MEGASONIC CLEANING OF WAFERS IN ELECTROLYTE SOLUTIONS: POSSIBLE ROLE OF ELECTRO-ACOUSTIC AND CAVITATION EFFECTS

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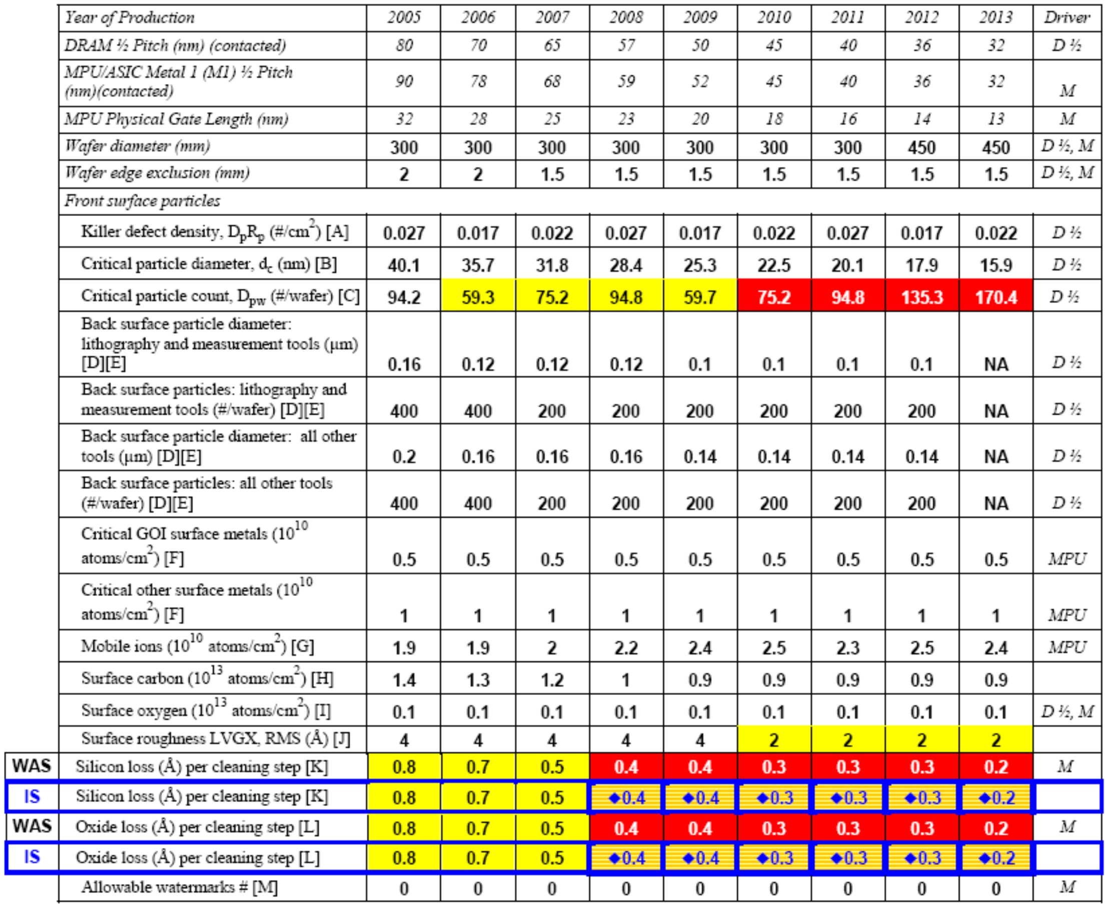
Outline

