Damage-Free Cleaning of Sub-50 nm Devices Using Directed Megasonics Technology in a Single Wafer Processor

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Introduction

It has been well established that single wafer cleaning tools can achieve reduced cycle times and improved cleaning performance relative to batch tools. Recently, a unique immersion-based single wafer processor, the Emersion$^{\text{TM}}$, was shown to achieve damage-free megasonic cleaning of sub-50 nm device structures with a corresponding high particle removal efficiency (PRE) [1]. In this paper, we investigate the mechanisms of cleaning and damage-free processing with the Emersion multiple transducer chamber. We present particle removal efficiency, sonoluminescence imaging data, and megasonics damage results for a wide range of operating conditions. These results are used to propose a model for the operation of the multiple transducers in the chamber.

Megasonics Transducer Configuration in Emersion Chamber

The Emersion single wafer chamber utilizes a unique configuration of three megasonic transducers. A key design objective was to take advantage of the exposure of the entire wafer surface, allowing for the application of multiple acoustic wavefronts to the wafer. It was expected that the combined action of these wavefronts would allow for the use of reduced megasonics power levels and reduced process times to eliminate damage without sacrificing cleaning.

The schematic shown in Fig. 1 shows the incorporation of three transducers into the processing chamber. The bottom transducer is similar in function to batch transducers. The front transducer introduces an oblique angle acoustic wavefront to the front(device) side of the wafer, while the back transducer introduces a similar wavefront to the backside of the wafer. The wafer is lifted via vertical sweeps, in order to completely pass through the upper transducer wavefronts multiple times. During processing, the bottom transducer is on during the entire process time of 30 seconds. Since the upper transducers are turned on only during the sweep sequences, the exposure time of any die on the wafer to the megasonics power is limited to milliseconds, thereby minimizing damage.

PRE Testing and Results

Fig. 2 summarizes results of a full factorial design of experiments which investigated the effects of transducer configuration and power level on particle removal efficiency. PRE tests were conducted using a 30 second dilute SC1 process on aged Si_3N_4 challenge wafers deposited by wet adsorption. The ternary plot shows a well defined center region where high PRE values are realized. Many of the data points within this region were achieved using surprisingly low megasonics power levels on the multiple transducers(eg. $<0.3\ W/cm^2$). Table 1 summarizes the effect of configuration and total power on the PRE showing that the configuration of the transducers is more important than the total power applied. The lowest total power case produced a much higher PRE than the highest total power case. The ability to achieve PRE values >95% using a dilute SC1 solution with a process time of only 30 seconds is unusual, given that traditional SC1 cleaning mechanisms rely upon etching and undercuttingof particles. Therefore, the transducer interactions are playing a major role.

Table 1: Effect of Megasonics Configuration and Total Power on PRE, showing importance of configuration .

Configuration in W/cm^2 (Bottom/Front/Back)	*Total Power Density(W/cm^2)*	*PRE(%)*
0/0/0.75	.75	95
1.2/0/0	1.2	39
0.2/0.2/0.2	0.6	92

