Optimization of Ultrasonic Cleaning for Erosion-Sensitive Microelectronic Components

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ABSTRACT

In this paper, we describe an experimental study undertaken to investigate ultrasonic fields in the frequency range 58 – 192 kHz with respect to their surface cleaning and erosion potential. Measurements are performed using three different methods—gravimetric weight-loss, surface profilometry, and precision turbidimetry—to assess these mechanisms for a variety of materials, including semiconductors. Conclusions are drawn regarding the nature of interaction between high-frequency, high-intensity ultrasonic fields and immersed surfaces. Recommendations are provided for optimal settings to maximize surface cleanability and minimize erodibility of sensitive substrates.

Keywords
Ultrasonic, cavitation, erosion, cleaning, silicon wafer

INTRODUCTION

Submicron particulate contamination is a leading cause of device failures and manufacturing process yield losses in many microelectronic industries, such as semiconductor devices, integrated circuits, hard disk drives, etc. As critical product dimensions shrink in an increasingly miniaturized market, the minimum size of particle that can cause defects continues to decrease as well, resulting in spiraling cleaning complexity and costs.

High-frequency (> 40 kiloHertz), high-intensity (> 50 Watts per square inch of immersed surface) ultrasound [12] is used to remove micrometer and submicron-sized particles from components and sub-assemblies [1], [3], [4], [5], [6]. However, in cleaning of semiconductor wafers and other erodible substrates, components or precision assemblies, concerns about cavitational erosion damage to the surfaces and to surface features [10] have restricted the applied frequency to the megasonic range (> 1 MegaHertz). The omni-directionality of ultrasonic fields characteristic of cavitation bubble implosions [2], as opposed to the uni-directionality of megasonics associated with acoustic streaming [7], is a key advantage that needs to be fully leveraged. While megasonics cause minimal erosion, their cleaning effectiveness, especially for strongly-adhered particles, is also limited due to absence of significant cavitation forces. Hence, the proper harnessing of ultrasonic fields, with frequencies in the 60 – 200 kiloHertz range, to maximize surface particle removal while minimizing erosion is a critical need of the hour. A theoretical approach to this was presented in [8], and is explored further here using experimental techniques.

This research addresses the stated problem by adopting a classical process optimization approach. Quantification of surface erosion and surface cleaning on selected substrates by a variety of techniques (weight-loss measurements, surface profilometry, precision turbidimetry to estimate ultrasonically-extracted particulate concentration in the liquid medium, etc.) for several ultrasonic field parametric settings (frequency, input power, time, substrate material) is carried out in the laboratory. The experimental results are analyzed, within a theoretical framework, to derive semi-empirical relationships between acoustic field properties, substrate properties and observed erosion/ cleaning rates. Optimum ultrasonic field settings are then formulated on the basis of these analyses, pending field validation.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

State-of-the-art ultrasonic equipment donated by Crest Ultrasonics Corporation Inc. (Trenton, New Jersey) have been used for the experimental part of the studies reported here. Two sets of equipment have been used here: A 132 kHz generator and tank system, and a dual-frequency (58/192, 172/192 kHz) generator and tank system. The dual-frequency system is an innovation of Crest Ultrasonics Corp. The two frequencies are direct-bonded using diagonally-placed transducer stacks. A repeatable equilateral triangularity is achieved, with both frequencies in every triangle. There is a separate generator for each frequency, and each frequency is transmitted at maximum efficiency.

The input power to the ultrasonic tank is a maximum of 500 watts. Transmitted cavitation intensity in the liquid medium is measured in Watts per square inch using a ppb™ Cavitation Probe that is designed to capture the cavitation "signal" separately from the prevailing acoustic field "noise".

A simple analytical balance with 0.01 mg resolution is used to measure weight loss from coupons exposed to various ultrasonic fields. Surface roughness has been measured with both a mechanical "stylus" perthometer, as well as with a laser-based profilometer. The latter method makes use of a mathematical relationship between scattered light and surface roughness [14].

A Merck Turbiquant™ 3000 IR precision turbidimeter with a lower detection limit of 0.0001 NTU (nephelometric turbidity units) has been used to measure suspended particle concentration in liquids. Turbidity is defined as the reduction of transparency of a liquid caused by the presence of undissolved matter; in the context of this study, it is an indirect measure of surface particle contamination that is removed ultrasonically and suspended in the liquid.

The following specimens were used to conduct the experiments.

