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Damage-Free Cleaning of Advanced Structure Using Timely Energized Bubble Oscillation Megasonic Technology

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Abstract. The use of highly corrosive chemicals to remove nano-particles on the surface of the wafer, results in substrate losses. This has resulted in the use of megasonics which provides acoustic cavitation to remove small particles. The megasonic wave does generate bubble cavitation which applies mechanical force to wafer structure, the violent cavitation such as transit cavitation or micro jet will damage the patterned structures [1,2]. A new megasonic technology is proposed in this paper, this technology provides stable control of bubble cavitation, without pattern damage at the different modes. The technology shows better particle performance when compared with the industry standard two-fluid nozzle cleaning technology. This Timely Energized Bubble Oscillation mode provides stable cavitation with a wide power window. It is unlike conventional megasonic which creates transit cavitation and damage when the bubble implodes. This new megasonic technology can be used to clean “sensitive” structures at 28nm and below without any pattern damage.

Introduction

As feature sizes shrink and the density of circuitry structures increase, the “killer defect” the minimum defect size that can cause a chip to fail in a yield test—decreases. It is more difficult to remove random defects from smaller, denser chips, especially when the defect size is smaller than the dimension of the so called “boundary layer” on the wafer surface and the cleaning efficiency drops to near zero. Less force can be delivered to small particles using megasonic cleaning due to the thickness of the boundary layer. The removal of small particles in megasonic cleaning is mainly due to gas cavitation. This conclusion was further supported by sonoluminescence measurements [3,4]. For better particle removal, a study about enhancement of cavitation activity with megasonic found that, the dependency of the optimal pulse-off time on the gas concentration is investigated and an optimal process range for the dissolved gas content is identified pulsed high frequency ultrasound and supersaturation, the choice of the pulsing conditions is constrained by the trade-off between the effective sonication time and the desire to have a sufficient amount of active bubbles. [5]. Conventional megasonic also faces a big challenging due to the damage of fragile pattern structures as the technology node migrates to 40nm and below. The megasonic wave does generate bubble cavitation which applies mechanical force to wafer structure, the violent cavitation such as transit cavitation or micro jet will damage the patterned structures [1,2].

As shown in Fig 1, when cycle numbers of bubble cavitation increase, the temperature of gas and vapor will increase, finally the temperature inside bubble during compression will reach implosion temperature T_i (normally T_i is as high as a few thousands ℃), and violent micro jet forms as shown in Fig. 1C. This bubble implosion generated violent micro jet, as Fig. 2 shows, it can damage the fine patterned structure on the wafer, especially when the feature size shrinks to 40nm and smaller [2,6].

In this paper, a new TEBO (Timely Energized Bubble Oscillation) megasonic technology is applied for damage-free cleaning on pattern wafer. It provides multi-parameter control of bubble cavitation, which involves the formation of stable bubble oscillation using rapid changes of pressure, without bubble implosion or collapse during megasonic cleaning processing and without the pattern damage that result from transit cavitation in conventional megasonic cleaning. This is different from the change of pulse parameters in other literature [5].

Figs. 3A to 3C show a simplified model of bubble cavitation. 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.

The ideal gas equation can be expressed as follows:

$$p_0 v_0 / T_0 = pv/T \tag{1}$$

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

In order to simplify the calculation, assuming there is no change of temperature of gas then there is no change in temperature during the compression or compression is very slow and temperature increase is cancelled by the liquid surrounding the bubble. So that the mechanical work w_m done 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:

$$\begin{aligned} w_m &= \int_0^{x0-1} pSdx = \int_0^{x0-1} (S(x_0 p_0)/(x_0 - x))dx = Sx_0 p_0 \int_0^{x0-1} dx/(x_0 - x) \\ &= - Sx_0 p_0 \ln (x_0 - x) \Big|_0^{x0-1} = Sx_0 p_0 \ln (x_0) \end{aligned} \tag{2}$$

Where, S is area of cross section of cylinder, x_0 the length of the cylinder, p_0 pressure of gas inside cylinder before compression.

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

$$\Delta T = Q/(mc) = \beta w_m /(mc) = \beta S x_0 p_0 \ln (x_0)/ (mc) \tag{3}$$

where, Q is thermal energy converted from mechanical work,β is the ratio of thermal energy to total mechanical energy produced by sonic pressure, m mass of gas inside the bubble, c gas specific heat coefficient.

