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Impact of Acoustical Reflections on Megasonic Cleaning Performance

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Electrical measurements have shown a direct impact of reflection of acoustic waves back into a transducer. Impedance measurements illustrate in specific cases the existence of multiple resonance peaks when reflected acoustic waves are present. Current and voltage measurements have confirmed this result. From these results, one can already conclude that acoustic reflections have a large impact on the operation of a transducer. Furthermore, it is shown that for megasonic cleaning tools with a face-to-face configuration of transducer and wafer, a precise control over the distance (control over the reflections) between the transducer and wafer is very important. Particle Removal Efficiency (PRE) measurements immediately show a major dependence on the position of the wafer. The PRE dependence is directly linked to the forward power consumed by the transducer, which is largely influenced by the position of the wafer or, in other words, by the reflection of acoustic waves.

Introduction

The performance of the megasonic cleaning effect is dependent on several process parameters (e.g. frequency (1), dissolved gas in the cleaning liquid (2,3), applied power (3), acoustic field geometry (4), refreshment of the cleaning liquid, wafer positions, chemical concentrations (5), …). However, the importance of each individual process parameter is still not sufficiently clear, although megasonic cleaning is widely used in the semiconductor industry. Even the physical mechanisms, which are responsible for the removal of particles (Schlichting streaming, microstreaming and acoustic cavitation), are still under debate. The underlying reason is that basic physical processes and forces, which are involved in the cleaning process, are little understood. All these uncertainties make it very difficult to optimize megasonic cleaning tools to the ever more stringent requirements of the semiconductor industry. The process window of physical forces in which structures can be cleaned without creating damage narrows continuously. As a result, a precise control over the physical forces during megasonic cleaning is extremely important. A more thorough insight into the fundamentals of megasonic cleaning is therefore one of the first and necessary steps to optimize megasonic cleaning.

Here, it is shown that the acoustic field geometry can have a large impact on the performance of megasonic transducers. A reflection of acoustic waves back into a transducer imposes mechanical constraints on the piezoelectric material. This effect can be described with electrical and stress-strain relationships, which are applicable to piezo-electric materials (6);

$$D_i = \varepsilon_{ij} E_j + e_{ijk} T_{jk} \qquad [1]$$

$$\sigma_{ij} = e_{ijk} E_k + s_{ijkl} T_{kl} \qquad [2]$$

where D is the electrical displacement, σ is the strain field, E is the electrical field, T is the stress field, e is defined as the piezo-electrical strain constants and ε and s describe the dielectric and elastic properties under conditions of constant stress and constant electric field, respectively. A confinement of piezoelectric material when an electric field is applied, results in stress (eq. 2). This stress contributes to the electrical displacement and changes the relation between *E* and *D*. As a result, acoustic reflections back into a transducer changes the electrical behavior of a transducer.

Experimental

Experimental set-ups

All described tests have been performed with a face-to-face configuration between the transducer and the wafer or damping material. Two different megasonic tools are used to demonstrate the effect of acoustic reflections on the performance of a transducer. The first experimental system is a 200 mm single wafer megasonic tool (see Fig. 1(a)). A 1 MHz megasonic nozzle is moved at a constant speed over the rotating wafer and will be

