Fundamentals of Megasonic Cleaning and Common Techniques Used for Measuring Acoustic Cavitation

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Contamination Challenge and Yield Loss in Integrated Circuit Industry

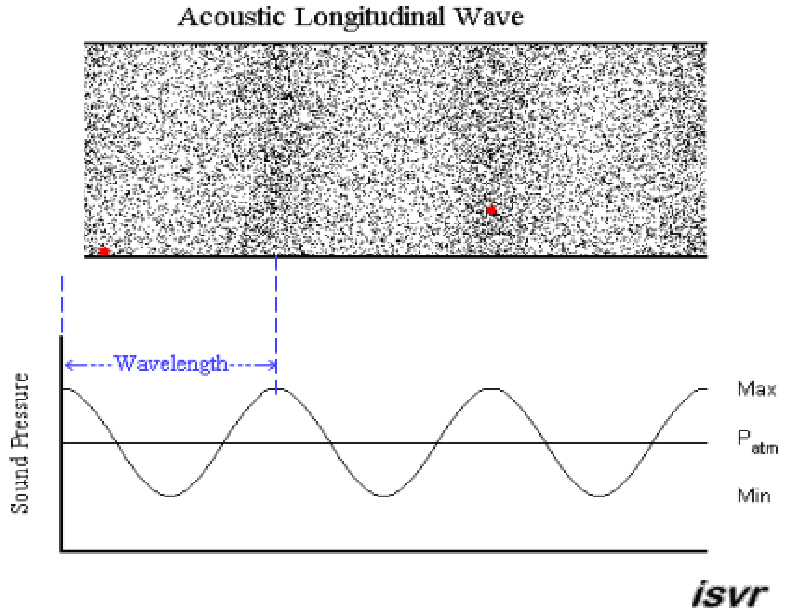
	2011	2012	2013
Killer defect density, (#/cm^2)	0.004	0.005	0.007
Critical particle diameter (nm)	17.9	15.9	14.2
Critical particle count, (#/wafer)	13	13	13
Silicon and oxide loss (Å) per cleaning step	0.1	0.1	0.1
Critical surface metals (10^{10} atoms/cm^2)	1.0	1.0	1.0

ITRS Roadmap-2011

- Particulate impurities on the wafer critically affects the device performance, reliability, and product yield of integrated circuits.
  - 50% of yield losses are due to particle contamination.
  - Critical particle diameter and total particle count to be 14.2 nm and 13 #/wafer respectively for a 300 mm wafer by 2013
  - Silicon and oxide loss to be less than 0.1 Å per cleaning step.

Megasonic Cleaning Process

- **Sound waves with frequency of ~ 1 MHz or greater used in combination with different cleaning chemistries for particle removal**

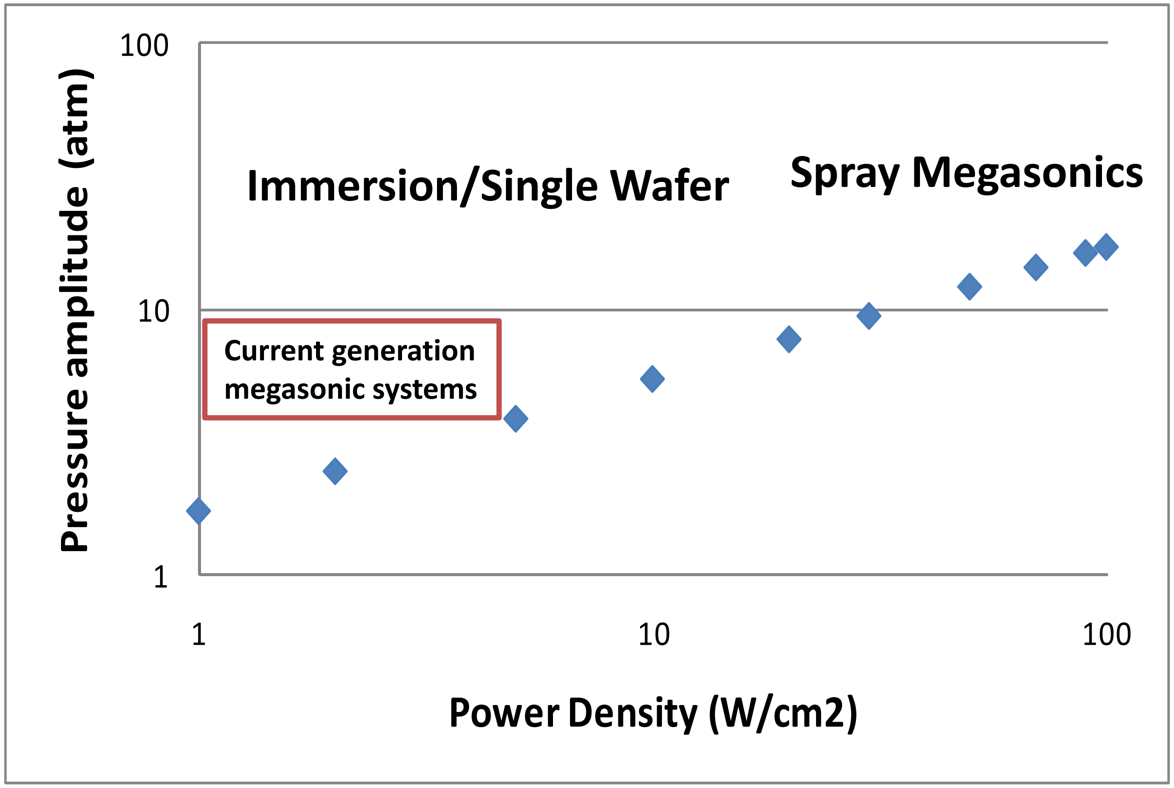


Adapted from
http://wwwnew.isvr.soton.ac.uk/spcg/tutorial/tutorial/Tutorial_files/Web-basics-nature.htm

- Advantage: High particle removal efficiency (PRE)
- Disadvantage: May cause damage to fragile features

Sound Pressure Amplitude

At 25 °C, density of water 997 kg/m3 and speed of sound in water = 1497 m/sec



•Note: *Pressure amplitude is gauge pressure and not absolute*

- Pressure amplitude (a) of sound wave propagating at a speed c in a medium of density ρ_o is given by

