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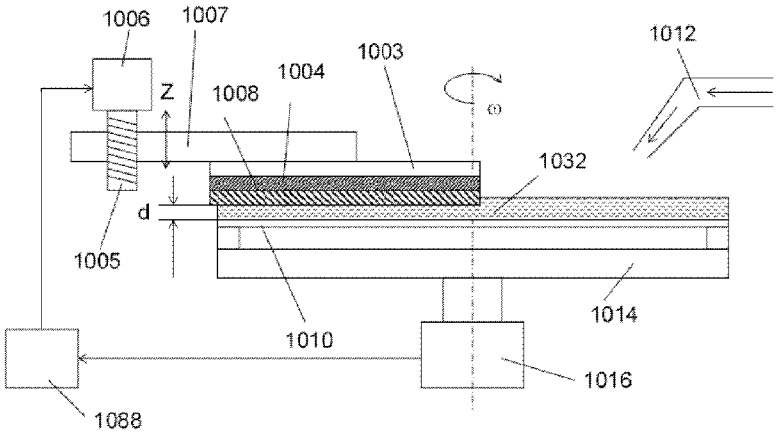

Fig. 1A

(57) Abstract: A method for cleaning semiconductor substrate (1010,2010) without damaging patterned structure on the semiconductor substrate (1010,2010) using ultra/mega sonic device (1003,2003) comprises applying liquid into a space between a substrate (1010,2010) and an ultra/mega sonic device (1003,2003); setting an ultra/mega sonic power supply at frequency f1 and power P1 to drive the ultra/mega sonic device (1003,2003); before bubble cavitation in the liquid damaging patterned structure on the substrate (1010,2010), setting the ultra/mega sonic power supply at zero output;after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at frequency f1 and power P1 again;detecting power on time at power P1 and frequency f1 and power off time separately or detecting amplitude of each waveform output by the ultra/mega sonic power supply;comparing the detected power on time with a preset time τ1, or comparing the detected power off time with a preset time τ2, or comparing detected amplitude of each waveform with a preset value, if the detected power on time is longer than the preset time τ1, or the detected power off time is shorter than the preset time τ2, or the detected amplitude of any waveform is larger than the preset value, shut down the ultra/mega sonic power supply and send out an alarm signal.

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METHODS AND APPARATUS FOR CLEANING SEMICONDUCTOR WAFERS

FIELD OF THE INVENTION

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

SUMMARY

[0008] One method of the present invention is to achieve a damage free ultra or mega sonic cleaning on a semiconductor 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 repeating above steps till the semiconductor 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 or mega sonic cleaning on a semiconductor 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 repeating above steps till the semiconductor 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 or mega sonic cleaning on a semiconductor 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 repeating above steps till the semiconductor 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 structure; 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 or mega sonic cleaning on a semiconductor 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 repeating above steps till the semiconductor 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 structure; and τ_2 is a time interval that the bubble size decreases to a value much smaller than the space in patterned structure.

[0012] Another method of the present invention is to achieve a damage free ultra or mega sonic cleaning on a semiconductor wafer with patterned structure by monitoring the ultra or mega sonic power supply operation status for maintaining a stable bubble cavitation. The method comprises the following steps: applying liquid into a space between a semiconductor wafer and an ultra or mega sonic device; setting an ultra or mega sonic power supply at frequency f_1 and power P_1 to drive the ultra or mega sonic device; before bubble cavitation in the liquid damaging patterned structure on the semiconductor wafer, setting the ultra or mega sonic power supply at zero output; after temperature inside bubble cooling down to a set temperature, setting the ultra or mega sonic power supply at frequency f_1 and power P_1 again; detecting power on time at power P_1 and frequency f_1 and power off time separately; comparing the detected power on time at power P_1 and frequency f_1 with a preset time τ_1, if the detected power on time is longer than the preset time τ_1, shut down the ultra or mega sonic power supply and send out an alarm signal; comparing the detected power off time with a preset time τ_2, if the detected power off time is shorter than the preset time

τ_2, shut down the ultra or mega sonic power supply and send out an alarm signal; repeating above steps till the semiconductor wafer is cleaned.

[0013] Another method of the present invention is to achieve a damage free ultra or mega sonic cleaning on a semiconductor wafer with patterned structure by monitoring the ultra or mega sonic power supply operation status for maintaining a stable bubble cavitation. The method comprises the following steps: applying liquid into a space between a semiconductor wafer and an ultra or mega sonic device; setting an ultra or mega sonic power supply at frequency f_1 and power P_1 to drive the ultra or mega sonic device; before bubble cavitation in the liquid damaging patterned structure on the semiconductor wafer, setting the ultra or mega sonic power supply at zero output; after temperature inside bubble cooling down to a set temperature, setting the ultra or mega sonic power supply at frequency f_1 and power P_1 again; detecting amplitude of each waveform output by the ultra or mega sonic power supply; comparing detected amplitude of each waveform with a preset value, if the detected amplitude of any waveform is larger than the preset value, shut down the ultra or mega sonic power supply and send out an alarm signal, where the preset value is larger than waveform amplitude at normal operation; repeating above steps till the semiconductor wafer is cleaned.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIGS. 1A-1B depict an exemplary wafer cleaning apparatus using ultra or mega sonic device;

[0015] FIGS. 2A-2G depict variety of shape of ultra or mega sonic transducers;

[0016] FIG. 3 depicts bubble cavitation during wafer cleaning process;

[0017] FIGS. 4A-4B depict a transit cavitation damaging patterned structure on a wafer during wafer cleaning process;

[0018] FIGS. 5A-5C depict thermal energy variation inside bubble during wafer cleaning process;

[0019] FIGS. 6A-6C depict an exemplary wafer cleaning method;

[0020] FIGS. 7A-7C depict another exemplary wafer cleaning method;

[0021] FIGS. 8A-8D depict another exemplary wafer cleaning method;

[0022] FIGS. 9A-9D depict another exemplary wafer cleaning method;

[0023] FIGS. 10A-10B depict another exemplary wafer cleaning method;

[0024] FIGS. 11A-11B depict another exemplary wafer cleaning method;

[0025] FIGS. 12A-12B depict another exemplary wafer cleaning method;

[0026] FIGS. 13A-13B depict another exemplary wafer cleaning method;

[0027] FIGS. 14A-14B depict another exemplary wafer cleaning method;

[0028] FIGS. 15A-15C depict a stable cavitation damaging patterned structure on a wafer during wafer cleaning process;

[0029] FIG. 16 depicts another exemplary wafer cleaning apparatus using ultra or mega sonic device;

[0030] FIG. 17 depicts an exemplary wafer cleaning apparatus using ultra or mega sonic device;

[0031] FIGS. 18A-18C depict another exemplary wafer cleaning method;

[0032] FIG. 19 depicts another exemplary wafer cleaning method;

[0033] FIG. 20 depicts an exemplary control system for monitoring the sonic power supply operation status;

[0034] FIG. 21 depicts one exemplary detection system for monitoring the sonic power supply operation status;

[0035] FIG. 22 depicts another exemplary detection system for monitoring the sonic power supply operation status;

[0036] FIGS. 23A-23C depict an exemplary voltage attenuation circuit for monitoring the sonic power supply operation status;

[0037] FIGS. 24A-24C depict an exemplary shaping circuit for monitoring the sonic power supply operation status;

[0038] FIGS. 25A-25C depict an exemplary main controller for monitoring the sonic power supply operation status;

[0039] FIG. 26 depicts the sonic power supply still oscillates several periods after the host computer shuts down the sonic power supply; and

[0040] FIGS. 27A-27C depict an exemplary amplitude detection circuit for monitoring the sonic power supply operation status.

DETAILED DESCRIPTION

[0041] FIGS. 1A and 1B show an exemplary wafer cleaning apparatus using an ultra or mega sonic device. The wafer cleaning apparatus includes wafer 1010, wafer chuck 1014 being rotated by rotation driving mechanism 1016, nozzle 1012 delivering liquid, such as cleaning chemicals or de-ionized water 1032, ultra/mega sonic device 1003 and ultra/mega sonic power supply. The ultra/mega sonic device 1003 further includes piezoelectric transducer 1004 acoustically coupled to resonator 1008. The transducer 1004 is electrically excited such that it vibrates and the resonator 1008 transmits high frequency sound energy into the liquid. Bubble cavitation generated by the ultra/mega sonic energy oscillates particles on the wafer 1010. Contaminants are thus vibrated away from the surfaces of the wafer 1010, and removed from the surfaces of the wafer 1010 through the flowing liquid 1032 supplied by the nozzle 1012.

[0042] FIGS. 2A to 2G show a top view of ultra/mega sonic devices according to the present invention. The ultra/mega sonic device 1003 shown in FIGS. 1A and 1B can be replaced by different shape of ultra/mega sonic devices 2003, 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.

[0043] FIG. 3 shows a bubble cavitation during compression phase. The shape of bubble 3052 is gradually compressed from a spherical shape A to an apple shape G, finally the bubble 3052 reaches to an implosion status I and forms a micro jet. As shown in FIGS. 4A and 4B, the micro jet is very violent (can reach a few thousands atmospheric pressures and a few thousands ^{0}C), which can damage the fine patterned structure 4034 on the wafer 4010, especially when the feature size t shrinks to 70 nm and smaller.

[0044] 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.

[0045] The idea gas equation can be expressed as follows:

$$p_0v_0/T_0=pv/T \quad (1)$$

[0046] where, p_0 is pressure inside bubble before compression, v_0 initial volume of bubble before compression, T_0 temperature of gas inside bubble before compression, p is pressure inside bubble in compression, v volume of bubble in compression, T temperature of gas inside bubble in compression.

[0047] 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 bubble compression (from volume N unit to volume 1 unit or compression ratio = N) can be expressed as follows:

$$w_m = \int_0^{x^0-1} pSdx=\int_0^{x^0-1} (S(x_0p_0)/(x_0-x))dx = Sx_0p_0\int_0^{x^0-1}dx/(x_0-x)$$

$$= - Sx_0p_0\ln (x_0-x) \Big|_0^{x^0-1} = Sx_0p_0\ln (x_0) \quad (2)$$

[0048] Where, S is area of cross section of cylinder, x0 the length of the cylinder, p0 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).

[0049] 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 bubble (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 T after one time of compression of bubble can be expressed in the following formula:

$$\Delta T = Q/(mc) = \beta\, w_m /(mc) = \beta\, S x_0 p_0 \ln(x_0)/(mc) \qquad (3)$$

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}C.

[0050] The temperature T_1 of gas inside bubble after first time compression can be calculated as:

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

[0051] 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:

$$T_2 = T1 - \delta T = T_0 + \Delta T - \delta T \qquad (5)$$

[0052] Where δT is temperature decrease after one time of expansion of the bubble, and δT is smaller than ΔT.

[0053] When the second cycle of bubble cavitation reaches the minimum bubble size, the temperature T3 of gas and or vapor inside bubble will be:

$$T3 = T2 + \Delta T = T_0 + \Delta T - \delta T + \Delta T = T_0 + 2\Delta T - \delta T \qquad (6)$$

[0054] When the second cycle of bubble cavitation finishes, the temperature T4 of gas and/or vapor inside bubble will be:

$$T4 = T3 - \delta T = T_0 + 2\Delta T - \delta T - \delta T = T_0 + 2\Delta T - 2\delta T \quad (7)$$

[0055] Similarly, when the nth cycle of bubble cavitation reaches the minimum bubble size, the temperature T_{2n-1} of gas and or vapor inside bubble will be:

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

[0056] When the nth cycle of bubble cavitation finishes, the temperature T_{2n} of gas and/or vapor inside bubble will be:

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

[0057] 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.

[0058] From equation (8), implosion cycle number n_i can be written as following:

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

[0059] From equation (10), implosion time τ_i can be written as following:

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

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

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

[0060] 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.

Table 1

$\Delta T - \delta T$ (^0C)	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

[0061] 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 show 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 output, 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:

[0062] Step 1: Put ultra/mega sonic device adjacent to surface of wafer or substrate set on a chuck or tank;

[0063] Step 2: Fill chemical liquid or gas (hydrogen, nitrogen, oxygen, or CO_2) doped water between wafer and the ultra/mega sonic device;

[0064] Step 3: Rotate chuck or oscillate wafer;

[0065] Step 4: Set power supply at frequency f_1 and power P_1;

[0066] Step 5: Before temperature of gas and vapor inside bubble reaches implosion temperature T_i, (or time reaches $\tau_1 < \tau_i$ 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.

[0067] 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.

[0068] Step 7: repeat Step 1 to Step 6 until wafer is cleaned.

[0069] 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).

[0070] 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.

[0071] 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.

[0072] Step 1: Based on Table 1, choosing 5 different time τ_1 as design of experiment (DOE) conditions.

[0073] 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.

[0074] 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).

[0075] 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.

[0076] Step 1 to step 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.

[0077] 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:

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

[0078] It was clear that the τ_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 τ_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.

[0079] 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 bubble cannot be cooled down enough, which will gradually shift average temperature of gas and vapor inside bubble 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.

[0080] FIGS. 8A to 8D show another embodiment of wafer cleaning method using an 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 wafer cleaning method of setting ultra/mega sonic power supply at frequency f_1 and power with increasing amplitude of waveform in step 4. FIG. 8B shows another wafer 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 wafer 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 another wafer cleaning method of setting ultra/mega sonic power supply at frequency f_1 and power with increasing first and decreasing later amplitude of waveform in step 4.

[0081] FIGS. 9A to 9D show another embodiment of wafer cleaning method using an 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 wafer 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 wafer 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 wafer cleaning method of setting ultra/mega sonic power supply at frequency f_3 first, frequency f_1 later and frequency f_3 last, f_1 is

higher than f_3 in step 4. FIG. 9D shows another wafer cleaning method of setting ultra/mega sonic power supply at frequency f_1 first, frequency f_3 later and frequency f_1 last, f_1 is higher than f_3 in step 4.

[0082] Similar to method shown in FIG. 9C, the ultra/mega sonic power supply 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.

[0083] Again similar to method shown in FIG. 9C, the ultra/mega sonic power supply 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.

[0084] Again similar to method shown in Fig. 9C, the ultra/mega sonic power supply 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.

[0085] Again similar to method shown in Fig. 9C, the ultra/mega sonic power supply 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.

[0086] Again similar to method shown in Fig. 9C, the ultra/mega sonic power supply 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.

[0087] Again similar to method shown in Fig. 9C, the ultra/mega sonic power supply 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.

[0088] 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 according to the present invention. FIG. 10A shows waveform of the 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:

[0089] Step 1: Put an ultra/mega sonic device adjacent to surface of wafer or substrate set on a chuck or tank;

[0090] Step 2: Fill chemical liquid or gas doped water between wafer and the ultra/mega sonic device;

[0091] Step 3: Rotate chuck or oscillate wafer;

[0092] Step 4: Set power supply at frequency f_1 and power P_1;

[0093] Step 5: Before temperature of gas and vapor inside bubble reaches implosion temperature T_i, (total time $\tau_1$elapse), 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.

[0094] 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.

[0095] Step 7: repeat Step 1 to Step 6 until wafer is cleaned.

[0096] 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.

[0097] FIGS. 11A to 11B show another embodiment of wafer cleaning method using an 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 supply 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.

[0098] FIGS. 12A to 12B show another embodiment of wafer cleaning method using an 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 supply at frequency f_2 and power P_2, where f_2 is higher than f_1, and P_2 is equal to P_1.

[0099] FIGS. 13A to 13B show another embodiment of wafer cleaning method using an 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 supply at frequency f_2 and power P_2, where f_2 is higher than f_1, and P_2 is less than P_1.

[00100] FIGS. 14A to 14B show another embodiment of wafer cleaning method using an 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 supply 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.

[00101] FIGS. 4A and 4B show that patterned structure is damaged by the violent micro jet. FIGS. 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 on wafer 15010 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 is disclosed as follows:

[00102] Step 1: Put an ultra/mega sonic device adjacent to surface of wafer or substrate set on a chuck or tank;

[00103] Step 2: Fill chemical liquid or gas doped water between wafer and the ultra/mega sonic device;

[00104] Step 3: Rotate chuck or oscillate wafer;

[00105] Step 4: Set power supply at frequency f_1 and power P_1;

[00106] 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;

[00107] 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 and power P_1 again;

[00108] Step 7: repeat Step 1 to Step 6 until wafer is cleaned.