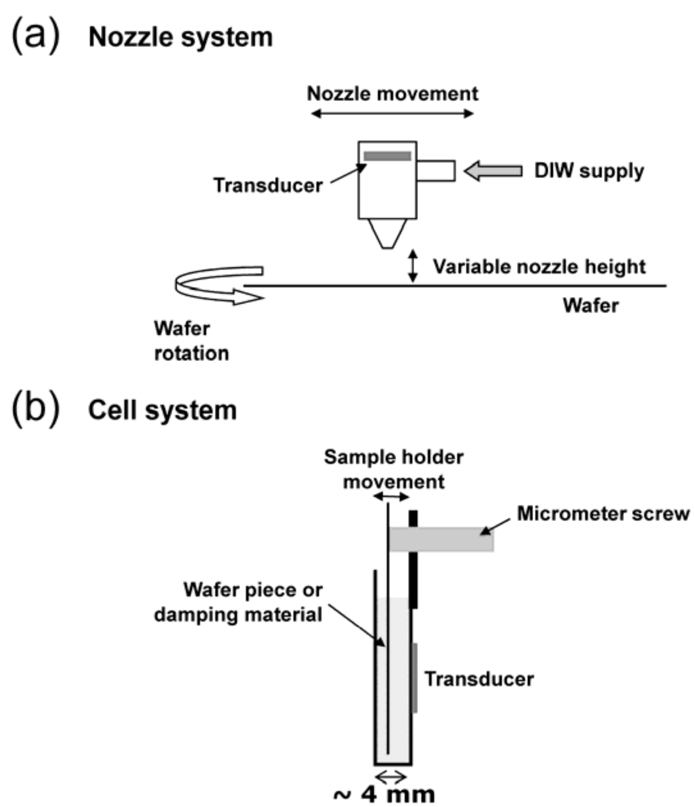

Figure 1. Schematic representation of the experimental setups, e.g. the nozzle (upper image) and the small cell system (lower image)

referred to as the nozzle system (7,8). The active diameter of the cylindrical megasonic transducer is 11 mm. The liquid is flowing out of the exhaust port of the nozzle and the acoustic waves are propagating within the resulting liquid-column. The acoustic waves are converged to a point in the vicinity of the exhaust port, which is about 4 mm below the exhaust (9). The height of the nozzle can be adjusted with an accuracy of 10 µm with respect to the center of the wafer. The cleaning liquid is DIW with a controlled amount of dissolved O_2 gas. All results shown in this paper are obtained with a nozzle speed of 50 cm/min, a wafer rotation of 1000 rpm and a water flow of 1.5 l/min. The water was saturated with O_2 gas. The second system is a small megasonic cell with the same type of transducer mounted to a glass cell (see Fig. 1(b)). The liquid is DIW and the dissolved gases are not controlled. The inner dimensions of the cell are 4 x 20 x 40 mm^3 and a sample piece or thin damping material can be immersed in the cell.

The transducers of both systems are driven by a combination of a function generator and an amplifier. The electrical signals delivered to the transducers are measured with a current and voltage probe, which are directly connected to an oscilloscope. Furthermore, the piezoelectric transducer of the cell is also characterized by impedance analyzer measurements. The electrical impedance measurements are made with an Agilent HP 4294 impedance analyzer.

Results

Influence of acoustic reflections on the electrical properties of a transducer

Electrical measurements can give an idea about the resonance frequency of the transducer and the acoustical power delivered to the liquid. It is known that impedance analyzer measurements can be influenced by reflections and acoustical standing waves in the propagating medium (10). For the electrical impedance measurements, a wafer piece or a thin slice of damping material (Aptflex F28, 1.5 mm thick) is placed in front of the transducer at a distance of only a few mm. Figure 2 shows measurements of the impedance and phase as function of the frequency. The left and right axes show the impedance and phase, respectively. The left column represents the measurements when a wafer piece is present and the right column shows the tests with a thin slice of damping material in front of the transducer. In both cases, the distance to the transducer is varied, and some typical results are shown in Fig. 2. The duration of each measurement point is sufficiently long so that a standing wave between the wafer and transducer is developed. The real part of the impedance and the phase angle are measured in the frequency range of 0.9 to 1.1 MHz in steps of 0.5 kHz. The measurements clearly show an influence of reflected acoustic waves on the impedance and phase data. The acoustic reflections can be decreased by using a damping material (right column in Fig. 2) and, in this case, only one resonance peak for both phase and impedance can be detected, which is the fundamental resonance of the transducer. The frequency-offset between the phase and impedance data is attributed to the parasitic capacitance of the transducer that is resulting from the small thickness of the utilized piezoceramic and its high dielectric constant. Furthermore, the WFHM of the impedance peak is quite large (around 40 kHz), which is caused by a thin slice of damping material that is unable to absorb all the acoustic waves. A variation of the distance between transducer and damping material has only a minor effect on the impedance peak, because its width and position vary only slightly. If a wafer piece is present (left column Fig. 2), the impedance peaks change drastically. At several wafer positions, more than one impedance or phase peak is present. The FWHM of the impedance peak is much smaller (~ 15 kHz) compared to the case when the damping material is used. The existence of several resonance peaks at certain wafer positions can make it difficult to use a feedback loop that corrects for a shift of the resonance frequency. To conclude, acoustic reflections have a large impact on the resonance frequencies of a transducer.

