

METHOD AND APPARATUS FOR MEGASONIC CLEANING OF PATTERNED SUBSTRATES

by Inventors

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BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates generally to surface cleaning and, more particularly, to a method and apparatus for megasonic cleaning of a semiconductor substrate following
10 fabrication processes.

2. Description of the Related Art

[0002] Megasonic cleaning is widely used in semiconductor manufacturing operations and can be employed in a batch cleaning process or a single wafer cleaning process. For a batch cleaning process, the vibrations of a megasonic transducer creates sonic pressure waves in the
15 liquid of the cleaning tank which contains a batch of semiconductor substrates. A single wafer megasonic cleaning process uses a relatively small transducer above a rotating wafer, wherein the transducer is scanned across the wafer, or in the case of full immersion a single wafer tank system is used. In each case, the main particle removal mechanisms with megasonic cleaning are due to cavitation and acoustic streaming. Cavitation is the rapid forming and collapsing of
20 microscopic bubbles generated from dissolved gas when sonic energy is applied to a liquid medium. Upon collapse, the bubbles release energy which assists in particle removal through breaking the various adhesion forces which adhere the particle to the substrate. Acoustic streaming is the fluid motion induced by the acoustic wave through the fluid when RF power is applied to a piezoelectric transducer.

25 [0003] Figure 1A is a schematic diagram of a batch megasonic cleaning system. Tank 100 is filled with a cleaning solution. Wafer holder 102 includes a batch of wafers to be cleaned. Transducer 104 creates pressure waves through sonic energy with frequencies near 1 Megahertz (MHz). These pressure waves, in concert with the appropriate chemistry to control particle re-adhesion, provide the cleaning action. Because of the long cleaning time required for batch
30 cleaning systems, as well as chemical usage, efforts have been focused on single wafer cleaning systems in order to decrease chemical usage, increase wafer-to-wafer control, and decrease defects in accordance with the International Technology Roadmap for Semiconductors (ITRS)

requirements. Batch systems suffer from another disadvantage in that the delivery of megasonic energy to the multiple wafers in the tank is non-uniform and can result in 'hot spots' due to constructive interference, or 'cold spots' due to destructive interference, each being caused by reflection of the megasonic waves from both the multiple wafers and from the megasonic tank. Constructive interference can cause damage to sensitive features or pattern on the wafer substrate, and thus the average energy must be lowered to ensure any hot-spots are below the damage threshold. In cases of cold spots, insufficient cleaning occurs, and therefore, a higher megasonic energy must be applied in order to reach all regions of the wafers in wafer holder 102. In either case, a compromise must be reached to minimize damage while still providing high enough average energy to enable cleaning.

[0004] Figure 1B is a schematic diagram of a single wafer cleaning tank. Here, tank 106 is filled with a cleaning solution. Wafer 110, supported by carrier 108, is submerged in the cleaning solution of tank 106. Transducer 104 supplies the energy to clean wafer 110. The cleaning solutions are typically designed to modify the zeta potential between the surfaces of the wafer and a particle removed from the surface of the wafer through the acoustic energy supplied by transducer 104 to prevent particle re-attachment. The cleaning solution concentration should be maintained within a fairly tight range in order to maintain a suitable zeta potential between the surfaces. However, for features such as lines, contacts, spaces, vias, etc., defined on a surface of the substrate, the particle may redeposit on the surface of the substrate due to the inability to maintain a specific cleaning solution concentration, i.e., replenish the cleaning solution, at the particle-substrate interface within the region defined by the feature. Further, in the case of a transducer oriented perpendicular to the substrate surface (as in a single-tank megasonic system), high-aspect ratio features may shadow, or shield, the lower regions of the feature from megasonic energy and cavitation. For a transducer oriented parallel to the wafer surface, cavitation can occur within the feature, but acoustic streaming is not in the most favorable direction to facilitate moving a detached particle away from the substrate. However, this configuration causes gaps 114a-c between the respective crystals. One other shortcoming of this configuration is that gaps result in regions not being supplied with a comparable level of acoustic energy, due to the collimated nature of the acoustic energy supplied by the piezo electric crystals. Consequently, certain regions of wafer 110 do not see a uniform acoustic energy, resulting in uneven cleaning.

[0005] Additionally, electro-deposition operations, in particular electroless plating, is commonly used for the deposition of a film on a substrate. For example, a copper film may be

deposited on a substrate through electroless plating. One of the shortcomings of electroless plating is that the presence of any bubble formation in the features of a patterned substrate undergoing electroless plating will lead to voids in subsequent plating operations. Another shortcoming of electroless plating into high aspect ratio features is mass transport of the fresh reactants from the solution into the features, and mass transport of byproducts out of the same features.

[0006] In view of the foregoing, there is a need for a method and apparatus to provide a single wafer megasonic cleaning configuration that is capable of replenishing cleaning chemistry into regions defined by the feature in order to prevent a particle removed by the acoustic energy from re-depositing on the wafer. In addition, there is a need for controlling bubble formation in the vicinity of features undergoing electroless plating operations and improving mass transport of reactants and by-products into and out of high aspect ratio features.

SUMMARY OF THE INVENTION

[0007] Broadly speaking, the present invention fills these needs by providing a method and apparatus for supplying acoustic energy into the feature for dislodging a particle and for replenishing the cleaning chemistry into the feature region to assist in the removal of detached particles. In addition, the invention provides a system and method for controlling bubble formation and improving mass transport during electroless plating operations. It should be appreciated that the present invention can be implemented in numerous ways, including as a method, a system, or an apparatus. Several inventive embodiments of the present invention are described below.