When the bubble reaches the minimum size of 1 micron as shown in Fig.3B, the high temperature, will cause some liquid molecules surrounding bubble evaporate. After then, the sonic pressure becomes negative and bubble starts to increase its size. In this reverse process, the hot gas and vapor with pressure PG will do work to the surrounding liquid surface. At the same time, the negative sonic pressure PM is pulling bubble to expansion direction as shown in Fig.3C, therefore the negative sonic pressure PM 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 T0 or the liquid temperature.

When the nth cycle of bubble cavitation finishes, the temperature T2n of gas and/or vapor inside bubbler as shown in Fig.1B will be:

$$T_{2n} = T_0 + n\Delta T - n\delta T = T_0 + n(\Delta T - \delta T) \quad (4)$$

Where δT is temperature decrease after one time of expansion of the bubble, and $\delta T$is smaller than ΔT.

As cycle number n of bubble cavitation increase, as shown in Fig.1C. 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 forms as shown in Fig.1C.

From equation (4), implosion time τ_i can be written as following:

$$\tau_i = n_i t_1 = t_1((T_i - T_0 - \Delta T)/(\Delta T - \delta T) + 1) = n_i/f_1 = ((T_i - T_0 - \Delta T)/(\Delta T - \delta T) + 1)/f_1 \quad (5)$$

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

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.4A to 4C shows a method to achieve a damage-free ultra or megasonic cleaning on a wafer with patterned structure by maintaining a stable bubble cavitation according to the present invention. Fig.4A shows waveform of power supply outputs, and Fig.4B shows the temperature curve corresponding to each cycle of cavitation, and Fig. 4C shows the bubble size expansion during each cycle of cavitation. before temperature of gas and vapor inside bubble reaches implosion temperature, set power supply output to zero watts, therefore the temperature of gas inside bubble start to cool down quickly since the temperature of liquid or water is much lower than gas temperature. After temperature of gas inside bubble decreases to room temperature, set power supply at specified frequency and power again. Repeat cycle until wafer is cleaned.

Experimental

Tests were carried out on an ACM single wafer cleaning tool, equipped with TEBO (Timely Energized Bubble Oscillation) megasonic. The process used TEBO megasonic with functional water (ultra-dilute ammonia with dissolved H_2 gas), instead of traditional standard Clean 1 (SC1) solution, to remove fine particles. [7]. Fig. 5 shows the experimental apparatus with a TEBO megasonic device.

PRE (Particle Removal Efficiency) test was processed with blanket silicon wafers coated with 60nm PSL particles applied using spin coating and the particle count measured on a KLA-Tencor Surfscan SP3 prior to and after cleaning. In this test, PRE is calculated with the formula [(Pre-Post/Pre)*100].

To verify the TEBO megasonic cleaning technology with different modes did not create pattern damage, wafers with fragile structure were also used in the test. There are two types of pattern wafers, Type 1 were Si-Ge loop pattern wafers, in this structure the oxide cap covered on the poly gate was removed and polysilicon is exposed as in Fig. 6. Type 2 were poly gate pattern wafers, the poly-Si gate CD size is 28nm with aspect ratio of 1:5.

Result and Discussion

The PRE test results with different TEBO modes on blanket wafers are shown in Fig. 7.

It is shown that PRE increases as megasonic power increases. Most of particles were removed at each TEBO mode, and the particle remove efficiency is more than 80% with the different TEBO megasonic mode and power.

The same TEBO cleaning processes which was used to process the blanket silicon wafers as shown in Fig. 4 were applied to wafers with the damage-sensitive structures, the pattern damage status was observed by a bright-field defect inspection tool.

The cleaning efficiency was compared between conventional jet spray and TEBO megasonic with both Si-Ge loop pattern wafers and poly gate pattern wafers. Table 1 shows the combined particle performance and Damage evaluation. From the test results, TEBO megasonic cleaning process has significant improvement of particle performance with no pattern damage with different TEBO megasonic mode and power.

The same mode with different power showed different properties. From Type 1 (Si-Ge loop pattern wafer) test, mode 2 with megasonic power 30w, 40w and 50w, the higher the energy, the better the particle removal effect. Meanwhile, no pattern damage occurred in this mode.

