide efficient cleaning with regard to some kinds of relatively large particles. But, to provide adequate particle removal efficiency for smaller particles, the larger particles need to be discharged with more energy thereby increasing the risk of damaging the device structures being cleaned. In accordance with the present invention, nozzle orifices that are smaller in diameter and have smoother walls and edges provide smaller aerosol crystals and damage can be reduced while maintaining high particle removal efficiency. This is because even though decreasing the nozzle orifice diameter generally reduces the overall fluid conductivity of a nozzle having a given number of orifices, more nozzle orifices can be used in the same amount of space. Thus, a desired fluid conductivity for providing high particle removal efficiency can be provided for a nozzle with smaller nozzle orifices by increasing the number of nozzle orifices. Preferably, in accordance with the present invention, EDM is used to form nozzle orifices because EDM can provide nozzle orifices that are smaller in diameter and that have smoother walls and edges than can be achieved with other techniques such a laser drilling.

[0027] In order to more concretely illustrate the invention, the invention will now be described in the context of an enhancement to one representative cryogenic cleaning tool commercially available under the trade designation ARIES from FSI International, Inc., Chaska, Minn. Referring now to **FIG. 2**, wherein like numerals represent like components throughout the several Figures, an apparatus **10** is illustrated for the treatment of the surface of an object, such as a microelectronic workpiece **12**. The present invention is useful for treating any type of microelectronics workpiece, including but not limited to those provided during any stage of the manufacturing of integrated circuits, flat panel displays, hard drives, multiple chip modules, and the like. Additionally, the invention is useful for treating masks used for microlithography processes including x-ray masks, and any semiconductor substrates including but not limited to gallium arsenide wafers or wafers comprising silicon.

[0028] Apparatus 10 basically comprises a movable chuck **14** that supports the microelectronic workpiece **12** within an aerosol chamber **16** and a nozzle **18**. The nozzle **18** may be rotatably adjustable and translatable in accordance with U.S. Pat. No. 5,942,037. The apparatus **10** is used for treating a surface **13** of the substrate, e.g. microelectronic workpiece **12**. Such treatment can be any coating, cleaning, or the like treatment wherein the nozzle **18** provides an aerosol, liquid or gas to impinge surface **13**. For the purposes of a specific description, the apparatus **10** will be described as a cryogenic aerosol cleaning apparatus used for cleaning contaminants from the surface of a silicon wafer.

[0029] The illustrated chuck **14** is preferably of the type exhibiting a linear movement within a predetermined range to move the entire side of the workpiece **12** through the stream discharged from nozzle **18**. The present invention is also applicable to systems utilizing rotational chucks (not shown) whereby rotary movement of the workpiece **12** is produced in order to impinge its surface with the streams from the nozzle **18**. Alternatively, in accordance with one embodiment of the present invention, the nozzle may be translatable in the direction parallel to the surface of the wafer. Such translation may be in addition to movement of the chuck, or independent from movement of the chuck while the chuck and the wafer remain stationary to accomplish a similar result. The term chuck is used to mean a device that functionally supports or otherwise holds the object to be treated. In the case where the chuck moves linearly or rotationally, the chuck also includes the appropriate slide or guide mechanism or turntable components. However, where the chuck is stationary, it may be merely a functional support mechanism.

[0030] The apparatus **10** is particularly applicable for cryogenic aerosol cleaning used for cleaning contaminants from microelectronic devices during any desired stage of processing such devices. Cryogenic aerosols may be derived from a wide range of one or more suitable materials. Examples include argon, nitrogen, carbon dioxide, and/or water as well as mixtures thereof. For example, mixtures of argon and nitrogen may be used. Specific examples of argon cryogenic aerosols combined with nitrogen are disclosed in U.S. Pat. Nos. 5,062,898, 5,209,028 and 5,294,261, all to McDermott et al, and U.S. Pat. No. 5,377,911 to Bauer et al, the entire disclosures of each of which are hereby incorporated by reference for all purposes. Nitrogen alone is presently preferred when treating smaller and generally has at least two advantages over argon/nitrogen mixtures. First, nitrogen aerosol ice is smaller in size than argon/nitrogen aerosol ice. Second, the molecular mass of argon is greater than the molecular mass of nitrogen. As a consequence, cryogen aerosols derived from nitrogen have a lesser tendency to damage structures but can be discharged with enough energy to achieve good particle removal efficiency with regard to small microelectronic features.