[0008] In one embodiment, a method for cleaning a semiconductor substrate is provided. The method initiates with generating acoustic energy oriented in a substantially perpendicular direction to a surface of a semiconductor substrate. Then, acoustic energy oriented in a substantially parallel direction to the surface of the semiconductor substrate is generated. Each orientation of the acoustic energy may be simultaneously generated (in phase) or alternately generated (out of phase).

[0009] In another embodiment, an apparatus for cleaning a semiconductor substrate is provided. The apparatus includes a base and at least one sidewall extending from the base. The sidewall is substantially perpendicular to the base. A first megasonic transducer affixed to the base is included. A second megasonic transducer affixed to the sidewall is also included. The

first megasonic transducer is oriented in a substantially orthogonal manner to the second megasonic transducer.

[0010] In yet another embodiment, a system for cleaning a semiconductor substrate is provided. The system includes a tank having an inner cavity defined by a base and at least one sidewall extending therefrom. The tank is configured to retain a volume of a liquid within the inner cavity. A substrate support configured to support and rotate a semiconductor substrate about an axis of the semiconductor substrate is included. The substrate support is further configured to support and rotate the semiconductor substrate in the inner cavity of the tank. A first megasonic transducer coupled to the base is included. A top surface of the megasonic transducer is substantially parallel to a bottom surface of the semiconductor substrate. A second megasonic transducer is coupled to the at least one sidewall. The first megasonic transducer is configured to generate acoustic energy associated with a direction substantially perpendicular to the bottom surface of the semiconductor substrate. The second megasonic transducer is configured to generate acoustic energy associated with a direction substantially parallel to the bottom surface of the semiconductor substrate.

[0011] In still yet another embodiment, a method for electroless plating of a substrate is provided. The method initiates with immersing a substrate into a plating solution. Then, a film is deposited onto a surface of the substrate. Also, acoustic energy is transferred to the plating solution. The acoustic energy is directed at the surface of the substrate to control bubble formation at the surface of the substrate using a transducer oriented substantially parallel to the wafer surface in one embodiment. In another embodiment, the acoustic energy is directed at the surface of the substrate to improve mass transfer of the reactants and by-products at the surface of the substrate using a transducer oriented substantially perpendicular to the wafer surface.

[0012] In another embodiment, an apparatus for electroless plating of a substrate is provided. The apparatus includes a tank configured to retain a plating solution and a transducer configured to transfer acoustic energy to the plating solution.

[0013] Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings, and like reference numerals designate like structural elements.

[0015] Figure 1A is a schematic diagram of a batch megasonic cleaning system.

[0016] Figure 1B is a schematic diagram of a single wafer cleaning tank.

[0017] Figure 2 is a simplified megasonic cleaning apparatus in accordance with one embodiment of the invention.

5 [0018] Figure 3 is an alternative embodiment to the megasonic cleaning apparatus illustrated in Figure 2.

[0019] Figure 4 is an enlarged cross-sectional view of a megasonic cleaning apparatus in accordance with one embodiment of the invention.

[0020] Figure 5 is an alternative embodiment of the megasonic cleaning tank of Figure 4.

10 [0021] Figure 6 is a flow chart diagram illustrating the method operations for cleaning a semiconductor substrate through megasonic cleaning in accordance with one embodiment of the invention.

[0022] Figure 7A is a simplified schematic diagram of a megasonic transducer being used in an electroless plating operation in accordance with one embodiment of the invention.

15 [0023] Figure 7B is an alternate embodiment of the electroless plating vessel of Figure 7A.

[0024] Figure 8A is a simplified schematic diagram of a cleaning apparatus in which acoustic energy is used to clean a substrate in accordance with one embodiment of the invention.

[0025] Figure 8B is an alternate embodiment of the cleaning apparatus of Figure 8A.

[0026] Figure 8C is yet another embodiment of the cleaning apparatus of Figure 8A.

20 [0027] Figure 8D is still yet another embodiment of the cleaning apparatus of Figure 8A.

[0028] Figure 9 is a simplified schematic diagram of a cleaning apparatus having two acoustic energy generators in accordance with one embodiment of the invention.

[0029] Figure 10A is a simplified schematic diagram of a cleaning apparatus configured to clean opposing sides of a substrate in accordance with one embodiment of the invention.

25 [0030] Figure 10B is a simplified schematic diagram of an alternative embodiment of the cleaning apparatus of Figure 10A.

[0031] Figure 11 is a flow chart diagram illustrating the method operations for applying acoustic energy to clean a surface of the substrate in accordance with one embodiment of the invention.

30 **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

[0032] An invention is described for a system, apparatus and method that provides a megasonic cleaning scheme optimized for providing acoustic energy directly into a defined feature of a patterned substrate and for replenishing the region defined by the feature with cleaning

chemistry. It will be obvious, however, to one skilled in the art, that the present invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the present invention. Figures 1A and 1B are described in the "Background of the Invention" section.