[00109] 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:

[00110] Step 1: Similar to Table 1, choosing 5 different time τ_1 as design of experiment (DOE) conditions,

[00111] 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;

[00112] 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).

[00113] 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.

[00114] Step 1 to step 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.

[00115] All cleaning methods described from FIGS. 7 to FIGS. 14 can be applied in or combined with the method described in FIGS. 15.

[00116] FIG. 16 shows a wafer cleaning apparatus using an ultra/mega sonic device. The wafer cleaning apparatus includes 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 FIG. 16.

[00117] FIG. 17 shows a wafer cleaning apparatus using an ultra/mega sonic device. The wafer cleaning apparatus includes 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, an ultra/mega sonic device 17072 attached to outside wall of the cleaning tank 17074, and an 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 FIG. 17.

[00118] FIGS. 18A to 18C show another embodiment of wafer cleaning method using an 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.

[00119] FIG. 19 shows another embodiment of wafer cleaning method using an 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.

[00120] 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.

[00121] In the above embodiments, all the critical process parameters of sonic power supply, such as power, frequency, power on time (τ_1) and power off time (τ_2) are preset in a power supply controller, but no real-time monitoring was provided during the wafer cleaning process. Patterned structure damage cannot be avoided if the sonic power supply operation abnormal occurs during the wafer cleaning process. Hence, there needs an apparatus and method for real-time monitoring the sonic power supply operation status. If the parameters are not in the normal range, the sonic power supply should be shut down and an alarm signal should be sent out and reported.

[00122] FIG. 20 shows an exemplary control system with a detection system for monitoring operation parameters of the sonic power supply during wafer cleaning process using an ultra/mega sonic device according to the present invention. The exemplary control system includes a host computer 2080, a sonic power supply 2082, a sonic transducer 2003, a detection system 2086, and a communication cable 2088. The host computer 2080 sends sonic parameter settings, such as power setting P_1, power on time setting τ_1, power setting P_2, power off time setting τ_2, and frequency setting, and control commands, for example, power enable command, to the sonic power supply 2082. The sonic power supply 2082 generates sonic waveforms after receiving these commands and sends the sonic waveforms to the sonic transducer 2003 for cleaning the wafer 2010. Meanwhile, the parameter settings sent by the host computer 2080 and actual sonic power supply 2082 outputs are read by the detection system 2086. The detection system 2086 compares the actual outputs from the sonic power supply 2082 with the parameter settings sent by the host computer 2080, and then sends the comparison results to the host computer 2080 through the communication cable 2088. If the actual outputs from the sonic power supply 2082 are different from the parameter settings sent by the host computer 2080, the detection

system 2086 sends an alarm signal to the host computer 2080. The host computer 2080 receives the alarm signal and shuts down the sonic power supply 2082 to prevent further damage to the patterned structures on the wafer 2010.

[00123] FIG. 21 shows one exemplary detection system for monitoring operation parameters of the sonic power supply during wafer cleaning process using an ultra/mega sonic device according to the present invention. The detection system includes a voltage attenuation circuit 2190, a shaping circuit 2192, a main controller (FPGA) 2194, a communication circuit (RS 232/485) 2196 and a power circuit 2198.

[00124] FIGS. 23A to 23C show an exemplary voltage attenuation circuit of the present invention. When a sonic signal output from the sonic power supply 2082 is first read in, it has relatively high amplitude value, as shown in FIG. 23B. The voltage attenuation circuit 2190 is designed to use two operational amplifiers 23102 and 23104 to reduce the amplitude value of the waveform as shown in FIG. 23C. The attenuation rate of the voltage attenuation circuit 2190 is set in the range of 5 to 100, preferred 20. The voltage attenuation can be expressed in the following formula:

$V_{out}=(R_2/R_1)*V_{in}$

Assuming $R_1=200k$, $R_2=R_3=R_4=10K$, $V_{out}=(R_2/R_1)*V_{in}=V_{in}/20$

Where V_{out} is amplitude value output by the voltage attenuation circuit 2190, V_{in} is amplitude value input to the voltage attenuation circuit 2190, R_1, R_2, R_3, R_4 are resistances of the two operational amplifiers 23102 and 23104.

[00125] The output of the voltage attenuation circuit 2190 connects to the shaping circuit 2192. The waveform output from the voltage attenuation circuit 2190 is input to the shaping circuit 2192 to convert sinusoidal wave into square wave which can be dealt with by the main controller (FPGA) 2194. FIGS. 24A to 24C show an embodiment of the shaping circuit according to the present invention. As shown in FIG. 24A, the shaping circuit 2192 includes a window comparator 24102 and an OR gate 24104. When $V_{cal-}<V_{in}<V_{cal+}$, $V_{out}=0$, else $V_{out}=1$, where V_{cal-} and V_{cal+} are two threshold values, V_{in} is the input value of the shaping circuit, V_{out} is the output value of the shaping circuit. After the waveform passing the voltage attenuation circuit 2190,

the waveform (sinusoidal wave) is input to the shaping circuit 2192. The shaping circuit 2192 converts the sinusoidal wave into square wave as shown in FIG. 24C.

[00126] The square wave output from the shaping circuit 2192 is input to the main controller (FPGA) 2194. FIGS. 25A to 25C show an embodiment of the main controller (FPGA) of the present invention. As shown in FIG. 25A, the main controller (FPGA) 2194 includes a pulse conversion module 25102 and a periodic measurement module 25104. The pulse conversion module 25102 is used to convert the pulse signal of τ_1 time to the high level signal, and the low level signal of τ_2 time remains the same, as shown in FIGS. 25B and 25C. Circuit symbols of the pulse conversion module 25102 are shown in FIG. 25A, where Clk_Sys is 50MHz clock signal, Pulse_In is the input signal, Pulse_Out is the output signal. The periodic measurement module 25104 is used to measure the time of high level and low level by means of counter. Circuit symbols of the periodic measurement module 25104 are shown in FIG. 25A, where Clk_Sys is 50MHz clock signal, Pulse_In is the input signal, Pulse_Out is the output signal.

τ_1= Counter_H*20ns, τ_2= Counter_L*20ns.

Where Counter_H is the number of high level, Counter_L is the number of low level.

[00127] The main controller (FPGA) 2194 compares the calculated power on time with a preset time τ_1, if the calculated power on time is longer than the preset time τ_1, the main controller (FPGA) 2194 sends out an alarm signal to the host computer 2080 and the host computer 2080 receives the alarm signal and shuts down the sonic power supply 2082. The main controller (FPGA) 2194 compares the calculated power off time with a preset time τ_2, if the calculated power off time is shorter than the preset time τ_2, the main controller (FPGA) 2194 sends out an alarm signal to the host computer 2080 and the host computer 2080 receives the alarm signal and shuts down the sonic power supply 2082. The model of the main controller (FPGA) 2194 can select Altera Cyclone Ⅳ EP4CE22F17C6N.

[00128] As shown in FIG. 26, due to characteristics of apparatus itself, the sonic power supply 2082 still oscillates several periods after the host computer 2080 shuts

down the sonic power supply 2082. The time τ_3 of the several periods is also measured by the main controller (FPGA) 2194. The time τ_3 can be obtained by experiments. Therefore, the actual power on time is equal to τ-τ_3, where τ is the time calculated by the periodic measurement module 25104, τ_3 is the time of the sonic power supply 2082 oscillating several periods after the host computer 2080 shuts down the sonic power supply 2082. The main controller (FPGA) 2194 compares the actual power on time with a preset time τ_1, if the actual power on time is longer than the preset time τ_1, the main controller (FPGA) 2194 sends out an alarm signal to the host computer 2080.

[00129] As shown in FIG. 21, the communication circuit 2196 is established as an interface to the host computer 2080. The communication circuit 2196 realizes RS232/RS485 serial communication with the host computer 2080 to read parameter settings from the host computer 2080 and send comparison results to the host computer 2080.

[00130] As shown in FIG. 21, in order to provide DC1.2V, DC3.3V and DC5V for the whole system, the power circuit 2198 is designed to convert DC15V to the target voltage.

[00131] FIG. 22 shows another exemplary detection system for monitoring operation parameters of the sonic power supply during wafer cleaning process using an ultra/mega sonic device according to the present invention. The detection system includes a voltage attenuation circuit 2290, an amplitude detection circuit 2292, a main controller (FPGA) 2294, a communication circuit (RS 232/485) 2296 and a power circuit 2298.

[00132] FIGS. 23A to 23C show an exemplary voltage attenuation circuit of the present invention. When a sonic signal output from the sonic power supply 2082 is first read in, it has relatively high amplitude value, as shown in FIG. 23B. The voltage attenuation circuit 2290 is designed to use two operational amplifiers 23102 and 23104 to reduce the amplitude value of the waveform as shown in FIG. 23C. The attenuation rate of the voltage attenuation circuit 2290 is set in the range of 5 to 100, preferred 20.

[00133] FIGS. 27A to 27C show an exemplary amplitude detection circuit of the present invention. The amplitude detection circuit 2292 includes a reference voltage generating circuit and a comparison circuit. As shown in FIG. 27B, the reference voltage generating circuit is designed to use a D/A convertor 27118 to convert digital inputs from the main controller (FPGA) 2294 to analog DC reference voltages V_{ref+} and V_{ref-}, as shown in FIG. 27C. The comparison circuit is designed to use a window comparator 27114 and a AND gate 27116 to compare the attenuated amplitude V_{in} output from the voltage attenuation circuit 2190 with the reference voltages V_{ref+} and V_{ref-}, if the attenuated amplitude V_{in} exceeds the reference voltages V_{ref+} and V_{ref-}, the amplitude detection circuit 2292 sends out an alarm signal to the host computer 2080 and the host computer 2080 receives the alarm signal and shuts down the sonic power supply 2082 for avoiding damaging patterned structures on the wafer 2010.

[00134] The present invention provides a method for cleaning substrate without damaging patterned structure on the substrate using ultra/mega sonic device, including the following steps:

[00135] Step 1: applying liquid into a space between a substrate and an ultra/mega sonic device;

[00136] Step 2: setting an ultra/mega sonic power supply at frequency f_1 and power P_1 to drive the ultra/mega sonic device;

[00137] Step 3: before bubble cavitation in the liquid damaging the patterned structure on the substrate, setting the ultra/mega sonic power supply at zero output;

[00138] Step 4: after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 again;

[00139] Step 5: detecting power on time at power P_1 and frequency f_1 and power off time separately;

[00140] Step 6: comparing the detected power on time at power P_1 and frequency f_1 with a preset time τ_1, if the detected power on time is longer than the preset time τ_1, shut down the ultra/mega sonic power supply and send out an alarm signal;

[00141] Step 7: comparing the detected power off time with a preset time τ_2, if the detected power off time is shorter than the preset time τ_2, shut down the ultra/mega sonic power supply and send out an alarm signal;

[00142] Step 8: repeating step 1 to step 7 till the substrate is cleaned.

[00143] In an embodiment, the step 5 further comprises: attenuating amplitude of the waveform output by the ultra/mega sonic power supply; converting sinusoidal wave of which amplitude is attenuated into square wave; converting pulse signal of the power on time to high level signal, and the low level signal of power off time remaining the same; measuring the time of high level and low level for comparing with the preset time τ_1 and the preset time τ_2.

[00144] The attenuation rate is set in the range of 5 to 100, and preferably 20.

[00145] In an embodiment, the actual power on time is equal to τ-τ_3, wherein τ is the measured time of high level, τ_3 is the time of the ultra/mega sonic power supply oscillating several periods after the ultra/mega sonic power supply is shut down. Compare the actual power on time with the preset time τ_1, if the actual power on time is longer than the preset time τ_1, shut down the ultra/mega sonic power supply and send out an alarm signal. The present invention provides another method for cleaning substrate without damaging patterned structure on the substrate using ultra/mega sonic device, including the following steps:

[00146] Step 1: applying liquid into a space between a substrate and an ultra/mega sonic device;

[00147] Step 2: setting an ultra/mega sonic power supply at frequency f_1 and power P_1 to drive the ultra/mega sonic device;

[00148] Step 3: before bubble cavitation in the liquid damaging patterned structure on the substrate, setting the ultra/mega sonic power supply at zero output;

[00149] Step 4: after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 again;

[00150] Step 5: detecting amplitude of each waveform output by the ultra/mega sonic power supply;

[00151] Step 6: comparing detected amplitude of each waveform with a preset value, if the detected amplitude of any waveform is larger than the preset value, shut down the ultra/mega sonic power supply and send out an alarm signal, where the preset value is larger than waveform amplitude at normal operation;

[00152] Step 7: repeating step 1 to step 6 till the substrate is cleaned.

[00153] In an embodiment, the method further comprises: attenuating amplitude of the waveform output by the ultra/mega sonic power supply; obtaining analog DC reference voltages V_{ref+} and V_{ref-}; comparing the attenuated amplitude V_{in} with the reference voltages V_{ref+} and V_{ref-}, if the attenuated amplitude V_{in} exceeds the reference voltages V_{ref+} and V_{ref-}, shut down the ultra/mega sonic power supply and send out an alarm signal.

[00154] The present invention provides an apparatus for cleaning semiconductor substrate using ultra/mega sonic device, comprising a chuck, an ultra/mega sonic device, at least one nozzle, an ultra/mega sonic power supply, a host computer, and a detection system. The chuck holds a semiconductor substrate. The ultra/mega sonic device is positioned adjacent to the semiconductor substrate. The at least one nozzle injects chemical liquid on the semiconductor substrate and a gap between the semiconductor substrate and the ultra/mega sonic device. The host computer sets the ultra/mega sonic power supply at frequency f_1 and power P_1 to drive the ultra/mega sonic device, before bubble cavitation in the liquid damaging patterned structure on the semiconductor substrate, setting the ultra/mega sonic power supply at zero output, after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 again. The detection system detects power on time at power P1 and frequency f1 and power off time separately, comparing the detected power on time at power P1 and frequency f1 with a preset time τ_1, if the detected power on time is longer than the preset time τ_1, the detection system sends out an alarm signal to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply, comparing the detected power off time with a preset time τ_2, if the detected power off time is shorter than the preset time τ_2, the detection system sends out an alarm signal

to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply.

[00155] In an embodiment, the ultra/mega sonic device is further coupled with the nozzle and positioned adjacent to the semiconductor substrate, and the energy of the ultra/mega sonic device is transmitted to the semiconductor substrate through the liquid column out of the nozzle.

[00156] The present invention provides another apparatus for cleaning semiconductor substrate using ultra/mega sonic device, comprising a chuck, an ultra/mega sonic device, at least one nozzle, an ultra/mega sonic power supply, a host computer, and a detection system. The chuck holds a semiconductor substrate. The ultra/mega sonic device is positioned adjacent to the semiconductor substrate. The at least one nozzle injects chemical liquid on the semiconductor substrate and a gap between the semiconductor substrate and the ultra/mega sonic device. The host computer sets the ultra/mega sonic power supply at frequency f_1 and power P_1 to drive the ultra/mega sonic device, before bubble cavitation in the liquid damaging patterned structure on the semiconductor substrate, setting the ultra/mega sonic power supply at zero output, after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 again. The detection system detects amplitude of each waveform output by the ultra/mega sonic power supply, comparing detected amplitude of each waveform with a preset value, if detected amplitude of any waveform is larger than the preset value, the detection system sends out an alarm signal to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply, wherein the preset value is larger than waveform amplitude at normal operation.

[00157] In an embodiment, the ultra/mega sonic device is further coupled with the nozzle and positioned adjacent to the semiconductor substrate, and the energy of the ultra/mega sonic device is transmitted to the semiconductor substrate through the liquid column out of the nozzle.

