METHODS AND APPARATUS FOR CLEANING SEMICONDUCTOR WAFERS

FIELD OF THE INVENTION

[0001] The present invention generally relates to method and apparatus for cleaning semiconductor wafer. More particularly, relates to controlling the bubble cavitation generated by ultra or mega sonic device during the cleaning process to achieve a stable or controlled cavitation on the entire wafer, which removes fine particles efficiently without damaging the device structure on the wafer.

BACKGROUND

[0002] Semiconductor devices are manufactured or fabricated on semiconductor wafers using a number of different processing steps to create transistor and interconnection elements. Recently, the transistors are built from two dimensions to three dimensions such as finFET transistors. To electrically connect transistor terminals associated with the semiconductor wafer, conductive (e.g., metal) trenches, vias, and the like are formed in dielectric materials as part of the semiconductor device. The trenches and vias couple electrical signals and power between transistors, internal circuit of the semiconductor devices, and circuits external to the semiconductor device.

[0003] In forming the finFET transistors and interconnection elements on the semiconductor wafer may undergo, for example, masking, etching, and deposition processes to form the desired electronic circuitry of the semiconductor devices. In particular, multiple masking and plasma etching step can be performed to form a pattern of finFET and or recessed areas in a dielectric layer on a semiconductor wafer that serve as fin for the transistor and or trenches and vias for the interconnection elements. In order to removal particles and contaminations in fin structure and or trench and via post etching or photo resist ashing, a wet cleaning step is necessary. Especially, when device manufacture node migrating to 14 or 16 nm and beyond, the side wall loss in fin and or trench and via is crucial for maintaining the critical dimension. In order to reduce or eliminate the side wall loss, it is important to use moderate, dilute chemicals, or sometime de-ionized water only. However, the dilute chemical or de-ionized water usually is not efficient to remove the particles in the fin structure and or trench and via. Therefore the mechanical force such as ultra or mega sonic is needed in order to remove those particles efficiently. Ultra sonic

or mega sonic wave will generate bubble cavitation which applies mechanical force to wafer structure, the violent cavitation such as transit cavitation or micro jet will damage those patterned structures. To maintain a stable or controlled cavitation is key parameters to control the mechanical force within the damage limit and at the same time efficiently to remove the particles.

[0004] Mega sonic energy coupled with nozzle to clean semiconductor wafer is disclosed in U.S. Pat. No. 4,326,553. The fluid is pressurized and mega sonic energy is applied to the fluid by a mega sonic transducer. The nozzle is shaped to provide a ribbon-like jet of cleaning fluid vibrating at ultra/mega sonic frequencies for the impingement on the surface.

[0005] A source of energy vibrates an elongated probe which transmits the acoustic energy into the fluid is disclosed in U.S. Pat. No. 6,039,059. In one arrangement, fluid is sprayed onto both sides of a wafer while a probe is positioned close to an upper side. In another arrangement, a short probe is positioned with its end surface close to the surface, and the probe is moved over the surface as wafer rotates.

[0006] A source of energy vibrates a rod which rotates around it axis parallel to wafer surface is disclosed in U.S. Pat. No. 6,843,257 B2. The rod surface is etched to curve groves, such as spiral groove.

[0007] It is needed to have a better method for controlling the bubble cavitation generated by ultra or mega sonic device during the cleaning process to achieve a stable or controlled cavitation on the entire wafer, which removes fine particles efficiently without damaging the device structure on the wafer.

SUMMARY

[0008] One method of the present invention is to achieve a damage free ultra/mega-sonic cleaning on a wafer with patterned structure by maintaining a stable bubble cavitation. The stable bubble cavitation is controlled by setting a sonic power supply with power P_1 at a time interval shorter than τ_1, and setting the sonic power supply with power P_2 at a time interval longer than τ_2, and repeat above steps till the wafer is cleaned, where power P_2 is equal to zero or much smaller than power P_1, τ_1 is a time interval that the temperature inside bubble raises to a critical implosion temperature; and τ_2 is a time interval that the temperature inside bubble falls down to a temperature much lower than the critical implosion temperature.

[0009] Another method of the present invention is to achieve a damage free ultra/mega sonic cleaning on a wafer with patterned structure by maintaining a stable bubble cavitation. The stable bubble cavitation is controlled by setting a sonic power supply with frequency f_1 at a time interval shorter than τ_1, and setting the sonic power supply with frequency f_2 at a time interval longer than τ_2, and repeat above steps till the wafer is cleaned, where f_2 is much higher than f_1, better to be 2 times or 4 times higher, τ_1 is a time interval that the temperature inside bubble raises to a critical implosion temperature; and τ_2 is a time interval that the temperature inside bubble falls down to a temperature much lower than the critical implosion temperature.