[0033] The embodiments of the present invention provide a system and method for optimizing the cleaning efficiency of megasonic cleaning of patterned substrates. As used herein, substrate and wafer are interchangeable. By supplying two megasonic transducers oriented orthogonally, where one transducer is substantially parallel to a surface of a substrate being cleaned and the other transducer is substantially perpendicular to the surface of a substrate being cleaned, both cavitation effects and acoustic streaming effects are optimized. That is, the megasonic transducer that is substantially parallel to the surface of the substrate is able to supply acoustic energy directly into the features of a patterned substrate. The acoustic energy supplied directly into the features induces cavitation to dislodge any particles within the features. On the other hand, the megasonic transducer that is oriented in a substantially perpendicular manner relative to the surface of a substrate being cleaned, is able to provide acoustic streaming parallel to the wafer surface. The acoustic streaming induces eddies or turbulence in the region around the feature and inside of the feature. Consequently, chemical transport into and out of the feature is enhanced to enable chemical cleaning within the feature.

[0034] Additionally, the embodiments described herein provide a system and method for improving the deposition quality of an electroless plating operation through the application of megasonic energy. The application of megasonic energy induces cavitation which assists in the collapses of bubbles formed during the plating process. The size to which the bubbles grow before collapse depends on the frequency of the megasonic energy applied. Therefore, the formation of bubbles at the surface undergoing the plating operation may be controlled through the application of megasonic energy with the plating operation.

[0035] Figure 2 is a simplified megasonic cleaning apparatus in accordance with one embodiment of the invention. Megasonic cleaning apparatus 110 includes a tank having side walls 118 and 122, both of which extend from base 120. The tank contains cleaning solution 112. Cleaning solution 112 may be any suitable cleaning solution used for megasonic cleaning and has properties which facilitate removable particles as well as inhibit re-deposition of particles on a surface of substrate 116. As used herein, cleaning solution and cleaning chemistry are interchangeable. As can be seen, substrate 116 is immersed in cleaning solution

112 and is supported by carrier 114. It will be apparent to one skilled in the art that any suitable means for supporting substrate 116 in cleaning solution 112 of the megasonic cleaning tank may be used here. The megasonic cleaning tank is coupled to megasonic transducers 124 and 126. Megasonic transducer 126 is oriented perpendicular to the bottom surface 117 of substrate
5 116. Thus, transducer 126 provides acoustic streaming parallel to the bottom surface 117 as will be shown below. Megasonic transducer 124 is oriented parallel to bottom surface 117 of substrate 116. Therefore, transducer 124 provides acoustic energy which is able to access features, i.e., vias, holes, trenches, etc., to induce cavitation within those features. That is, the horizontal and vertical transducers relative to the wafer surface orientation provides acoustic
10 streaming and mass transport assist particle removal and chemical fluid exchange to the wafer surface and cavitation to dislodge and remove particles bonded to the substrate surface.

[0036] Figure 3 is an alternative embodiment to the megasonic cleaning apparatus illustrated in Figure 2. Here, substrate 116 is oriented in a vertical position rather than the horizontal position of Figure 2. It will be apparent to one skilled in the art that substrate 116 may be
15 supported by any suitable substrate support means, e.g., a substrate carrier, rollers, etc. Substrate 116 is immersed in cleaning solution in 112 which is contained in a cavity defined by base 120 and sidewalls 118 and 122 of the megasonic cleaning tank. It should be appreciated that the shape of megasonic cleaning tank may be any shape suitable to provide the transfer of acoustic energy from transducers in a manner where one transducer provides acoustic energy in
20 a substantially perpendicular direction to the surface of the substrate and the other transducer provides acoustic energy in a substantially parallel direction to the surface of the substrate. In one embodiment, the perpendicular direction of the acoustic energy is between about 5 degrees of normal, i.e. 90 ± 5 degrees, wherein the normal is relative to the surface of the substrate. In another embodiment, the parallel direction of the acoustic energy is between about 5 degrees of
25 parallel, i.e. 0 ± 5 degrees, wherein the parallel direction is parallel to the surface of the substrate or a plane parallel to the surface of the substrate. Thus, the shape of the base may be rectangular, square, or even circular, where the side walls are configured, to allow for the placement of a megasonic transducer which transfers acoustic energy in an orthogonal orientation as compared to the acoustic energy transmitted by the base megasonic transducer. It
30 should be appreciated that cleaning solution 112 may be any commercially available cleaning solution such as cleaning solutions available from DUPONT Electronic Technologies, EKC Technology, Inc., or ASHLAND Corporation.

[0037] Figure 4 is an enlarged cross-sectional view of a megasonic cleaning apparatus in accordance with one embodiment of the invention. Here, patterned surface 117 of substrate 116 is shown in more detail, i.e., the features of the patterned surface are illustrated. Substrate 116 is immersed in cleaning solution 112 which is contained within a cavity defined between sidewall 118, sidewall 122 and base 120 of the megasonic cleaning tank. It should be appreciated that substrate 116 may be rotated about its axis through a suitable substrate support. Megasonic transducers 124 and 126 include transducer element 124a and 126a, respectively, and resonator element 124b and 126b, respectively. Megasonic transducers 124 and 126 may be any suitable megasonic transducer commercially available. Megasonic transducers typically generate energy in the frequency range of 500 KiloHertz (KHz) to 5 Megahertz (MHz). It will be apparent to one skilled in the art that the particular materials chosen for the megasonic transducer will determine the frequency range generated. Suitable materials include piezo electric materials and piezo ceramic materials, e.g., quartz, and sapphire.