Fig. 8 shows a SEM image of one test condition: Si-Ge loop pattern wafers, mode 2, 50W, which no damage occurred and all particles were removed.

Fig. 9 shows Si-Ge loop pattern wafers tested with mode 2 and 40w defect distribution map and review data, only one remaining tiny surface particle was not removed.

From Type 2 (poly gate pattern wafer) test, mode 3 with megasonic power 30w, 40w and 50w, only one condition found defect, after review, it is found that it is pattern damage. Fig. 10 shows poly gate pattern wafer tested with mode 3 and 50W, defect distribution map and review data, it is easy to see that one of the lines has been knocked off.

Under the same megasonic power, different modes also show different properties, taking 50w as an example. In the test of Type1, mode 3 is more damaging to the pattern structure than mode 2. As can be seen from Fig. 11, several adjacent lines have been completely stripped away.

From the experimental results, choosing the suitable TEBO megasonic mode and power can get satisfactory particle removal performance without pattern damage. It is well known that cavitation induced bubble explosion is the main reason of pattern damage.

Conclusion

A new megasonic technology is proposed in this paper, this technology provides stable control of bubble cavitation, without pattern damage at the different modes. The technology shows better particle performance when compared with industry standard fluid nozzle cleaning technology. This TEBO mode provides stable cavitation with a wide power window. It is unlike conventional megasonic which creates transit cavitation and damage when the bubble implodes. This timely energized bubble oscillation technology can be used to clean “sensitive” structures at 28nm and below without any pattern damage.