[0010] Another method of the present invention is to achieve a damage free ultra/mega-sonic cleaning on a wafer with patterned structure by maintaining a stable bubble cavitation with bubble size less than space in patterned structure. The stable bubble cavitation with bubble size less than space in patterned structure is controlled by setting a sonic power supply at power P_1 for a time interval shorter than τ_1, and setting the sonic power supply at power P_2 for a time interval longer than τ_2, and repeat above steps till the wafer is cleaned, where P_2 is equal to zero or much smaller than P_1, τ_1 is a time interval that the bubble size increases to a critical size equal to or larger than the space in patterned structures; and τ_2 is a time interval that the bubble size decreases to a value much smaller than the space in patterned structure.

[0011] Another method of the present invention is to achieve a damage free ultra/mega-sonic cleaning on a wafer with patterned structure by maintaining a stable bubble cavitation with bubble size less than space in patterned structure. The stable bubble cavitation with bubble size less than space in patterned structure is controlled by setting a sonic power supply with frequency f_1 for a time interval shorter than τ_1, and setting the sonic power supply with frequency f_2 for a time interval longer than τ_2, and repeat above steps till the wafer is cleaned, where f_2 is much higher than f_1, better to be 2 times or 4 times higher, τ_1 is a time interval that the bubble size increases to a critical size equal to or larger than the space in patterned structures; and τ_2 is a time interval that the bubble size decreases to a value much smaller than the space in patterned structure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIGs.1A-1B depict an exemplary wafer cleaning apparatus using ultra/mega sonic device;

[0013] FIGs.2A-2G depict variety of shape of ultra/mega sonic transducers;

[0014] FIG. 3 depicts bubble cavitation during wafer cleaning process;

[0015] FIGs.4A-4B depict a transit cavitation damaging patterned structure on a wafer during cleaning process;

[0016] FIGs.5A-5C depict thermal energy variation inside bubble during cleaning process;

[0017] FIGs.6A-6C depict an exemplary wafer cleaning method;

[0018] FIGs.7A-7C depict another exemplary wafer cleaning method;

[0019] FIGs.8A-8D depict another exemplary wafer cleaning method;

[0020] FIGs.9A-9D depict another exemplary wafer cleaning method;

[0021] FIGs.10A-10B depict another exemplary wafer cleaning method;

[0022] FIGs.11A-11B depict another exemplary wafer cleaning method;

[0023] FIGs.12A-12B depict another exemplary wafer cleaning method;

[0024] FIGs.13A-13B depict another exemplary wafer cleaning method;

[0025] FIGs.14A-14B depict another exemplary wafer cleaning method;

[0026] FIGs.15A-15C depict a stable cavitation damaging patterned structure on a wafer during cleaning process;

[0027] FIG.16 depicts another exemplary wafer cleaning apparatus using ultra/mega sonic device; and

[0028] FIG.17 depicts an exemplary wafer cleaning apparatus using ultra/mega sonic device;

[0029] FIGs.18A-18C depict another exemplary wafer cleaning method;

[0030] FIG.19 depicts another exemplary wafer cleaning method;

DETAILED DESCRIPTION

[0031] Figs. 1A to 1B show a wafer cleaning apparatus using a ultra/mega sonic device. The wafer cleaning apparatus consists of wafer 1010, wafer chuck 1014 being rotated by rotation driving mechanism 1016, nozzle 1012 delivering cleaning chemicals or de-ionized water 1032, and ultra/mega sonic device 1003 and ultra/mega sonic power

supply. The ultra/mega sonic device 1003 further consists of piezoelectric transducer 1004 acoustically coupled to resonator 1008. Transducer 1004 is electrically excited such that it vibrates and the resonator 1008 transmits high frequency sound energy into liquid. The bubble cavitation generated by the ultra/mega sonic energy oscillates particles on wafer 1010. Contaminants are thus vibrated away from the surfaces of the wafer 1010, and removed from the surfaces through the flowing liquid 1032 supplied by nozzle 1012.

[0032] Figs. 2A to 2G show top view of ultra/mega sonic devices according to the present invention. Ultra/mega sonic device 1003 shown in Fig.1 can be replaced by different shape of ultra/mega sonic devices 3003, i.e. triangle or pie shape as shown in Fig, 2A, rectangle as shown in Fig, 2B, octagon as shown in Fig. 2C, elliptical as shown in Fig. 2D, half circle as shown in Fig. 2E, quarter circle as shown in Fig. 2F, and circle as shown in Fig. 2G.

[0033] Fig. 3 shows a bubble cavitation during compression phase. The shape of bubbler is gradually compressed from a spherical shape A to an apple shape G, finally the bubble reaches to an implosion status I and forms a micro jet. As shown in Fig.4A and 4B, the micro jet is very violent (can reaches a few thousands atmospheric pressures and a few thousands ^{0}C), which can damage the fine patterned structure 4034 on the semiconductor wafer 4010, especially when the feature size t shrinks to 70 nm and smaller.

