# THE PHYSICAL REMOVAL OF NANOSCALE PARTICLES FROM SURFACES

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## INTRODUCTION

As device feature size continues to shrink, (currently at about 120 nm and expected to shrink to 25 nm by the year 2011[1]), the removal of nano-scale particles continue to present tremendous challenges to the industry. The cleaning of structured surfaces with submicron deep trenches and vias (holes) is even more challenging since particles get trapped in these structures. Pulsating flow at MHz frequencies provides the best approach to removing these particles. High intensity sound waves generate pressure fluctuations and acoustic streaming which provide sufficient hydrodynamic drag force to detach the particles from the surface.[2,3] It is important to understand how acoustic streaming helps in the removal of these nanoscale particles and from a practical point of view know the advantages and the limitations of this cleaning technique in nano-scale particles removal.

## PHYSICAL MODEL

One of the most important aspects of megasonic cleaning is the thickness of the acoustic boundary layer, which is as very small as compared to a typical hydrodynamic boundary layer at the same velocity. The acoustic boundary layer thickness is a function of the acoustic frequency ω ($\omega = 2\pi f$) and the viscosity of the cleaning liquid ν,

$$\delta_{ac} = (2\nu/\omega)^{0.5} \qquad (1)$$

The acoustic boundary layer thickness in water at 850 kHz is 610 nm. On the other hand, hydrodynamic (turbulent) boundary layer thickness is given by

$$\delta_H = 0.16(\nu/Ux)^{\frac{1}{7}} \cdot x \qquad (2)$$

where $U$ is the fluid velocity and $x$ is the distance from the leading edge of the wafer. The boundary layer thickness in water (at 4 m/s, a velocity equivalent to the acoustic streaming velocity at 850 kHz) is 2,570,000 nm at distance 4 inches downstream the leading edge of the substrate.

The acoustic pressure waves can be modeled as a plane wave traveling between two infinite length parallel planes. The megasonic oscillation amplitude for plane wave is $A = \sqrt{\frac{2I}{\rho_0 c_0}}$. Acoustic streaming velocity at center of the tank is defined as [4]

$$u = \frac{8\pi^2}{3\rho_l c^4} \cdot If^2\left(\frac{h^2}{4} - z_1^2\right) \qquad (3)$$

where $\rho_l$ is the density of the cleaning liquid, $c$ the sound speed in liquid, $I$ the intensity of the megasonic wave, $f$ the frequency of the megasonic wave, $h$ the distance between the walls of the tank, $z_1$ the distance between the wall and the edge of the sound beam.

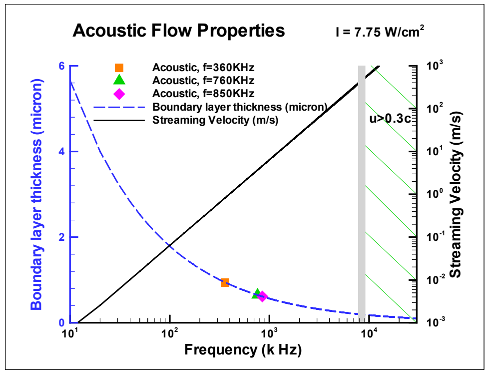


Fig.1 Boundary layer thickness and acoustic streaming velocity *vs.* acoustic frequency.

As the frequency increases, the acoustic streaming velocity also increases but the boundary layer thickness decreases as shown in figure1. The thinner acoustic boundary layer exposes submicron and nano-scale particles on the surface to larger velocities of bulk flow and therefore increases the drag force and the particle removal efficiency.

The drag force on a spherical particle in a Newtonian fluid can be expressed by:

$$F_d = \frac{\pi}{8} C_D \rho_l d_p^2 u^2 \qquad (4)$$

where $C_D$ is drag coefficient, $\rho_l$ the density of the cleaning liquid, $d_p$ the diameter of the particle and $u$ the streaming velocity. The electrical double layer force, according to HHF model, is the force interacting between a sphere and a plate with constant potential. [5] The dominant particle adhesion force[5] is the van der Waals force and adhesion-induced deformation which can be expressed as:

$$F_a = F_{vdw} + F_{deformation} = \frac{AR}{6z_0^2}\left(1 + \frac{a^2}{Rz_0}\right) \qquad (5)$$

where $A$ is the Hamaker constant, $R$ the particle radius, $z_0$ the distance between particle and substrate (usually it is assumed as 4Å), and $a$ the contact radius that may result from adhesion-induced deformation.