$$a = \sqrt{(2I\rho_o c)}$$

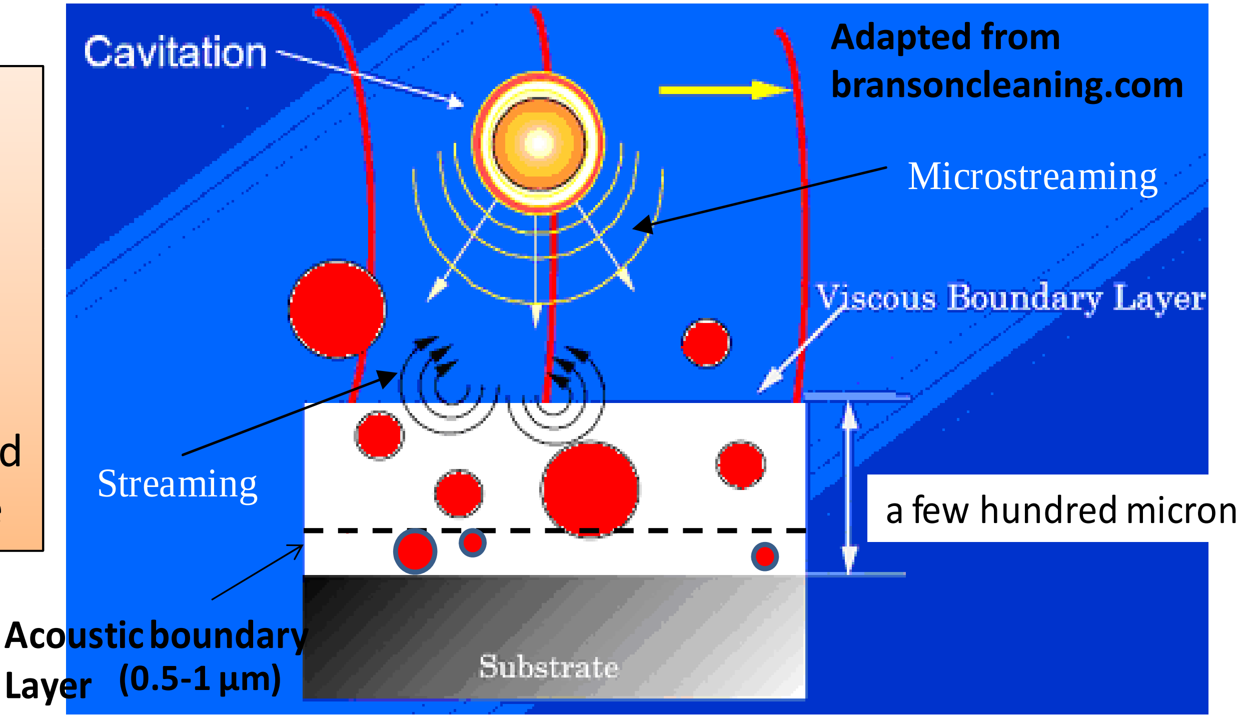
  - a is the pressure amplitude of the sound wave in Pa
  - I is the power density of the transducer in W/m^2
  - ρ_o is the density of the medium in kg/m^3
  - c is the speed of sound in the medium in m/sec

Assumptions: 1) No viscous loss and 2) No bubbles in the medium

Effects of Acoustic Wave Propagation Through a Liquid

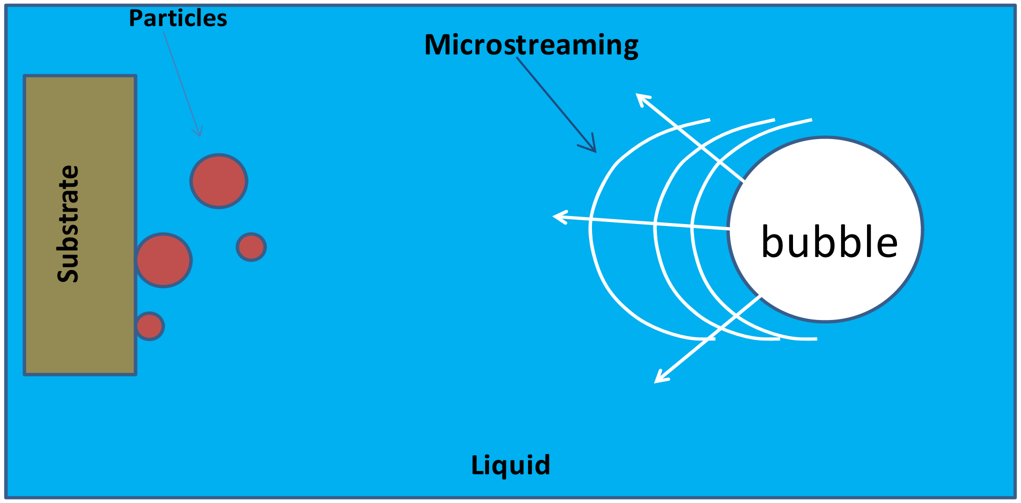
- **Reduction in Liquid Boundary Layer Thickness on a Surface**
- **Acoustic Streaming: Eckart, Schlichting , and Rayleigh**
- **Acoustic Cavitation: Stable and Transient**

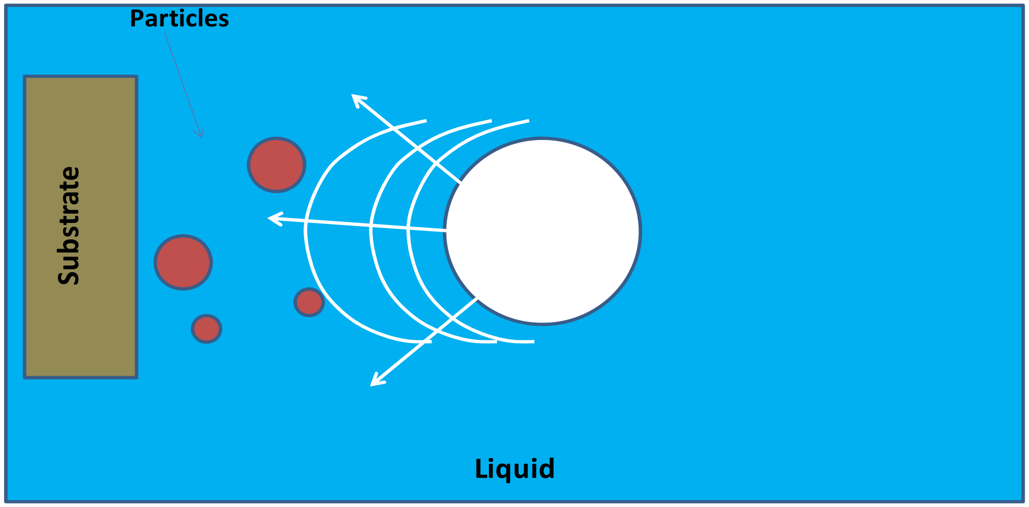
Stable Cavitation entails only small oscillations of bubbles about an equilibrium size, while transient cavitation is characterized by large bubble size variations and eventual bubble collapse



Adapted from bransoncleaning.com

Microstreaming (due to Stable Cavitation)





- **Microstreaming occurs due to oscillating bubbles acting as secondary sources of sound**

- **It often results in significant fluid movement and can be instrumental in particle removal during megasonic cleaning**