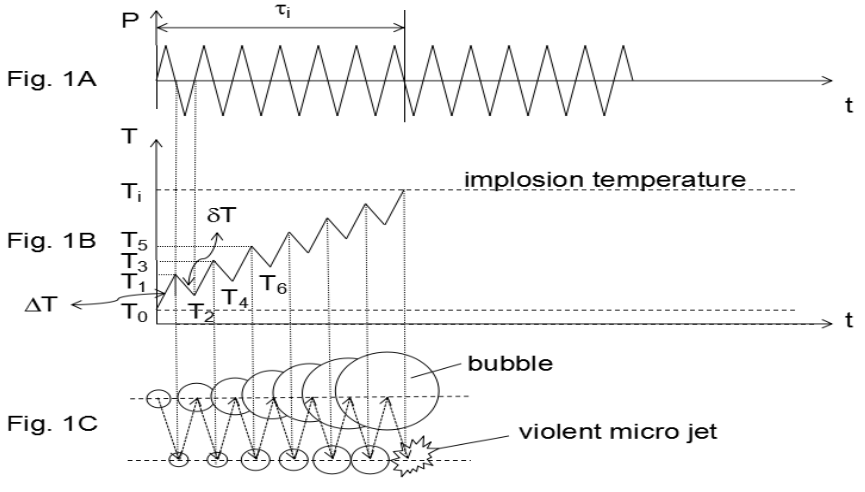

Fig. 1: Simplified Model-Conventional Megasonic Cleaning

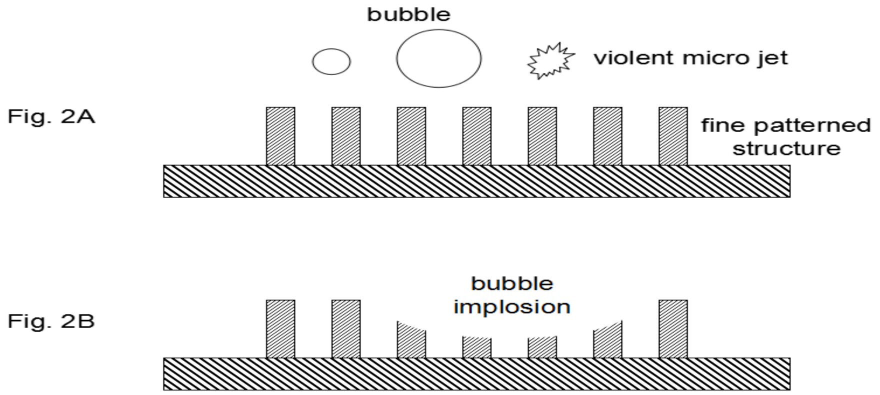

Fig. 2: Violent cavitation leads to pattern damage

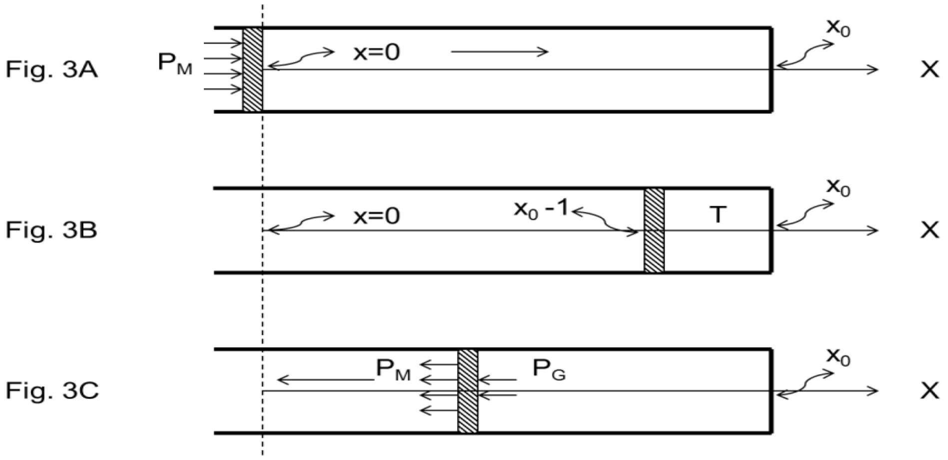

Fig. 3: Simplified model of bubble cavitation

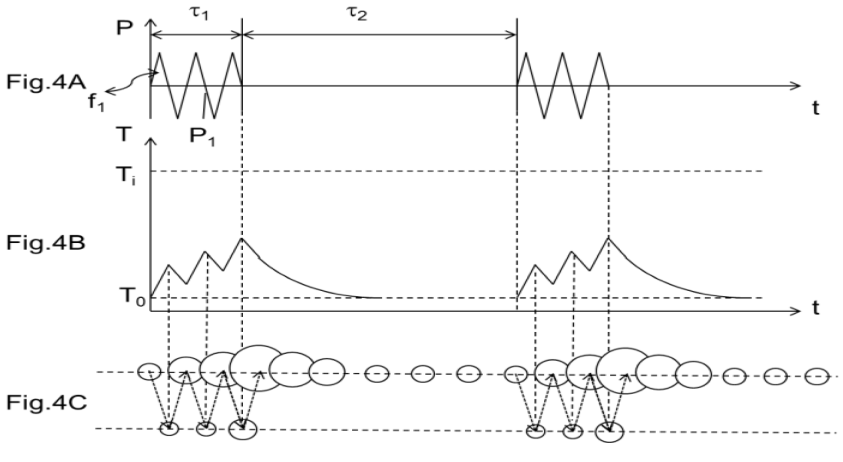

Fig. 4: Simplified Model- TEBO Megasonic Cleaning