[00158] The present invention provides another apparatus for cleaning semiconductor substrate using ultra/mega sonic device, comprising a cassette, a tank,

an ultra/mega sonic device, at least one inlet, an ultra/mega sonic power supply, a host computer, and a detection system. The cassette holds at least one semiconductor substrate. The tank holds the cassette. The ultra/mega sonic device is attached to outside wall of the tank. The at least one inlet is used for filling chemical liquid into the tank to immerse the semiconductor substrate. The host computer sets the ultra/mega sonic power supply at frequency f_1 and power P_1 to drive the ultra/mega sonic device, before bubble cavitation in the liquid damaging patterned structure on the semiconductor substrate, setting the ultra/mega sonic power supply at zero output, after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 again. The detection system detects power on time at power P1 and frequency f1 and power off time separately, comparing the detected power on time at power P1 and frequency f1 with a preset time τ_1, if the detected power on time is longer than the preset time τ_1, the detection system sends out an alarm signal to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply, comparing the detected power off time with a preset time τ_2, if the detected power off time is shorter than the preset time τ_2, the detection system sends out an alarm signal to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply.

The present invention provides another apparatus for cleaning semiconductor substrate using ultra/mega sonic device, comprising a cassette, a tank, an ultra/mega sonic device, at least one inlet, an ultra/mega sonic power supply, a host computer and a detection system. The cassette holds at least one semiconductor substrate. The tank holds the cassette. The ultra/mega sonic device is attached to outside wall of the tank. The at least one inlet is used for filling chemical liquid into the tank to immerse the semiconductor substrate. The host computer sets the ultra/mega sonic power supply at frequency f_1 and power P_1 to drive the ultra/mega sonic device, before bubble cavitation in the liquid damaging patterned structure on the semiconductor substrate, setting the ultra/mega sonic power supply at zero output, after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at

frequency f_1 and power P_1 again. The detection system detects amplitude of each waveform output by the ultra/mega sonic power supply, comparing detected amplitude of each waveform with a preset value, if detected amplitude of any waveform is larger than the preset value, the detection system sends out an alarm signal to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply, wherein the preset value is larger than waveform amplitude at normal operation.

[00159] 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.

What is claimed is:

1. A method for cleaning substrate without damaging patterned structure on the 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 the ultra/mega sonic device;

before bubble cavitation in the liquid damaging patterned structure on the substrate, setting the ultra/mega sonic power supply at zero output;

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

detecting power on time at power P1 and frequency f1 and power off time separately;

comparing the detected power on time at power P1 and frequency f1 with a preset time τ_1, if the detected power on time is longer than the preset time τ_1, shut down the ultra/mega sonic power supply and send out an alarm signal;

comparing the detected power off time with a preset time τ_2, if the detected power off time is shorter than the preset time τ_2, shut down the ultra/mega sonic power supply and send out an alarm signal;

repeating above steps till the substrate being cleaned.

2. The method of claim 1, wherein detecting power on time at power P1 and frequency f1 and power off time separately, comprises:

attenuating amplitude of the waveform output by the ultra/mega sonic power supply;

converting sinusoidal wave of which amplitude is attenuated into square wave;

converting pulse signal of the power on time to high level signal, and the low level signal of power off time remaining the same;

measuring the time of high level and low level for comparing with the preset time τ_1 and the preset time τ_2.

3. The method of claim 2, wherein the attenuation rate is set in the range of 5 to 100.

4. The method of claim 1, wherein the actual power on time is equal to τ-τ_3, wherein τ is the measured time of high level, τ_3 is the time of the ultra/mega sonic power supply oscillating several periods after the ultra/mega sonic power supply is shut down.

5. The method of claim 4, wherein comparing the detected power on time at power P1 and frequency f1 with a preset time τ_1, if the detected power on time is longer than the preset time τ_1, shut down the ultra/mega sonic power supply and send out an alarm signal, comprises:

comparing the actual power on time with the preset time τ_1, if the actual power on time is longer than the preset time τ_1, shut down the ultra/mega sonic power supply and send out an alarm signal.

6. A method for cleaning substrate without damaging patterned structure on the 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 the ultra/mega sonic device;

before bubble cavitation in the liquid damaging patterned structure on the substrate, setting the ultra/mega sonic power supply at zero output;

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

detecting amplitude of each waveform output by the ultra/mega sonic power supply;

comparing detected amplitude of each waveform with a preset value, if the detected amplitude of any waveform is larger than the preset value, shut down the

ultra/mega sonic power supply and send out an alarm signal, wherein the preset value is larger than waveform amplitude at normal operation;

repeating above steps till the substrate being cleaned.

7. The method of claim 6, further comprising:

attenuating amplitude of the waveform output by the ultra/mega sonic power supply;

obtaining analog DC reference voltages V_{ref+} and V_{ref-};

comparing the attenuated amplitude V_{in} with the reference voltages V_{ref+} and V_{ref-}, if the attenuated amplitude V_{in} exceeds the reference voltages V_{ref+} and V_{ref-}, shut down the ultra/mega sonic power supply and send out an alarm signal.

8. An apparatus for cleaning semiconductor substrate using ultra/mega sonic device, comprising:

a chuck, holding a semiconductor substrate;

an ultra/mega sonic device, being positioned adjacent to the semiconductor substrate;

at least one nozzle, injecting chemical liquid on the semiconductor substrate and a gap between the semiconductor substrate and the ultra/mega sonic device;

an ultra/mega sonic power supply;

a host computer, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 to drive the ultra/mega sonic device, before bubble cavitation in the liquid damaging patterned structure on the semiconductor substrate, setting the ultra/mega sonic power supply at zero output, after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 again;

a detection system, detecting power on time at power P1 and frequency f1 and power off time separately, comparing the detected power on time at power P1 and frequency f1 with a preset time τ_1, if the detected power on time is longer than the preset time τ_1, the detection system sends out an alarm signal to the host computer,

and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply, comparing the detected power off time with a preset time τ_2, if the detected power off time is shorter than the preset time τ_2, the detection system sends out an alarm signal to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply.

9. The apparatus of claim 8, wherein the detection system includes a voltage attenuation circuit, a shaping circuit, a main controller, a communication circuit and a power circuit.

10. The apparatus of claim 9, wherein the voltage attenuation circuit reduces the amplitude value of the waveform output by the ultra/mega sonic power supply.

11. The apparatus of claim 10, wherein the attenuation rate of the voltage attenuation circuit is set in the range of 5 to 100.

12. The apparatus of claim 9, wherein after the waveform passing the voltage attenuation circuit, the waveform (sinusoidal wave) is input to the shaping circuit, the shaping circuit converts the sinusoidal wave into square wave.

13. The apparatus of claim 9, wherein the main controller includes a pulse conversion module and a periodic measurement module, the pulse conversion module converts the pulse signal of τ_1 time to the high level signal, and the low level signal of τ_2 time remains the same, the periodic measurement module measures the time of high level and low level by means of counter.

14. The apparatus of claim 9, wherein the main controller compares the measured power on time with the preset time τ_1, if the measured power on time is longer than the preset time τ_1, the main controller sends out the alarm signal to the host computer, the main controller compares the measured power off time with the

preset time τ_2, if the measured power off time is shorter than the preset time τ_2, the main controller sends out the alarm signal to the host computer.

15. The apparatus of claim 13, wherein the actual power on time is equal to τ-τ_3, where τ is the time measured by the periodic measurement module, τ_3 is the time of the ultra/mega sonic power supply oscillating several periods after the host computer shuts down the ultra/mega sonic power supply, the main controller compares the actual power on time with the preset time τ_1, if the actual power on time is longer than the preset time τ_1, the main controller sends out the alarm signal to the host computer.

16. The apparatus of claim 9, wherein the communication circuit is established as an interface to the host computer, the communication circuit realizes RS232/RS485 serial communication with the host computer.

17. The apparatus of claim 9, wherein the power circuit converts DC15V to a target voltage.

18. The apparatus of claim 8, wherein the ultra/mega sonic device is further coupled with the nozzle and positioned adjacent to the semiconductor substrate, the energy of the ultra/mega sonic device is transmitted to the semiconductor substrate through the liquid column out of the nozzle.

19. An apparatus for cleaning semiconductor substrate using ultra/mega sonic device, comprising:

a chuck, holding a semiconductor substrate;

an ultra/mega sonic device, being positioned adjacent to the semiconductor substrate;

at least one nozzle, injecting chemical liquid on the semiconductor substrate and a gap between the semiconductor substrate and the ultra/mega sonic device;

an ultra/mega sonic power supply;

a host computer, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 to drive the ultra/mega sonic device, before bubble cavitation in the liquid damaging patterned structure on the semiconductor substrate, setting the ultra/mega sonic power supply at zero output, after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 again;

a detection system, detecting amplitude of each waveform output by the ultra/mega sonic power supply, comparing detected amplitude of each waveform with a preset value, if the detected amplitude of any waveform is larger than the preset value, the detection system sends out an alarm signal to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply, wherein the preset value is larger than waveform amplitude at normal operation.

20. The apparatus of claim 19, wherein the detection system includes a voltage attenuation circuit, an amplitude detection circuit, a main controller, a communication circuit and a power circuit.

21. The apparatus of claim 20, wherein the voltage attenuation circuit reduces the amplitude value of the waveform output by the ultra/mega sonic power supply.

22. The apparatus of claim 20, wherein the amplitude detection circuit includes a reference voltage generating circuit and a comparison circuit, the reference voltage generating circuit converts digital inputs from the main controller to analog DC reference voltages V_{ref+} and V_{ref-}, the comparison circuit compares the attenuated amplitude V_{in} output from the voltage attenuation circuit with the reference voltages V_{ref+} and V_{ref-}, if the attenuated amplitude V_{in} exceeds the reference voltages V_{ref+} and V_{ref-}, the amplitude detection circuit sends out the alarm signal to the host computer.

23. The apparatus of claim 19, wherein the ultra/mega sonic device is further coupled with the nozzle and positioned adjacent to the semiconductor substrate, the energy of the ultra/mega sonic device is transmitted to the semiconductor substrate through the liquid column out of the nozzle.

24. An apparatus for cleaning semiconductor substrate using ultra/mega sonic device, comprising:

a cassette, holding at least one semiconductor substrate;

a tank, holding the cassette;

an ultra/mega sonic device, being attached to outside wall of the tank;

at least one inlet, for filling chemical liquid into the tank to immerse the semiconductor substrate;

an ultra/mega sonic power supply;

a host computer, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 to drive the ultra/mega sonic device, before bubble cavitation in the liquid damaging patterned structure on the semiconductor substrate, setting the ultra/mega sonic power supply at zero output, after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 again;

a detection system, detecting power on time at power P1 and frequency f1 and power off time separately, comparing the detected power on time at power P1 and frequency f1 with a preset time τ_1, if the detected power on time is longer than the preset time τ_1, the detection system sends out an alarm signal to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply, comparing the detected power off time with a preset time τ_2, if the detected power off time is shorter than the preset time τ_2, the detection system sends out an alarm signal to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply.

25. The apparatus of claim 24, wherein the detection system includes a voltage attenuation circuit, a shaping circuit, a main controller, a communication circuit and a power circuit.

26. An apparatus for cleaning semiconductor substrate using ultra/mega sonic device, comprising:

a cassette, holding at least one semiconductor substrate;

a tank, holding the cassette;

an ultra/mega sonic device, being attached to outside wall of the tank;

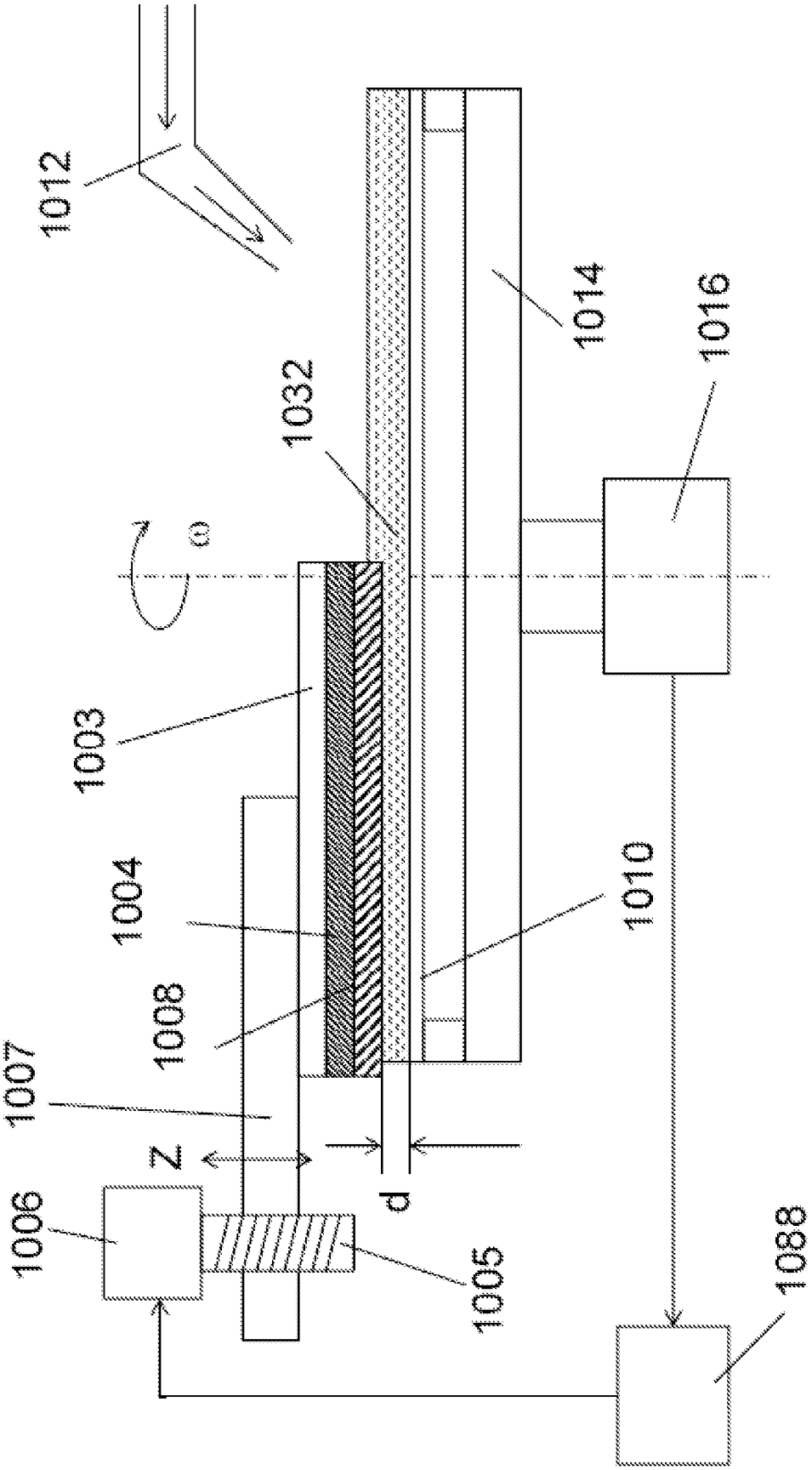
at least one inlet, for filling chemical liquid into the tank to immerse the semiconductor substrate;

an ultra/mega sonic power supply;

a host computer, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 to drive the ultra/mega sonic device, before bubble cavitation in the liquid damaging patterned structure on the semiconductor substrate, setting the ultra/mega sonic power supply at zero output, after temperature inside bubble cooling down to a set temperature, setting the ultra/mega sonic power supply at frequency f_1 and power P_1 again;

a detection system, detecting amplitude of each waveform output by the ultra/mega sonic power supply, comparing detected amplitude of each waveform with a preset value, if the detected amplitude of any waveform is larger than the preset value, the detection system sends out an alarm signal to the host computer, and the host computer receives the alarm signal and shuts down the ultra/mega sonic power supply, wherein the preset value is larger than waveform amplitude at normal operation.

27. The apparatus of claim 26, wherein the detection system includes a voltage attenuation circuit, an amplitude detection circuit, a main controller, a communication circuit and a power circuit.