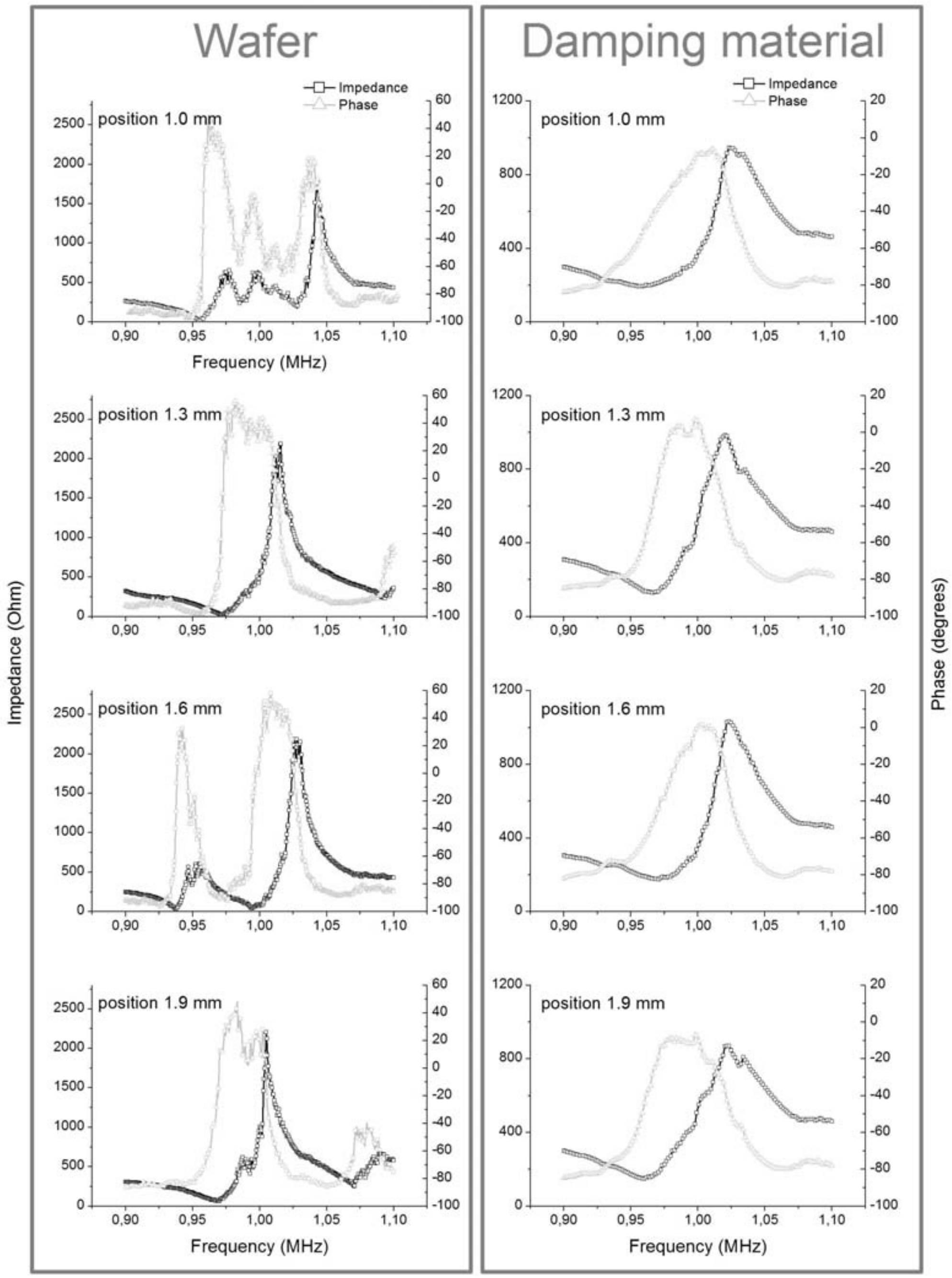

Figure 2. Impedance and phase measurements of the transducer as function of the frequency. The left column shows graphs when a wafer is inserted at 4 different distances from the transducer, while the right column shows the same measurements when the wafer is replaced with a piece of damping material.

In order to get an overview of the resonance dependence of the transducer on the reflection of acoustic waves, the small cell was connected to an amplifier/function generator setup. For each position of the damping material or wafer piece, the frequency that corresponds to a zero frequency shift between the voltage and current signal is plotted. In the upper image of Fig. 3, the resonance frequency is plotted as function of the distance between the damping material (minimizes acoustic reflection) and the transducer. There was always only one resonance frequency present; however, a zero phase shift could not be obtained completely for all damping material positions. The origin of this non-zero phase shift is the fact that a clamping