[0031] As shown best in **FIG. 2**, the aerosol chamber **16** defines an enclosed interior space having an exhaust duct **20**. Within the aerosol chamber **16**, the movable chuck **14** is provided. The movable chuck **14** includes a surface for supporting a microelectronic workpiece **12** thereon and is movably supported so that the surface **13** of the microelectronic workpiece **12** to be treated can be completely moved through the impingement area of the nozzle **18**. Movable chuck **14** may include any conventional mechanism for securing the microelectronic workpiece **12** to its surface facing nozzle **18**, such as by vacuum openings that open to the supporting surface for holding the microelectronic workpiece **12** against it. Mechanical fasteners or clips, suction devices, bemovilli style components, electrostatic devices and electromagnetic devices also are known for fastening the wafer to the chuck. These and others may be utilized. The movable chuck **14** is further supported within the aerosol chamber **16** to provide its necessary movement. In the particular embodiment of apparatus **10** shown, slides and guiding mechanisms are utilized to define the path of and facilitate movement of the movable chuck **14**. Moreover, an actuating mechanism **22** may be utilized to impart the movement to the movable chuck **14** along its guide path. Actuator mechanism **22** may comprise any conventional electric, mechanical, electromechanical, hydraulic, pneumatic, or the like actuator mechanism. The actuator mechanism **22** should have a range of motion sufficient that the surface **13** of microelectronic workpiece **12** can be moved entirely through the impingement area. An actuator rod **24** may be connected between the actuator mechanism **22** and the movable chuck **14**, and may also include a vacuum passage for providing the vacuum to the surface of the movable chuck **14** for securing the microelectronic workpiece **12**, as discussed above.

[0032] To control the fluid dynamics within the aerosol chamber **16**, a flow separator comprising a baffle plate **34** is preferably connected to an end of the movable chuck **14** and to extend into the exhaust duct **20**. Additionally, a shroud **36** is provided within the aerosol chamber **16** and comprises a plate connected to the aerosol chamber **16**, such as its upper wall, for controlling flow around the nozzle **18**. The controlling of the fluid dynamics within the aerosol chamber **16** by the baffle plate **34** and the shroud **36** are more fully described in U.S. Pat. No. 5,810,942. One purpose is to divide the post-impingement flow into positive streams C and D for preventing recontamination.

[0033] Nozzle **18** of the present invention is at least partially supported within the aerosol chamber **16** in a manner effective to discharge cryogenic aerosol onto workpiece **12** at a desired impingement angle. Optionally, in accordance with U.S. Pat. No. 5,942,037, nozzle **18** may be rotatably adjustable as indicated by arrow A and translatable along the direction of arrow B to adjust the spacing between nozzle **18** and the surface **13** of the workpiece **12**. Nozzle **18** is connected with a supply line **26**, which itself may be further connected with discreet supply lines **28** and **30** connected with the actual gas or liquid supplies of argon, nitrogen, or the like, as desired.

[0034] Also shown in **FIG. 2**, a make-up gas, preferably an inert gas such as nitrogen can be introduced into the aerosol chamber **16** at one or more locations indicated by way of supply conduits **38**. Although not necessary, such make-up gas is preferably introduced at the top and/or bottom of the aerosol chamber **16** at the other side thereof away from the exhaust. One reason for the use of the make-up gas is to compensate or make-up for slight pressure deviations (in the order of 5 to 10 percent) within the aerosol chamber caused by instabilities in the nozzle and pressure controls. By supplying the make-up gas, local pressure differentials are minimized and the positive overall pressure flow from the left to the right that is generated by the action of the aerosol streams, as illustrated in **FIG. 2**, is maintained. The make-up gas can be introduced into the aerosol chamber **16** through slots provided through the top and bottom walls of the aerosol chamber **16**. Conventional gas supply techniques can be used. Moreover, it is contemplated that reduced vacuum levels in the chamber **16** may provide improvements in particle removal efficiency or may help to reduce damage. For example, see U.S. Pat. No. 5,961,732 to Patrin et al., the entire disclosure of which is incorporated by reference herein by reference for all purposes.

[0035] With reference to **FIG. 3**, the orientation of orifices **40** relative to workpiece **12** defines the angle of impingement a of the substance that is used to treat the surface **13** of the workpiece **12**. In the case of a cryogenic cleaning apparatus, the substance preferably comprises the frozen cryogenic crystals and gas stream. Optionally, in accordance with U.S. Pat. No. 5,942,037, the nozzle **18** may be rotatably mounted within the aerosol chamber **16** so that the angle α can be varied depending on the desired cleaning angle. Thus, the nozzle is useful or more efficient in a wider range of applications. Specifically, the processing of substrates including deep trenches and other surface features may be more thoroughly accomplished by orienting the aerosol spray direction more perpendicular to the substrate surface where α is 45 degrees to 90 degrees. For processing a very flat surface, the aerosol spray may be provided at a very shallow grazing angle that is close to an angle α of near 0 degrees to 45 degrees. The angle α may be anywhere between near 0 degrees and 90 degrees depending on the application. Depending on the surface features of the substrate, e.g. workpiece **12**, the angle α may be altered from substrate to substrate or during the cleaning of a single substrate.