[0038] The orientation of megasonic transducer 124 relative to megasonic transducer 126 allows for optimal energy and mass transport benefits for improved cleaning of patterned substrate 116. Megasonic transducer 124 provides acoustic energy that is capable of accessing the features of surface 117 of substrate 116. Here, the acoustic energy will induce cavitation in order to dislodge particle 132 which is adhered to an inner surface of the feature of surface 117. In order to prevent re-attachment of particle 132 to the inner surface, megasonic transducer 126 provides acoustic energy which causes acoustic streaming as illustrated by arrows 130. Acoustic streaming is the fluid motion induced by the velocity gradient in the fluid when subjected to acoustic energy. Acoustic streaming is a function of frequency and delivered intensity and provides a strong localized flow of cleaning solution whose sheer force is the primary particle removal agent. The flow caused by the acoustic streaming, as illustrated by arrows 130, causes eddies 134 within the features defined on surface 117. Eddies 134, also referred to as turbulence, improves mass transport into and out of the features, allowing fresh cleaning solution to be introduced into the features defined on surface 117 and also sweeps away any removed particles dislodged from the features through cavitation caused by the acoustic energy delivered into the features from megasonic transducer 124.

[0039] Arrows 128 of Figure 4, represent the acoustic energy delivered inside the features of bottom surface 117 from megasonic transducer 124. As mentioned above, acoustic energy 128 induces cavitation to dislodge particle 132. It should be appreciated that turbulence or eddies 134 helps to improve reactant/byproduct transfer into and out of the features, especially high

aspect ratio features. However, direct energy is delivered into the feature in order to provide cavitation and particle removal. Thus, the orientation of megasonic transducers parallel and perpendicular to a surface of the wafer provides both the direct energy for cleaning features defined on the surface of the substrate and for the chemical transfer into the features.

5 [0040] Figure 5 is an alternative embodiment of the megasonic cleaning tank of Figure 4. Here, substrate 116 is oriented in a vertical position rather than a horizontal position. Accordingly, megasonic transducer 126 provides the direct energy, illustrated by arrows 128, for dislodging particle 132 from features defined on surface 117 of substrate 116. Megasonic transducer 124 provides the acoustic streaming illustrated by arrows 130 which causes eddies
10 134 in order to sweep away particle 132 and introduce fresh cleaning solution into the features of bottom surface 117. As cleaning solution 112 is specifically designed for a single wafer cleaning operation, it should be appreciated that as the reactant/byproduct concentration of cleaning solution 112 is changed, the cleaning characteristics will likewise change. That is, cleaning solution 112 inside high aspect ratio features, e.g., the features on surface 117 of
15 substrate 116, cleans the inside of the high aspect ratio feature. As the cleaning occurs, the concentration of the cleaning solution in that feature may change, thus changing the interface properties and zeta potential between the particle and substrate surface. This change may allow particle 132 to re-adhere to a surface of substrate 116 since the cleaning solution may not maintain a suitable or consistent zeta potential between the surfaces of particle 132 and surface
20 117. Thus, the acoustic streaming, or more accurately, eddies 134 caused by the acoustic streaming, prevents this from happening by improving mass transport and replenishing the cleaning solution in the feature.

[0041] Figure 6 is a flow chart diagram illustrating the method operations for cleaning a semiconductor substrate through megasonic cleaning in accordance with one embodiment of
25 the invention. The method initiates with operation 140 where a cleaning vessel, coupled to two separate transducers, is provided. For example, the cleaning vessel illustrated with reference to Figures 2 through 5 may be provided here. The method then advances to operation 142 where a substrate is immersed into a cleaning solution contained in the cleaning vessel. It should be appreciated that the immersed substrate is oriented such that one megasonic transducer is
30 substantially parallel to a surface to be cleaned on the substrate and the second megasonic transducer is substantially perpendicular to the surface of the substrate to be cleaned. In other words, the transducers are oriented in such a way that the respective acoustic energies transferred to the cleaning solution from each transducer are approximately orthogonal to each

other, i.e., oriented at about a right angle to each other. As mentioned above, the cleaning solution may be commercially available cleaning solution specifically designed for single-wafer cleaning and also may even be de-ionized water. The method then proceeds to operation 144 where the substrate is rotated. Here, the substrate may be rotated through any suitable means
5 known in the art.

[0042] The method of Figure 6 then moves to operation 146 where acoustic energy is generated in a substantially perpendicular direction to a surface of the substrate. Here, the acoustic energy directly impinges high aspect ratio features in order to provide cavitation for particle removal during cleaning of the high aspect ratio features. The method then advances to operation 148
10 where the acoustic energy is generated in a substantially parallel direction to the surface of the substrate. Here, the acoustic energy causes eddies which help improve reactant/byproduct transfer into an out-of-the-high aspect ratio features. In other words, the acoustic streaming helps replenish chemistry in order to prevent particles from re-depositing on a surface of the wafer being cleaned. Additionally, the acoustic streaming enhances the transport of particles
15 one they are detached. It should be appreciated that the acoustic energy generated in a substantially perpendicular direction and the acoustic energy generated in the substantially parallel direction may be simultaneously applied or they may be alternately applied or some combination thereof. More specifically, the transducers may be powered at the same time or alternately, i.e., the transducers may be in phase or out of phase.

[0043] Figure 7A is a simplified schematic diagram of a megasonic transducer being used in an electroless plating operation in accordance with one embodiment of the invention. Here, electroless plating vessel 150 contains plating solution 152. Substrate 154 is supported inside electroless plating vessel 150. As is generally known electroless plating occurs by the immersion of components in a plating solution. The plating solution generally consists of a
25 soluble metal salt and a reducing agent. The metal salts are reduced onto an oxide-free surface. Thus, a metal film may be deposited on a surface, e.g., copper, nickel, etc. However, any bubble formation on or near the surface in which the metal is deposited, may cause voids in the resulting metal film. Thus, by coupling megasonic transducer 156 to electroless plating vessel 150, acoustic energy 160 is capable of being directed to the surface of substrate 154, through
30 plating solution 152 which is in contact with the megasonic transducer and the substrate, in order to collapse any bubbles that might be present. Accordingly, a more reliable and uniform film may be deposited on surface 155 of substrate 154.