[0034] Figs. 5A to 5C show simplified model of bubble cavitation according to the present invention. As sonic positive pressure acting on the bubble, the bubble reduces its volume. During this volume shrinking process, the sonic pressure P_M did a work to the bubble, and the mechanical work converts to thermal energy inside the bubble, therefore temperature of gas and/or vapor inside bubble increases.

[0035] The idea gas equation can be expressed as follows:

[0036] $p_0v_0/T_0=pv/T$ (1),

[0037] where, p_0 is pressure inside bubbler before compression, v_0 initial volume of bubble before compression, T_0 temperature of gas inside bubbler before compression, p is pressure inside bubbler in compression, v volume of bubble in compression, T temperature of gas inside bubbler in compression.

[0038] In order to simplify the calculation, assuming the temperature of gas is no change during the compression or compression is very slow and temperature increase is cancelled by liquid surrounding the bubble. So that the mechanical work w_m did by sonic

pressure P_M during one time of bubbler compression (from volume N unit to volume 1 unit or compression ratio = N) can be expressed as follows:

[0039] $w_m = \int_0^{x0-1} pSdx = \int_0^{x0-1} (S(x_0p_0)/(x_0-x))dx = Sx_0p_0\int_0^{x0-1} dx/(x_0-x)$

$$= - Sx_0p_0 \ln (x_0-x) \Big|_0^{x0-1} = Sx_0p_0 \ln (x_0) \quad (2)$$

Where, S is area of cross section of cylinder, x_0 the length of the cylinder, p_0 pressure of gas inside cylinder before compression. The equation (2) does not consider the factor of temperature increase during the compression, so that the actual pressure inside bubble will be higher due to temperature increase. Therefore the actual mechanical work conducted by sonic pressure will be larger than that calculated by equation (2).

If assuming all mechanical work did by sonic pressure is partially converted to thermal energy and partially converted mechanical energy of high pressure gas and vapor inside bubble , and such thermal energy is fully contributed to temperature increase of gas inside of bubbler (no energy transferred to liquid molecules surrounding the bubble), and assuming the mass of gas inside bubble staying constant before and after compression, then temperature increase ΔT after one time of compression of bubble can be expressed in the following formula:

$$\Delta T = Q/(mc) = \beta w_m /(mc) = \beta Sx_0p_0 \ln (x_0)/ (mc) \quad (3)$$

where, Q is thermal energy converted from mechanical work, β ratio of thermal energy to total mechanical works did by sonic pressure, m mass of gas inside the bubble, c gas specific heat coefficient. Substituting $\beta = 0.65$, S=1E-12 m^2, x_0=1000 μm=1E-3 m (compression ratio N = 1000), p_0=1 kg/cm^2= 1E4 kg/m^2, m =8.9E-17 kg for hydrogen gas, c = 9.9E3 J/(kg ^{0}k) into equation (3), then ΔT = 50.9 ^{0}k.

The temperature $T_1$of gas inside bubbler after first time compression can be calculated as

[0040] $T_1 = T_0 + \Delta T = 20\ ^0C + 50.9\ ^0C = 70.9\ ^0C$ (4)

[0041] When the bubble reaches the minimum size of 1 micron as shown in Fig.5B. At such a high temperature, of cause some liquid molecules surrounding bubble will evaporate. After then, the sonic pressure become negative and bubble starts to increase its size. In this reverse process, the hot gas and vapor with pressure P_G will do work to the surrounding liquid surface. At the same time, the sonic pressure P_M is pulling bubble to expansion direction as shown in Fig.5C, therefore the negative sonic pressure P_M also do

partial work to the surrounding liquid too. As the results of the joint efforts, the thermal energy inside bubble cannot be fully released or converted to mechanical energy, therefore the temperature of gas inside bubble cannot cool down to original gas temperature T_0 or the liquid temperature. After the first cycle of cavitation finishes, the temperature T_2 of gas in bubble will be somewhere between T_0 and T_1 as shown in Fig.6B. Or T_2 can be expressed as

[0042] $T_2 = T1 - \delta T = T_0 + \Delta T - \delta T$ (5)

[0043] Where δT is temperature decrease after one time of expansion of the bubble, and δT is smaller than ΔT.