[0036] Preferably, the nozzle **18** of the present invention is also adjustable toward or away from the surface **13**. The distance x (see **FIG. 3**) between the lower edge of the nozzle and the substrate surface can be adjusted to optimize any specific process. Moreover, with substrates of varying thicknesses, it is possible to manipulate the spray nozzle **18** to maintain a fixed spray travel distance x to the substrate surface over the variable thickness substrate surface.

[0037] Nozzle **18**, in accordance with the present invention, is illustrated in more detail in **FIGS. 4 through 7**.

Generally, the nozzle **18** comprises an outer tube **90**, an inner tube **92**, an end cap **94**, an end cap **95** and a fitting **96**, which preferably is a part of a VCR fitting as discussed in U.S. Pat. No. 5,942,037 for connection with a supply tube. As shown in **FIG. 9**, the fitting **96** includes an internal passage **98** that opens from a side of the fitting **96**, as illustrated, to communicate with the supply (not shown) of material from which cryogenic aerosol will be derived. At the other end of the fitting **96**, a tube portion **100** is provided through which the passage **98** also passes. Surrounding the tube portion **100**, the outer tube **90** is connected to the surface **102** of the fitting **96**. Preferably, the outer tube **90** and the tube portion **100** are concentrically arranged. The outer tube **90** can be conventionally connected with surface **102** by welding. The inner tube **92** is preferably butted with and connected to the tube portion **100**, such as by welding. At the other end of the nozzle **18**, the end cap **95** is sealingly connected to the end of the inner tube **92** and is nested within the end cap **94** that seals the end of the outer tube **90** and supports both the inner and outer tubes **92** and **90**, respectively. Preferably, end cap **94** maintains the concentric relationship of the outer tube **90** and inner tube **92**.

[**0038**] By this construction, a first cavity **104** is defined within the outer tube **90** by its internal surface **91**, the outer surface **93** of the inner tube **92**, the surface **102** of the fitting **96** and the end cap **94**. A second internal cavity **106** is also defined within the inner tube **92** and the tube portion **100** of fitting **96** as defined by the interior surfaces thereof and the end cap **95**.

[**0039**] The inner tube **92** is preferably provided with a series of longitudinally aligned orifices **108** as can be seen best in **FIG. 6**. The orifices **108** need not be arranged in this manner, however, and in some cases so not need to be aligned. For example, some orifices **108** may be radially displaced by 180 degrees from others. The orifices **108** provide communication between the second internal cavity **106** and the first internal cavity **104**. The jet impingement orifices **40** are provided in a longitudinally aligned series through the outer tube **90** to provide communication from the first internal cavity **104** and the outside of the nozzle **18**. More specifically, the jet impingement orifices **40** direct the discharged material therein toward the workpiece **12**, in the direction and angle of impingement as discussed above and shown in **FIG. 3**.

[**0040**] In accordance with the present invention, inner orifices **108** are desirably radially angularly offset with respect to orifices **40**. Preferably, the inner orifices **108** are angularly offset from the orifices **40** by an angle ω in the range of 45 to 180 degrees, most preferably about 90 degrees.

[**0041**] As noted above, smaller orifices provide smaller aerosol crystals, which can help to minimize damage to device structures being cleaned. In accordance with the present invention, the orifices **40** are preferably formed by EDM. It is noted that any known or future developed material removal process that can provide orifices having characteristics similar to those achieved by EDM may be used. EDM is a thermal erosion process in which material is removed by a series of recurring electrical discharges between an electrode and a workpiece in the presence of a dielectric fluid. By using EDM, the orifices **40** can be made in desired fine sizes and with smoother walls and edges than can be achieved with other material removal processes, such as by laser drilling, for example. Moreover, smoother walls and edges can help to minimize turbulence, which also helps to provide smaller aerosol crystals and also helps to improve the size uniformity of such aerosol crystals. All of these can help to minimize or substantially eliminate damage to device structures being cleaned while maintaining high particle removal efficiency.