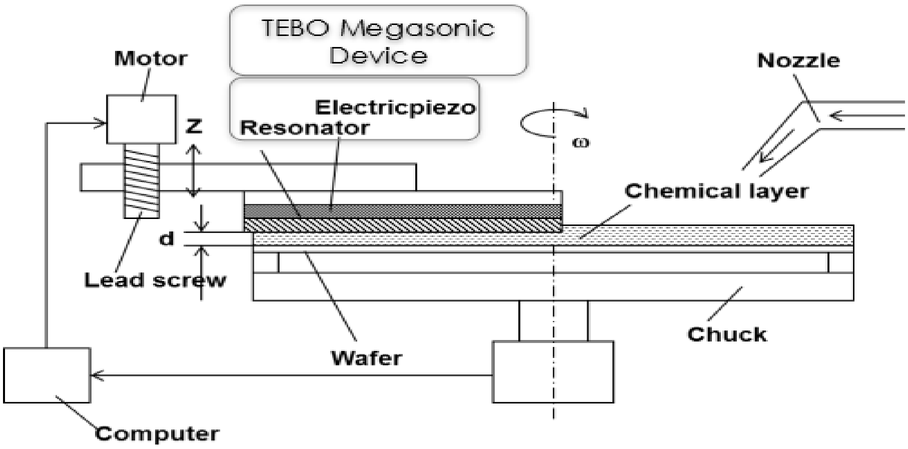

Fig. 5: Wafer cleaning apparatus using TEBO megasonic device

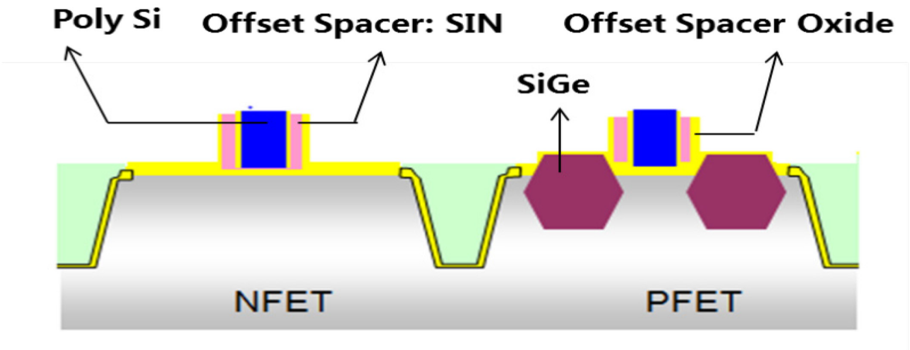

Fig. 6: Wafer cross section of Si-Ge Loop pattern wafer structures

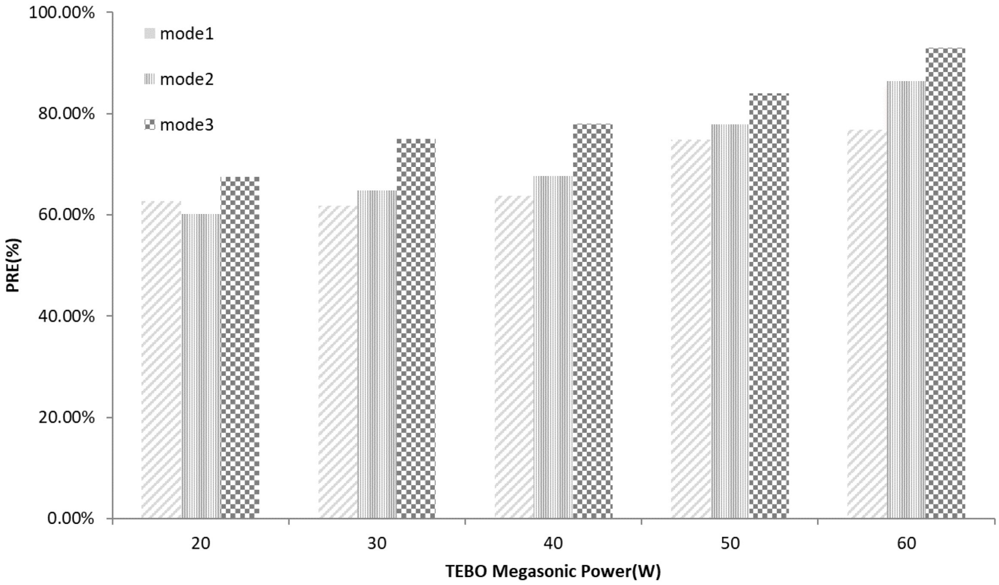

Fig. 7: Particle removal efficiency of different TEBO mode with f-water, particle size@60nm