[0044] When the second cycle of bubble cavitation reaches the minimum bubble size, the temperature T3 of gas and or vapor inside bubbler will be

[0045] $T3 = T2 + \Delta T = T_0 + \Delta T - \delta T + \Delta T = T_0 + 2\Delta T - \delta T$ (6)

[0046] When the second cycle of bubble cavitation finishes, the temperature T4 of gas and/or vapor inside bubbler will be

[0047] $T4 = T3 - \delta T = T_0 + 2\Delta T - \delta T - \delta T = T_0 + 2\Delta T - 2\delta T$ (7)

[0048] Similarly, when the nth cycle of bubble cavitation reaches the minimum bubble size, the temperature T_{2n-1} of gas and or vapor inside bubbler will be

[0049] $T_{2n-1} = T_0 + n\Delta T - (n-1)\delta T$ (8)

[0050] When the nth cycle of bubble cavitation finishes, the temperature T_{2n} of gas and/or vapor inside bubbler will be

[0051] $T_{2n} = T_0 + n\Delta T - n\delta T = T_0 + n(\Delta T - \delta T)$ (9)

[0052] As cycle number n of bubble cavitation increase, the temperature of gas and vapor will increase, therefore more molecules on bubble surface will evaporate into inside of bubble 6082 and size of bubble 6082 will increase too, as shown in Fig.6C. Finally the temperature inside bubble during compression will reach implosion temperature T_i (normally T_i is as high as a few thousands ^{0}C), and violent micro jet 6080 forms as shown in Fig.6C.

[0053] From equation (8), implosion cycle number n_i can be written as following:

[0054] $n_i = (T_i - T_0 - \Delta T)/(\Delta T - \delta T) + 1$ (10)

[0055] From equation (10), implosion time τ_i can be written as following:

[0056] $\tau_i = n_i t_1 = t_1((T_i - T_0 - \Delta T)/(\Delta T - \delta T) + 1)$

$= n_i/f_1 = ((T_i - T_0 - \Delta T)/(\Delta T - \delta T) + 1)/f_1$ (11)

Where, t_1 is cycle period, and f_1 frequency of ultra/mega sonic wave.

[0057] According to formulas (10) and (11), implosion cycle number n_i and implosion time τ_i can be calculated. Table 1 shows calculated relationships among implosion cycle number n_i, implosion time τ_i and (ΔT - δT), assuming Ti = 3000 ^{0}C, ΔT =50.9 ^{0}C, T_0= 20 ^{0}C, f_1 = 500 KHz, f_1 = 1 MHz, and f_1 = 2 MHz.

[0058] Table 1

ΔT - δT (^{0}C)	0.1	1	10	30	50
n_i	29018	2903	291	98	59
τ_i (ms) f_1 =500 KHz	58.036	5.806	0.582	0.196	0.118
τ_i (ms) f_1 =1 MHz	29.018	2.903	0.291	0.098	0.059
τ_i (ms) f_1 =2 MHz	14.509	1.451	0.145	0.049	0.029

[0059] In order to avoid damage to patterned structure on wafer, a stable cavitation must be maintained, and the bubble implosion or micro jet must be avoided. Figs.7A to 7C shows a method to achieve a damage free ultra or mega-sonic cleaning on a wafer with patterned structure by maintaining a stable bubble cavitation according to the present invention. Fig.7A shows waveform of power supply outputs, and Fig.7B shows the temperature curve corresponding to each cycle of cavitation, and Fig. 7C shows the bubble size expansion during each cycle of cavitation. Operation process steps to avoid bubble implosion according to the present invention are disclosed as follows:

[0060] Step 1: Put ultra/mega sonic device adjacent to surface of wafer or substrate set on a chuck or tank;

[0061] Step 2: Fill chemical liquid or gas (hydrogen, nitrogen, oxygen, or CO_2) doped water between wafer and the ultra/mega sonic device;

[0062] Step 3: Rotate chuck or oscillate wafer;

[0063] Step 4: Set power supply at frequency f_1 and power P_1 ;

[0064] Step 5: Before temperature of gas and vapor inside bubble reaches implosion temperature T_i, (or time reach $\tau_1 < \tau_i$ as being calculated by equation (11)), set power supply output to zero watts, therefore the temperature of gas inside bubble start to cool down since the temperature of liquid or water is much lower than gas temperature.

[0065] Step 6: After temperature of gas inside bubble decreases to room temperature T_0 or time (zero power time) reaches τ_2 , set power supply at frequency f_1 and power P_1 again.

[0066] Step 7: repeat Step 1 to Step 6 until wafer is cleaned.

[0067] In step 5, the time τ_1 must be shorter than τ_i in order to avoid bubble implosion, and τ_i can be calculated by using equation (11).

[0068] In step 6, the temperature of gas inside bubble is not necessary to be cooled down to room temperature or liquid temperature; it can be certain temperature above room temperature or liquid temperature, but better to be significantly lower than implosion temperature T_i.

[0069] According to equations 8 and 9, if (ΔT - δT) can be known, the τ_i can be calculated. But in general, (ΔT - δT) is not easy to be calculated or measured directly. The following method can determine the implosion time τ_i experimentally.

[0070] Step 1: Based on Table 1, choosing 5 different time τ_1 as design of experiment (DOE) conditions,

[0071] Step 2: choose time τ_2 at least 10 times of τ_1, better to be 100 times of τ_1 at the first screen test

[0072] Step 3: fix certain power P_0 to run above five conditions cleaning on specific patterned structure wafer separately. Here, P_0 is the power at which the patterned structures on wafer will be surely damaged when running on continuous mode (non-pulse mode).