[**0042**] The size of an orifice such as the orifice **40** can be characterized in any desired way. For example, the diameter of the orifice **40** at either side of the orifice **40** as formed through the wall of the tube **90** can be measured and used to identify the diameter of the orifice **40**. Measurement of a small diameter orifice can be accomplished by using optical microscopy or scanning electron microscopy or the like. If microscopy techniques are used to measure the diameter of the orifice **40**, the diameter of the orifice **40** at the outside surface of the tube **90** is preferably used to characterize the orifice **40**. If the diameter of the orifice **40** is measurable at the inside surface of the tube **90**, such as by being viewable by a microscope or the like, the diameter of the orifice **40** at the inside surface of the tube **90** may be used, together with or independently from the diameter of the orifice **40** at the outside surface of the tube **40**. For example, if the diameter of the orifice **40** changes through the wall of the tube **40**, an average of the inside surface and outside surface diameters may be used to characterize the diameter of the orifice **40**. Moreover, other factors may be used to characterize the orifice **40** such as angle of the wall of the orifice itself, the area of either side of the orifice, as well as the major and minor diameters of the orifice. Holes are measured with an optical microscope having a calibrated eyepiece reticle scale or a microscope with a stage micrometer, or by using magnifying optical comparator.

[**0043**] In one exemplary embodiment, the orifices **40** of the nozzle **18** are formed by EDM and have a diameter that is less than 0.0050 inches. More preferably, the orifices **40** have a diameter that is less than 0.0030 inches and even more preferably less than 0.0025 inches. Preferably, for any given orifice diameter, the tolerance on the diameter is plus or minus 0.0005 inches and more preferably 0.0002 inches. Any number of orifices **40** may be used to achieve any desired fluid conductivity for the nozzle **18** as mentioned above. For example, where the orifices **40** have a diameter of 0.0025 inches plus or minus 0.0002 inches, the orifices **40** may be spaced apart, on center, by 0.0283 inches (about 35 orifices per inch). The number of orifices **40** may be determined by considering the size of the microelectronics device desired to be treated. In any case nozzle **18** is preferably designed so that the orifices **40** are as small as possible without reducing particle removal efficiency or increasing damage.

[**0044**] The present invention will now be described with reference to the following illustrative examples.

1. Experimental Procedure:

[**0045**] A. Equipment:

TABLE 1

ANTARES ® CX 200 mm Advanced Cleaning System
MSP 2300 Particle Deposition System

TABLE 1-continued

Process Monitor Wafers
SiO2 Challenge Wafers (described below)
Sematech Poly Line Damage Assessment Wafer (Modified as described below)
Tencor TBI-SP1
Optical Microscope
FSI Zeta 200 mm Tool

[0046]

	Nozzles			
Nozzle	Outer Wall Thickness	Number of Holes	Hole Size	Holes Made By
Nozzle_1 (comparative)	0.010	129	>0.0045"	Laser Drilling
Nozzle_2	0.010	129	0.0045"	EDM
Nozzle_3	0.020	129	0.0045"	EDM
Nozzle_4	0.010	418	0.0025"	EDM

B. SiN Challenge Wafer Prep Procedure:

[0047] Twenty SiO2 challenge wafers were used in this experiment. A challenge wafer is a wafer that has had particles purposely deposited on the surface the wafer so that the wafer can be cleaned and the cleaning efficiency of a particular process can be determined. A summary of the pre-clean, contamination, and processing sequences for these wafers is given below.

[0048] 1. Clean wafers in an FSI Zeta 200 mm tool with the initial wafer clean recipe (IWC). This is a wet clean of the wafers prior to depositing particles. The IWC uses a sulfuric/hydrogen peroxide clean followed by an ammonium hydroxide/hydrogen peroxide clean.

2. Measure wafers on Tenecor TB1-SP1: Recipe "SPC0.09HT_cx"—high speed. This recipe is a standard SP1/TB1 high throughput particle measurement recipe in the oblique mode for particles >/=90 nm.

3. Contaminate wafers.

3a. Use MSP 2300 Particle Deposition System to "full" deposit SiO2 particles at >0.09 microns.

4. Measure wafers on Tenecor TB1-SP1: Recipe "SPC0.09HT_cx"—high speed.

5. Run experiment in ANTARES®CX-200 using test nozzles.

6. Measure wafers on Tenecor TB1-SP1: Recipe "SPC0.09HT_cx"—high speed. There were an average of 4876 initial SiO2 particles at >0.09 microns on each of the SiO2 challenge wafers.

C. Preparation of Poly Line Damage Assessment Wafer:

[0049] A poly line damage assessment wafer was obtained from Sematech. The line widths and spaces were modified using a wet isotropic etch in a Magellan tool to achieve the desired final line widths. Measurements of line widths and spaces were verified using the Applied Materials SEM Vision Instrument. The poly line height was approximately 225 angstroms. The cell containing the inspected poly lines was named "Line Cell." Included in this cell were five blocks labeled A, B, C, D, and E. Each block consisted of various line and space widths that can be found in Table 6. Each block was approximately 4 mm in length. Two of these blocks were inspected for each damage assessment test. The wafer was orientated such that the cells containing the poly lines would run perpendicular to the aerosol. Experience has shown this orientation results in the most damage.