The particles are removed through the rolling Removal Mechanism [6] Particle rolling removal mechanism is shown in Fig.2.

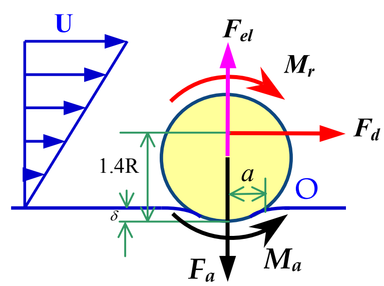


Fig.2 Rolling removal mechanism

In this paper, only the drag force $F_d$, electrical double layer force $F_{el}$, and adhesion force $F_a$ are considered. The ratio of the removal moment to the adhesion resisting moment, RM, is given by:

$$RM = \frac{Removal\ \ moment}{Adhesion\ resisting\ \ moment} = \frac{F_d(1.4R-\delta)+F_{el}\cdot a}{F_a \cdot a} \qquad (6)$$

where R is the particle radius and $a$ the contact radius. When the removal moment overcomes the adhesion resisting moment, namely, when RM>1, the particle is removed by rolling.

## RESULTS AND DISCUSSION

For acoustic streaming flow with constant intensity, higher frequency leads to a larger drag force because of larger streaming velocity and thinner acoustic boundary layer. Naturally, the adhesion force and electrical double layer force are independent of the frequency. Figure 3 shows that higher acoustic frequency leads to larger removal/adhesion moment ratios. The figure shows that the removal of 100 nm silica and PSL particles is achievable using DI water and acoustic streaming with flow frequencies larger than 270 kHz and 1.6MHz, respectively. To physically remove silica particles down to 10 nm, megasonic flow with frequency larger than 1.3MHz is necessary when using DI water as shown in Figure 4.

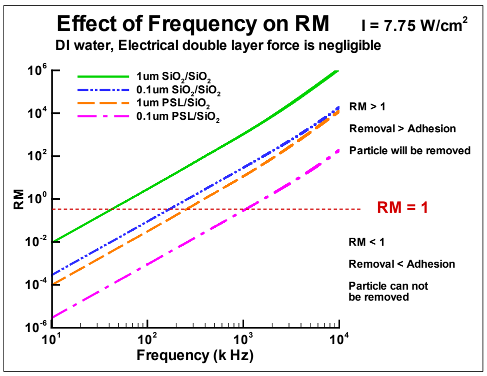


Fig.3 Effect of acoustic wave frequency on RM

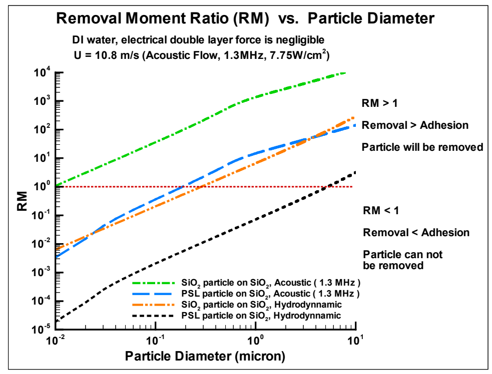


Figure 4. Effect of particle size on RM

## CONCLUSIONS

High frequency acoustic streaming is a promising technique for nano-scale particle removal from both flat and structured surfaces. Using DI water, the removal of nano-size particles down to 10 nm from flat surface was shown at a frequency above 1.3 MHz. As the frequency increases, the acoustic boundary layer thickness decreases and the streaming velocity increases thereby increasing the drag force and consequently the removal moment. By utilizing the electrical double layer force as a repulsive force (by using basic chemistry,) the removal of 10nm silica particles from flat surfaces can be accomplished using megasonic cleaning above 800 kHz.

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