Cavitation in Ultrasonic Cleaning and Cell Disruption

It is important to quantify the cavitation energy in all applications ranging from ultrasonic cleaners to cell disruptors. A cavitation meter measures the energy intensity and frequency within ultrasonic and megasonic cleaners, including probes with side-mounted sensors that can be placed within the megasonic jet streams and single wafer cleaners, as well as those resembling a beaker to quantify the energy emanating from the ultrasonic horns used for cell disruption and homogenizing.

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Ultrasonic and megasonic cleaners are used in varied applications to clean substrate surfaces. In a typical assembly, a cleaning system includes a tank that holds a fluid medium such as an aqueous solution, which generally includes additives such as surfactants and detergents that enhance the cleaning performance of the system. Lately, more distinctive means of delivery have been utilized, particularly for single wafer applications. In one example, megasonics is diverted into a stream of fluid that impacts the substrate surface. In another, megasonics imparts directly on a film of fluid no more than a few millimeters thick on the wafer surface. Ultrasonics can also be delivered via an ultrasonic horn, which is a popular method not for cleaning but for cell disruption, emulsification, and homogenizing of biological matter. In both cleaning and cell disruption applications, it is the phenomenon of cavitation that drives the actions.

FUNDAMENTALS OF CAVITATION

The term “ultrasonic” represents sonic waves having a wave frequency above approximately 20 kHz and includes both the traditional ultrasonic cleaning spectrum which extends in frequency from approximately 20 kHz to 500 kHz, and the more recently used megasonic cleaning spectrum which extends in frequency from about 0.5 MHz to about 5 MHz. The device used for cell disruption has traditionally been the ultrasonic horn. This device works at a fixed frequency, normally between 20 and 50 kHz, and is designed to be resonant in the longitudinal mode of vibration.

In a typical ultrasonic cleaner, a transducer mounted on the bottom generates high frequency vibrations in the cleaning tank in response to an electrical signal input. Once generated, the transducer vibrations propagate through the fluid medium in the cleaning tank until they reach the substrate to be cleaned. Cavitation bubbles are

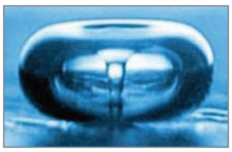

Figure 1: Photograph of liquid jet formation during cavitation bubble collapse.[3]

formed and grow when a liquid is put in significant state of tension. Liquids, though unable to support shear stresses, can support compressive stresses, and for short periods, tensile stresses.[2] The acoustic pressure wave undergoes a compression and rarefaction cycle, and the pressure in the liquid becomes a negative during the rarefaction portion of the cycle. When the negative pressure falls below the vapor pressure of the fluid medium, the ultrasonic wave can cause voids or cavitation bubbles to form in the fluid medium.

Coleman et al showed a remarkable photograph (Figure 1) of a bubble collapsing near a boundary.[3] Once the cavitation is generated, a cavitation bubble may undergo two different kinds of radial oscillations. One may oscillate nonlinearly during many cycles of the acoustic wave, termed "stable cavitation." The other may grow rapidly and collapse (i.e. implode) violently in one or two acoustic cycles, termed "transient cavitation."[4] During bubble implosion, surrounding fluid quickly flows to fill the void created by the collapsing bubble. This flow results in an intense shock wave which is uniquely suited to substrate surface cleaning. Specifically, bubble implosions that occur near or at the substrate surface will generate shock waves that can dislodge contaminants and other soils from the substrate surface. When the bubble collapses, pressure up to 20,000 psi and a "high local temperature, possibly in the order of 5,000K,"[5] are achieved.

In almost all cleaning applications, it is important to control the cavitation energy. When an insufficient amount of cavitation energy is provided, undesirably long process times may be required to obtain a desired level of cleaning, or in some cases, a desired level of surface cleaning may not be achievable. On the other hand, excessive cavitation energy near a substrate having delicate surfaces or components can cause substrate damage. The levels of cavitation energy are also critical in assuring complete and rapid cell disruption. The presence of solid impurities and dissolved gas determines the threshold of cavitation. Many use tap water, which varies widely in solid and gas content. A simple way of ensuring more uniform results is to use distilled water and then degass it. The liquid can now be engassed by bubbling the desired gas through it, which will ensure optimal cavitation.[2]

The bubble dynamics in the acoustic field is described by the well-known Rayleigh-Plesset equation as:

$$R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2=\frac{1}{\rho}\left[P_i-P_\infty-\frac{2\sigma}{R}-\frac{4\mu}{R}\left(\frac{dR}{dt}\right)\right]$$

Where R is the radius (m) of cavitation bubble at any time, μ is the viscosity of the liquid medium (Ns/m^2), σ is the surface tension (N/m), P_i is the pressure inside the bubble (N/m^2) and P_∞ is the pressure in the liquid far from the bubble (N/m^2).[6] Studies have shown that high density low viscosity, and middle range surface tensions and vapor pressure are the ideal conditions for most intense cavitation.[7] There are significant temperature effects on these properties, and cavitation itself will be dramatically affected with increasing temperature.