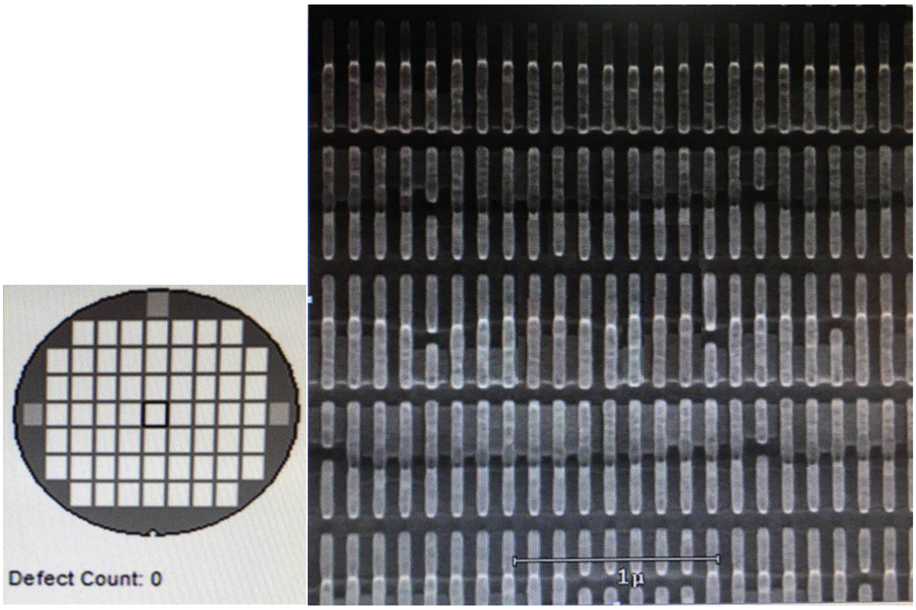

Fig. 8: Si-Ge loop pattern wafers, mode 2, 50W SEM data

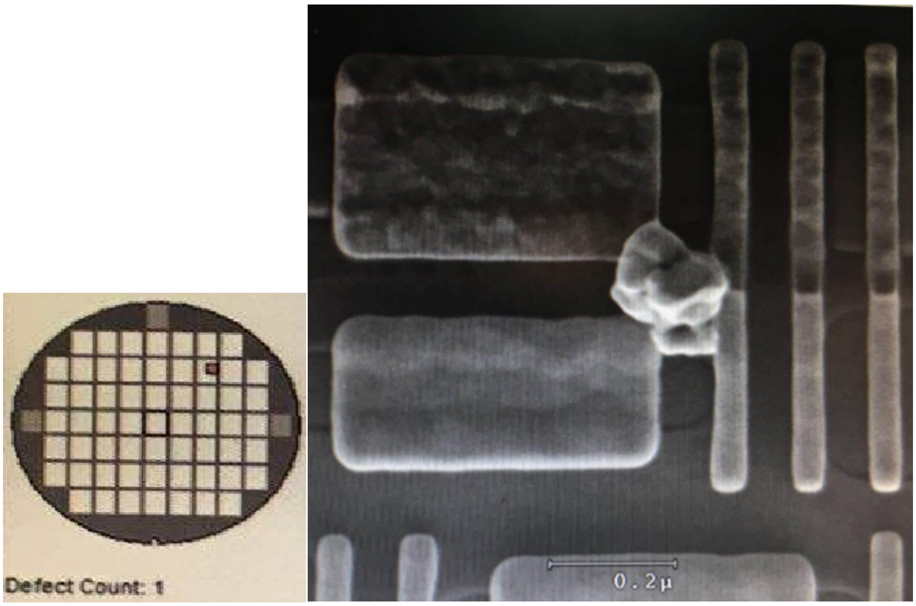

Fig. 9: Si-Ge loop pattern wafers, mode 2, 40W defect distribution map and review map

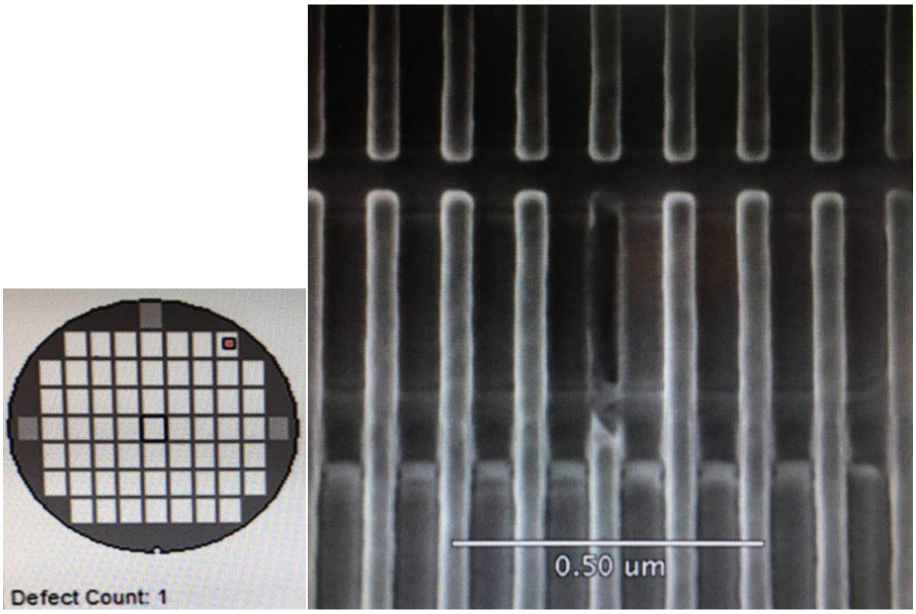

Fig. 10: Poly gate pattern wafer, mode 3, 50W defect distribution map and review data