1012
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1016
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ω
1003
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1008
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1010
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d
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1005
1088

Fig. 1A

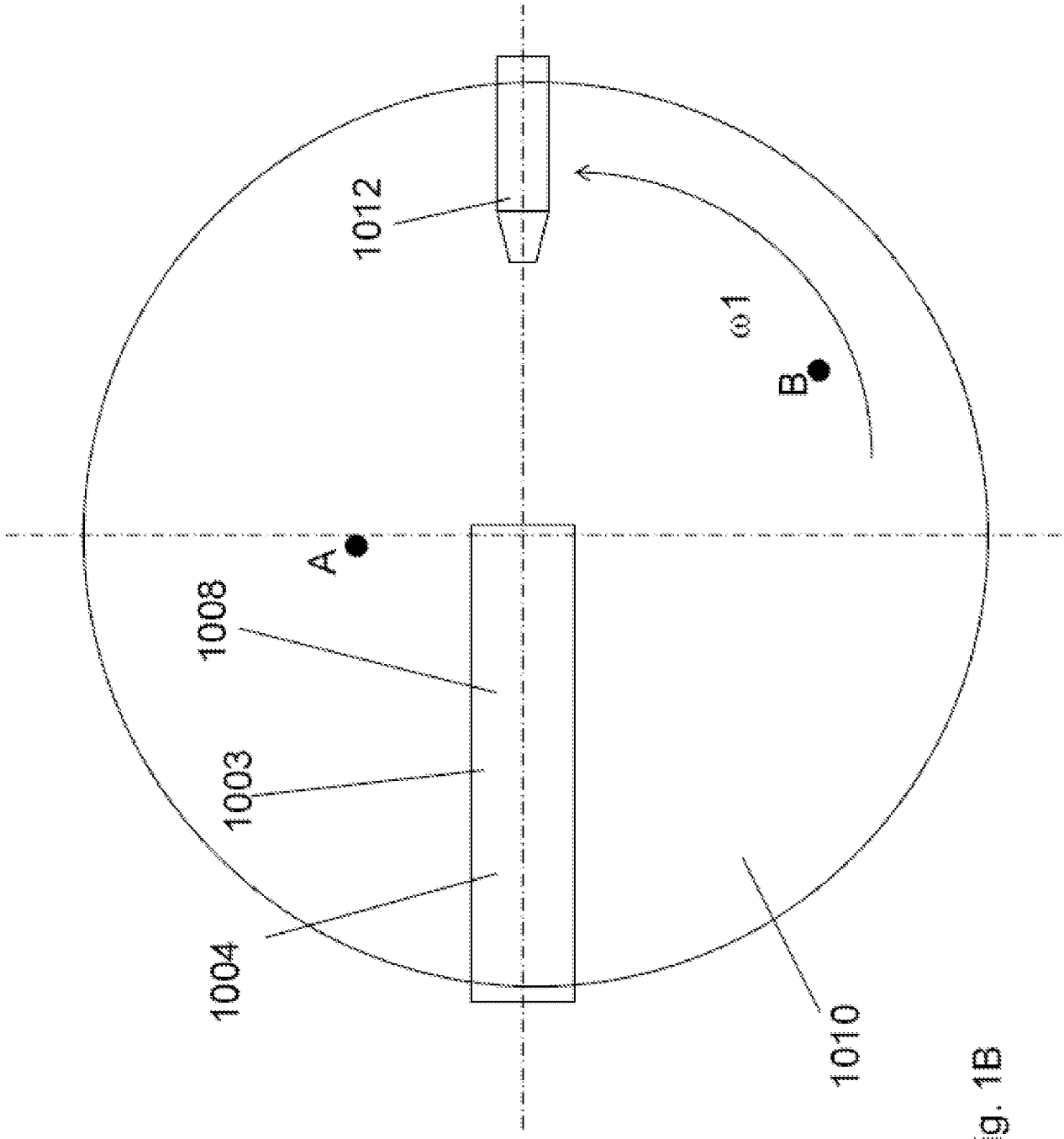


Fig. 1B

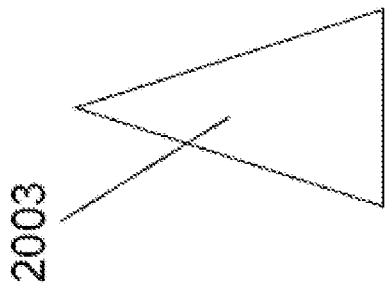


Fig. 2A

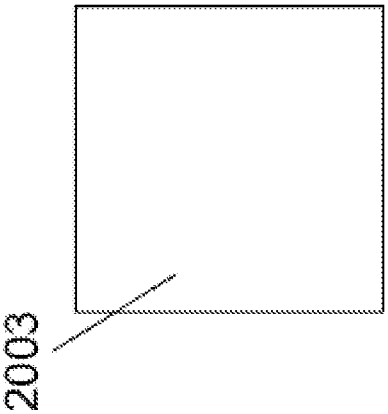


Fig. 2B

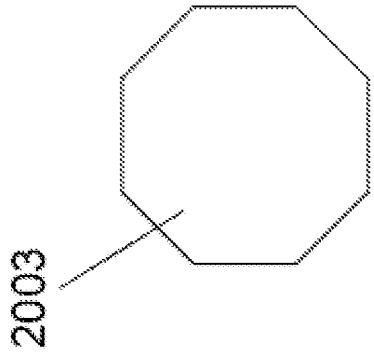


Fig. 2C

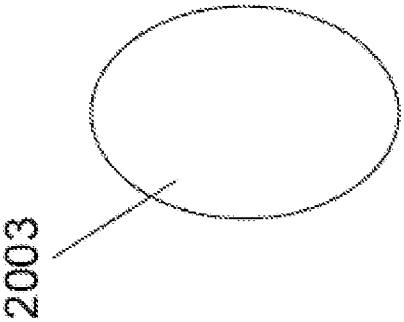


Fig. 2D

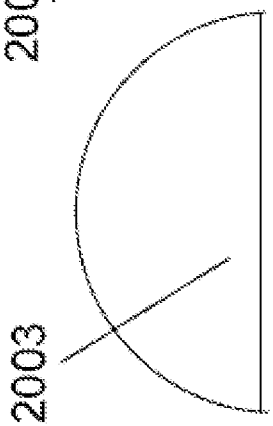


Fig. 2E

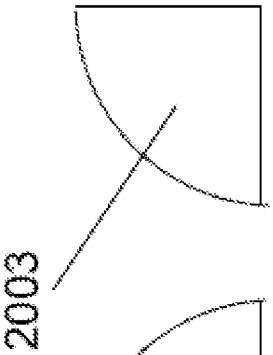


Fig. 2F

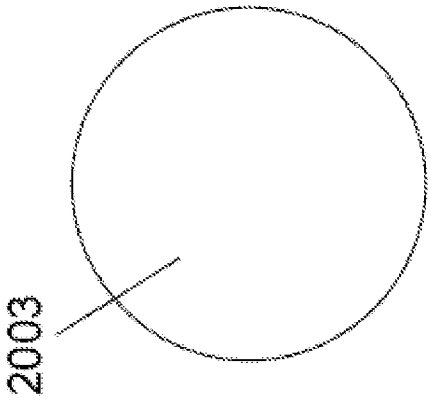


Fig. 2G

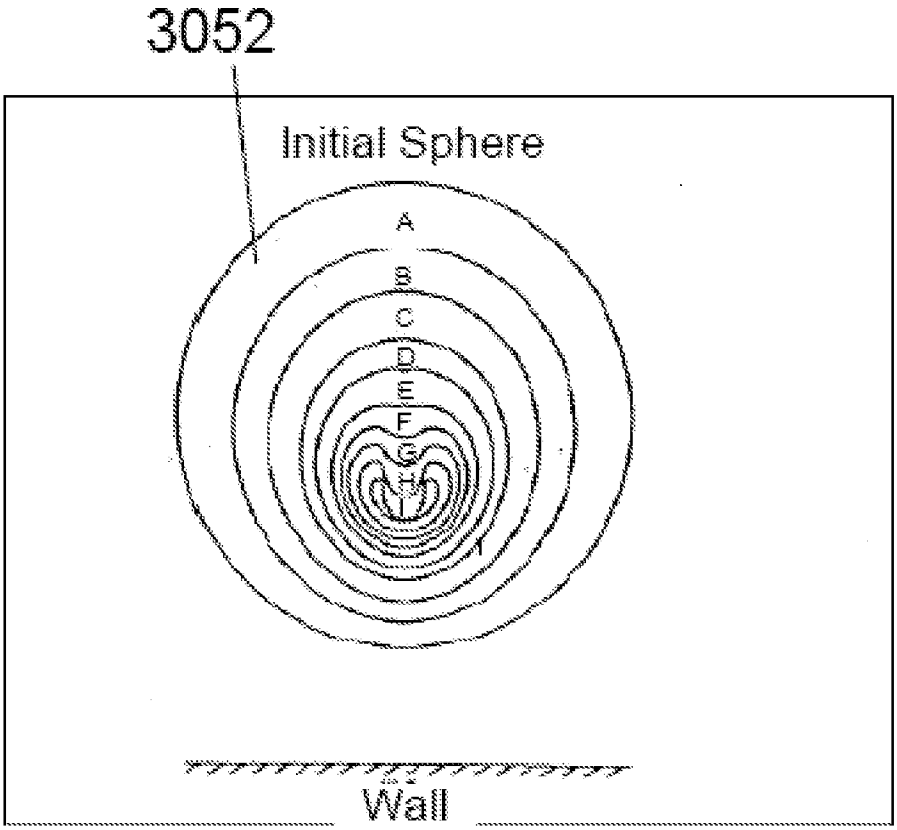


Fig. 3

Fig. 4A

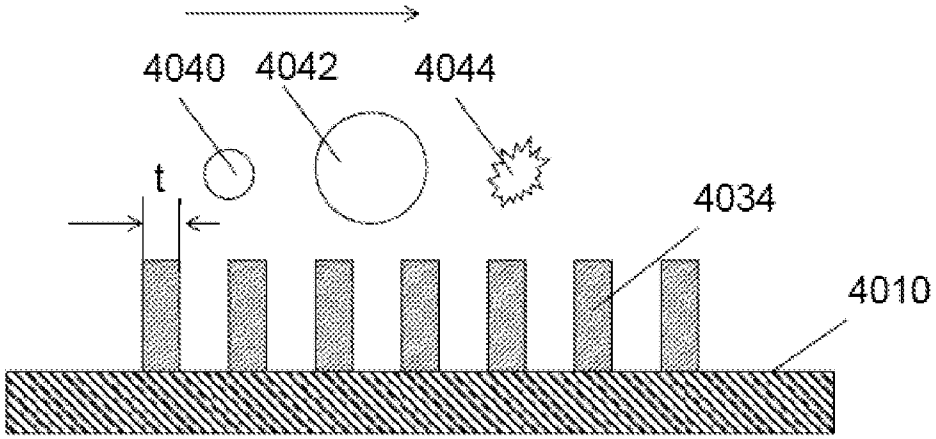


Fig. 4B

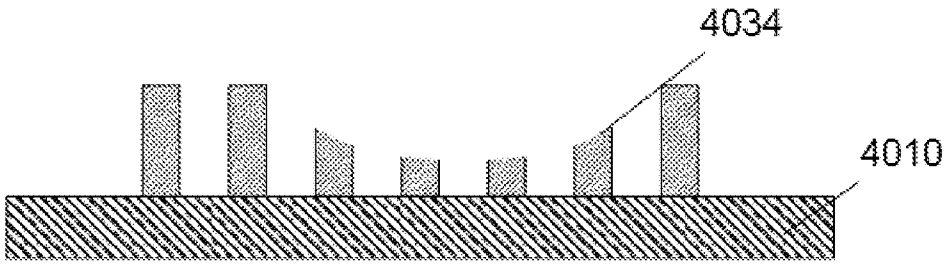


Fig. 5A

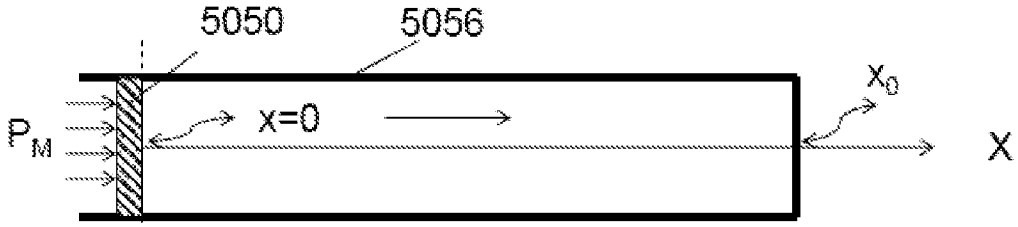


Fig. 5B

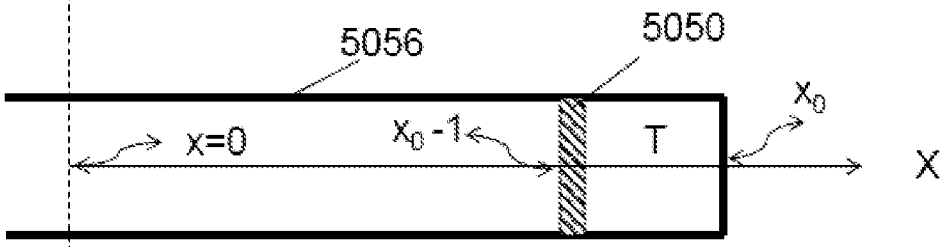
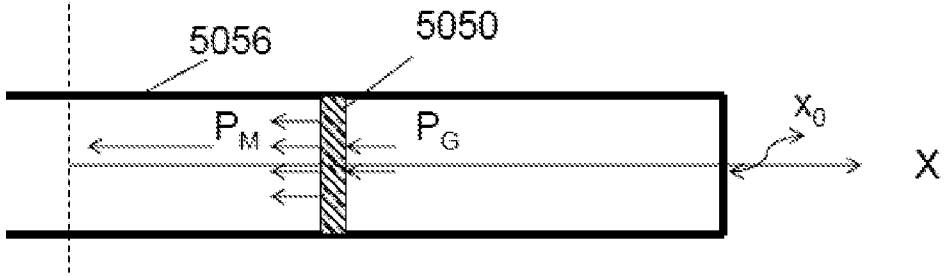