Another factor that affects the size of the cavitation bubbles and the corresponding cavitation energy is the frequency of the ultrasonic wave. Specifically, at higher wave frequencies there is less time for the bubble to grow. The result is smaller bubbles and a corresponding reduction in cavitation energy. Low frequency ultrasound has superior particle removal efficiencies (PRE) for large particles, and that high frequency ultrasound is best suited for submicron particles.[8]

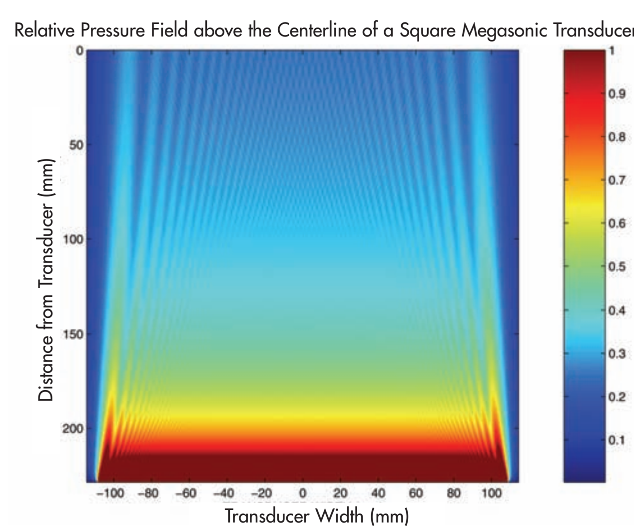

Figure 2: Numerical simulation of a megasonic transducer.
(Image courtesy of PPB Megasonics)

Another factor that affects cavitation energy is the intensity of the ultrasonic wave (i.e. wave amplitude) produced by the transducers. In greater detail, higher wave intensities cause each point along the wave to oscillate over a larger pressure range (between rarefaction and compression), which in turn, produces larger cavitation bubbles and larger cavitation energy. Thus, there is a direct correlation between the intensity of the ultrasonic wave, the pressure range that the fluid medium oscillates between, and cavitation energy.

There also exists a constructive/destructive pattern generated by the transducer(s) in the bath. Depending on the location within the bath, you may have ultrasound arriving in phase, generating constructive interference, and in another location, it will be out of phase, generating destructive interference. Tank manufactures change the pattern by sweeping the frequencies, thereby improving the uniformity within the bath. As a consequence, portions of a substrate that are located at different locations within the bath will experience different levels of cavitation energy. It has been somewhat challenging to uniformly clean a substrate. Figure 2 shows a numerical simulation of a 1 MHz megasonic bath with a square plate transducer on the bottom. The constructive/destructive pattern is evident, even though only one transducer is shown. The energy is directed primarily over the transducer because the overall dimension of the transducer is much larger than the wavelength of the ultrasound.

In additional to cavitation, there is another effect from ultrasound, acoustic streaming, which occurs when the momentum absorbed from the acoustic field manifests itself as a flow of the liquid in the direction of the sound field. There is a second type of streaming associated that occurs near small obstacles placed within a sound field, called "microstreaming," generated by the oscillations of an acoustically driven bubble.[1] This can lead to additional biology effects and enhanced cleaning effects. The microstreaming associated with bubble motion can be very significant in biological systems. Suspended cells or macromolecules are carried in streaming orbits and may be brought momentarily into the boundary layer near a bubble once during each traverse of an orbit. When in this boundary layer, they may be distorted or fragmented by the high shearing stresses.[2]

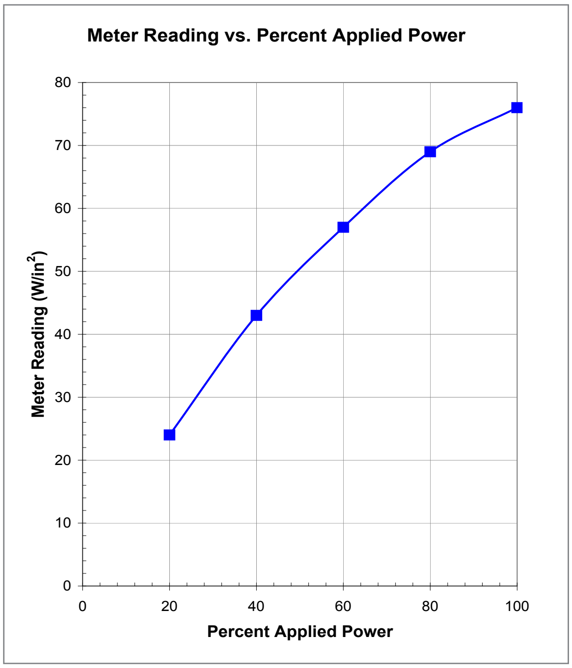

Chart 1: Cavitation meter readings versus applied generator power. (Chart courtesy of J.M. Kolyer of Boeing)