capacitance is associated with a transducer element. During the measurements, the clamping capacitance was not corrected for, which means that the real resonance frequency lies not exactly at a zero phase shift.

In the lower part of Fig. 3, the damping material is replaced by a wafer piece. The difference between both images in Fig. 3 immediately shows the huge impact of acoustic reflections back into a transducer. At certain wafer positions, several resonance frequencies are present. It is even possible that the current waveform is clearly distorted (several frequencies present in the Fourier transform of the signal) for some resonance frequencies. Both images in Fig. 3 show a clear periodicity, which corresponds to half of the wavelength of the acoustic waves.

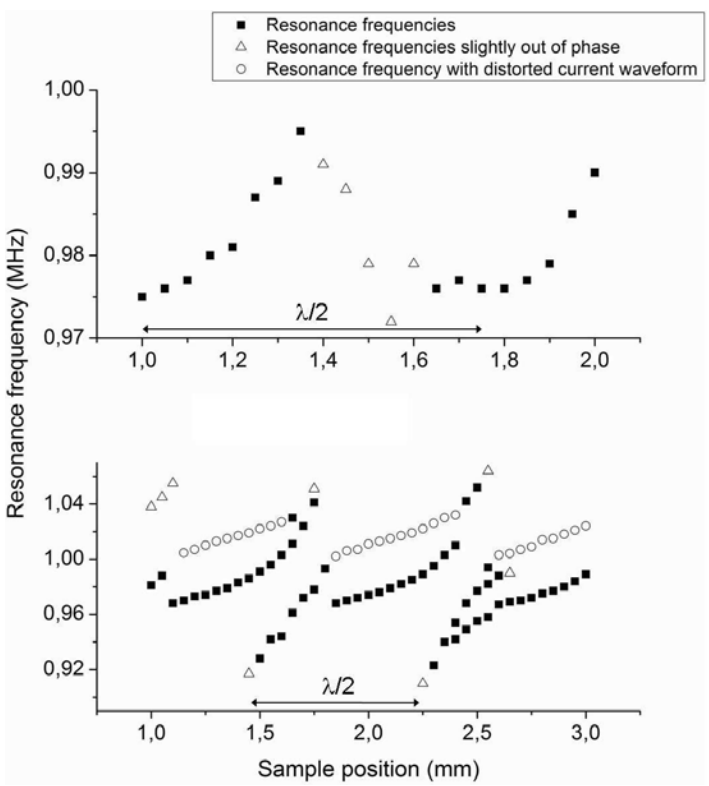

Figure 3. Frequencies that correspond to a zero phase shift between the voltage and current signals are shown. The distance between transducer and damping material is changed in the upper image, while the damping material is replaced with a wafer piece in the lower image.