Fig. 5C



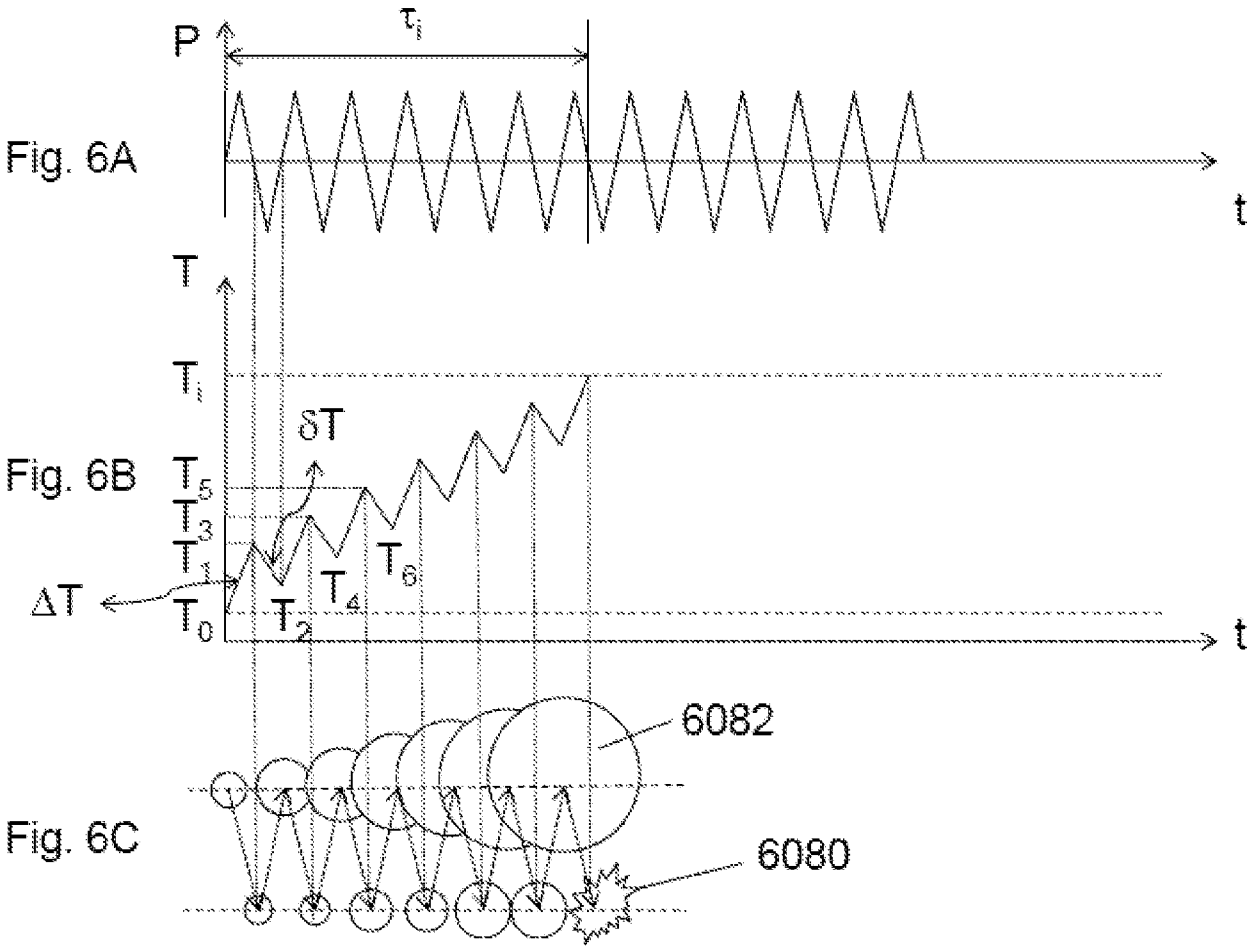
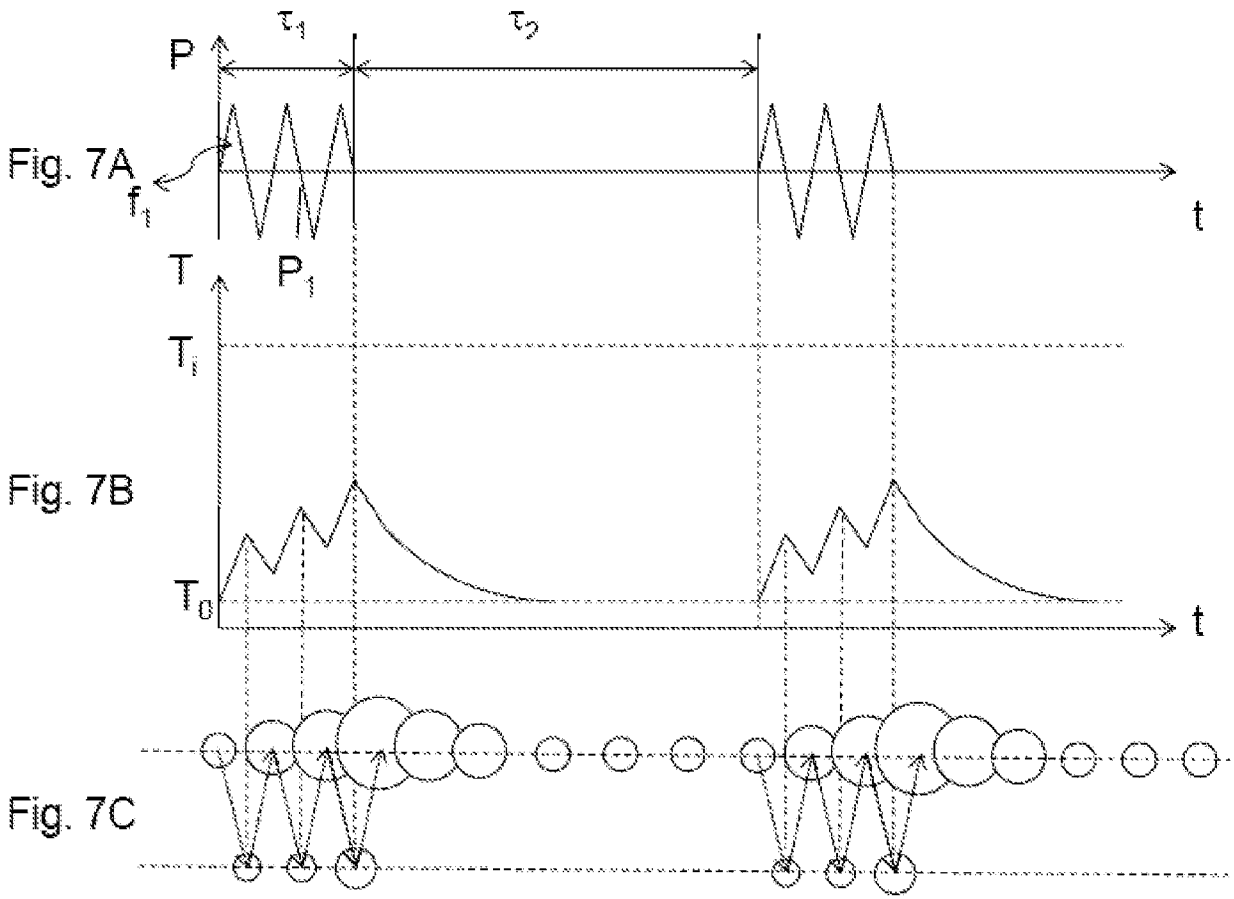


Fig. 6A

Fig. 6B

Fig. 6C


τ1
τ2
P
Fig. 7A
f1
t
T
P1
T1
Fig. 7B
T0
t
Fig. 7C

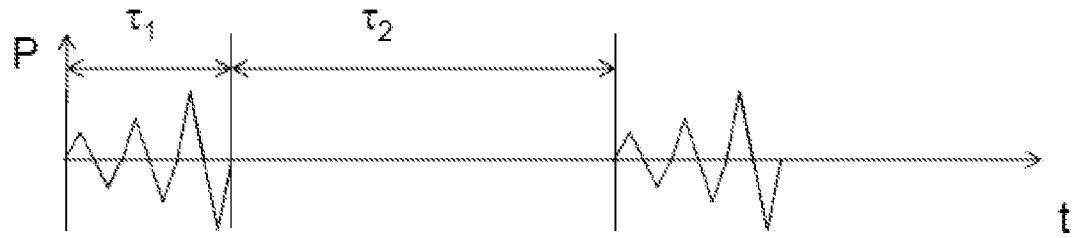


Fig. 8A

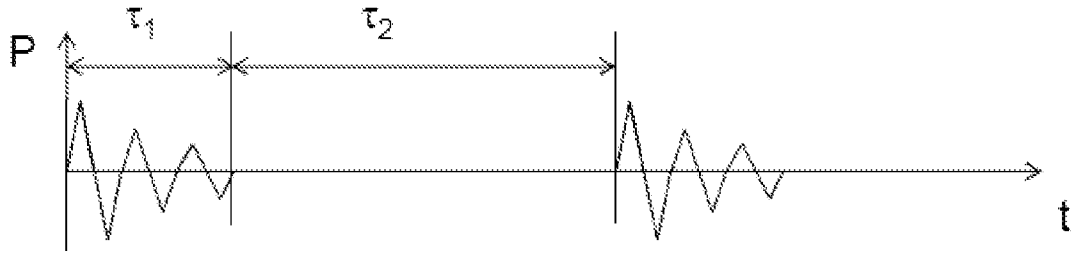


Fig. 8B

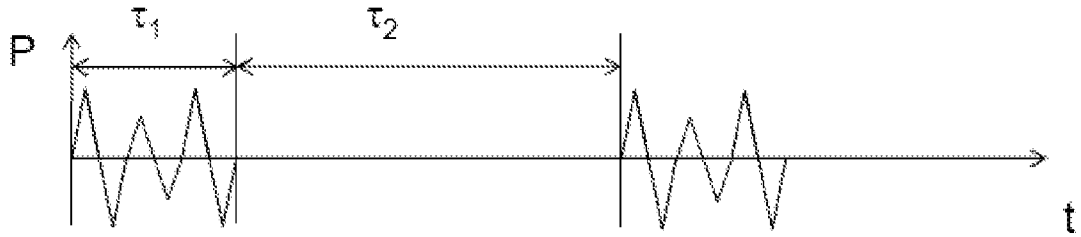


Fig. 8C

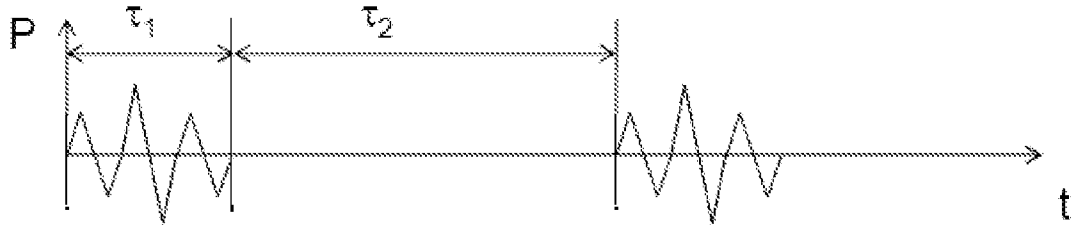


Fig. 8D

Fig. 9A

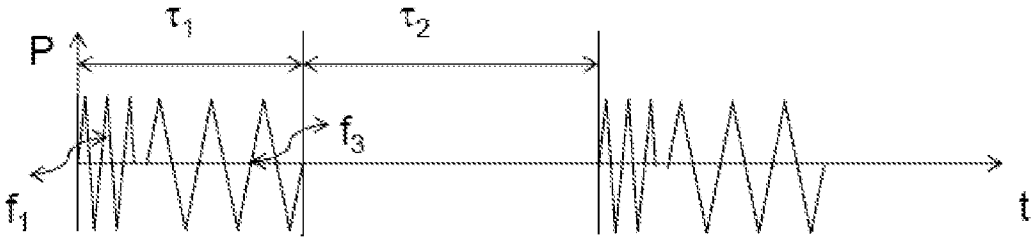


Fig. 9B

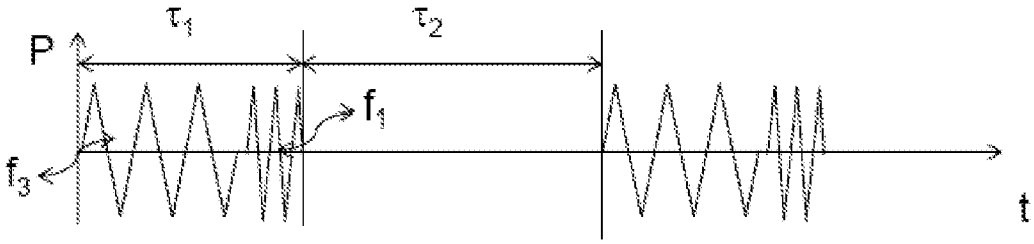


Fig. 9C

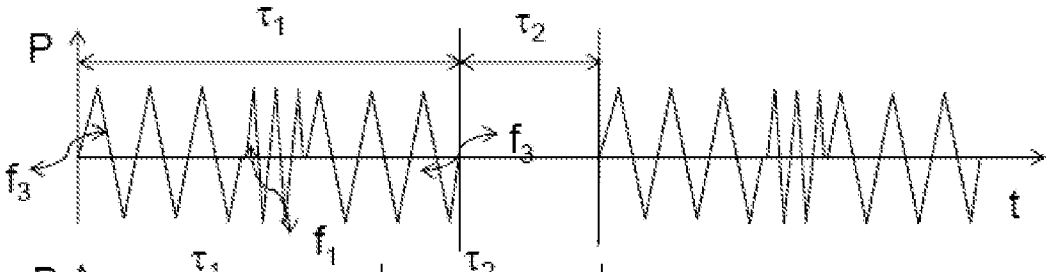
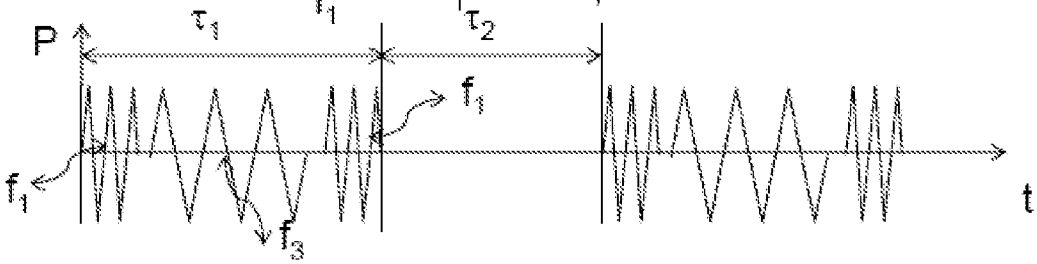


Fig. 9D



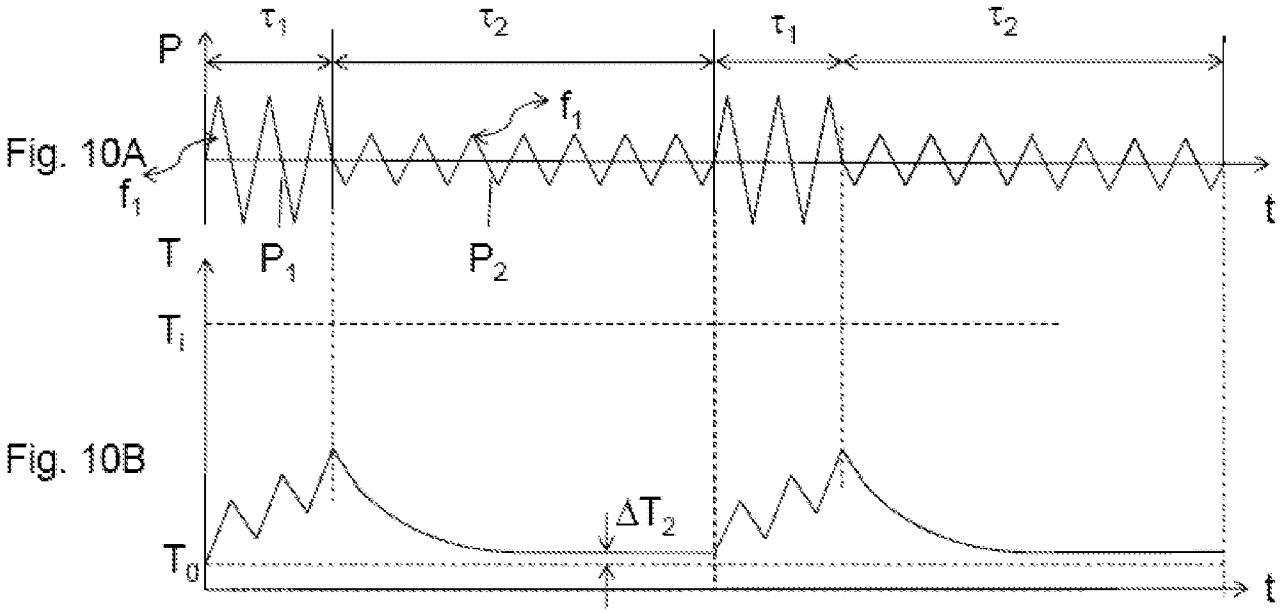

τ1
τ2
τ1
τ2
P
f1
Fig. 10A
f1
t
T
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Fig. 10B
ΔT2
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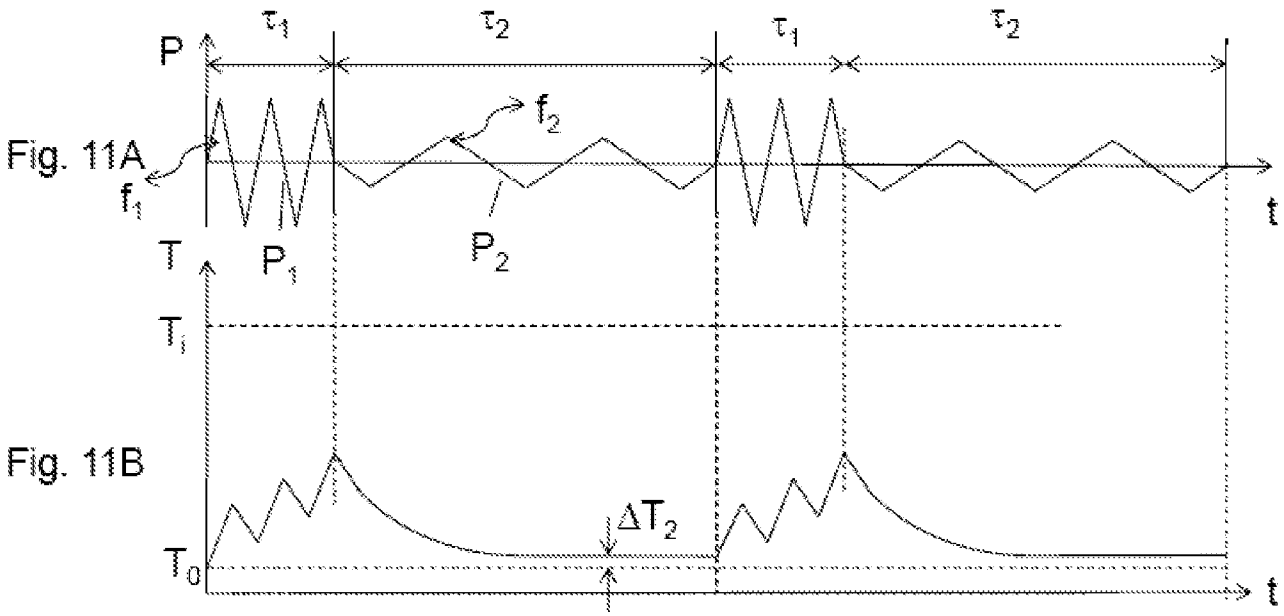