Sonoluminescence Testing and Results

The PRE results described above suggested that some unusual acoustic effects were occurring in the chamber. The most likely explanation was thought to be cavitation events and possible Lamb wave generation. In order to provide a direct indication of these phenomena, sonoluminescence imaging was performed. Sonoluminescence refers to the photon emission that occurs when a collapsing cavitation bubble heats the gas within to temperatures that are high enough to generate incandescent light. In these tests an optical imaging system was mounted on top of the Emersion chamber to quantitatively measure sonoluminescence within the chamber, as shown in Fig. 3a. Several combinations of transducer configuration and power were investigated. Figure 3b shows a typical light intensity distribution looking down into the chamber. In this image, the front and bottom transducers were each powered to a value of <1W/cm^2. The dark region corresponds to the wafer interior and backside. The large bright spots are due to the collapse of large gas bubbles in the off-site test stand that did not use degassed DI water. The same data is plotted in Fig. 3c in 3-d form. It is evident that the cavitation reaches a maximum at the wafer front surface. Similar data for other configurations and power levels is summarized in Fig. 4. This curve shows the photon intensity profile along the axis between the two transducers, with the wafer front surface located at X= -0.2cm. The notation for the power densities is “bottom /front /back”. It is evident from these results that the front and back transducers play a dominant role in increasing the cavitation. The flat line curve at low bottom power was used to demonstrate the signal to noise ratio. The case with high power applied to the back transducer(0/0/1.9 W/cm^2) gave an unusual, but not unexpected result, as shown in Fig. 3d and Fig. 4. The expected large number of cavitation events at the wafer backside is clearly seen. However, it is important to note the high level of cavitation on the front side of the wafer. Previous studies have implicated the presence, and the damaging effects, of Lamb waves when backside transducers are used in single wafer spin systems [2]. However, *this is the first reported case of acoustic cavitation caused by the use of backside megasonics*. This explains the high PRE for this case. The low power condition with all three transducers firing at 0.2W/cm^2 showed a very uniform cavitation profile, which gave a high PRE of 92%.

Megasonics Damage Results

Table 2 summarizes megasonics damage results on 70nm poly-Si lines for several cases of interest with the corresponding PRE and sonoluminescence data.

Table 2: Effect of Megasonics Configuration and Power on PRE, 70nm Device Damage and sonoluminescence

Configuration (W/cm^2)	*PRE (%)*	*No. Damage Sites*	*Sonoluminscence @ wafer front side (arb. units).*
0.6/0.7/0	92-98	0	14.9
0/0/1.9	95	598	21.7
0/0/0.7	24	139	NA
0.2/0.2/0.2	92	NA	10

Data collected on 45 nm poly-Si lines showed similar trends, although the data set is not as complete. The configuration with a balanced power distribution of <1 W/cm^2 on the bottom and front transducers produced a high PRE without statistical damage. It is interesting to note that when low power levels were used, the number of damage sites was usually either zero or in single digits. Further investigation into this effect is ongoing. A typical isolated damage site is shown in Fig. 5.

Theory of Megasonic Cleaning and Damage with Multiple Transducers

Particle removal mechanisms from the bottom transducer are identical to those of similar transducers in a batch tank, but are enhanced due to the higher convective and acoustic streaming flow rates. However, the bottom transducer acting alone cannot achieve high PRE values. The highest PRE values are only achieved when a combination of two or more transducers are used. The front transducer, acting directly upon the device side of the wafer has been shown to result in a significant improvement in PRE, especially when acting in concert with the bottom transducer. The sonoluminscence results show that the cavitation intensity is much larger and more uniform for the combined transducers. It appears that the close proximity of the front transducer, which is incident at an oblique angle, concentrates the megasonics energy at the fluid/air interface which the wafer travels through during sweeps. The optimized sweep rate enhances particle removal but limits the exposure time of any individual wafer die to milliseconds to avoid device damage.

The sonoluminescence results indicate that much of the improvement in PRE with multiple transducers is due to cavitation from the back transducer. Since there are no direct acoustic effects acting on the wafer front side, we propose that Lamb waves created within the wafer are responsible for both the high PRE and damage (only at high power levels). The back wave, incident upon the wafer backside at an angle,θ, results in reflected, transmitted and absorbed waves. Since direct transmission through the wafer is unlikely at oblique angles, much of the incident energy will be absorbed in the wafer. The absorbed component causes flexural vibration of the wafer, known as Lamb waves [3]. These vibrational states are resonant nodes that can create significant shear stresses and pressure gradients which cause device damage. Continuity of wave motion at the interface between the surface and the fluid requires that the solid(wafer) displacement wave, λ_S, generate a longitudinal wave in the fluid, λ_l , as given by Eq. 1. It is this regenerated wavefront on the front side of the wafer that results in the unusual cleaning, and sonoluminescence results.

$$\lambda_S = \lambda_l \csc \theta \qquad (1)$$

Equation 1 and previous studies [2, 3] indicate that there exists an optimal angle θ that will produce maximum vibrational intensity. Of course, the front transducer, which is incident at the same oblique angle, can also contribute to Lamb wave generation. The combined effects of all three transducers enhance the traditional particle removal forces (e.g., hydrodynamic rolling moments, acoustic cavitation), and introduce additional removal mechanisms from energy concentration at the wafer/fluid/air interface and from Lamb waves.