Oscillation amplitude of stable bubbles is on the order of few microns

Stable Cavitation

Correlation Between Frequency of Oscillation of Stable Bubbles and their Size

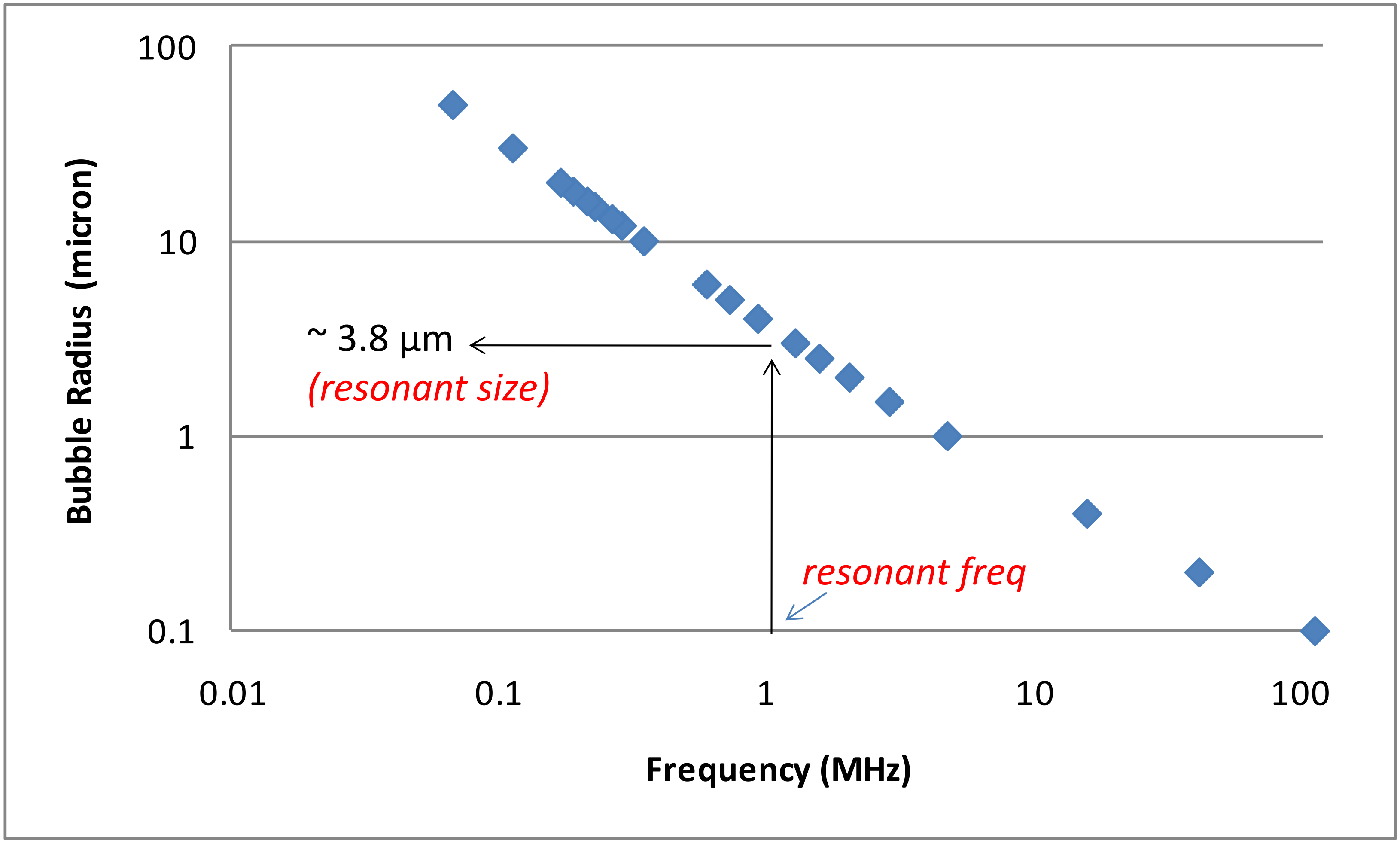
$$f_r = (2\pi)^{-1}\left[\frac{3\gamma}{\rho R_r{}^2}\left(P_o + \frac{2\sigma}{R_r}\right) - \frac{2\sigma}{\rho R_r{}^3}\right]^{1/2}$$

ρ is the density of the liquid, f_r is the resonant frequency of the bubble, R_r is the radius of the resonating bubble, γ is the ratio of specific heat of the gas dissolved in liquid , P_o is the steady pressure (atmospheric) in the absence of the sound field, σ is the surface tension of liquid

- When surface tension effect can be neglected,

$$f_r = (2\pi)^{-1}\left[\frac{3\gamma P_o}{\rho R_r{}^2}\right]^{1/2}$$

Correlation Between Frequency of Oscillation of Stable Bubbles and their Resonant Size



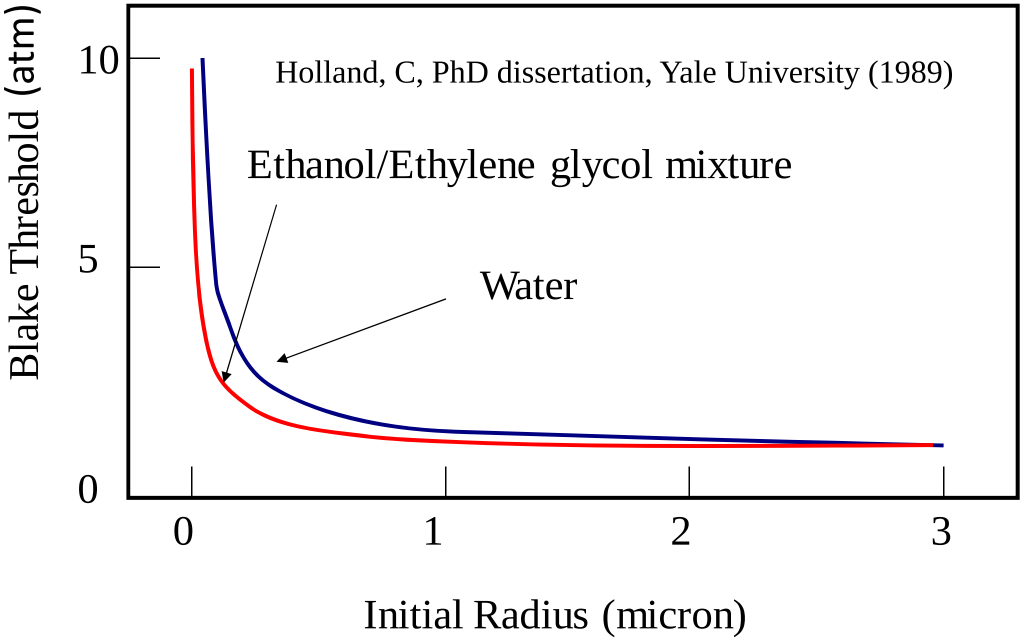
Transient Cavitation

Blake Threshold

Blake Threshold Pressure is the minimum pressure required for explosive growth of a gas bubble

$$P_B = P_0 + \frac{8\sigma}{9}\left[\frac{3\sigma}{2\left[P_0 + \left(\frac{2\sigma}{R_B}\right)\right]R_B{}^3}\right]^{1/2}$$