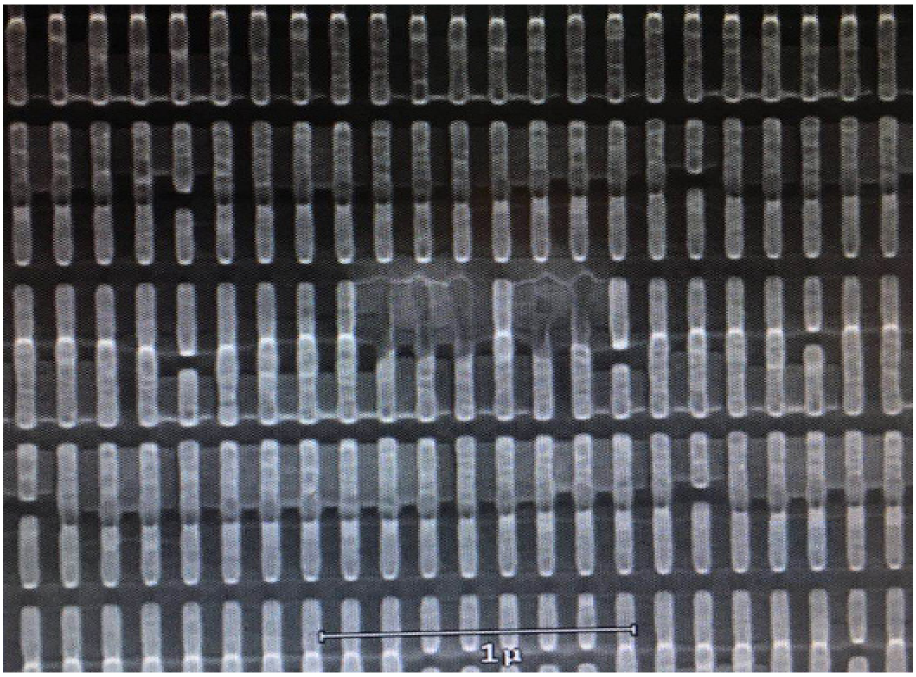

Fig. 11: Si-Ge loop pattern wafers, mode 3, 50W defect review data

Table 1: Comparison of different TEBO modes in terms of damage and particle performance, Conventional two-fluid nozzle Spray: SC1 flow:100ml/min; N2 flow: 20L/min

Structure	Cleaning Method	TEBO Mode	Chemical	Megasonic Power/W	Pattern Damage Y/N	Damage Count	Normalized Particle remaining
Si-Ge loop pattern wafers	two-fluid nozzleSpray	SC1 flow 100ml/min. N2 flowrate: 20LPM)	SC1	NA	N	0	4
					N	0	6
					N	0	7
	TEBO Megasonic	Mode 1	DIO3 & Ultra Dilute NH4OH	30W	N	0	4
				40W	N	0	3
				50W	N	0	0
	TEBO Megasonic	Mode 2	DIO3 & Ultra Dilute NH4OH	30W	N	0	3
				40W	N	0	1
				50W	N	0	0
	TEBO Megasonic	Mode 3	DIO3 & Ultra Dilute NH4OH	30W	N	0	1
				40W	N	1	0
				50W	Y	5	0
Poly	TEBO Megasonic	Mode 1	DIO3 & Ultra Dilute NH4OH	30W	N	0	0
				40W	N	0	0
				50W	N	0	0
	TEBO Megasonic	Mode 2	DIO3 & Ultra Dilute NH4OH	30W	N	0	0
				40W	N	0	0
				50W	N	0	0
	TEBO Megasonic	Mode 3	DIO3 & Ultra Dilute NH4OH	30W	N	0	0
				40W	N	0	0
				50W	Y	1	0

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