Fig. 11A

Fig. 11B

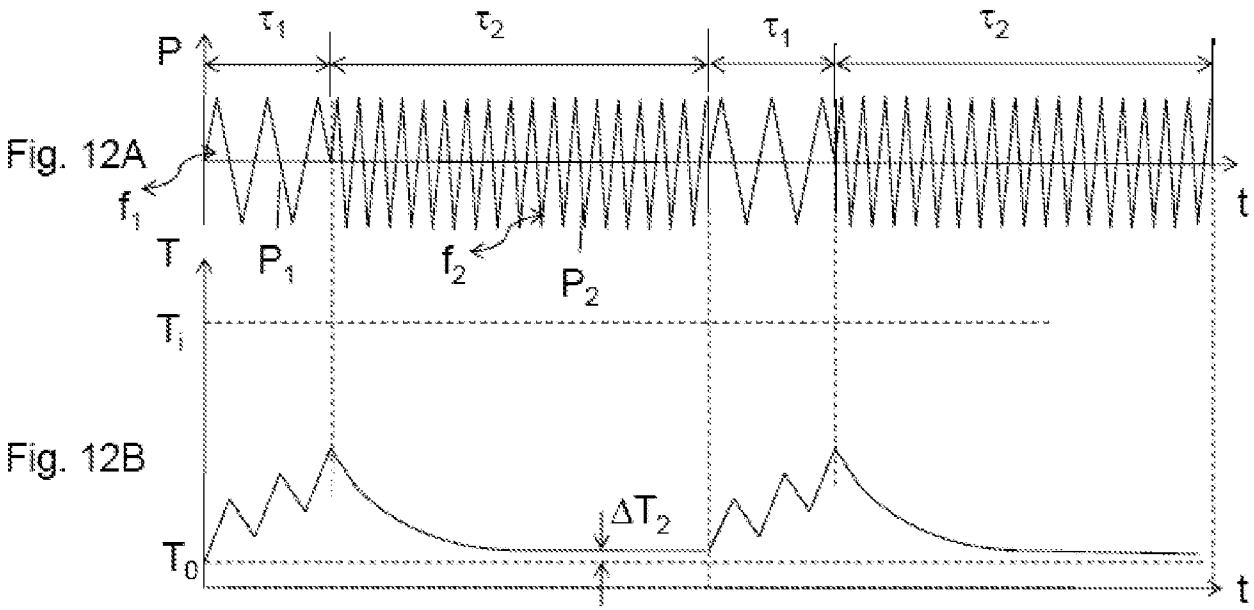


Fig. 12A

Fig. 12B

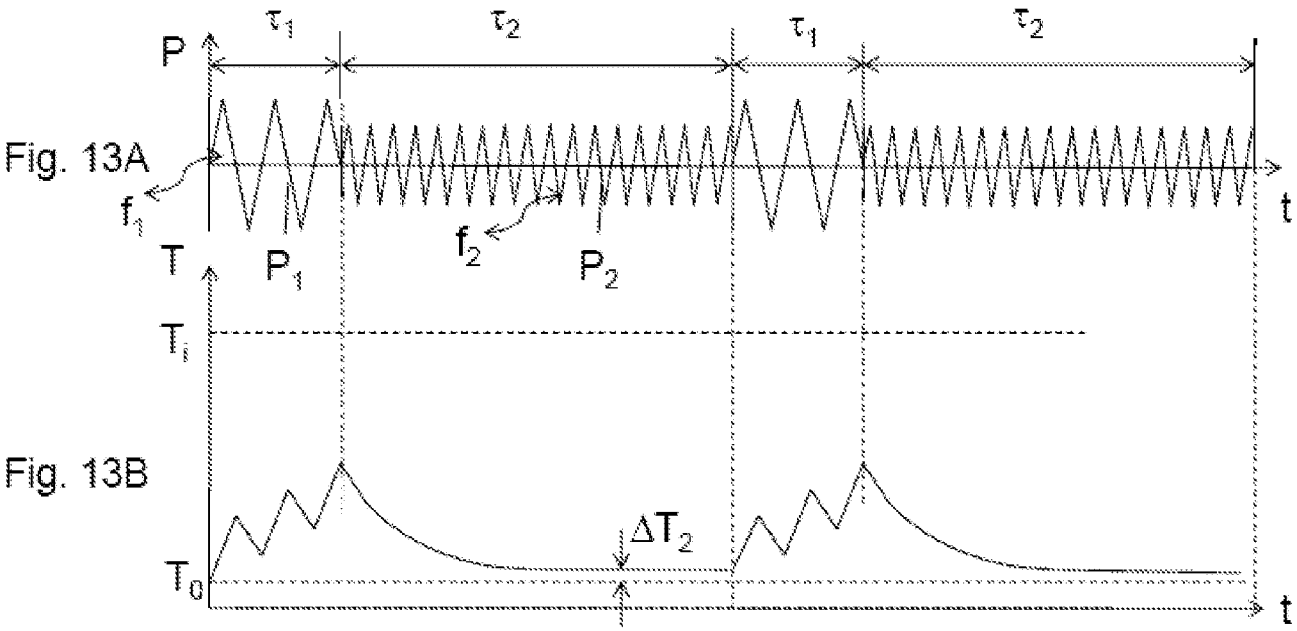


Fig. 13A

Fig. 13B

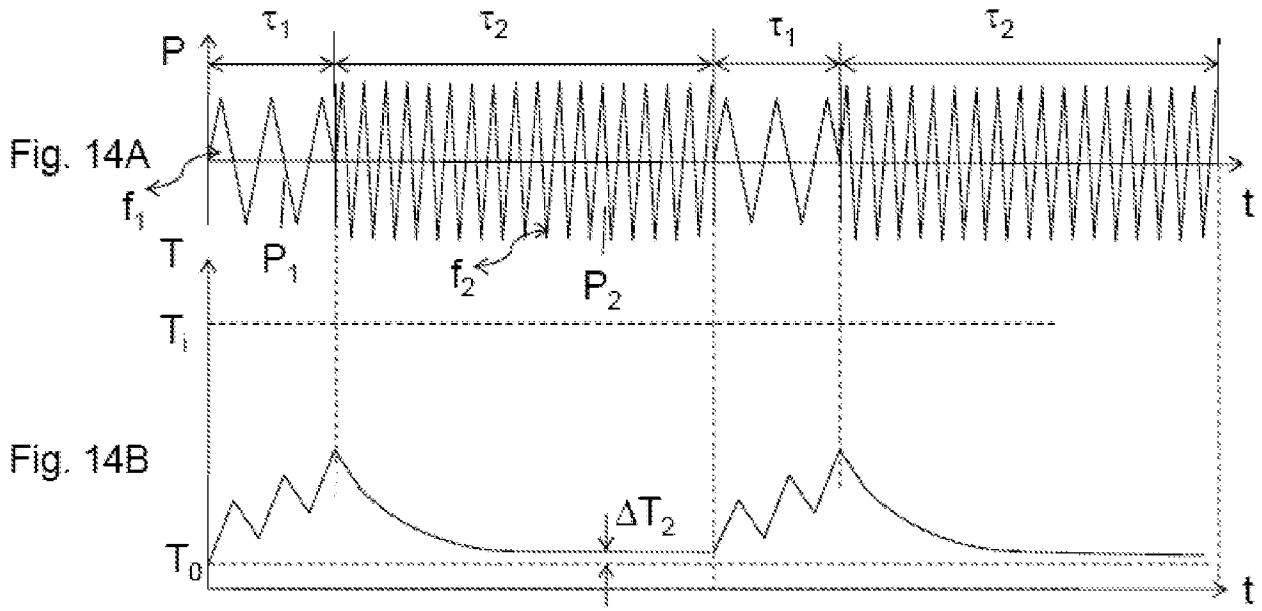

P
τ1
τ2
τ1
τ2
Fig. 14A
f1
t
T
P1
f2
P2
T1
Fig. 14B
ΔT2
T0
t

Fig. 15A

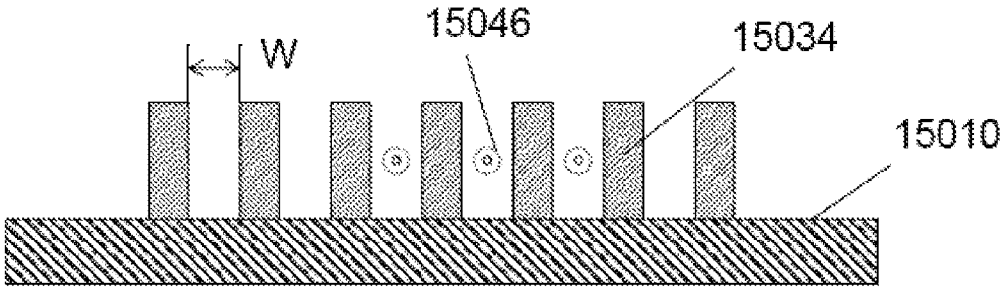


Fig. 15B

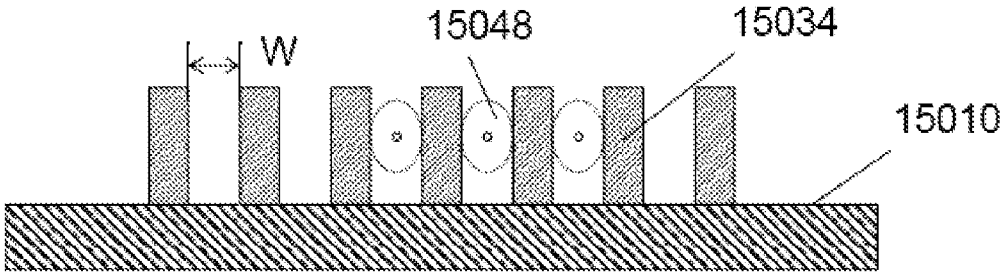
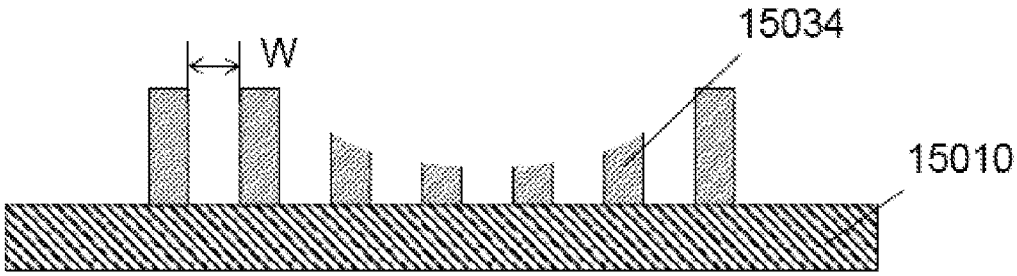