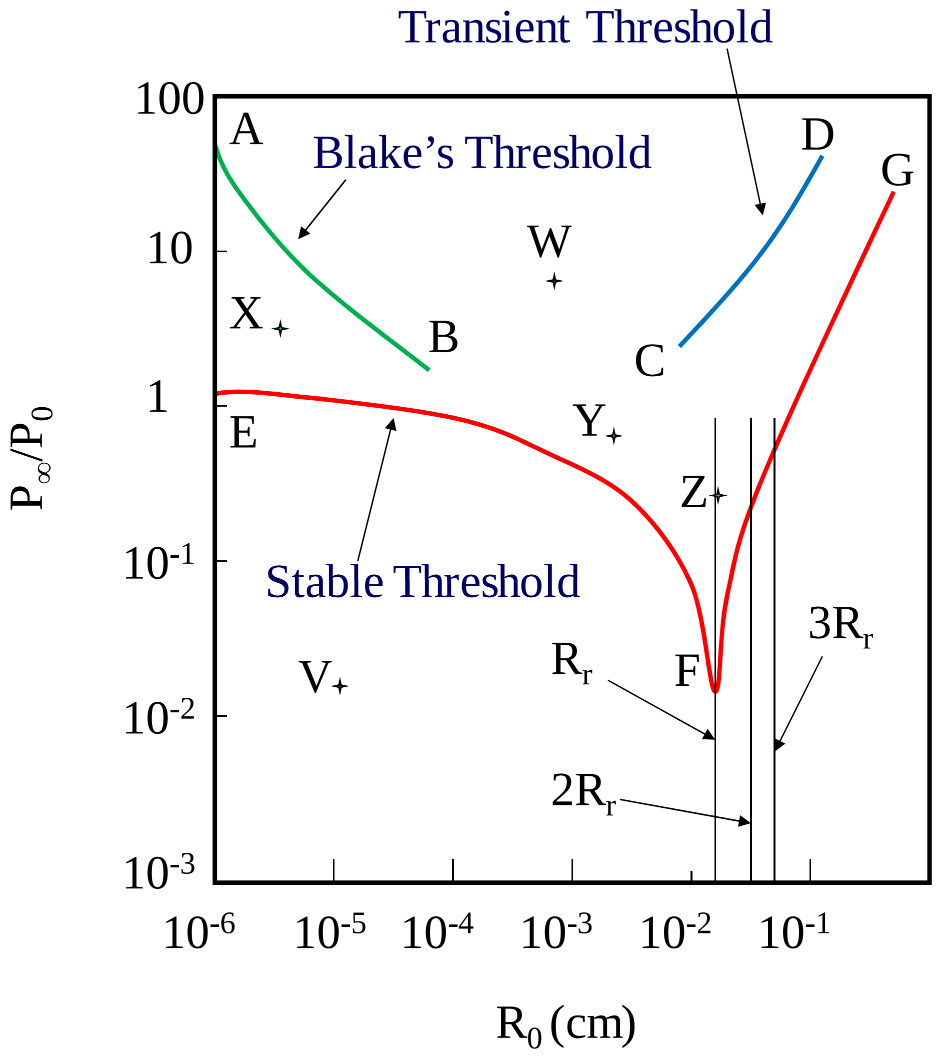
where P_B is the Blake threshold pressure, σ is the surface tension of the liquid, P_0 is the equilibrium pressure of the liquid, and R_B is the initial gas bubble radius



Holland, C, PhD dissertation, Yale University (1989)

The Blake threshold for water is higher than that for a mixture of ethylene glycol and ethanol due to the higher surface tension of water (0.072 Vs 0.032 N/m while density and viscosity are same)

Various Thresholds and their Significance in Transient Cavitation



Blake threshold, stable threshold and transient threshold for saturated water at an initial pressure of 1 bar and a source frequency of 20 KHz

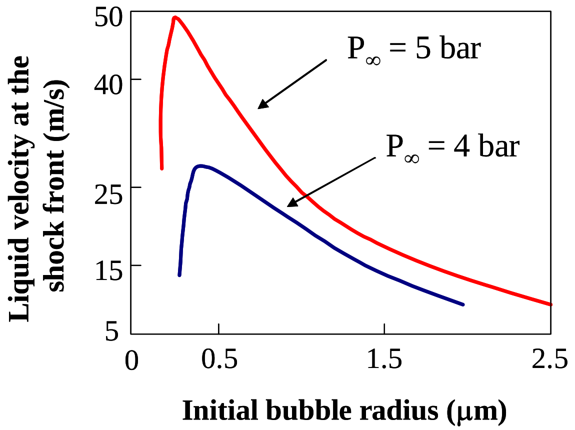
P_∞ = acoustically applied pressure
P_0 = equilibrium pressure of the liquid
R_0 = initial radius of bubble
R_r = resonant size of bubble

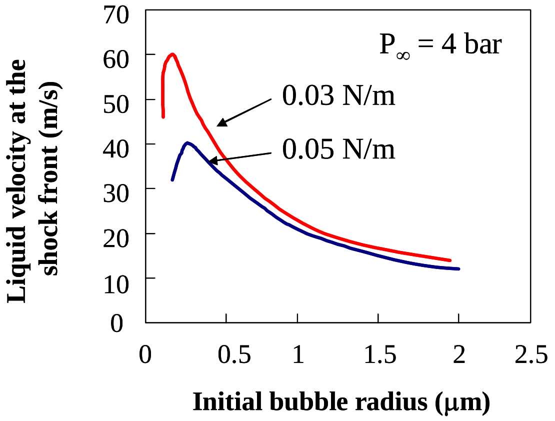
Adapted from: E. Neppiras, Ultrasonics, 18, pp. 201-209 (1980)

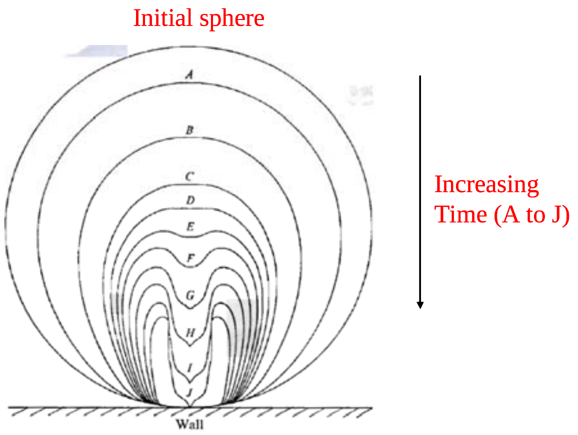
Consequence of Transient Cavitation

Shock Wave and Fluid Jet Formation

- ❖ Dynamics of bubble collapse depend on the distance of separation between the solid boundary and the bubble center
- ❖ Distance is three times or greater the radius of the bubble → shock waves are emitted
- ❖ Distance is lower than three times the bubble radius → liquid jet formation







V. Minsier, J. Proost,, Ultrason. Sonochem., In Press (2007)

M. Plesset and R. Chapman, The Journal of Fluid Mechanics, vol 47, 2, pp. 283-290 (1971)

Common Techniques Used for Characterizing Cavitation

Acoustic Emission Based
(pressure field in the liquid)

Measured using a Hydrophone

Sonoluminescence Based
(light emission from cavitating bubbles)

Measured using a Photomultplier Tube (PMT) and/or a spectrometer

Measurement of Size Distribution of Stable Bubbles Using Hydrophone Data

Pressure sensitive Tip (Dia =1.0 mm)

Conversion of pressure to electrical signal

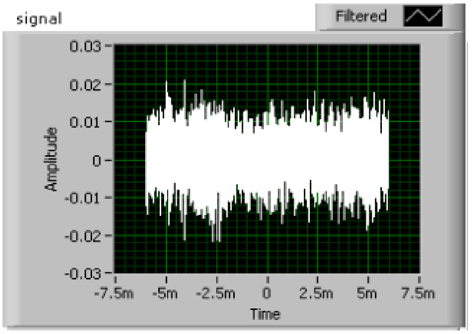
HNR-1000 Hydrophone

Electrical signal to oscilloscope

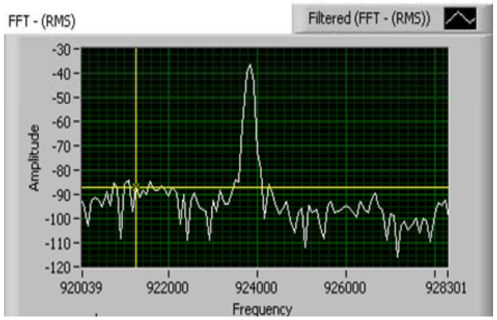
Oscilloscope (PCI-5102 and NI- USB 5133) (10-20 samples per µsec, few million samples per acquisition)