D. Experimental Design:

[0050] The experiment was designed to determine particle adder performance, particle removal efficiency and poly line damage assessment using an LFLP (Low Flow Low Pressure) (Ar:N2 3:1) @45° Nozzle Angle process recipe for all nozzles as well as an AspectClean™ (N2Only) @60° Nozzle Angle recipe with the standard nozzle only. Regarding the angles, see **FIG. 3** and the description thereof above.

[0051] A separate run of three clean bare silicon process monitor wafers was used to determine particle adder performance for each of the four nozzles. Particle adder performance was evaluated to characterize each nozzle in terms of how the nozzle added particles to the wafers. The process monitor wafers were run through the ANTARES®CX using the appropriate 2-pass process recipe developed for each nozzle. No dummy wafers were used. The wafer numbers used in the tables refer to the slot number of the wafer carrier. Particle adders were determined for ≧0.09 micron, ≧0.12 micron and ≧0.15 micron particle sizes using the Tencor TB1-SP1. See Table 3 for results.

[0052] Twenty SiO2 challenge wafers were made with the MSP 2300 Particle Deposition System, aged for approximately 20-25 days and used for particle removal efficiency evaluation for all nozzles. Four SiO2 challenge wafers were run through the ANTARES®CX using the appropriate 2-pass process recipe for each nozzle. In all cases initial, pre, and post SiO2 particles were measured on the Tencor TB1-SP1 at ≧0.09 micron to determine particle removal efficiency. See Tables 4 and 5 for results.

[0053] An approximately 2"×2" Sematech poly line damage assessment sample was taped to a 200 mm silicon substrate and microscopically inspected for damage with the number of damage sites recorded for each line width. The sample was then processed through the ANTARES®CX with the standard nozzle using the appropriate 4-pass process recipe. The wafer was orientated such that the cells containing the poly lines would run perpendicular to the aerosol. Experience has shown this orientation results in the most damage. The sample was then microscopically reinspected for damage with the number of damage sites recorded for each line width. This procedure was repeated for each of the remaining nozzles and recipes. See Table 6 for results.

[0054] The ANTARES®CX process recipes used for each of the nozzles are given in Table 2 below.

TABLE 2

Process Recipes for Each Nozzle

Gas	Gas Set (slpm)	Chuck Speed (in/sec)	# Passes	Dewar Back Press (psia)	PT3 (psig)	Chamber Pressure (Torr)	Nozzle Angle (degrees)
			Nozzle_1: LFLP				
Argon	246	0.9	2	109	72 ± 1	50	45
N2	82		or				
**CN2	400		4				
			Nozzle_1: AspectClean ™				
*N2	360	0.9	2	55	72 ± 1	50	60
N2	135						
**CN2	300						
			Nozzle_2: LFLP				
Argon	159	0.9	2	105	73 ± 1	50	45
N2	53		or				
**CN2	400		4				
			Nozzle_3: LFLP				
Argon	186	0.9	2	90	74 ± 1	50	45
N2	62		or				
**CN2	400		4				
			Nozzle_4: LFLP				
Argon	168	0.9	2	105	72 ± 1	50	45
N2	56		or				
**CN2	400		4				

*Total N2 Flow: N2 Flow thru Argon MFC (.719 × 360) = 259 slpm
N2 Flow thru N2 MFC = 135 slpm

394 slpm Total N2 Flow

**curtain nitrogen

E. Results:

[0055] Results of the particle adder, SiN particle removal efficiency and poly line damage assessment experiments are shown in Tables 3, 4, 5, and 6 below.

TABLE 3

Particle Adders Summary Table (2-Passes)

		Adders Nozzle				
		Nozzle_1		Nozzle_2	Nozzle_3	Nozzle_4
		Recipe				
		LFLP	AspectClean	LFLP	LFLP	LFLP
Wafer 24	@≧0.09 microns	−3	0	1	14	6
Wafer 20		2	10	11	−2	8
Wafer 10		−4	4	12	−4	9
Wafer 24	@≧0.12 microns	−4	−2	0	7	8
Wafer 20		2	10	7	1	5
Wafer 10		−3	1	11	−1	3
Wafer 24	@≧0.15 microns	−4	−5	5	7	6
Wafer 20		1	8	4	−3	−3
Wafer 10		−6	−1	9	−3	5

Particle adder results for all nozzles/recipes were satisfactory at ≧0.09 micron.