[0044] Figure 7B is an alternate embodiment of the electroless plating vessel of Figure 7A. Here, a second megasonic transducer is introduced substantially perpendicular to substrate 154. Thus, transducer 158 allows for acoustic streaming to be used to clear away any particles from the surface of substrate 154 during the electroless plating process. That is, the acoustic
5 streaming from transducer 158 improves mass transfer of the reactants and by-products at the surface of substrate 154. It should be appreciated that electroless plating vessel 150 may include the capability to re-circulate or replenish plating solution 152. Here inlet 164 may provide fresh plating solution to plating vessel 150, while outlet 166 is used for the removal of displaced plating solution. It will be apparent to one skilled in the art that the plating solution
10 may be re-circulated through inlet 164 and outlet 166 as an alternative to a once pass system. In one embodiment, plating solution 152 is overflow dumped to waste collection or drain. Furthermore, the position of inlet 164 and outlet 166, as well as the shape of the plating vessel may be any suitable position or shape, respectively, in order to perform the electroless plating operation.

[0045] In summary, the above described invention, with reference to Figures 2-7B, describes a method and a system for optimizing the cleaning efficiency for patterned substrates. By orienting two megasonic transducers, one in a horizontal orientation and another in a vertical orientation, relative to a surface of the substrate to be cleaned, the cavitation and the acoustic streaming properties associated with the megasonic energy are optimized. The horizontally
20 oriented megasonic transducer, i.e., oriented substantially parallel to the substrate surface, has a line of sight into the feature so that acoustic energy may be delivered into the feature to provide cavitation. The cavitation will dislodge any particles inside the feature.

[0046] The vertically oriented megasonic transducer, i.e., oriented substantially perpendicular to the substrate surface, delivers acoustic streaming parallel to the surface of the wafer. The acoustic streaming causes eddies and turbulence for removing the dislodged particle and also
25 replenishes the cleaning chemistry within the feature, e.g., a high aspect ratio feature, to further assure that the dislodged particle does not re-attach to a surface within the feature. In essence, the acoustic streaming allows for chemical cleaning within the feature by replenishing the cleaning chemistry within the feature. It should be appreciated that the embodiments described
30 herein may also be applied to applications where it is desirable to enhance a chemical reaction. For example with respect to resist stripping the embodiments described herein will assist the mass transport of reactants to remove reacted material. That is, the acoustic streaming described above will enhance mass transfer.

[0047] Figure 8A is a simplified schematic diagram of a cleaning apparatus in which acoustic energy is used to clean a substrate in accordance with one embodiment of the invention. Cleaning apparatus 218 consists of base 228 and sidewalls 232 extending from the base. Inner cavity 220 is defined between base 228 and sidewalls 232. Cleaning apparatus 218 includes
5 acoustic energy generator 223 which consists of transducer 224 affixed to resonator 226. In one embodiment, acoustic energy generator 223 generates megasonic energy, i.e., transducer 224 is a megasonic transducer. It should be appreciated that while the embodiments described herein refer to megasonic energy, the invention may be applied to any acoustic energy. Acoustic energy generator 223 is positioned at a lower corner of cleaning apparatus 218. One
10 skilled in the art will appreciate that resonator 226 of acoustic energy generator 223 is in contact with a cleaning solution. Thus, the acoustic energy is transferred through the cleaning solution to the substrate in order to assist in the cleaning process.

[0048] Continuing with Figure 8A, acoustic energy generator 223 is configured to generate acoustic waves oriented in a substantially parallel direction relative to bottom surface 222a of
15 substrate 222. The acoustic waves substantially parallel to bottom surface 222a are represented by lines 234. Extension arm 238 extends from sidewall 232 and defines a corridor between base 228 and extension arm 238. Extension arm 238 may be any suitable length. Reflective surface 230 is an angled portion of base 228. Here, acoustic waves generated by acoustic energy generator 223 are reflected off of surface 230 toward a bottom surface 222a of substrate
20 222. The reflected acoustic energy is represented by lines 236. Reflective surface 230 is angled so that the substantially parallel acoustic energy waves 234 are directed in a substantially perpendicular orientation relative to bottom surface 222a as depicted by lines 236. For example, the angle between surface 230 and base 228 is about 45 degrees.

[0049] Still referring to Figure 8A, it should be appreciated that a direction of the acoustic
25 waves is decoupled from the source of the acoustic energy. Additionally, the configuration of cleaning apparatus 218 allows outside access to the components of acoustic energy generator 223. In one embodiment, cleaning apparatus 218 may be a low profile tank, i.e., substrate 222 is positioned within about one half inch of base 228. It should be appreciated that base 228 may be extended past surface 230 as represented by section 228a. In this embodiment, the
30 region defined between section 228a, section 232a, the elevated portion of base 228, and surface 230, defines a void. In another embodiment, surface 230 is adjustable in order to modulate the angle between surface 230 and base 228. Accordingly, the movement of surface 230 causes the reflected acoustic energy to sweep surface 222a of substrate 230. Consequently,

the reflected acoustic energy may be concentrated around an edge region of substrate 222 rather than the center region of the substrate so that the edge region sees an equivalent amount of energy. Of course, substrate 222 is rotating here as illustrated below.