Labview Signal express

pressure - time raw data

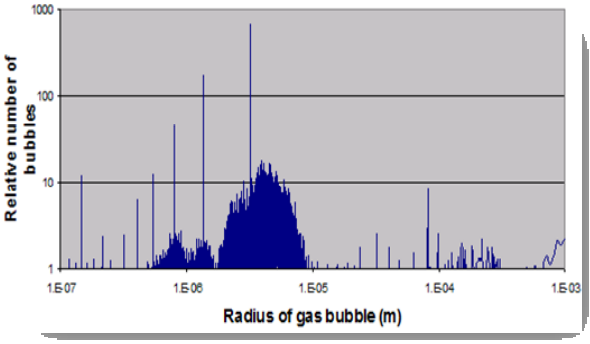


FFT



$$f_r = (2\Pi)^{-1}\left[\frac{3\gamma}{\rho R_r^{\,2}}\left(P_o + \frac{2\sigma}{R_r}\right) - \frac{2\sigma}{\rho R_r^{\,3}}\right]^{1/2}$$

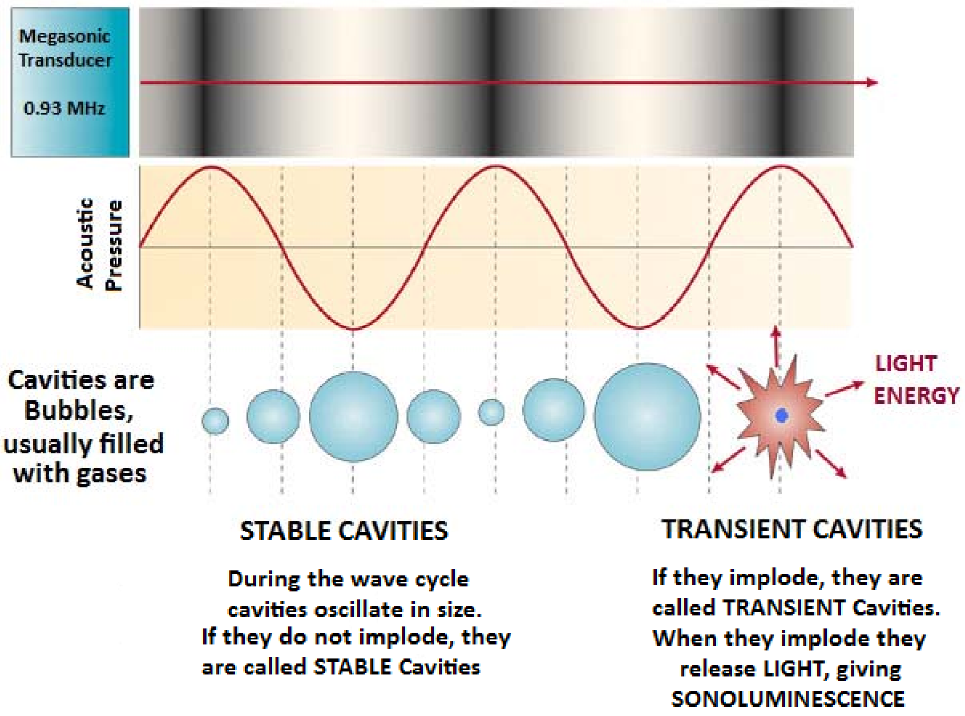
Bubble size distribution in Cavitating Liquid



*** ρ is the density of the liquid, f_r is the resonance frequency of the bubble, R_r is the radius of the resonating bubble, γ is the ratio of specific heats of the gas , P_0 is the steady pressure in the absence of the sound field, σ is the surface tension of liquid**

Sonoluminescence (SL) from Cavitating Bubbles

Figure adapted from:
Nature Reviews
Cancer **5**, 321-327 (2005)



During the wave cycle cavities oscillate in size. If they do not implode, they are called STABLE Cavities

If they implode, they are called TRANSIENT Cavities. When they implode they release LIGHT, giving SONOLUMINESCENCE

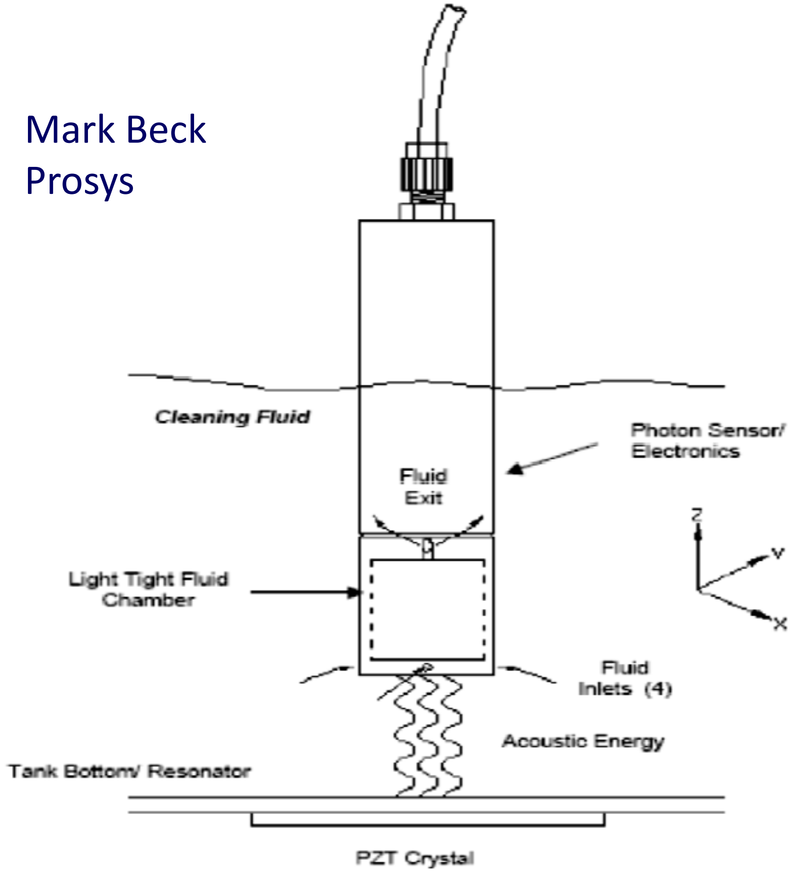
Suslick and Co-workers (*J. Phys. Chem. A 1999*) have reported T_{max} of ~ 4000 deg C for Argon saturated solutions.

- ***At collapse, the gas inside the cavity reaches extremely high temperatures (a few thousand degrees) and pressures (a few hundred bars).***
- ***Results in production of excited radical species***
- ***Excited species comes back to the ground state with photon emission.***

How to Measure Sonoluminescence (SL)??