To end this section of electrical measurements, an overview of the real (forward) electrical power delivered to the transducer is given. The real power equals the dissipated acoustical power in the liquid. Figure 4 represents the evolution of the real power as a function of the distance between the transducer and wafer/damping material. The solid line with the squares points shows the dependence of the real power as function of the variation of the wafer height. A very strong oscillation of the real power can be observed when reflection are present. If the wafer material is replaced with a thin slice of damping material, the oscillation is still present but it is clearly reduced (gray line with circular points in Fig. 4). Since the slice of damping material is too thin to absorb all the acoustic waves, a small oscillation of the real power can still be observed.

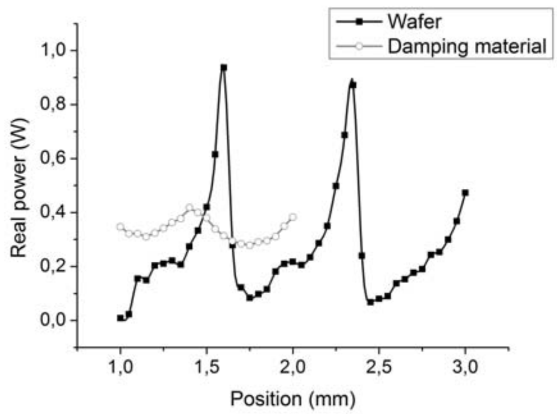

Figure 4. The real power delivered to the transducer as function of the position of the wafer (solid squares) and damping material (gray circles). A large oscillation of the real power is present when acoustic waves are reflected from the wafer.

<u>Influence of acoustic reflections on Particle Removal Efficiency (PRE) results</u>

The following measurements were performed with the nozzle system described in the experimental set-up section. The nozzle was driven with a function generator (peak-to-peak voltage of 2.05 V at a frequency of 1.02 MHz) and a high frequency amplifier (gain 100 x). The removal of particles is evaluated for 78 nm of SiO_2 particles deposited on a

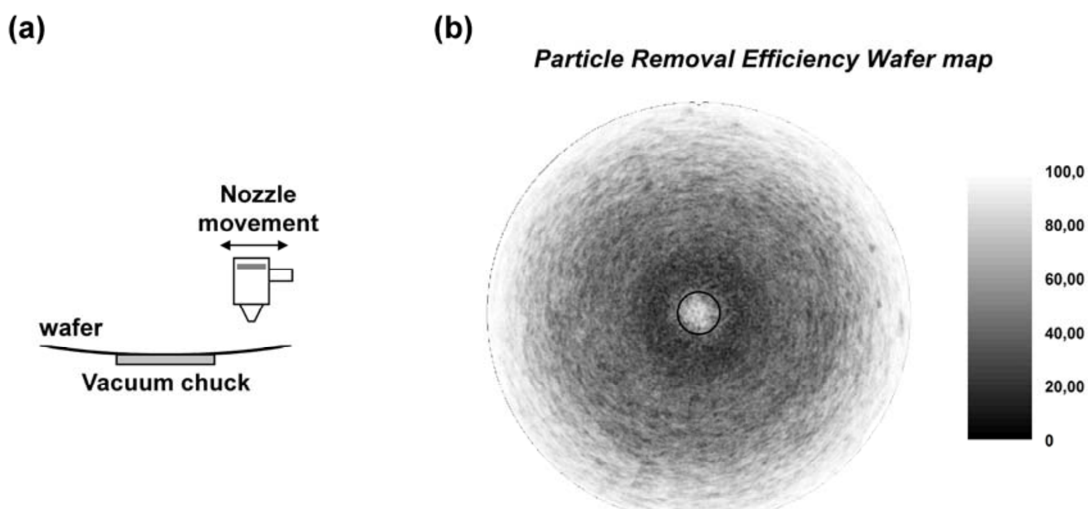

Figure 5. Image (a) shows the cross section of the nozzle set-up. Imperfections of the vacuum chuck cause a small flexion of the wafer. Image (b) represents a typical non-uniform PRE pattern obtained with the nozzle set-up.