- INTRODUCTION
- PROPOSED WORK
- EXPERIMENTAL MATERIALS AND METHODS
- RESULTS AND DISCUSSION
- SUMMARY
- FUTURE WORK

INTRODUCTION

Growth and Challenges

Integrated Circuit Industry

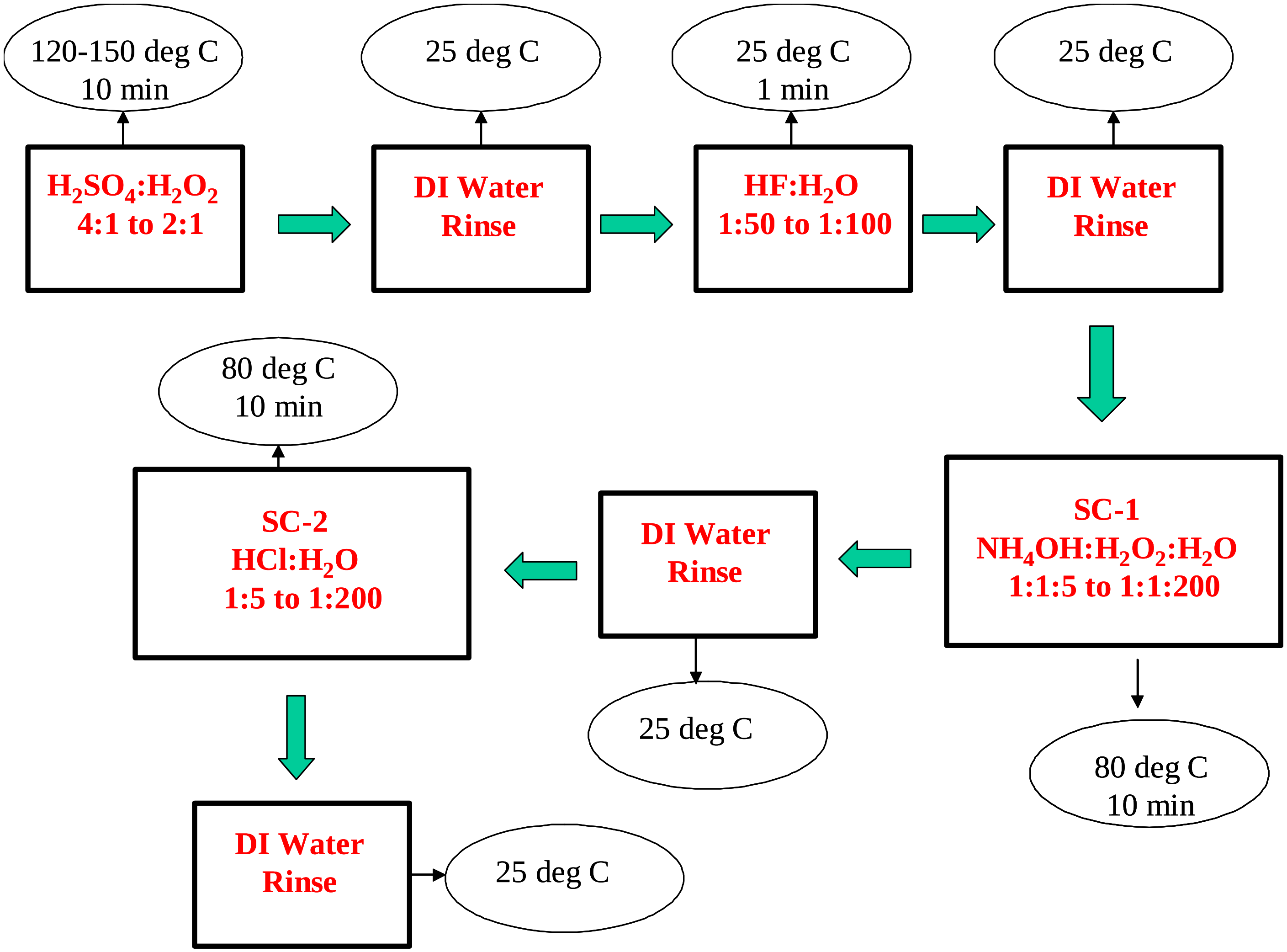


	Year of Production	2005	2006	2007	2008	2009	2010	2011	2012	2013	Driver
	DRAM ½ Pitch (nm) (contacted)	80	70	65	57	50	45	40	36	32	D ½
	MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)	90	78	68	59	52	45	40	36	32	M
	MPU Physical Gate Length (nm)	32	28	25	23	20	18	16	14	13	M
	Wafer diameter (mm)	300	300	300	300	300	300	300	450	450	D ½, M
	Wafer edge exclusion (mm)	2	2	1.5	1.5	1.5	1.5	1.5	1.5	1.5	D ½, M
	Front surface particles										
	Killer defect density, D_pR_p (#/cm^2) [A]	0.027	0.017	0.022	0.027	0.017	0.022	0.027	0.017	0.022	D ½
	Critical particle diameter, d_c (nm) [B]	40.1	35.7	31.8	28.4	25.3	22.5	20.1	17.9	15.9	D ½
	Critical particle count, D_{pw} (#/wafer) [C]	94.2	59.3	75.2	94.8	59.7	75.2	94.8	135.3	170.4	D ½
	Back surface particle diameter: lithography and measurement tools (µm) [D][E]	0.16	0.12	0.12	0.12	0.1	0.1	0.1	0.1	NA	D ½
	Back surface particles: lithography and measurement tools (#/wafer) [D][E]	400	400	200	200	200	200	200	200	NA	D ½
	Back surface particle diameter: all other tools (µm) [D][E]	0.2	0.16	0.16	0.16	0.14	0.14	0.14	0.14	NA	D ½
	Back surface particles: all other tools (#/wafer) [D][E]	400	400	200	200	200	200	200	200	NA	D ½