[0073] Step 4: Inspect the damage status of above five wafers by SEMS or wafer pattern damage review tool such as AMAT SEM vision or Hitachi IS3000, and then the implosion time τ_i can be located in certain range.

[0074] Step 1 to 4 can be repeated again to narrow down the range of implosion time τ_i. After knowing the implosion time τ_i, the time τ_1 can be set at a value smaller than $0.5\tau_i$ for safety margin. One example of experimental data is described as following.

[0075] The patterned structures are 55 nm poly-silicon gate lines. Ultra/mega sonic wave frequency was 1 MHz, and ultra/mega-sonic device manufactured by Prosys was used and operated in a gap oscillation mode (disclosed by PCT/CN2008/073471) for achieving better

uniform energy dose within wafer and wafer to wafer. Other experimental parameters and final pattern damage data are summarized in Table 2 as follows:

[0076] Table 2

Wafer ID	CO_2 conc. (18 μs/cm)	Process Time (sec)	Power Density (Watts/cm2)	Cycle Number	τ_1 (ms)	τ_2 (ms)	Number of Damage Sites
#1	18	60	0.1	2000	2	18	1216
#2	18	60	0.1	100	0.1	0.9	0

[0077] It was clear that the $\tau_1 = 2$ ms (or 2000 cycle number) introduced as many as 1216 damage sites to patterned structure with 55 nm feature size, but that the $\tau_1 = 0.1$ ms (or 100 cycle number) introduced zero (0) damage sites to patterned structure with 55 nm feature size. So that the τ_i is some number between 0.1 ms and 2 ms, more detail tests need to be done to narrow its range. Obviously, the cycle number related to ultra or mega sonic power density and frequency, the larger the power density, the less the cycle number; and the lower the frequency, the less the cycle number. From above experimental results, we can predict that the damage-free cycle number should be smaller than 2,000, assuming the power density of ultra or mega sonic wave is larger than 0.1wattsorcm^2, and frequency of ultra or mega sonic wave is equal to or less than 1MHz. If the frequency increases to a range larger than 1 MHz or power density is less than than 0.1watts/cm^2, it can be predicted that the cycle number will increase.

[0078] After knowing the time τ_1, then the time τ_2 can be shorten based on similar DEO method described above, i.e. fix time τ_1, gradually shorten the time τ_2 to run DOE till damage on patterned structure being observed. As the time τ_2 is shorten, the temperature of gas and or vapor inside bubbler cannot be cooled down enough, which will gradually shift average temperature of gas and vapor inside bubbler up, eventually it will trigger implosion of bubble. This trigger time is called critical cooling time. After knowing critical cooling time τ_c, the time τ_2 can be set at value larger than $2\tau_c$ for the same reason to gain safety margin.

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[0079] FIGs.8A to 8D show another embodiment of wafer cleaning method using a ultra/mega sonic device according to the present invention. The method is similar to that shown in Fig. 7A, except in step 4 setting ultra/mega sonic power supply at frequency f_1

and power with changing amplitude of waveform. Fig. 8A shows another cleaning method of setting ultra/mega sonic power at frequency f_1 and power with increasing amplitude of waveform in step 4. Fig. 8B shows another cleaning method of setting ultra/mega sonic power supply at frequency f_1 and power with decreasing amplitude of waveform in step 4. Fig. 8C shows another cleaning method of setting ultra/mega sonic power supply at frequency f_1 and power with decreasing first and increasing later amplitude of waveform in step 4. Fig. 8D shows further another cleaning method of setting ultra/mega sonic power at frequency f_1 and power with increasing first and decreasing later amplitude of waveform in step 4.

[0080] FIGs.9A to 9D show another embodiment of wafer cleaning method using a ultra/mega sonic device according to the present invention. The method is similar to that shown in Fig. 7A, except in step 4 setting ultra/mega sonic power supply at changing frequency. Fig. 9A shows another cleaning method of setting ultra/mega sonic power supply at frequency f_1 first then frequency f_3 later, f_1 is higher than f_3 in step 4. Fig. 9B shows another cleaning method of setting ultra/mega sonic power supply at frequency f_3 first then frequency f_1 later, f_1 is higher than f_3 in step 4. Fig. 9C shows another cleaning method of setting ultra/mega sonic power supply at frequency f_3 first, frequency f_1 later and f_3 last, f_1 is higher than f_3 in step 4. Fig. 9D shows another cleaning method of setting ultra/mega sonic power supply at frequency f_1 first, frequency f_3 later and f_1 last, f_1 is higher than f_3 in step 4.