Si wafer and aged for 2 hours in a relative humidity of 40 %. Cleaning performance is evaluated by measuring local PRE using light scattering in the haze mode (11,12). A typical measured PRE map shown in Fig. 5 indicates a non-uniform PRE (7). The radial non-uniformity is attributed to the existence of standing waves and is caused by a wafer which is slightly bent (see Fig. 5). This wafer flexion changes the face-to-face distance between the transducer and wafer and immediately influences the dissipated acoustical power (see Fig. 4). To prove this statement, PRE maps are recorded in combination with electrical measurements. The nozzle was positioned above the center of the wafer and the real power was measured at several wafer heights (see Fig. 6). Next, a PRE wafer map was recorded for each nozzle height and the average PRE in the centre of the wafer (circle with radius of 1 cm shown in Fig. 5) was calculated. Figure 6 shows a strong oscillatory response of the real power and the PRE as a function of the transducer to wafer distance. Both curves are linked to each other and oscillate with half of a wavelength of the acoustic waves. As a result, a direct correlation between reflected acoustic waves and particle removal efficiency data is established. Reflections change the part of the electrical input impedance, which is subject to electro-acoustical coupling described by eq. (1,2). This immediately influences the real electrical power delivered to the transducer, and thus the acoustical power delivered to the liquid. The observed oscillatory PRE response can thus be attributed to the oscillatory dependence of the power transmitted to the liquid.

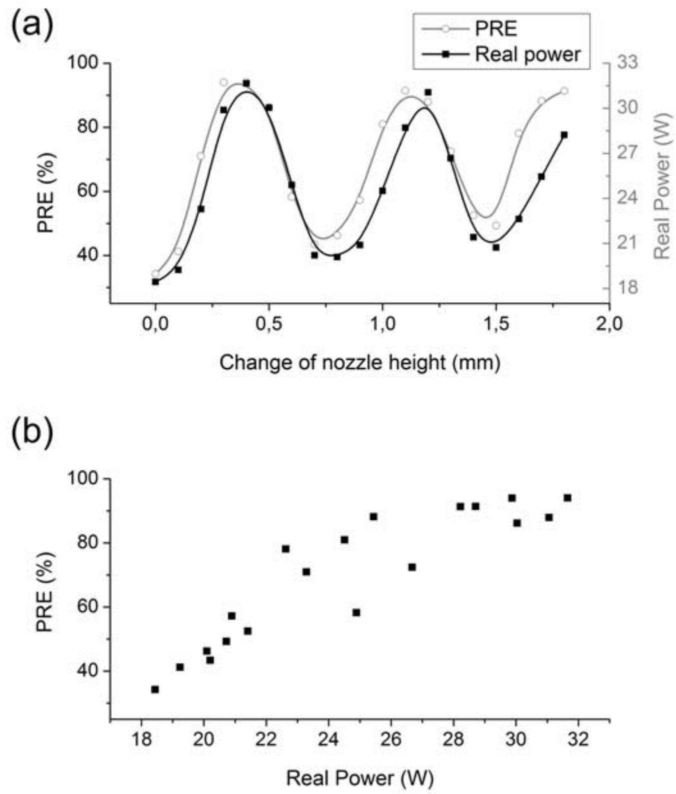

Figure 6. Image (a) shows the fluctuation of the real power delivered to the transducer and the PRE as a function of a variation of distance between transducer and wafer. The particle removal efficiency (PRE) and real power date follows the same trend. Image (b) confirms the correlation between the PRE and the real power.

Conclusions

To conclude, it is shown that reflected acoustic waves have a large impact on the performance of a transducer. In order to obtain an efficient cleaning, it is of large importance to control the reflection of acoustic waves. With the correct distance between wafer and transducer (resonance condition), the reflection of acoustic waves back into the transducer can even enhance the real power consumed by the transducer. This results in an increase of the dissipated acoustical power in the cleaning liquid and an improvement of the PRE.

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