[0056]

TABLE 4

SiO2 Particle Removal Efficiency Summary Table (2-Passes)

Wafer	Particle Removal Efficiency @≧0.09 microns Nozzle: Nozzle_1		Nozzle_2	Nozzle_3	Nozzle_4
	Recipe				
Wafer	LFLP	AspectClean ™	LFLP	LFLP	LFLP
20	99.90%	85.41%	96.40%	97.55%	97.31%
18	99.04%	86.47%	96.97%	98.40%	98.26%
16	98.95%	87.61%	96.76%	99.02%	98.15%
14	99.70%	87.90%	96.01%	98.08%	98.20%
Average	99.40%	86.85%	96.53%	98.26%	97.98%
Std Dev	0.47	1.14	0.42	0.62	0.45

Highest average PRE obtained with Nozzle_1 using LFLP (Ar:N2 3:1) @45° Nozzle Angle recipe. Lowest PRE obtained with Nozzle_1 using AspectClean ™ (N2Only) @60° Nozzle Angle recipe.

[0057] Individual PRE summary tables per bin size for each of the nozzles/recipes are shown in the Table 5 below.

TABLE 5

SiO2 Particle Removal Efficiency Summary Table Per Bin Size for Each Wafer

	0.09–0.12	0.12–0.15	0.15–0.20	0.20–0.30	Area	Total Rslt
Run 1 Summary/LFLP 2-pass/Nozzle_1/20 Days Old						
Wafer 20	99.27%	102.22%	100.05%	100.56%	94.59%	99.90%
Wafer 18	99.18%	93.53%	99.70%	99.59%	93.75%	99.04%
Wafer 16	98.48%	98.95%	99.90%	97.35%	96.77%	98.95%
Wafer 14	100.43%	96.54%	100.20%	97.35%	84.38%	99.70%
Average	99.34%	97.81%	99.96%	98.72%	92.37%	99.40%
Std. Dev.	0.81%	3.68%	0.21%	1.62%	5.48%	0.47%
Run 2 Summary/LFLP 2-pass/Nozzle_2/20 Days Old						
Wafer 20	93.03%	97.42%	98.58%	99.19%	100.00%	96.40%
Wafer 18	94.41%	94.74%	99.35%	99.59%	96.00%	96.97%
Wafer 16	94.81%	91.69%	99.23%	97.93%	92.86%	96.76%
Wafer 14	93.94%	93.24%	98.90%	94.72%	93.10%	96.01%
Average	94.05%	94.27%	99.02%	97.86%	95.49%	96.53%
Std. Dev.	0.76%	2.44%	0.35%	2.20%	3.33%	0.42%
Run 3 Summary/LFLP 2-pass/Nozzle_3/21 Days Old						
Wafer 20	94.63%	97.70%	99.56%	100.40%	97.96%	97.55%
Wafer 18	97.38%	97.57%	99.45%	99.02%	93.55%	98.40%
Wafer 16	97.90%	99.02%	99.90%	100.21%	95.83%	99.02%
Wafer 14	96.91%	94.02%	99.95%	98.11%	82.61%	98.08%
Average	96.70%	97.08%	99.72%	99.43%	92.49%	98.26%
Std. Dev.	1.44%	2.14%	0.25%	1.07%	6.83%	0.62%
Run 4 Summary/LFLP 2-pass/Nozzle_4/21 Days Old						
Wafer 20	94.67%	97.91%	99.09%	100.42%	95.65%	97.31%
Wafer 18	97.50%	94.43%	99.32%	99.20%	100.00%	98.26%
Wafer 16	97.01%	94.87%	99.54%	100.00%	94.29%	98.15%
Wafer 14	96.28%	98.68%	99.85%	100.21%	86.67%	98.20%
Average	96.37%	96.47%	99.45%	99.96%	94.15%	97.98%
Std. Dev.	1.24%	2.14%	0.32%	0.54%	5.55%	0.45%
Run 5 Summary/AspectClean 2-pass/Nozzle_1/25 Days Old						
Wafer 20	75.70%	91.19%	92.45%	92.68%	92.31%	85.41%
Wafer 18	76.72%	92.76%	93.46%	95.79%	92.31%	86.47%
Wafer 16	78.13%	98.93%	94.42%	92.52%	96.67%	87.61%
Wafer 14	80.44%	94.42%	92.96%	95.99%	112.50%	87.90%
Average	77.75%	94.33%	93.32%	94.24%	98.45%	86.85%
Std. Dev.	2.05%	3.34%	0.84%	1.90%	9.59%	1.14%

[0058]

TABLE 6

Poly Line Damage Assessment Summary Table (4-Passes)