[0050] Figure 8B is an alternate embodiment of the cleaning apparatus of Figure 8A. Cleaning apparatus 218 includes a tank configured to clean substrate 222, which is immersed in a cleaning solution contained within inner cavity 220. Megasonic transducer 224 is affixed to resonator 226 and generates acoustic energy directed towards reflective surface 230. Here, reflective surface 230 has a convex surface in contact with the cleaning solution of cleaning apparatus 218. Thus, acoustic energy generated by megasonic transducer 224 is reflected in a different pattern as compared to Figure 8A. Accordingly, the convex shape of reflector 230 causes the generated acoustic energy represented by lines 234 to scatter according to different angles as represented by lines 236. Thus, the reflected acoustic energy, represented by lines 236, impinges on a surface of substrate 222 at a variety of angles. In essence, reflective surface 230 takes a collimated source/acoustic wave and spreads the source/acoustic wave over a defined area. Furthermore, the energy gaps corresponding to the spaces between the piezo electric crystals, are eliminated through the reflection of the acoustic energy.

[0051] Figure 8C is yet another embodiment of the cleaning apparatus of Figure 8A. Cleaning apparatus 218 includes a tank containing cleaning solution having a base 228 with sidewalls 232 extending therefrom as in Figure 8A. However, cleaning apparatus 218 is shown having an alternate reflective surface 230 along with overflow or re-circulation capability. Reflective surface 230 includes a number of convex bumps in order to scatter the acoustic energy generated from acoustic energy generator 223. Thus, the acoustic energy generated in a substantially parallel direction within the corridor defined between base 228 and extension 238 alters a direction of the acoustic energy in order to spread out the reflected acoustic energy across bottom surface 222b of substrate 222. Of course, substrate 222 may be rotating along an axis of the substrate. It will be apparent to one skilled in the art that the rotation of substrate 222 may be provided by any suitable rotation means available. For example, a substrate carrier configured to support substrate 222 may be used to provide the rotational force. Alternatively, rollers supporting edges of substrate 222 may provide the rotational force.

[0052] Still referring to Figure 8C, cleaning apparatus 218 also includes inlet 229 and outlet 231. Inlet 229 provides the capability of flowing fresh cleaning solution into the cleaning apparatus. Outlet 231 is configured to provide an overflow for excess cleaning solution in one embodiment. In an alternative embodiment, outlet 231 may be in communication with inlet

229 through a pump in order to re-circulate the cleaning solution throughout the cleaning apparatus. It will be apparent to one skilled in the art that the cleaning solution is designed for single substrate cleaning applications. In addition, single substrate cleaning solutions are commonly available from companies such as EKC Inc, and Ashland, Inc.

5 [0053] Figure 8D is still yet another embodiment of the cleaning apparatus of Figure 8A. Here, reflective surface 230 has a concave shape. One skilled in the art will appreciate that reflected acoustic energy 236 is focused on a particular point of bottom surface 222a of substrate 222. Thus, reflective surface 230 takes the collimated acoustic energy 234 generated by the acoustic energy source 223 and focuses the energy. Reflective surface 230 may have a parabolic shape
10 in order to focus reflected rays 236 to a single point. Alternatively, reflective surface 230 may be cylindrically shaped in order to focus reflective rays along a line. Here again, reflective surface 230 may be moveable in order to sweep the acoustic energy across the surface of a rotating substrate. One skilled in the art will appreciate that numerous other shapes may be defined for reflective surface 230 in order to decouple a direction associated with generated
15 acoustic energy from acoustic energy source 223. That is, reflective surface 230 may be configured to scatter, focus, or evenly distribute the acoustic energy delivered from acoustic energy source 223.

[0054] Figure 9 is a simplified schematic diagram of a cleaning apparatus having two acoustic energy generators in accordance with one embodiment of the invention. Cleaning apparatus
20 218 includes acoustic energy generators 223 and 242, which may be megasonic transducers. Acoustic energy generators 223 and 242 are configured such that acoustic energy generated from each of the respective acoustic energy generators is oriented in a manner substantially parallel to either top surface 222b or bottom surface 222a of substrate 222. That is, acoustic energy generated from acoustic energy generator 242, represented by lines 240a and 240b, is
25 substantially parallel to top surface 222b and bottom surface 222a of substrate 222. Similarly, acoustic energy generated by acoustic energy generator 223 is also substantially parallel to bottom surface 222a.

[0055] Still referring to Figure 9, the cleaning apparatus may contain megasonic transducers 223 and 242 having faces both of which are substantially perpendicular relative to top and
30 bottom surfaces 222a and 222b of semiconductor substrate 222. Through reflective surface 230, acoustic energy 234 generated by megasonic transducer 223, is re-directed so that the acoustic energy is substantially perpendicular to bottom surface 222a of substrate 222. Thus, the acoustic energy generated by megasonic transducer 223 may be used to provide cavitation

in order to dislodge particles within features defined on bottom surface 222a. Megasonic transducer 242 provides acoustic streaming to remove the dislodged particles and refresh cleaning solution within the defined features. Further details of this cleaning action are described above with respect to Figures 2-7B. Of course, substrate 222 may be rotating as
5 illustrated in Figure 8C. Additionally, cleaning apparatus 218 may include overflow and re-circulation capabilities as illustrated with reference to Figure 8C.