- Aluminum coupons- 5 cm x 5 cm, 1 mm thick
- Ceramic coupons– 90% alumina, 30 mm x 30 mm, 5 mm thick
- Glass slides of dimension 22 mm x 50 mm, 2 mm thick
- Plastic buttons each weighing (approximately) 0.214 gms.
- Rubber (silicone) Septa each weighing (approximately) 0.2 gms.
- PTFE plastic coupon of 1.5 mm thickness
- Silicon wafers—as-cut, polished

The experimental procedures used in this study may be summarized as follows:

- Erosive mass loss is obtained by weighing sample coupons before and after exposure to an ultrasonic field. The coupon is fully dried in an oven to eliminate the contribution of residual moisture to the after-exposure reading.
- Surface roughness changes induced by exposure to an ultrasonic field are assessed by analysis with a Profilometer pre- and post-sonication.
- Surface particle removal efficiency is measured by ultrasonically extracting particles from the surface into a liquid medium multiple times, and measuring suspended particle concentration at each stage of extraction using a Precision Turbidimeter.

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EXPERIMENTAL DATA AND ANALYSIS

Figure 1 is an early illustration of the optimization concept. Acoustic streaming force (theoretical) and cavitation intensity (measured by the ppb™ Cavitation Probe) as measured in room-temperature water are plotted against ultrasonic frequency. The net force appears to have a minimum in the 100-130 kiloHertz range, a result in reasonable agreement with industrial experience. Typically, precision cleaning systems employ a "cascading frequency" strategy, where lower frequencies are utilized upstream to loosen well-adhered particles, followed by progressively increasing frequencies downstream that remove loose small particles, and transport them away from immersed surfaces. It is rare to see a single frequency in the 100-130 kiloHertz range employed as a stand-alone cleaning process.

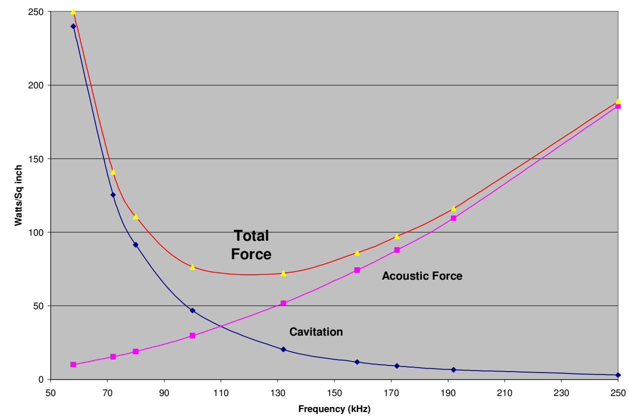

Figure 1: Total Ultrasonic Force in Liquid Medium as a Function of Frequency

Lower frequencies produce greater cavitation intensities, which are potentially harmful to erodible materials [10]. Gravimetric weight-loss studies have been conducted using coupons made of different materials that have been immersed in sonicated water for various periods of time. The data for various materials exposed to 58 kiloHertz ultrasonics are summarized in Figure 2. It is clear that erosive effects can vary by several orders of magnitude for the range of materials investigated. Other data (Figure 3) indicate that the same range may be seen for varying frequencies.

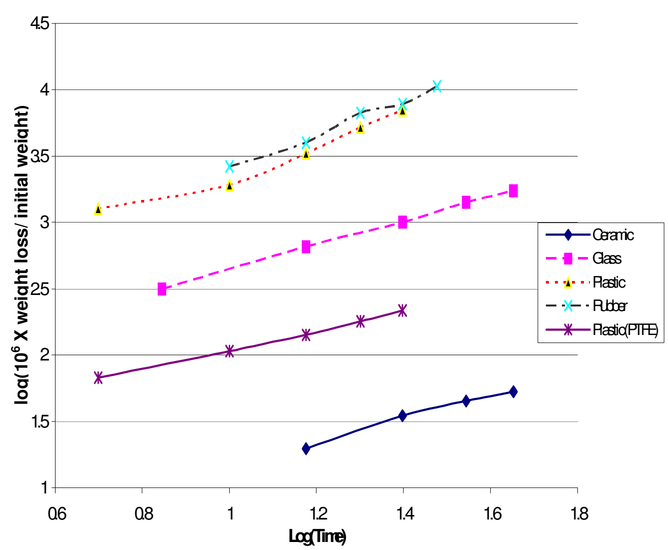

Figure 2: Effect of Coupon Material on Measured Erosion in a 58 kiloHertz Ultrasonic Field