	Pitch (microns)	Line (microns)	Space (microns)	# Damage Sites Nozzle_1 LFLP	Nozzle_1 AspectClean ™	Nozzle_2 LFLP	Nozzle_3 LFLP	Nozzle_4 LFLP
Block A	0.26	0.08	0.18	133	0	0	3	0
	0.28	0.07	0.21	342	1	0	15	0
	0.30	0.06	0.24	295	0	1	13	0
	0.34	0.06	0.28	154	0	1	11	0
	0.40	0.08	0.32	48	0	0	0	0
	0.60	0.12	0.48	7	0	0	2	0
	2.100	0.113	1.20	1278	2	2	40	0
		0.083	0.68					
			Total A	2257	3	4	84	0
Block B	0.28	0.09	0.19	11	0	1	0	0
	0.30	0.08	0.22	12	0	2	0	0
	0.32	0.08	0.24	22	0	0	0	0
	0.36	0.08	0.28	14	0	1	0	0
	0.40	0.09	0.31	6	0	0	1	0
	0.48	0.11	0.37	3	0	0	0	0
	0.72	0.12	0.60	5	0	0	0	0
	2.120	0.115	1.39	814	1	3	26	0
		0.088	0.67					
			Total B	887	1	7	27	0
Block C	0.30	0.11	0.19	0	0	0	0	0
	0.34	0.10	0.24	4	0	0	0	0
	0.36	0.10	0.26	2	0	1	0	0
	0.38	0.10	0.28	1	0	0	0	0
	0.42	0.11	0.31	1	0	0	0	0
	0.48	0.12	0.36	1	0	0	0	0
	0.56	0.13	0.43	0	0	0	0	0
	0.84	0.13	0.71	2	0	0	0	0
	2.140	0.121	1.31	808	2	0	17	0
		0.090	0.73					
			Total C	819	2	1	17	0
Block D	0.32	0.14	0.18	0	0	0	0	0
	0.36	0.12	0.24	1	0	0	0	0
	0.38	0.12	0.26	0	0	0	0	0
	0.40	0.12	0.28	1	0	0	1	0
	0.44	0.12	0.32	0	0	0	0	0
	0.48	0.13	0.35	1	0	1	0	0
	0.54	0.14	0.40	0	0	0	0	0
	0.64	0.15	0.49	0	0	0	0	0
	0.96	0.14	0.92	0	0	0	0	0
	2.160	0.131	1.33	480	1	0	14	0
		0.085	0.70					
			Total D	483	1	1	15	0
Block E	0.36	0.15	0.21	0	0	0	0	0
	0.40	0.14	0.26	0	0	0	1	0
	0.44	0.14	0.30	0	0	0	0	0
	0.46	0.14	0.32	0	0	0	0	0
	0.52	0.15	0.37	0	0	1	0	0
	0.54	0.15	0.39	0	0	0	0	0
	0.62	0.16	0.46	0	0	0	0	0
	0.72	0.16	0.56	0	0	0	0	0
	1.08	0.16	0.64	0	0	0	0	0
	2.180	0.169	1.34	380	0	0	12	0
		0.090	0.60					
			Total E	380	0	1	13	0
Total Defects per Nozzle				4826	7	14	156	0

Highest number of poly line defects obtained with Nozzle_1 using LFLP (Ar:N2 3:1) @45°Nozzle Angle recipe. Lowest poly line defect number obtained with Nozzle_4 LFLP (Ar:N2 3:1) @45° Nozzle Angle recipe.

F. SUMMARY:

[0059] Particle adder results of the Nozzle_1 processed with the LFLP (Ar:N2 3:1) recipe and the AspectClean™ (N2Only) @60° Nozzle Angle recipe as well as Nozzle_2, Nozzle_3, and Nozzle_4 processed with the LFLP (Ar:N2 3:1) recipes were satisfactory at ≧0.09 microns.

[0060] Average SiN particle removal efficiencies @≧0.09 microns when processing with the LFLP or AspectClean 2-Pass process recipes are shown in Table 7.

TABLE 7

SiO2 Particle Removal Efficiency Summary Table

Nozzle Type	Recipe	Particle Removal Efficiency @≧0.09 microns
Nozzle_1	LFLP	99.40%
Nozzle_1	AspectClean ™	86.85%
Nozzle_2	LFLP	96.53%
Nozzle_3	LFLP	98.26%
Nozzle_4	LFLP	97.98%

[0061] Total instances of Poly Line Damage Sites observed microscopically when processing with the LFLP or AspectClean 4-Pass process recipes are shown in Table 8.

TABLE 8

Poly Line Damage Summary Table

Nozzle Type	Recipe	Total Poly Line Damage Sites
Nozzle_1	LFLP	4826
Nozzle_1	AspectClean ™	7
Nozzle_2	LFLP	14
Nozzle_3	LFLP	156
Nozzle_4	LFLP	0

G. Additional Testing:

[0062] A damage assessment wafer was processed through the LFLP 2-pass recipe using Nozzle_4. This was a full wafer with the same structures used in the tests above. The wafer was sent out for damage analysis. The results are presented below in Table 9.