[0056] In another embodiment, reflective surface 230 of Figure 9 may reflect the acoustic energy at a slight angle relative to a normal of substrate surface 222a. A change in the angle that the acoustic energy impinges on the substrate surface allows for a reduction of oscillation
10 associated with the impedance. In one embodiment, the angle, relative to the normal of the surface of the substrate, is between about 3 degrees and about 6 degrees. The angle introduced reduces impedance variations caused by wafer run-out (wobble) during rotation. In another embodiment, acoustic energy source 223 is auto-tuned

[0057] Figure 10A is a simplified schematic diagram of a cleaning apparatus configured to
15 clean opposing sides of a substrate in accordance with one embodiment of the invention. Cleaning apparatus 218 includes acoustic energy generators 223 and 242a configured to provide acoustic energy to opposing surfaces of substrate 222. Acoustic energy generated from acoustic energy generator 223 is reflected from reflective surface 230 in order to clean bottom surface 222a of substrate 222. Acoustic energy generator 242a is configured to provide
20 acoustic energy to top surface 222b of 222 in order to facilitate cleaning of the top surface of the substrate. Here, acoustic energy generator 242a is configured to generate acoustic energy as represented by line 243 which is at a slight angle with respect to top surface 222b of substrate 222. In one embodiment, the angle defined between acoustic energy 240b and top surface 222b is between about zero degrees and five degrees. It should be appreciated that some of acoustic
25 energy 240b will be reflected from top surface 222b as illustrated by line 246. Thus, reflective surface 244a may be positioned to reflect the once reflected acoustic energy 246 back to top surface 222b as illustrated by line 248. Of course, the reflected energy will lose power each time it is reflected, however, the increased acoustic energy will assist in the cleaning of substrate 222.

[0058] Figure 10B is a simplified schematic diagram of an alternative embodiment of the
30 cleaning apparatus of Figure 10A. Here, three acoustic energy generators 223, 242a and 242b are provided with cleaning apparatus 218. Acoustic energy generator 223 provides acoustic energy to bottom surface 222a of substrate 222, and similarly acoustic energy generator 242b

provides acoustic energy to bottom surface 222a of substrate 222. Acoustic energy generator 242a is configured to provide acoustic energy to the top surface 222b as discussed above with reference to Figure 10A. Acoustic energy generator 242b generates acoustic energy which is directed at a slight angle to bottom surface 222a of substrate 222. In one embodiment, the angle between acoustic energy represented by line 240a and bottom surface 222a is between about zero degrees and about 5 degrees. Here again, acoustic energy 240a may be reflected from substrate 222a as represented by line 250. Therefore, reflector 244b may be positioned to reflect reflected acoustic energy 250 back to bottom surface 222a of substrate 222 as represented by line 252.

[0059] It should be appreciated that while reflective surface 230 is shown having a convex shape, reflective surface 230 may have any suitable shape including the shapes discussed above. Additionally, acoustic energy generators 223, 242a and 242b are megasonic transducers in one embodiment. Substrate 222 may also rotate around its axis during the cleaning process. Cleaning apparatus 218 may be configured to provide re-circulation and overflow capabilities as discussed with reference to Figure 8C.

[0060] Figure 11 is a flow chart diagram illustrating the method operations for applying acoustic energy to clean a surface of the substrate in accordance with one embodiment of the invention. The method initiates operation 260 where an acoustic energy oriented in a substantially parallel direction to a surface of a semiconductor substrate is generated from a first transducer. For example, the acoustic energy generated here may be the acoustic energy generated by acoustic energy generator 223 of Figures 8A-8D, 9, 10A and 10B. The method then advances to operation 262 where a direction associated with the acoustic energy from the first transducer is altered to a substantially perpendicular direction to the surface of the semiconductor substrate. Here, a reflective surface such as the reflective surface as discussed above with reference to Figures 8A-8D, 9, 10A and 10B, may alter the direction of the acoustic energy. It should be appreciated that the acoustic energy may be focused, scattered or evenly distributed. Thus, the reflective surface essentially decouples a direction of the acoustic energy from the source of the acoustic energy. Furthermore, the reflective surface may modulate or move in order to sweep the acoustic energy across a surface of a substrate to be cleaned.

[0061] The method of Figure 11 then advances to operation 264 where acoustic energy oriented in a substantially parallel direction to the surface of the semiconductor substrate is generated from a second transducer. Here, the second transducer may provide acoustic streaming in order to more efficiently clean the surface of the substrate. It should be appreciated that the acoustic

energy generated from the second transducer may be oriented at a slight angle to a surface of semiconductor substrate as described above with reference to Figures 10A and 10B. In addition, a third acoustic energy generator may be provided in order to direct acoustic energy toward an opposing surface from the surface which acoustic energy from the second transducer is directed at.

[0062] In summary, the above described invention, with reference to Figures 8A-11 describes a method and a system for optimizing the cleaning efficiency for semiconductor substrates. The cleaning apparatus eliminates dead zones by decoupling the acoustic waves from the acoustic generator. The decoupling effect is provided by a reflective surface positioned to reflect acoustic energy toward a surface of the substrate to be cleaned. Multiple transducers may be included to further increase the cleaning efficiency. In one embodiment, two transducers oriented in a substantially perpendicular manner relative to a surface of the substrate, are provided. Both transducers provides acoustic energy directed in a substantially parallel direction to the surface of the substrate, however, one acoustic energy stream is re-directed by a reflective surface so that the acoustic energy is substantially perpendicular to the substrate surface. The reflective surface may be composed of any material compatible with the cleaning solutions and reflective to the acoustic energy. For example, the reflective material may be stainless steel, quartz, Teflon, polypropylene, Silicon Carbide, or other materials which are compatible with the cleaning chemistry used in the system. In another embodiment, the reflective surface is configured to move about an axis associated with the reflective surface. Consequently, the acoustic energy may be swept across the surface of the substrate in order to distribute the acoustic energy more evenly over the substrate surface as the substrate is rotating.