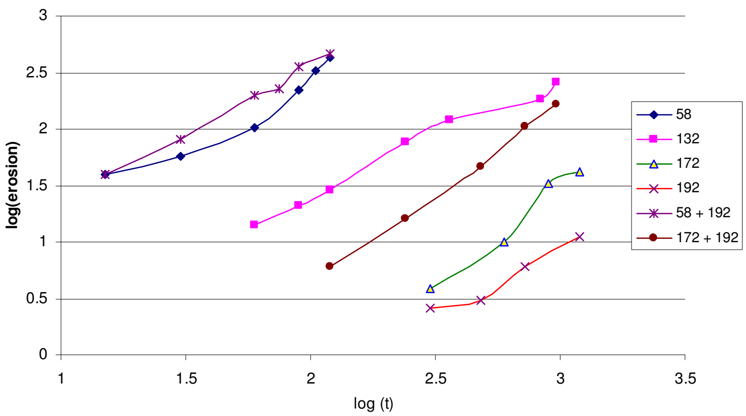

Figure 3: Time-Dependent Erosion Rate of Aluminum Foil Exposed to Various Ultrasonic Frequencies

The measured erosion rates may be correlated with material properties such as impact strength (Figure 4) for polymers and plastics, and with Knoop hardness for metals (Figure 5),

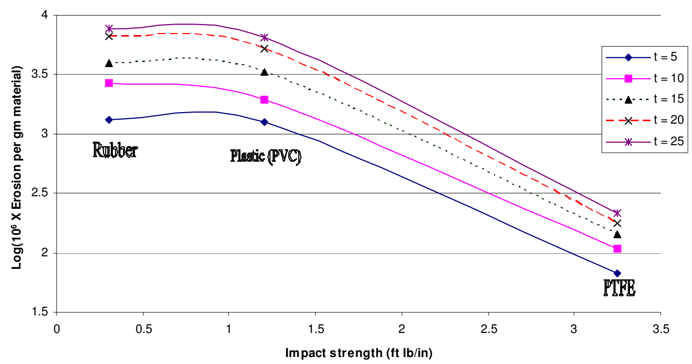

Figure 4: Correlation of Ultrasonic Erosivity with Impact Strength for Polymers and Plastics

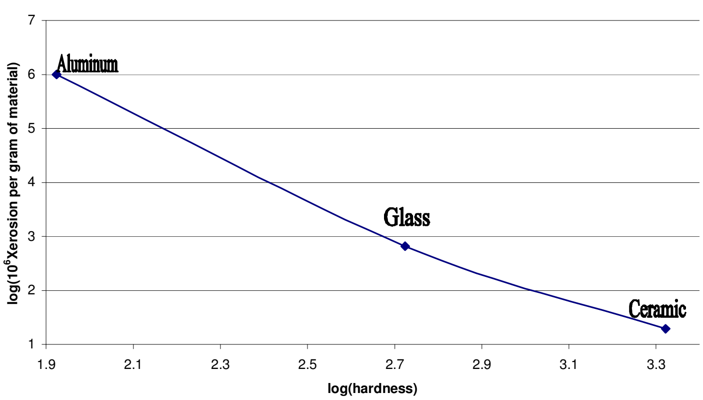

Figure 5: Correlation of Ultrasonic Erosivity with Knoop Hardness for Metals

Another symptom of cavitation erosion is the micro-roughening of a previously-smooth surface [13]. Data on surface roughness change induced by sonication were obtained using a laser profilometer. Representative data for a sonicated glass slide are shown in Figure 6. It is interesting to note that when a surface is initially very rough, ultrasonic exposure has a "polishing" effect that actually improves surface smoothness by "micro-machining" the protruding asperities; however, an initially smooth surface (on the nano-scale) becomes rougher when exposed to ultrasound. For semiconductor-grade polished silicon as well, this cyclical behavior is observable at all frequencies (Figure 7).