Fig. 15C



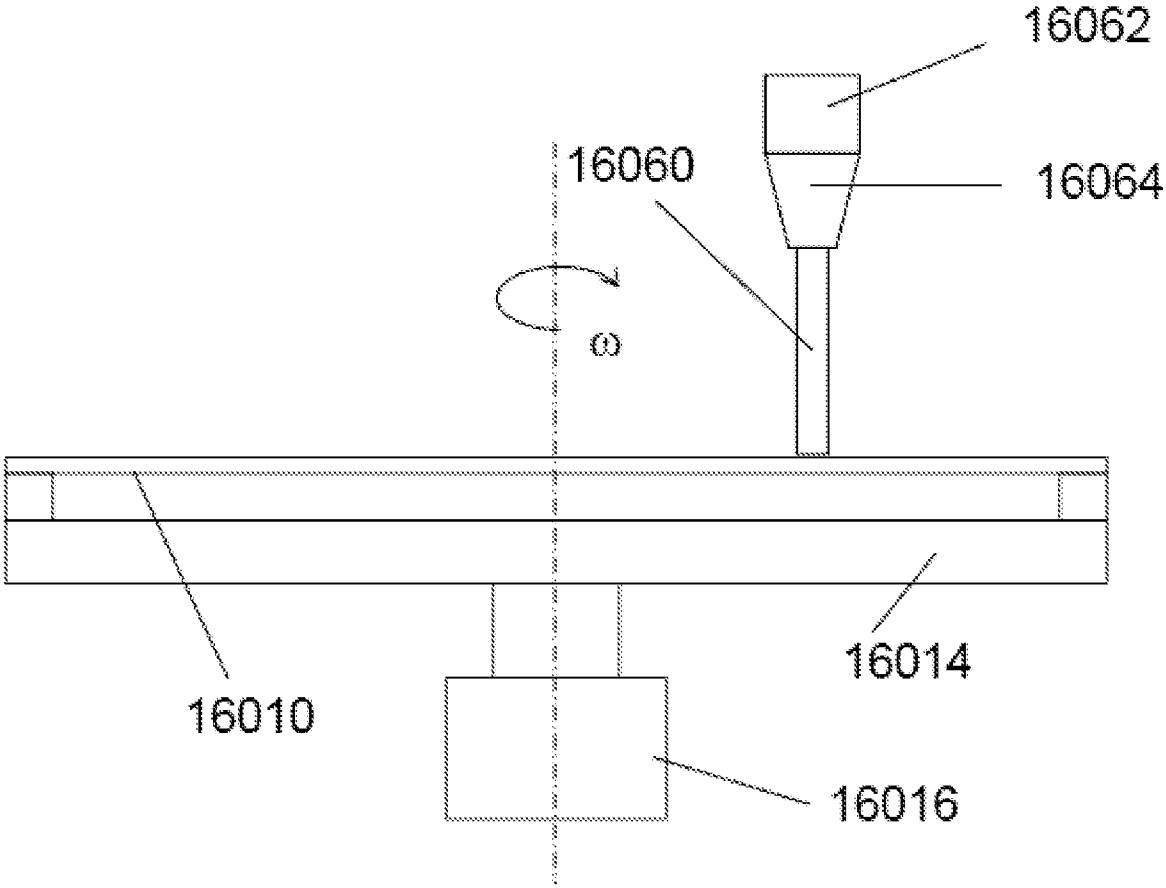


Fig. 16

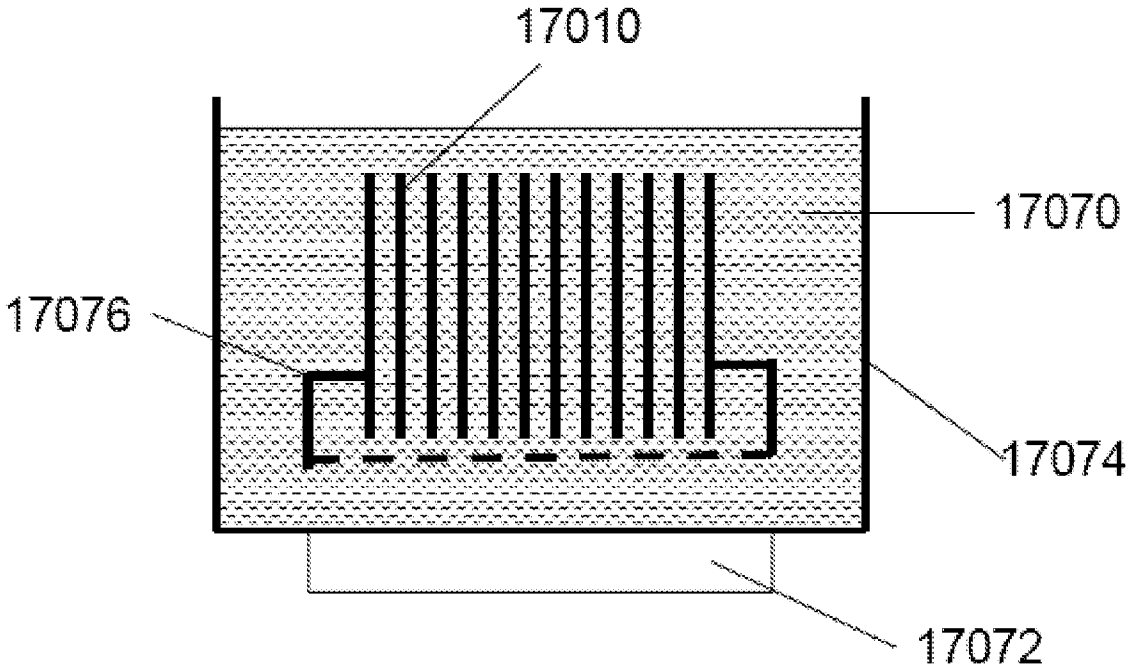


Fig. 17

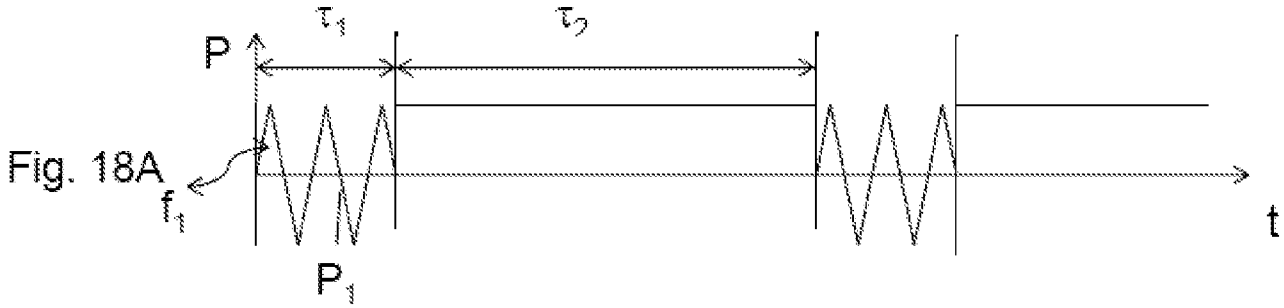


Fig. 18A

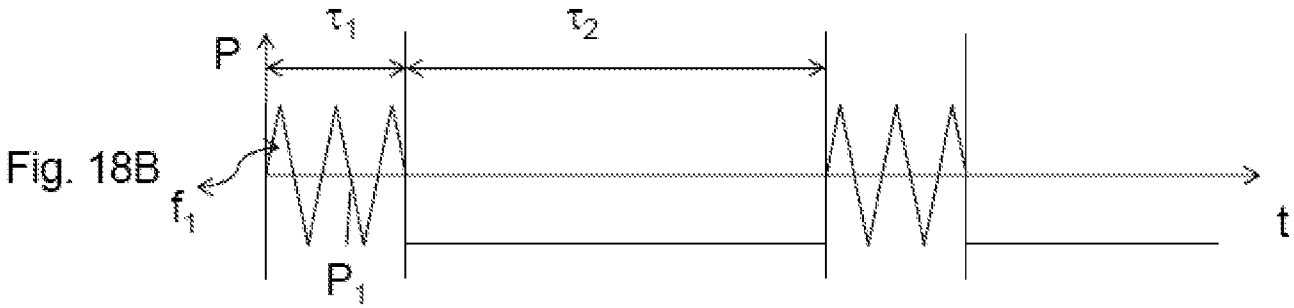


Fig. 18B

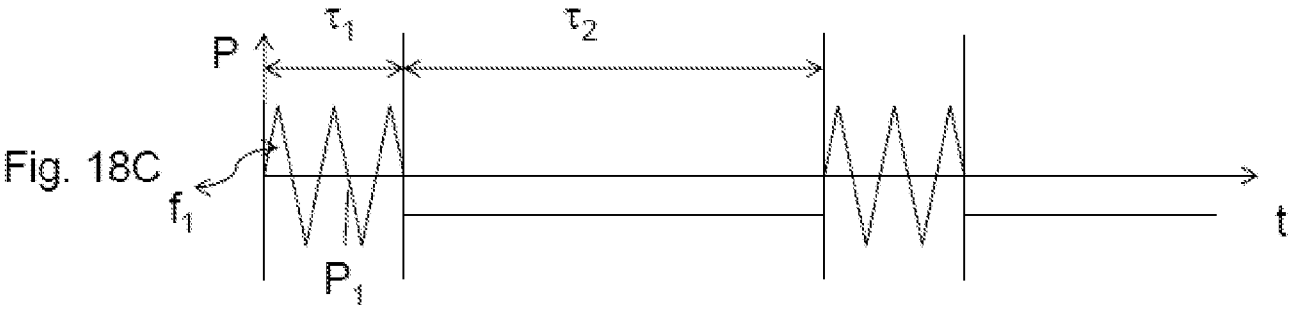
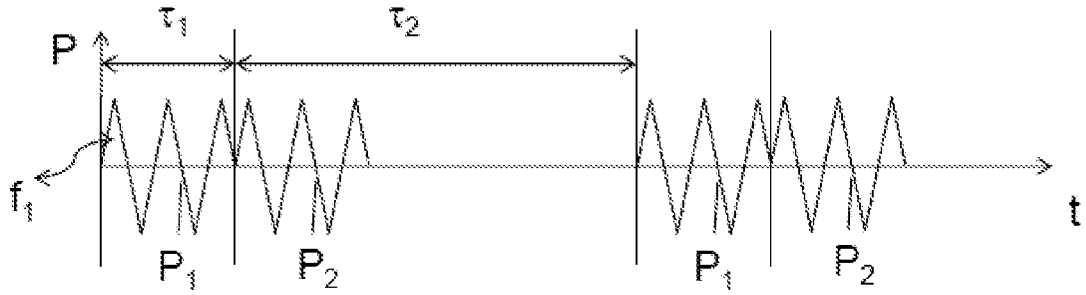


Fig. 18C

Fig. 19



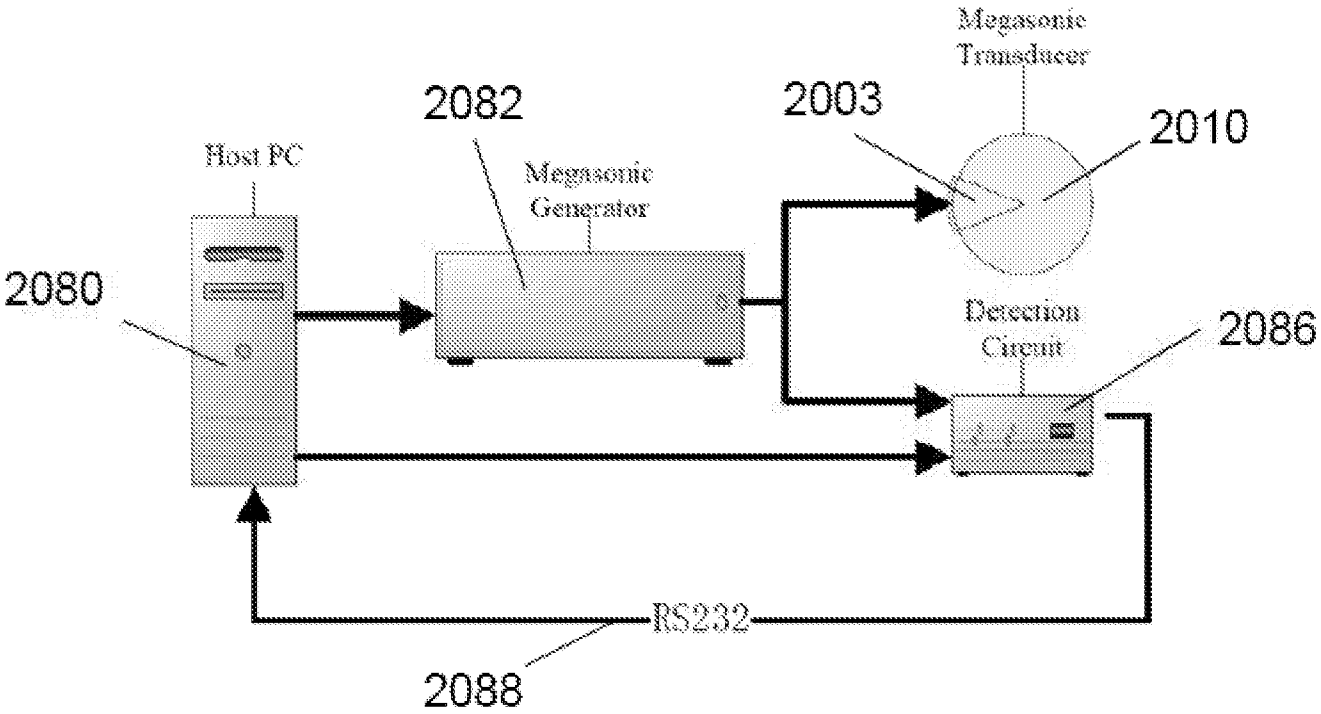

Megasonic
Transducer
2082
2003
2010
Host PC
Megasonic
Generator
2080
Detection
Circuit
2086
RS232
2088

Fig. 20

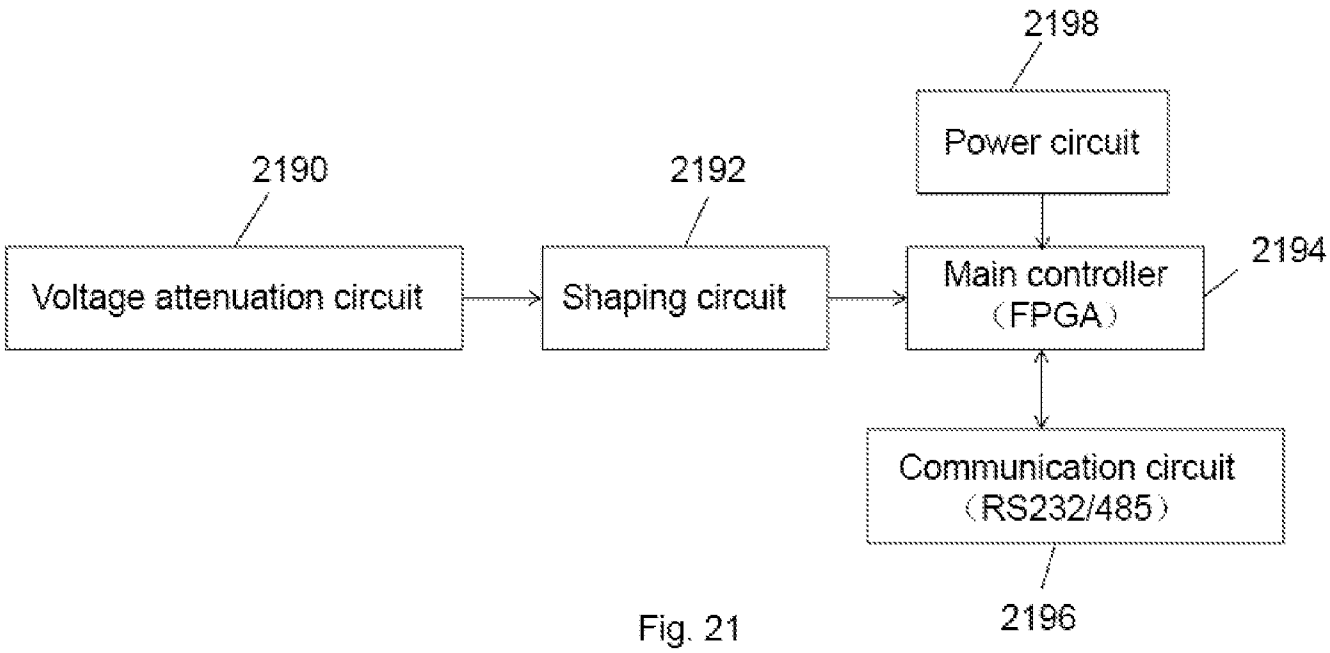

2198
Power circuit
2190
2192
2194
Voltage attenuation circuit
Shaping circuit
Main controller
（FPGA）
Communication circuit
（RS232/485）
2196

Fig. 21

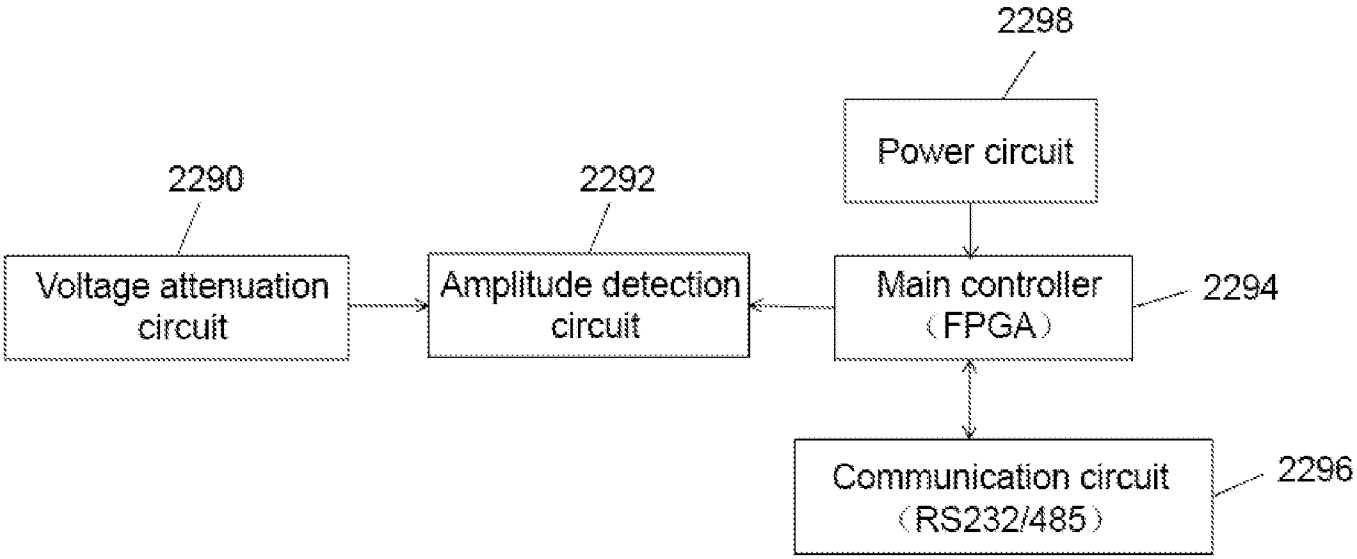

2298
Power circuit
2290
2292
Voltage attenuation circuit
Amplitude detection circuit
Main controller (FPGA)
2294
Communication circuit (RS232/485)
2296