TABLE 9

Nozzle	Recipe	Angle	Damage Sites	PRE
Nzl 4	LFLP	45°	24	98.6
Nzl 1 (comparative)	AspCln	60°	7	95.16
Nzl 4	AspCln	45°	4	91.98
Nzl 4	LFLP	60°	0	97.84

[0063] Two, one day old, wet dipped SiN challenge wafers were processed with Nozzle_4 through the LFLP 2-pass recipe and LFLP 4-pass recipe with a 45 degree nozzle angle. This was done to provide a direct Particle Removal Efficiency comparison between the CX and ZETA tools. Results were as follows:

[0064] LFLP 2-pass Nozzle_4: PRE=74% and 75% for CX and Zeta, respectively.

[0065] LFLP 4-pass Nozzle_4: PRE=77% and 78% for CX and Zeta, respectively.

[0066] Other embodiments of this invention will be apparent to those skilled in the art upon consideration of this specification or from practice of the invention disclosed herein. Various omissions, modifications, and changes to the principles and embodiments described herein may be made by one skilled in the art without departing from the true scope and spirit of the invention which is indicated by the following claims.

What is claimed is:

1. A nozzle for use in an apparatus for treating a surface of a microelectronic workpiece, the nozzle comprising a body portion having an outside wall that defines an inside cavity of the body portion and a plurality of nozzle orifices distributed along a length of the body portion and providing a path through the outside wall of the body portion wherein at least two of the plurality of nozzle orifices have a diameter less than 0.0045 inches.

2. The nozzle of claim 1, wherein the plurality of nozzle orifices are formed by electrical discharging machining a plurality of openings through the outside wall of the body portion.

3. The nozzle of claim 1, further comprising a distribution conduit within the inside cavity of the body portion, the distribution conduit comprising a plurality of delivery openings formed though a wall that defines an inside cavity of the distribution conduit and distributed along a length of the distribution conduit.

4. The nozzle of claim 1 in combination with an apparatus for treating a surface of a microelectronic workpiece.

5. The combination of claim 4, wherein the plurality of nozzle orifices are formed by electrical discharging machining a plurality of openings through the outside wall of the body portion.

6. The combination of claim 5, further comprising a distribution conduit within the inside cavity of the body portion, the distribution conduit comprising a plurality of delivery openings formed though a wall that defines an inside cavity of the distribution conduit and distributed along a length of the distribution conduit.

7. An apparatus for treating a surface of a microelectronic workpiece, the apparatus comprising:

a treatment chamber in which a microelectronic workpiece is positioned for treatment;

a nozzle at least partially positioned in the treatment chamber and operatively positioned relative to the microelectronic workpiece, the nozzle comprising a plurality of nozzle orifices distributed along a length of the nozzle in a manner effective to aim the plurality of nozzle orifices toward the microelectronic workpiece wherein at least two of the nozzle orifices have a diameter less than 0.0045 inches; and

a cryogenic material being discharged from the nozzle toward the workpiece.

8. The nozzle of claim 7, wherein the plurality of nozzle orifices are formed by electrical discharging machining a plurality of openings through a wall of the nozzle.

9. A method of treating a surface of a workpiece, the method comprising the steps of:

providing an apparatus for treating a surface of a microelectronic workpiece, the apparatus comprising:

a treatment chamber in which a microelectronic workpiece is positioned for treatment;

a nozzle at least partially positioned in the treatment chamber and operatively positioned relative to the microelectronic workpiece, the nozzle comprising a plurality of nozzle orifices distributed along a length of the nozzle and aimed toward the microelectronic workpiece wherein at least two of the nozzle orifices have a diameter less than 0.0045 inches; and,

causing a process fluid to be cryogenically discharged from the nozzle orifices onto the workpiece surface.

10. The method of claim 9, wherein the plurality of nozzle orifices of the nozzle are formed by electrical discharging machining a plurality of openings through a wall of the nozzle.

11. A method of making a nozzle for use in an apparatus for treating a surface of a microelectronic workpiece, the method comprising the steps of providing a body portion comprising a wall that defines an inside cavity of the body portion and forming a plurality of nozzle orifices distributed along a length of the body portion that provide a path through the outside wall of the body portion wherein at least two of the plurality of nozzle orifices have a diameter less than 0.0045 inches.

12. The method of claim 11, further comprising the step of forming the plurality of nozzle orifices by electrical discharging machining a plurality of openings through the wall of the nozzle.

13. The method of claim 11, further comprising the step of providing a distribution conduit within the inside cavity of the body portion, the distribution conduit comprising a plurality of delivery openings formed though a wall that defines an inside cavity of the distribution conduit and distributed along a length of the distribution conduit.

* * * * *