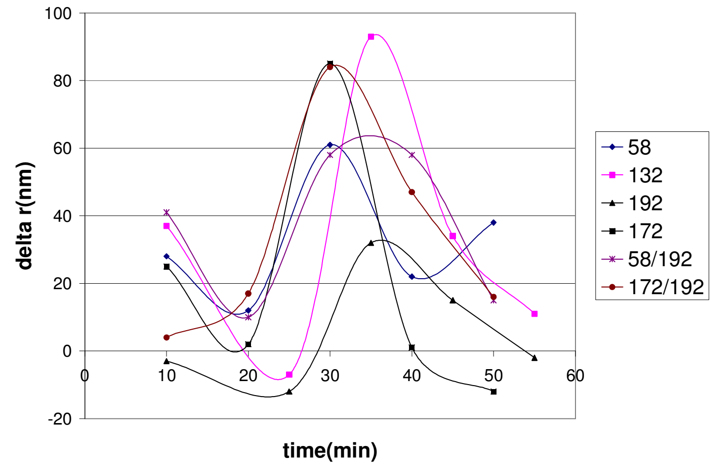

Figure 6: Ultrasonic "Micro-roughening" and "Micro-polishing" of a Glass Slide at Various Frequencies

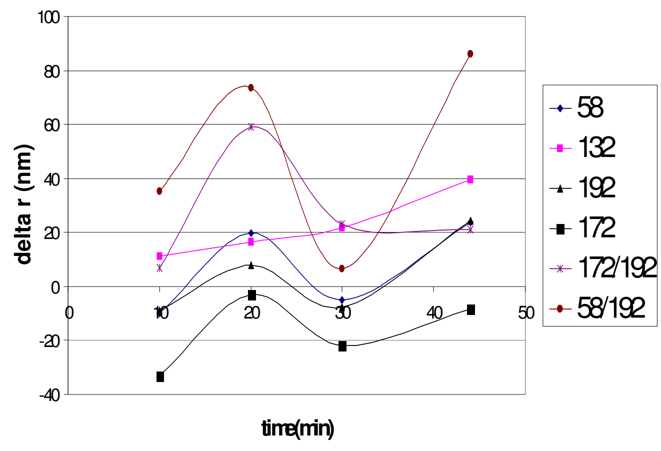

Figure 7: Ultrasonic "Microro-ughening" and "Micro-polishing" of a Polished Silicon Wafer at Various Frequencies

In general, the magnitudes of "micro-roughening" and "micro-polishing" are larger for more fragile materials, such as glass, when compared to higher fatigue-strength materials, such as polished silicon. When less-erodible materials are exposed to higher-frequency ultrasonics—i.e., > 100 kiloHertz—this cyclical behavior is less likely to be observed; instead, a more monotonic micro-roughening pattern may be observed. Hence, semiconductor substrate cleaning by ultrasonic means is particularly susceptible to the phenomenon of increasing surface roughness with time, and with applied power.

Figures 8 and 9 display data corresponding to multiple-stage ultrasonic (58 and 132 kiloHertz, respectively) particle extraction from an aluminum foil measured using precision turbidimetry. The initial slope of the curve represents surface cleanability, while the asymptotic value represents surface erodibility. These parameters have been defined and discussed in [11]. A steep initial slope and a low asymptote are highly desirable for most effective cleaning with minimum erosion.

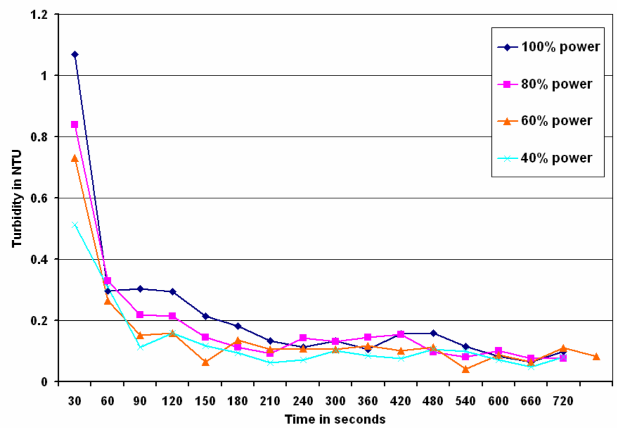

Figure 8: Multiple Ultrasonic Extraction Trend Curve for Aluminum Foil at 58 kHz

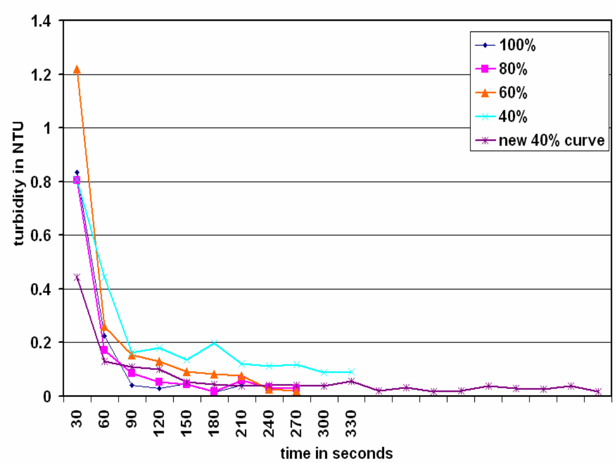

Figure 9: Multiple Ultrasonic Extraction Trend Curve for Aluminum Foil at 132 kHz