CAVITATION METERS

Ultrasonic cavitation can produce the cavitation noise spectrum including harmonics, subharmonics, and continuous of the driving frequency, and the relative intensity of ultrasonic cavitation can be acquired by analyzing the cavitation noise.[4] PPB Megasonics (Lake Oswego, OR) has developed a method to analyze the cavitation fields and measure the cavitation intensity by separating the acoustic energy intensity at a particular location in the ultrasonic fields into two components: the energy intensity due to the ultrasonic itself and the cavitation activity. The cavitation meter then outputs the RMS of the cavitation energy intensity (units of watts per square inch) and the frequency of the ultrasound. These meters are not hydrophones, which typically filter out the higher frequency cavitation signatures and inherently spatially average compression and rarefaction resulting in misleading data. The cavitation signature is superimposed on the acoustic measure, but has no spatial average component. The acoustic signa-

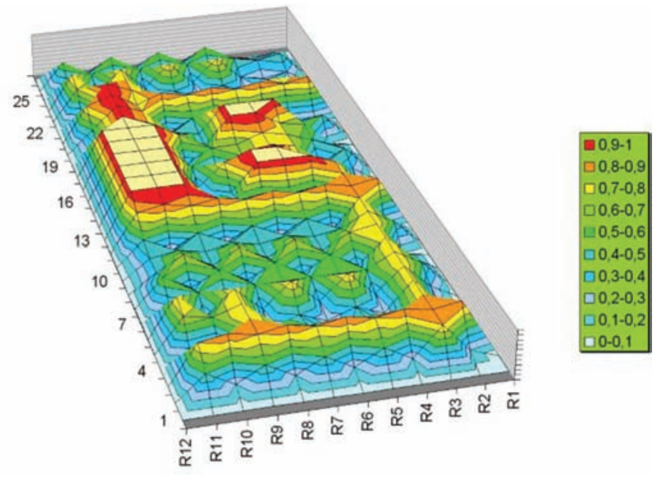

Figure 3: Mapping of a megasonic bath using the cavitation meter. (Image courtesy of Sebastian Barth)

Figure 4: Cavitation probe for megasonic jet streams.
(Image courtesy of PPB Megasonics)

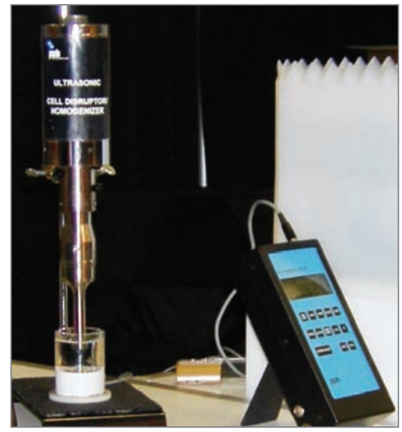

Figure 5: Cavitation probe for ultrasonic horns.
(Image courtesy of PPB Megasonics)

ture is removed, compression and rarefaction, leaving behind only the cavitation implosion forces.

The aluminum foil test is a rudimentary method sometimes used to evaluate ultrasonic baths. John Kolyer from Boeing has written articles on this topic, including one that compared the use of the foil test as compared to a cavitation meter. He states in the article: "A Meter That Works" that "…the Ultrasonic Energy Meter will take over the task of monitoring tank performance."[9] His data showed a dramatic improvement in accuracy and time to evaluate a bath using the cavitation meter. His article also charts how the energy measure of the unit changes with varying power settings from a standard 40 kHz bath, which are shown in Chart 1. It is clear that the measurements are directly proportional to the energy present within the bath. Figure 3, provided by a customer, shows a detailed mapping of a megasonic bath at mid-depth using the cavitation probe. The constructive/destructive patterns are quite evident, as are the subsequent peaks and valleys present within the bath.

The probes for ultrasonic cleaning applications have been specially designed to isolate any resonant affects by utilizing a chemically-resistant polymer to house a sensor mounted on an acoustically matched quartz lens. All-Quartz probes are used for megasonic applications, and quartz probes with side-mounted sensors, shown in Figure 4, have been developed for measurements within megasonic nozzle streams. A newly released "beaker" style probe, shown in Figure 5, has been introduced to quantify the energy emanating from ultrasonic horns used for cell disruption.

The cavitation meter has proven to be an invaluable metrology tool to quantify the energy within the ultrasonic and megasonic cleaners and those emanating from ultrasonic horns. Using the cavitation meter as a process control tool will improve both the yield and throughput of the cleaning and cell disruptor operations. NIST Traceable calibration certificates are available.

In early 2009, PPB Megasonics is introducing patented multi-sensor probes that provide real-time energy distribution profiles across wafer or other substrate surfaces being cleaned, vital in minimizing damage but also assuring effective cleaning. An early prototype is already being used by a leading megasonic manufacturer on a single-wafer cleaner. The first generation model will include up to 64 channels that are displayed simultaneously.

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