Cavitation Probe

Mark Beck
Prosys



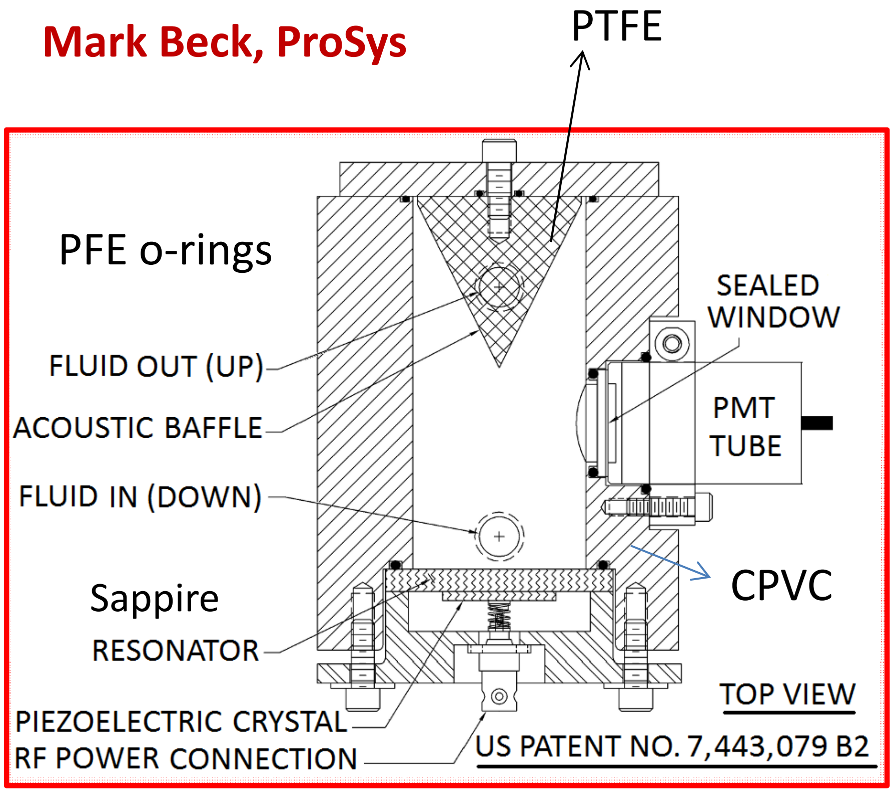
- Detects Sonoluminescence produced by Cavitation (Spectral Range 270 -650 nm)
- Real Time Monitoring of Cavitation Density

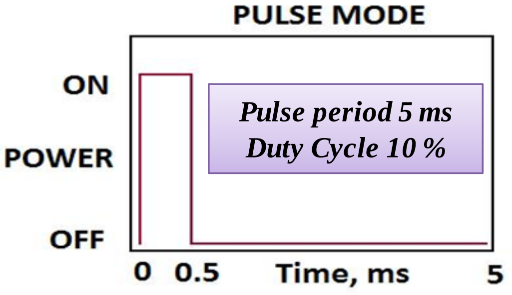
Cavitation Threshold Cell

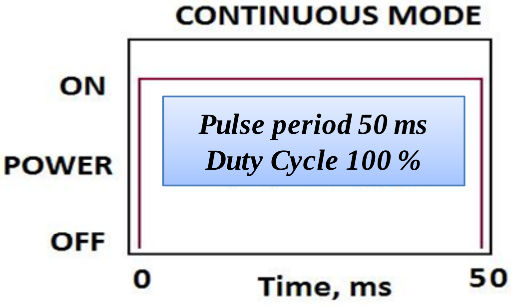
Mark Beck, ProSys

CT Cell Details

- *Volume = 163 cc, Length = 10.4 cm*
- *Internal Diameter = 4.8 cm*
- ***Frequency = 0.93 MHz***
- ***Wavelength Range = 270 to 650 nm***







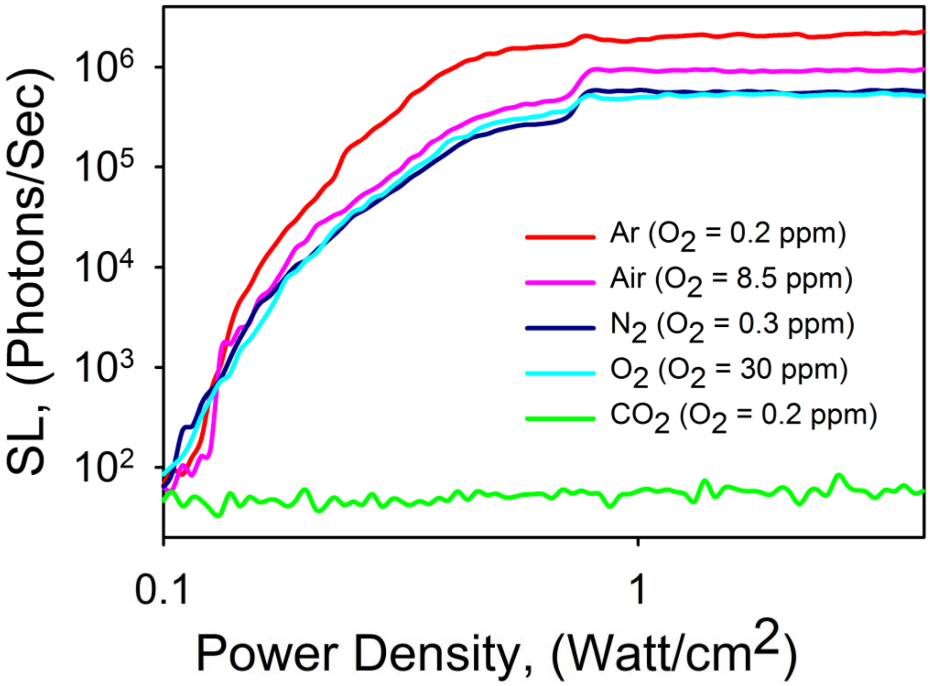
Sonoluminescence from DI Water Saturated with Different Gases

Gas	Relative Intensity	Thermal Conductivity (10^{-2} $Wm^{-1}K^{-1}$)
N_2	0.51	2.52
O_2	1.0	1.64
CO_2	0.36	1.56
He	0.48	14.3
Ne	1.33	4.72
Ar	12.5	1.73
Kr	21	0.94