Summary

The high PRE values achieved with the Emersion single wafer cleaning system are believed to be due to a combination of enhanced particle removal forces and an increased number of acoustic cavitation events which result from the use of combined acoustic wavefronts. It was demonstrated that the use of three transducers acting with low power densities can achieve a PRE of > 95%.

Key findings of this study include: 1) the generation of Lamb waves in the wafer by wavefronts incident on the back side; 2) the generation of a secondary fluid wavefront on the wafer front side from these Lamb waves; and 3) the first reported correlation between Lamb waves and acoustic cavitation events on the wafer front side.

References

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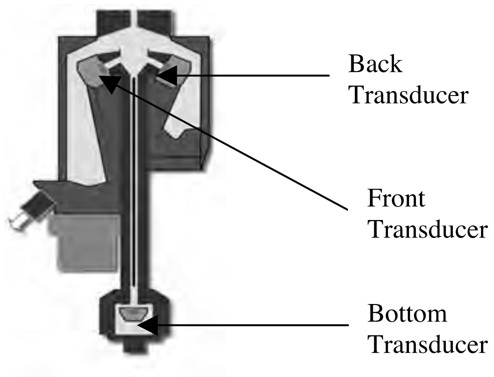


Figure 1: Emersion chamber diagram.

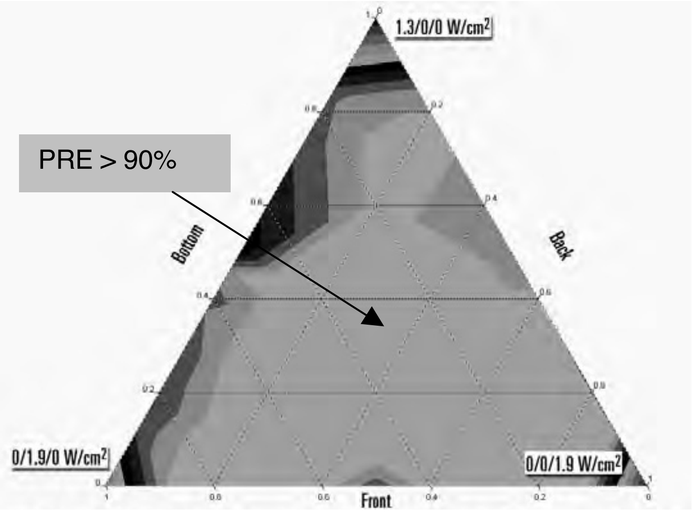
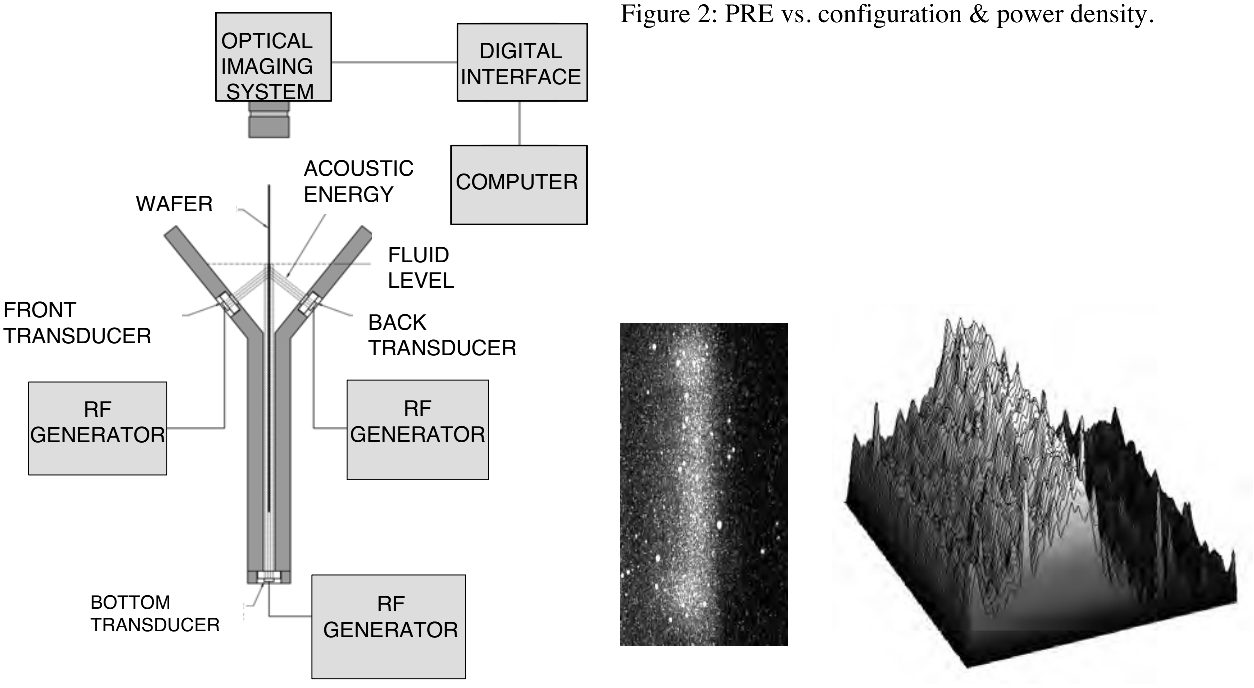
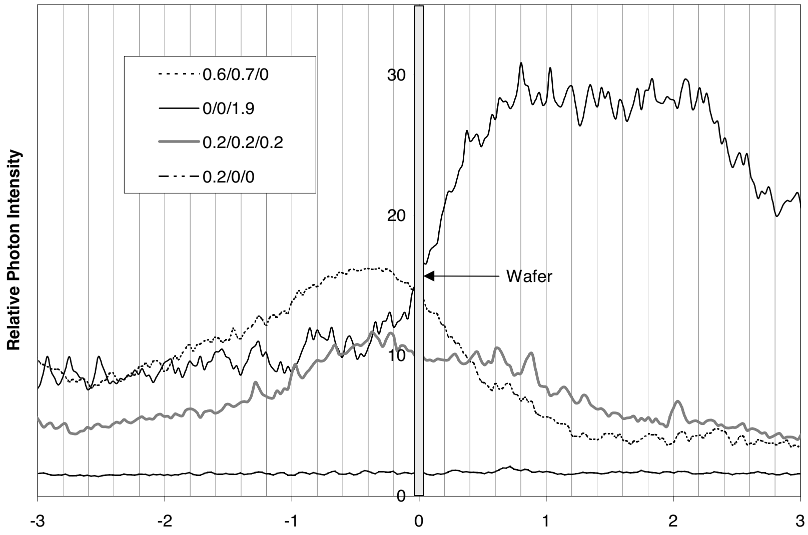


Figure 2: PRE vs. configuration & power density.



(a) (b) (c)

Figure 3: Sonoluminscence Measurements; a) test equipment;
b) and c) photon imaging results for bottom and front transducers turned on.



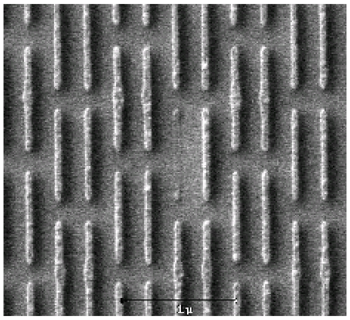


Figure 5. Isolated damage location on 45nm test structures.