Fig. 22

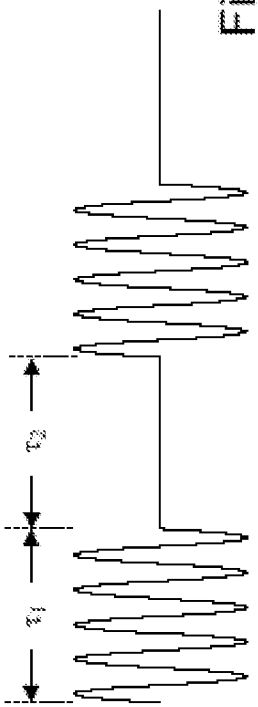


Fig. 23B

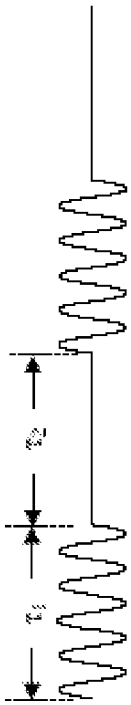


Fig. 23C

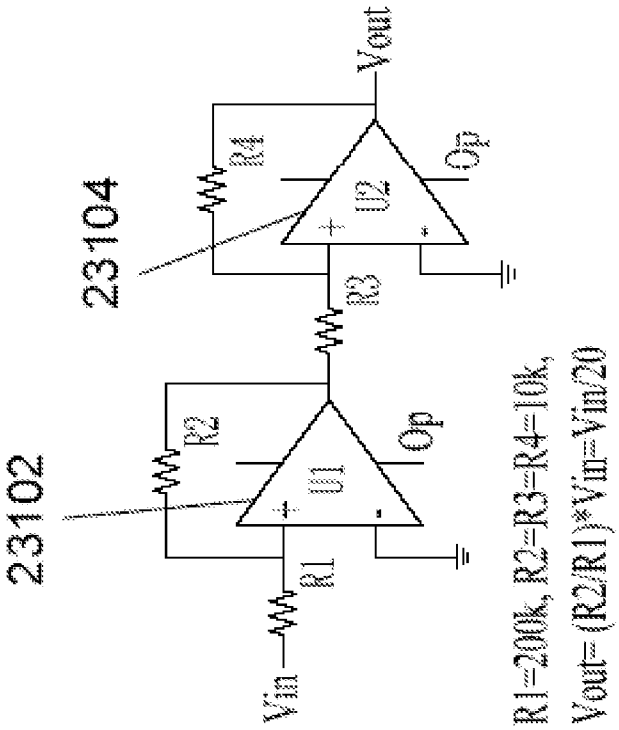


Fig. 23A

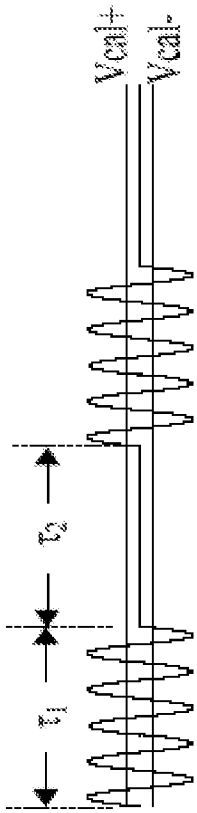


Fig. 24B

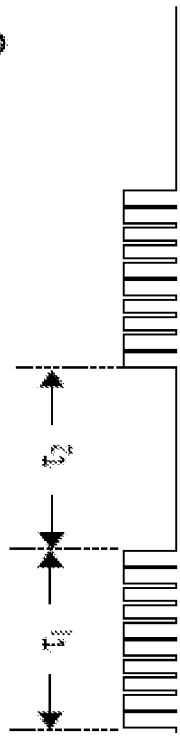


Fig. 24C

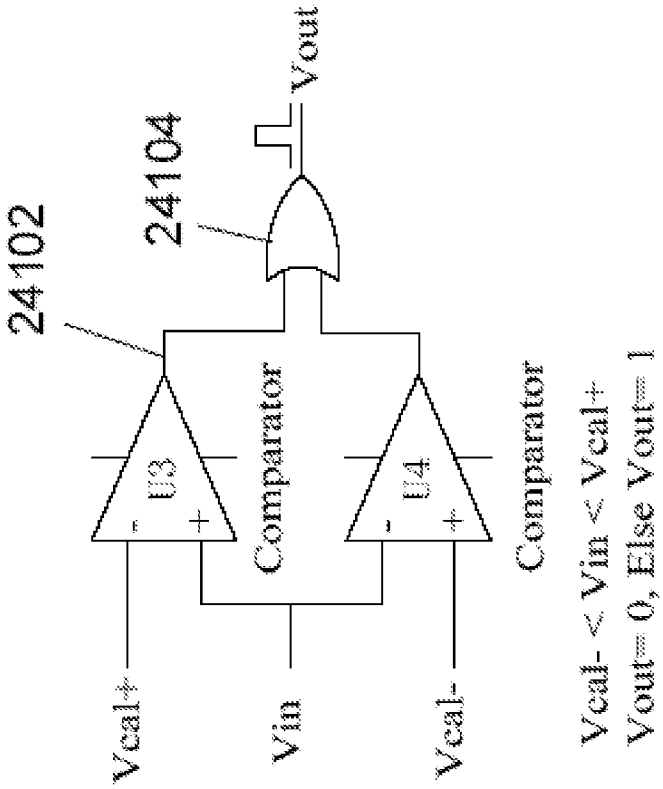


Fig. 24A

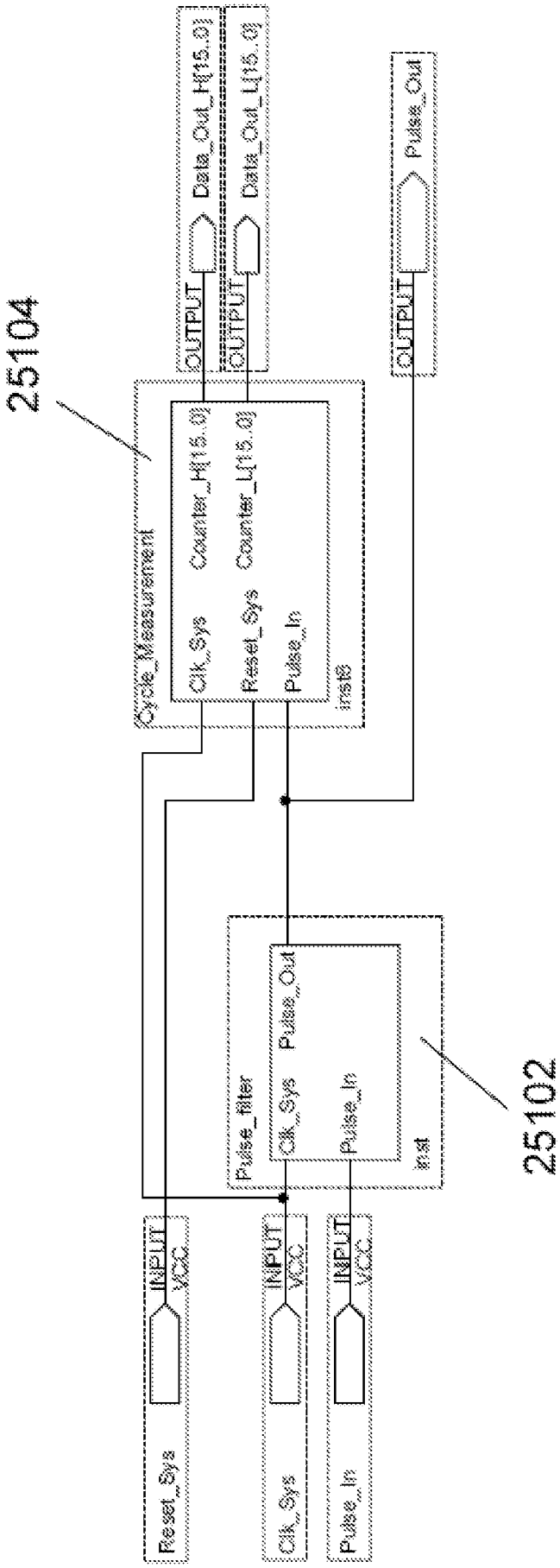

25104
Cycle_Measurement
Clk_Sys
Reset_Sys
Pulse_In
Counter_H[15..0]
Counter_L[15..0]
inst8
OUTPUT
Data_Out_H[15..0]
Data_Out_L[15..0]
Pulse_Out
Pulse_filter
inst
25102
INPUT
VCC
Reset_Sys
Clk_Sys
Pulse_In

Fig. 25A

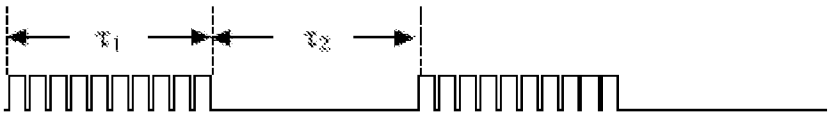


Fig. 25B

Fig. 25C

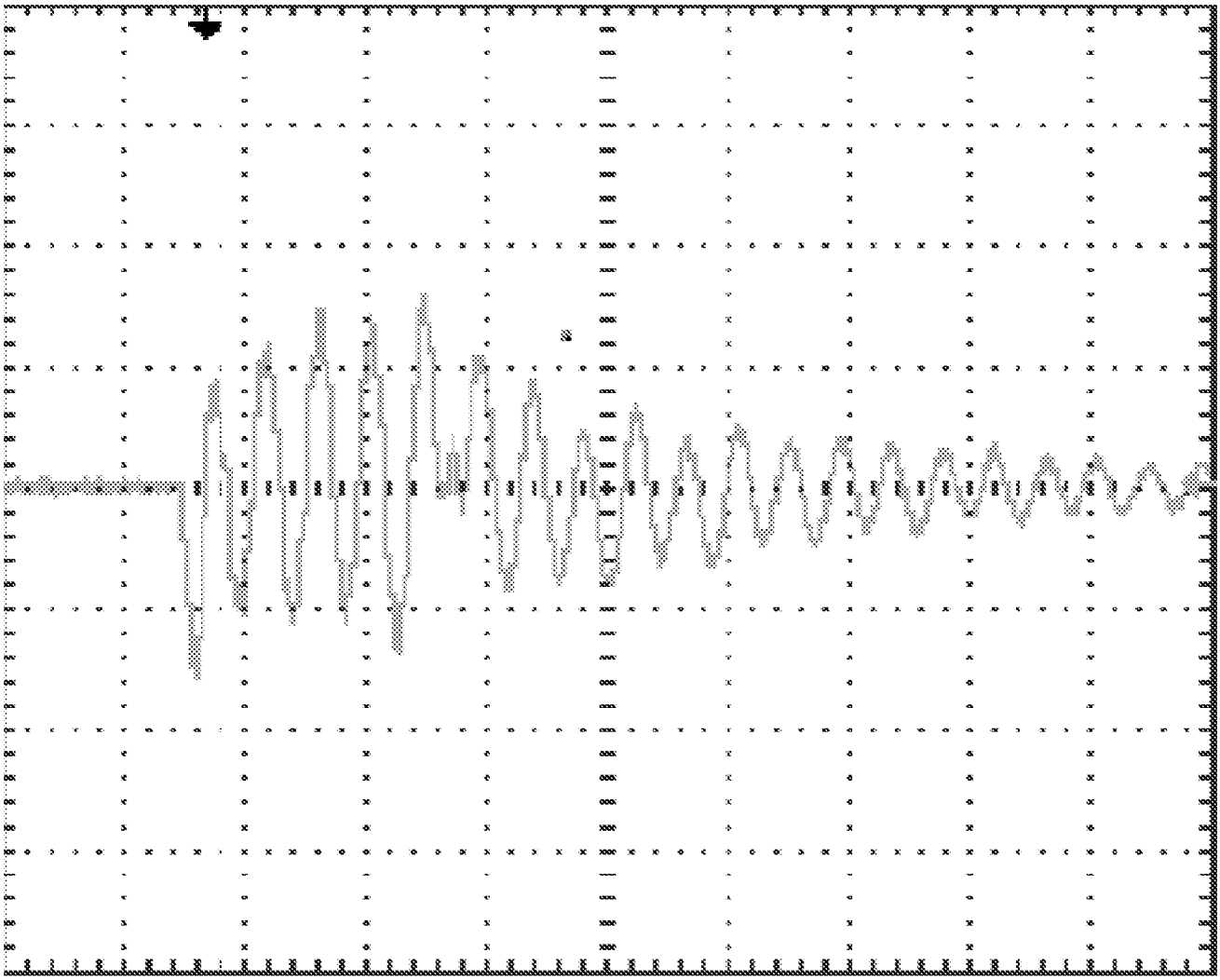


Fig. 26

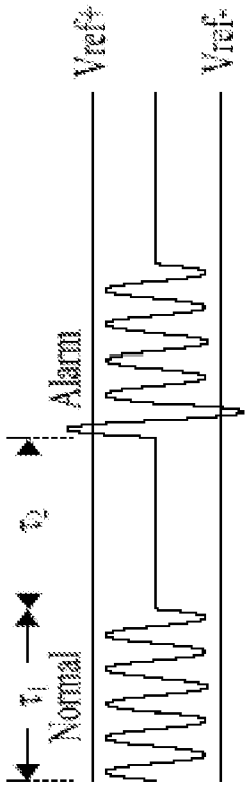


Fig. 27C

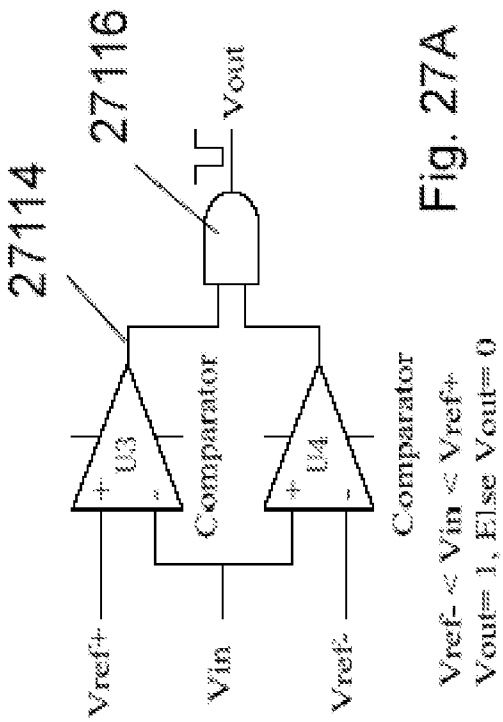


Fig. 27A

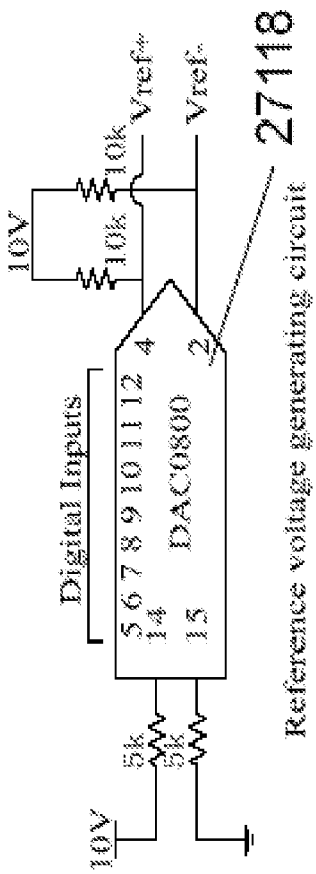


Fig. 27B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2016/078510

A. CLASSIFICATION OF SUBJECT MATTER

H01L 21/67(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01L; B81

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

CNABS,VEN,CNKI: wafer, pellet, crystal w plate, base w circle, substrate, ultra w sonic, mega w sonic, temperature, time, frequecy, power, amplitude

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 104900480 A (ACM RES SHANGHAI INC) 09 September 2015 (2015-09-09) the whole document	1-27
A	CN 104889102 A (ACM RES SHANGHAI INC) 09 September 2015 (2015-09-09) the whole document	1-27
A	CN 105414084 A (BEIJING SEVENSTAR ELECTRONICS CO LTD) 23 March 2016 (2016-03-23) the whole document	1-27
A	US 5044543 A (SHINKAWA KK) 03 September 1991 (1991-09-03) the whole document	1-27
A	US 7119019 B2 (INTEL CORP) 10 October 2006 (2006-10-10) the whole document	1-27

☐ Further documents are listed in the continuation of Box C.

☑ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 December 2016	**11 January 2017**

Name and mailing address of the ISA/CN	Authorized officer
STATE INTELLECTUAL PROPERTY OFFICE OF THE P.R.CHINA **6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088** **China**	**CHEN,Hua**
Facsimile No. **(86-10)62019451**	Telephone No. **(86-10)62085416**

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2016/078510

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
CN	104900480	A	09 September 2015	None			
CN	104889102	A	09 September 2015	None			
CN	105414084	A	23 March 2016	None			
US	5044543	A	03 September 1991	JP	2516806	B2	24 July 1996
				KR	930003141	B1	22 April 1993
				JP	H02224351	A	06 September 1990
US	7119019	B2	10 October 2006	US	2007085162	A1	19 April 2007
				US	2005227488	A1	13 October 2005