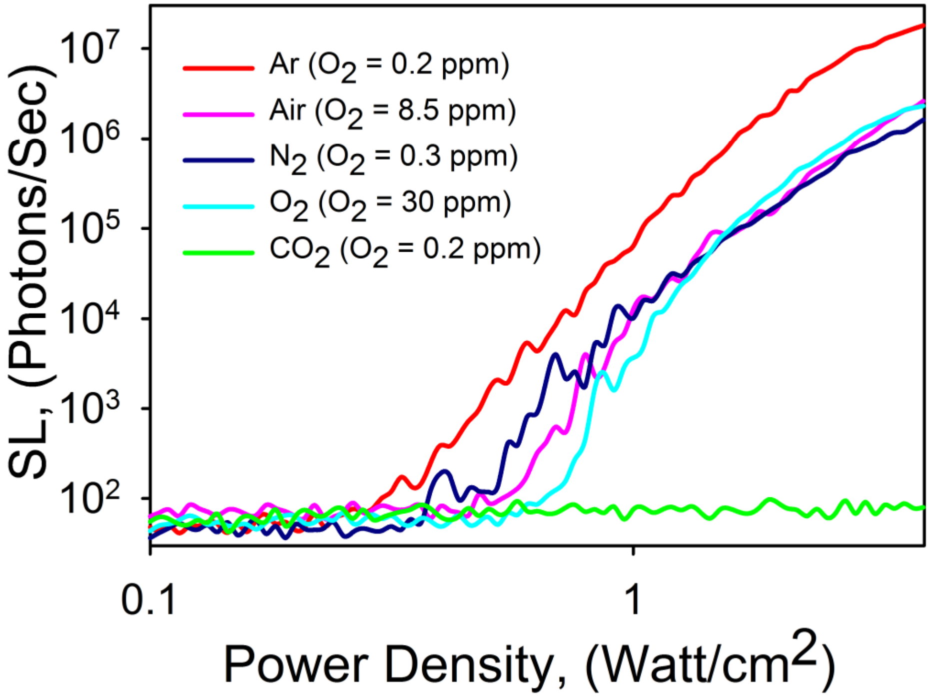
F. Young, J. Acoust. Soc. Am. Volume 60, 1, pp. 100-104 (1976)

- **Aqueous solution containing saturated level of gas was subjected to 20 KHz sound frequency at 10 W/cm^2 and SL was measured by a photomultiplier tube (165 to 650 nm)**
- **In general , gases with Higher thermal conductivity showed lower SL**

SL in DI Water Saturated With Different Gases



Pulse Mode

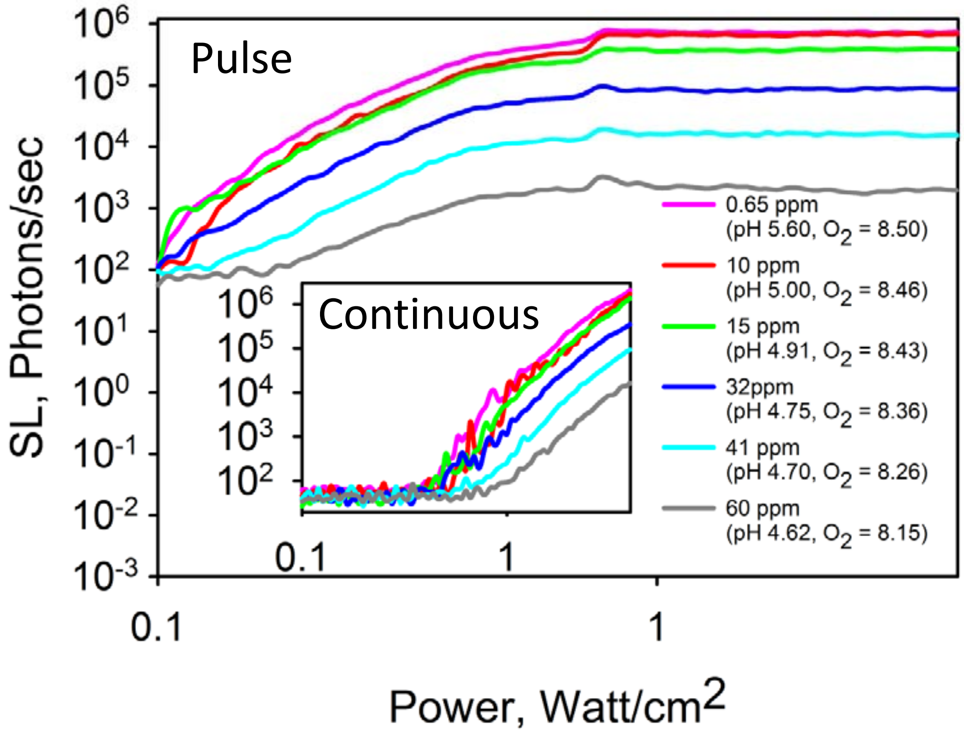


Continuous Mode

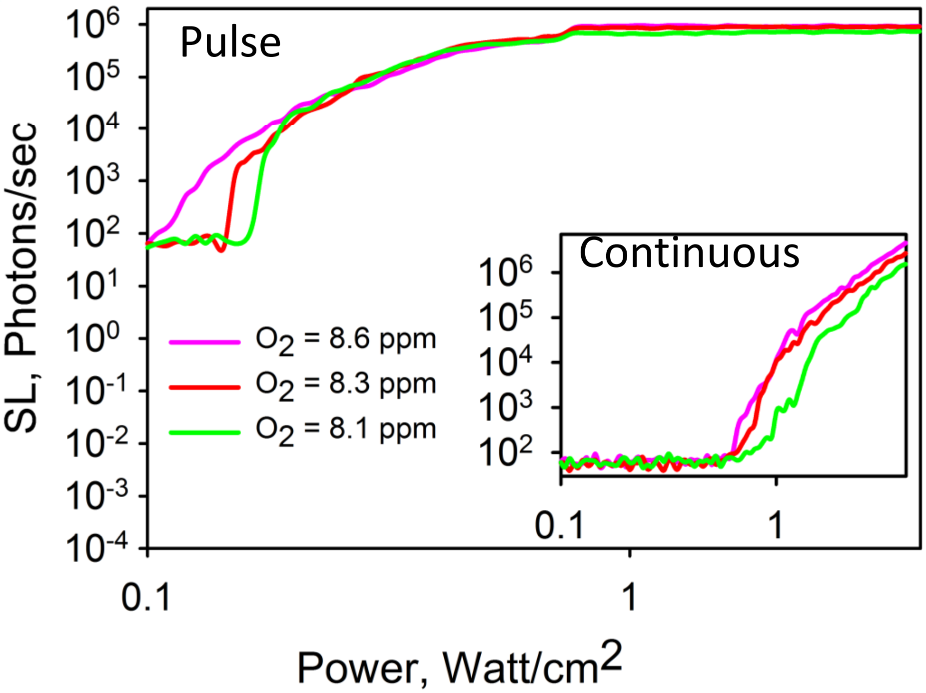
- **All gases except CO_2 (pH ~ 4, dissolved CO_2 ~ 1100 ppm) are capable of generating SL. CO_2 is completely incapable**

- **N_2 and O_2 saturated DI Water generates SL efficiently even though Ar, a gas believed to be essential for SL, is presumably absent**

Sonoluminescence Suppression by Bubbling of CO_2



CO_2 Effect



Vaccum Degassing Effect

CO_2 > 60 ppm suppresses SL almost completely. Addition of CO_2 decreases levels of other dissolved gases slightly.