[0063] Additionally, the embodiments described herein allow for a higher quality film deposition with respect to electroless plating operations. Through the application of megasonic energy during electroless plating operations, bubble formation may be controlled at the surface of the object undergoing the electroless plating operation. Through the cavitation properties associated with megasonic energy transferred to the plating solution, bubbles are effectively removed from the vicinity around the surface of the object, thereby allowing for the substantial elimination of voids within the deposited film.

[0064] Although the foregoing invention has been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the

details given herein, but may be modified within the scope and equivalents of the appended claims. In the claims, elements and/or steps do not imply any particular order of operation, unless explicitly stated in the claims.

What is claimed is:

Claims

1. A method for cleaning a semiconductor substrate, comprising:
generating acoustic energy oriented in a substantially perpendicular direction to a surface of a semiconductor substrate; and
generating acoustic energy oriented in a substantially parallel direction to the surface of the semiconductor substrate.
2. The method of claim 1, wherein the acoustic energy is megasonic energy generated through a megasonic transducer.
3. The method of claim 1, further comprising:
immersing a substrate into a cleaning solution contained within a vessel; and
rotating the immersed substrate.
4. The method of claim 1, wherein the method operation of generating acoustic energy oriented in a substantially perpendicular direction and generating acoustic energy oriented in a substantially parallel direction are performed simultaneously.
5. The method of claim 1, wherein the method operation of generating acoustic energy oriented in a substantially perpendicular direction and generating acoustic energy oriented in a substantially parallel direction are performed alternately.
6. The method of claim 1, wherein the method operation of generating acoustic energy oriented in a substantially parallel direction to the surface of the semiconductor substrate includes,
reflecting a portion of the acoustic energy from a reflection surface toward a surface of a semiconductor substrate.
7. The method of claim 6, further comprising:
modulating an angle of the reflection surface relative to a source of the acoustic energy.
8. An apparatus for cleaning a semiconductor substrate, comprising:
a base;

at least one sidewall extending from the base, the sidewall being substantially perpendicular to the base;

a first megasonic transducer affixed to the base; and

a second megasonic transducer affixed to the sidewall, wherein the first megasonic
5 transducer is oriented in a substantially orthogonal manner relative to the second megasonic transducer.

9. The apparatus of claim 8, wherein the base defines a shape selected from the group consisting of a square, a circle and a rectangle.

10. The apparatus of claim 8, wherein the apparatus is configured to contain a cleaning solution within a cavity defined by the base and the at least one sidewall.

11. The apparatus of claim 10, further including:

a semiconductor substrate immersed in the cleaning solution, the semiconductor substrate supported by a substrate support, a surface of the semiconductor substrate oriented substantially parallel to a surface of the first megasonic transducer, the surface of the semiconductor substrate further oriented substantially perpendicular to a surface of the second megasonic transducer.

12. The apparatus of claim 11, wherein the first megasonic transducer is configured to provide acoustic energy for cavitation purposes to features defined on the surface of the semiconductor substrate and the second megasonic transducer is configured to provide acoustic energy for acoustic streaming purposes to features defined on the surface of the semiconductor substrate.

13. The apparatus of claim 8, wherein one of the first megasonic transducer and the second megasonic transducer are configured to decouple a direction associated with a corresponding generated acoustic energy from a source of the corresponding acoustic
10 energy.

14. A system for cleaning a semiconductor substrate, comprising:

a tank having an inner cavity defined by a base and at least one sidewall extending therefrom, the tank configured to retain a volume of a liquid within the inner cavity;

a substrate support configured to support and rotate a semiconductor substrate about an axis of the semiconductor substrate, the substrate support further configured to support and
5 rotate the semiconductor substrate in the inner cavity of the tank;

a first megasonic transducer coupled to the base, a top surface of the megasonic transducer being substantially parallel to a bottom surface of the semiconductor substrate; and

a second megasonic transducer coupled to the at least one sidewall, wherein the first megasonic transducer is configured to generate acoustic energy associated with a direction substantially perpendicular to the bottom surface of the semiconductor substrate and wherein the second megasonic transducer is configured to generate acoustic energy associated with a direction substantially parallel to the bottom surface of the semiconductor substrate.

15. The system of claim 14, wherein the acoustic energy associated with the direction substantially perpendicular to the bottom surface of the semiconductor substrate provides cavitation energy for dislodging particles deposited within features defined on the bottom surface of the semiconductor substrate.

16. The system of claim 14, wherein the acoustic energy associated with the direction substantially parallel to the bottom surface of the semiconductor substrate provides acoustic streaming energy for replenishing a concentration of the liquid within features defined on the bottom surface of the semiconductor substrate.

17. The system of claim 14, wherein the first megasonic transducer and the second megasonic transducer operate in phase.

18. The system of claim 14, wherein the first megasonic transducer and the second megasonic transducer operate out of phase.

19. The system of claim 14, wherein a portion of the acoustic energy generated by the second megasonic transducer is generated toward a reflective surface associated with the base, the reflective surface configured to direct the acoustic energy toward a surface of the semiconductor substrate.

20. The system of claim 19, wherein the reflective surface is associated with a shape selected from the group consisting of substantially flat, concave, and convex.