[0081] Similar to method shown in Fig. 9C, the ultra/mega sonic power can be set at frequency f_1 first, at frequency f_3 later and at frequency f_4 at last in step 4, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

[0082] Again similar to method shown in Fig. 9C, the ultra/mega sonic power can be set at frequency f_4 first, at frequency f_3 later and at frequency f_1 at last in step 4, where f_4 is smaller than f_3, and f_3 is smaller than f_1

[0083] Again similar to method shown in Fig. 9C, the ultra/mega sonic power can be set at frequency f_1 first, at frequency f_4 later and at frequency f_3 at last in step 4, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

[0084] Again similar to method shown in Fig. 9C, the ultra/mega sonic power can be set at frequency f_3 first, at frequency f_4 later and at frequency f_1 at last in step 4, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

[0085] Again similar to method shown in Fig. 9C, the ultra/mega sonic power can be set at frequency f_3 first, at frequency f_1 later and at frequency f_4 at last in step 4, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

[0086] Again similar to method shown in Fig. 9C, the ultra/mega sonic power can be set at frequency f_4 first, at frequency f_1 later and at frequency f_3 at last in step 4, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

[0087] Figs.10A to 10B show another method to achieve a damage free ultra/mega-sonic cleaning on a wafer with patterned structure by maintaining a stable bubble cavitation in according to the present invention. Fig.10A shows waveform of power supply outputs, and Fig.10B shows the temperature curve corresponding to each cycle of cavitation. Operation process steps according to the present invention are disclosed as follows:

[0088] Step 1: Put ultra/mega sonic device adjacent to surface of wafer or substrate set on a chuck or tank;

[0089] Step 2: Fill chemical liquid or gas doped water between wafer and the ultra/mega sonic device;

[0090] Step 3: Rotate chuck or oscillate wafer;

[0091] Step 4: Set power supply at frequency f_1 and power P_1 ;

[0092] Step 5: Before temperature of gas and vapor inside bubble reaches implosion temperature T_i, (total time $\tau_1$elapes), set power supply output at frequency f_1 and power P_2, and P_2 is smaller than P_1. Therefore the temperature of gas inside bubble start to cool down since the temperature of liquid or water is much lower than gas temperature.

[0093] Step 6: After temperature of gas inside bubble decreases to certain temperature close to room temperature T_0 or time (zero power time) reach τ_2 , set power supply at frequency f_1 and power P_1 again.

[0094] Step 7: repeat Step 1 to Step 6 until wafer is cleaned.

[0095] In step 6, the temperature of gas inside bubble can not be cooled down to room temperature due to power P_2, there should be a temperature difference ΔT_2 existing in later stage of τ_2 time zone, as shown in Fig. 10B.

[0096] FIGs.11A to 11B show another embodiment of wafer cleaning method using a ultra/mega sonic device according to the present invention. The method is similar to that shown in Fig. 10A, except in step 5 setting ultra/mega sonic power at frequency f_2 and

power P_2, where f_2 is lower than f_1 and P_2 is less than P_1. Since f_2 is lower than f_1, the temperature of gas or vapor inside bubble increasing faster, therefore the P2 should be set significantly less than P1, better to be 5 or 10 times less in order to reduce temperature of gas and or vapor inside bubble.

[0097] FIGs.12A to 12B show another embodiment of wafer cleaning method using a ultra/mega sonic device according to the present invention. The method is similar to that shown in Fig. 10A, except in step 5 setting ultra/mega sonic power at frequency f_2 and power P_2, where f_2 is higher than f_1, and P_2 is equal to P_1.

[0098] FIGs.13A to 13B show another embodiment of wafer cleaning method using a ultra/mega sonic device according to the present invention. The method is similar to that shown in Fig. 10A, except in step 5 setting ultra/mega sonic power at frequency f_2 and power P_2, where f_2 is higher than f_1, and P_2 is less than P_1.

[0099] FIGs.14A-14B shows another embodiment of wafer cleaning method using a ultra/mega sonic device according to the present invention. The method is similar to that shown in Fig. 10A, except in step 5 setting ultra/mega sonic power at frequency f_2 and power P_2, where f_2 is higher than f_1, and P_2 is higher than P_1. Since f_2 is higher than f_1, the temperature of gas or vapor inside bubble increasing slower, therefore the P2 can be slightly higher than P1, but must make sure the temperature of gas and vapor inside bubbler decreases in time zone τ_2 comparing to temperature zone τ_1, as shown in Fig.14B

[00100] Fig.4A and 4B show that patterned structure is damaged by the violent micro jet. Fig.15A and 15B show that the stable cavitation can also damage the patterned structure on wafer. As bubble cavitation continues, the temperature of gas and vapor inside bubble increases, therefore size of bubble 15046 also increases as shown in Fig.15A. When size of bubble 15048 becomes larger than dimension of space W in patterned structure as shown in Fig.15B, the expansion force of bubble cavitation can damage the patterned structure 15034 as shown in Fig.15C. Another cleaning method according to the present invention are disclosed as follows:

[00101] Step 1: Put ultra/mega sonic device adjacent to surface of wafer or substrate set on a chuck or tank;

[00102] Step 2: Fill chemical liquid or gas doped water between wafer and the ultra/mega sonic device;

[00103] Step 3: Rotate chuck or oscillate wafer;

[00104] Step 4: Set power supply at frequency f_1 and power P_1 ;

[00105] Step 5: Before size of bubble reaches the same dimension of space W in patterned structures (time τ_1 elapse), set power supply output to zero watts, therefore the temperature of gas inside bubble starts to cool down since the temperature of liquid or water is much lower than gas temperature;

[00106] Step 6: After temperature of gas inside bubble continues to reduce (either it reaches room temperature T_0 or time (zero power time) reach τ_2 , set power supply at frequency f_1 power P_1 again;

[00107] Step 7: repeat Step 1 to Step 6 until wafer is cleaned;

[00108] In step 6, the temperature of gas inside bubble is not necessary to be cooled down to room temperature, it can be any temperature, but better to be significantly lower than implosion temperature T_i. In the step 5, bubble size can be slightly larger than dimension of patterned structures as long as bubble expansion force does not break or damage the patterned structure. The time τ_1 can be determined experimentally by using the following method:

[00109] Step 1: Similar to Table 1, choosing 5 different time τ_1 as design of experiment (DOE) conditions,

[00110] Step 2: choose time τ_2 at least 10 times of τ_1, better to be 100 times of τ_1 at the first screen test

[00111] Step 3: fix certain power P_0 to run above five conditions cleaning on specific patterned structure wafer separately. Here, P_0 is the power at which the patterned structures on wafer will be surely damaged when running on continuous mode (non-pulse mode).

[00112] Step 4: Inspect the damage status of above five wafers by SEMS or wafer pattern damage review tool such as AMAT SEM vision or Hitachi IS3000, and then the damage time τ_i can be located in certain range.

[00113] Step 1 to 4 can be repeated again to narrow down the range of damage time τ_d. After knowing the damage time τ_d, the time τ_1 can be set at a value smaller than 0.5 τ_d for safety margin.

[00114] All cleaning methods described from Figs.7 to Figs.14 can be applied in or combined with the method described in Figs. 15.

[00115] Fig.16 shows a wafer cleaning apparatus using a ultra/mega sonic device. The wafer cleaning apparatus consists of wafer 16010, wafer chuck 16014 being rotated by

rotation driving mechanism 16016, nozzle 16064 delivering cleaning chemicals or de-ionized water 16060, ultra/mega sonic device 16062 coupled with nozzle 16064, and ultra/mega sonic power supply. Ultra/mega sonic wave generated by ultra/mega sonic device 16062 is transferred to wafer through chemical or water liquid column 16060. All cleaning methods described from Figs.7 to Figs.15 can be used in cleaning apparatus described in Figs. 16.

[00116] Fig.17 shows a wafer cleaning apparatus using a ultra/mega sonic device. The wafer cleaning apparatus consists of wafers 17010, a cleaning tank 17074, a wafer cassette 17076 holding the wafers 17010 and being held in the cleaning tank 17074, cleaning chemicals 17070, a ultra/mega sonic device 17072 attached to outside wall of the cleaning tank 17074, and a ultra/mega sonic power supply. At least one inlet fills the cleaning chemicals 17070 into the cleaning tank 17074 to immerse the wafers 17010. All cleaning methods described from Figs.7 to Figs.15 can be used in cleaning apparatus described in Figs. 17.

[00117] FIGs.18A to 18C show another embodiment of wafer cleaning method using a ultra/mega sonic device according to the present invention. The method is similar to that shown in Fig. 7A, except in Step 5: Before temperature of gas and vapor inside bubble reaches implosion temperature T_i, (or time reach $\tau_1 < \tau_i$ as being calculated by equation (11)), set power supply output to a positive value or negative DC value to hold or stop ultra/mega sonic device to vibrate, therefore the temperature of gas inside bubble start to cool down since the temperature of liquid or water is much lower than gas temperature. The positive value of negative value can be bigger, equal to or smaller than power P_1.

[00118] FIGs.19 shows another embodiment of wafer cleaning method using a ultra/mega sonic device according to the present invention. The method is similar to that shown in Fig. 7A, except in Step 5: Before temperature of gas and vapor inside bubble reaches implosion temperature T_i, (or time reach $\tau_1 < \tau_i$ as being calculated by equation (11)), set power supply output at the frequency same as f_1 with reverse phase to f_1 to quickly stop the cavitation of bubble. Therefore the temperature of gas inside bubble start to cool down since the temperature of liquid or water is much lower than gas temperature. The positive value of negative value can be bigger, equal or less than power P_1. During above operation, the power supply output can be set at a frequency different from frequency f_1 with reverse phase to f_1 in order to quickly stop the cavitation of bubble.