For a given ultrasonic frequency, both surface erodibility and surface cleanability may be expected to increase with increasing power level; this is verified by laboratory turbidity data (shown in Figure 10) obtained using an aluminum foil exposed to 58 kiloHertz ultrasonics at input power levels varying from 40% to 100% of the maximum power of 500 Watts. From a field optimization viewpoint, however, their ratio must have its highest value, since this condition would represent the best relative value between the two. From Figure 10, it may be seen that this optimum field setting occurs at approximately 60% power level for an aluminum foil immersed in a 58 kiloHertz ultrasonic field; this determination must be made for every combination of surface to be cleaning and cleaning process. For example, a less-erodible substrate such as silicon may be cleaned at a higher power level (or lower frequency)l compared to soft aluminum metal without resulting in significant erosion. This will shift the optimum operating point accordingly.

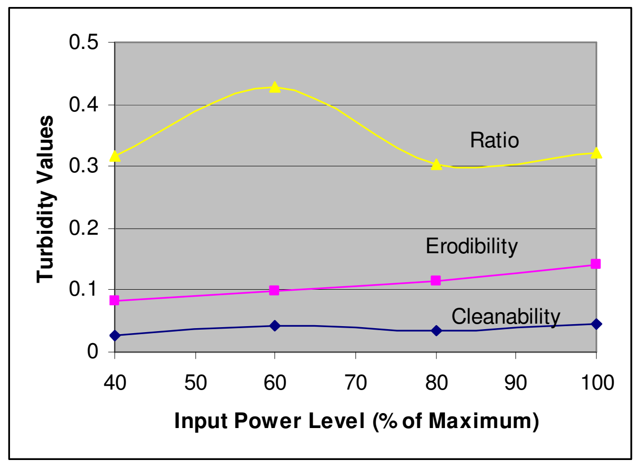

Figure 10: Optimization of Ultrasonic Power Amplitude Based on Cleanability and Erodibility of Immersed Surface

CONCLUSION

The optimization of an ultrasonic cleaning process for a given surface must be based on two measurable metrics—surface cleanability, and surface erodibility. The former must be maximized, and the latter minimized. More realistically, an optimum setting must be identified that provides the most acceptable compromise between the two, since it is highly likely that cavitation-based cleaning processes that result in high cleanability also result in high erodibility, and vice versa. While the gravimetric weight-loss technique and surface roughness tracking method outlined here can quantify the amount of cavitation-induced erosion that is taking place, these measurements will not provide any data on particle removal from surfaces, the ultimate objective of any cleaning process.

The multiple ultrasonic extraction procedure outlined in this paper, which removes particles from a surface and suspends them in a liquid medium, enables the indirect determination of surface cleanability (as well as erodibility), when used in combination with an instrument such as a precision turbidimeter that quantifies suspended particle concentration in the liquid. This simultaneous measurement of surface cleanability and erodibility makes it possible to identify the optimum ultrasonic field parameters (frequency, power amplitude, etc.) in a given surface-cleaning application. This methodology has been illustrated here using the example of an aluminum foil subjected to 58 kiloHertz ultrasonics.

An obvious refinement to this scheme is the use of a liquid-borne particle counter (LPC) [9] in place of a turbidimeter; the LPC provides particle size as well as count information, unlike a turbidimeter which displays just a single number representing the integrated total IR-light scattering cross-sectional area of all suspended particles. The particle size distribution is also a sensitive indicator of the onset of erosion [10], which tends to perturb it from "normal" distribution profiles. Additional investigations of ultrasonic surface cleaning and erosion are planned in this Laboratory that will make use of more powerful analytical tools such as the LPC, as well as an Atomic Force Microscope for characterization of subtler surface "nano-roughening" and "nano-polishing" effects. These highly-sensitive techniques are more suited to the study and optimization of ultrasonic cleaning of semiconductor wafers and other high-precision assemblies and components.

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BIOGRAPHY

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