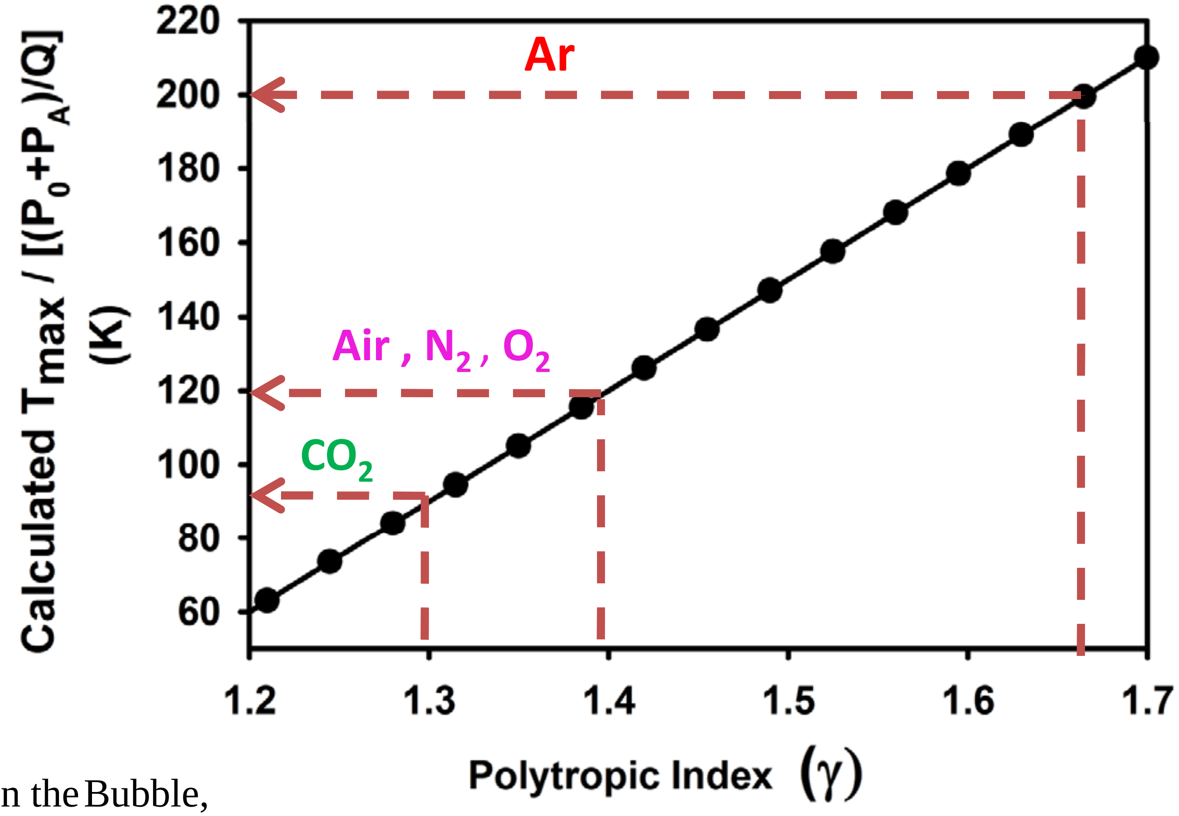
When Air-saturated DI Water is vaccum degassed to a comparable level, SL remains unaffected. Thus, SL suppression is due to added CO_2 and not due to removal of other gases upon addition of CO_2.

Dependence of Maximum Temperature Inside a Bubble on Gamma (C_p/C_v) of Dissolved Gas

- T_{max} , the Maximum temperature reached in an acoustic cavity depends on Gamma (γ) and is given by

$$T_{\max} = T_0\left[\frac{(P_0 + P_A)(\gamma - 1)}{Q}\right]$$

$$\frac{T_{\max}}{(P_0 + P_A)/Q} = T_0(\gamma - 1)$$



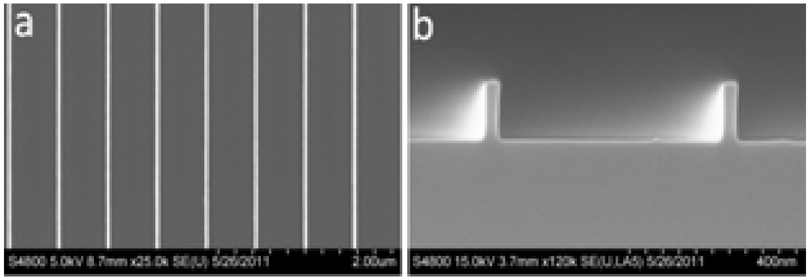
$T_{\max}$ = Max Temperature, Q = Initial Pressure in the Bubble,

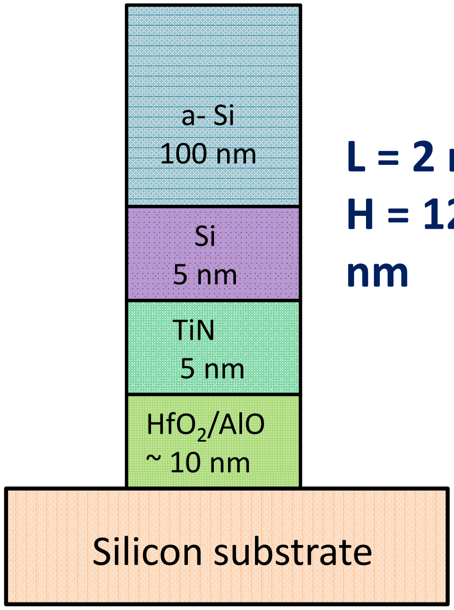
T_0 = Initial Temperature, γ = Polytropic Index

P_A = Acoustic Pressure Amplitude,

P_0 = Pressure in Bulk Solution in Absence of Sound Waves

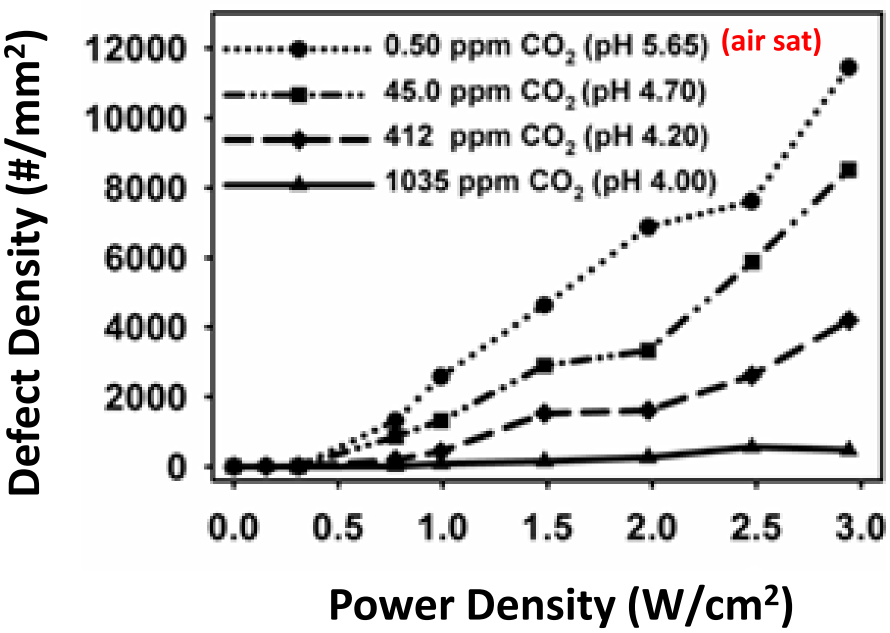
Effect of Dissolved Gases on Damage to Features





Courtesy of IMEC

L = 2 mm, W= 36 nm , H = 123 nm, S= 523 nm



Dissolved gases affect feature damage

Acknowledgements

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❖ IMEC for donating the test structures