[00119] Generally speaking, an ultra/mega sonic wave with the frequency between 0.1MHz~10MHz may be applied to the method disclosed in the present invention.

[00120] Although the present invention has been described with respect to certain embodiments, examples, and applications, it will be apparent to those skilled in the art that various modifications and changes may be made without departing from the invention.

CLAIMS

1. A method for cleaning semiconductor substrate without damaging patterned structure on said substrate using ultra/mega sonic device, comprising:

applying liquid into a space between a substrate and an ultra/mega sonic device;

setting an ultra/mega sonic power supply at frequency f_1 and power P_1 to drive said ultra/mega sonic device;

before bubble cavitation in said liquid damaging patterned structure on said substrate, setting said ultra/mega sonic power supply at frequency f_2 and power P_2 to drive said ultra/mega sonic device;

after temperature inside bubble cooling down to a set temperature, setting said ultra/mega sonic power supply at frequency f_1 and power P_1 again;

repeating above steps till said substrate being cleaned.

2. The method of claim 1, wherein said bubble cavitation damaging patterned structure on said substrate is caused by micro jet generated by bubble implosion.

3. The method of claim 1, wherein time interval between setting said power supply at frequency f_1 and power P_1 and setting said ultra/mega sonic power supply at frequency f_2 and power P_2 is shorter than 2,000 times of cycle period of waveform at frequency f_1.

4. The method of claim 1, wherein time interval between setting said power supply at frequency f_1 and power P_1 and setting said ultra/mega sonic power supply at frequency f_2 and power P_2 is shorter than $((T_i - T_0 - \Delta T)/(\Delta T - \delta T) + 1)/ f_1$, where T_i is gas and vapor temperature inside said bubble when said bubble implosion, T_0 temperature of said liquid, ΔT temperature increase after one time of compression of said bubbler, δT temperature decrease after one time of expansion of said bubbler.

5. The method of claim 1, wherein said bubble cavitation damaging patterned structure on said substrate is caused by bubble size growing bigger than space in patterned structure.

6. The method of claim 1, wherein said set temperature is near temperature of said liquid.

7. The method of claim 1, wherein said power value P_2 is set as zero.

8. The method of claim 1, wherein said frequency f_1 is equal to said frequency f_2, and said power value P_2 is smaller than said power value P_1.

9. The method of claim 1, wherein said frequency f_1 is higher than said frequency f_2, and said power value P_2 is smaller than said power value P_1.

10. The method of claim 1, wherein said frequency f_1 is lower than said frequency f_2, and said power value P_1 is equal to said power value P_2.

11. The method of claim 1, wherein said frequency f_1 is lower than said frequency f_2, and said power value P_1 is larger than said power value P_2.

12. The method of claim 1, wherein said frequency f_1 is lower than said frequency f_2, and said power value P_1 is smaller than said power value P_2.

13. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 with increased amplitude.

14. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 with decreased amplitude.

15. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 with increased amplitude at beginning and with decreased amplitude at later.

16. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 with decreased amplitude at first and with increased amplitude at later.

17. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 at frequency f_1 first and at frequency f_3 later, where f_3 is smaller than f_1.

18. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 at frequency f_3 first and at frequency f_1 later, where f_3 is smaller than f_1.

19. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 at frequency f_3 first, at frequency f_1 later and at frequency f_3 last, where f_3 is smaller than f_1.

20. The method of claim 1, wherein said ultra/mega sonic power supply outputs waveform at frequency f_1 first, at frequency f_3 later and at frequency f_1 last, where f_3 is smaller than f_1.

21. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 at frequency f_1 first, at frequency f_3 later and at frequency f_4 at last, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

22. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 at frequency f_4 first, at frequency f_3 later and at frequency f_1 at last, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

23. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 at frequency f_1 first, at frequency f_4 later and at frequency f_3 at last, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

24. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 at frequency f_3 first, at frequency f_4 later and at frequency f_1 at last, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

25. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 at frequency f_3 first, at frequency f_1 later and at frequency f_4 at last, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

26. The method of claim 1, wherein said ultra/mega sonic power supply outputs power P_1 at frequency f_4 first, at frequency f_1 later and at frequency f_3 at last, where f_4 is smaller than f_3, and f_3 is smaller than f_1.

27. The method of claim 1, wherein said frequency f_2 is equal to zero, said power value P_2 is a positive value.

28. The method of claim 1, wherein said frequency f_2 is equal to zero, said power value P_2 is a negative value.

29. The method of claim 1, wherein said frequency f_2 is equal to f_1, and phase of f_2 is set as reverse to phase of f_1.

30. The method of claim 1, wherein said frequency f_2 is different from f_1, and phase of f_2 is set as reverse to phase of f_1.