	Critical GOI surface metals (10^{10} atoms/cm^2) [F]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	MPU
	Critical other surface metals (10^{10} atoms/cm^2) [F]	1	1	1	1	1	1	1	1	1	MPU
	Mobile ions (10^{10} atoms/cm^2) [G]	1.9	1.9	2	2.2	2.4	2.5	2.3	2.5	2.4	MPU
	Surface carbon (10^{13} atoms/cm^2) [H]	1.4	1.3	1.2	1	0.9	0.9	0.9	0.9	0.9	
	Surface oxygen (10^{13} atoms/cm^2) [I]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	D ½, M
	Surface roughness LVGX, RMS (Å) [J]	4	4	4	4	4	2	2	2	2	
WAS	Silicon loss (Å) per cleaning step [K]	0.8	0.7	0.5	0.4	0.4	0.3	0.3	0.3	0.2	M
IS	Silicon loss (Å) per cleaning step [K]	0.8	0.7	0.5	◆0.4	◆0.4	◆0.3	◆0.3	◆0.3	◆0.2	
WAS	Oxide loss (Å) per cleaning step [L]	0.8	0.7	0.5	0.4	0.4	0.3	0.3	0.3	0.2	M
IS	Oxide loss (Å) per cleaning step [L]	0.8	0.7	0.5	◆0.4	◆0.4	◆0.3	◆0.3	◆0.3	◆0.2	
	Allowable watermarks # [M]	0	0	0	0	0	0	0	0	0	M

ITRS Requirements

- Fifty Percent of yield losses due to particle contamination
- Over 200 cleaning steps
- Critical particle diameter and count to be 25 nm and 59 #/wafer respectively for a 300 mm wafer
- Particulate impurities on the wafer critically affects the device performance, reliability, and product yield of integrated circuits

Typical Wafer Cleaning Sequence



H_2SO_4:H_2O_2
4:1 to 2:1

120-150 deg C
10 min

DI Water Rinse

25 deg C

HF:H_2O
1:50 to 1:100

25 deg C
1 min

DI Water Rinse

25 deg C

SC-1
NH_4OH:H_2O_2:H_2O
1:1:5 to 1:1:200

80 deg C
10 min

DI Water Rinse

25 deg C

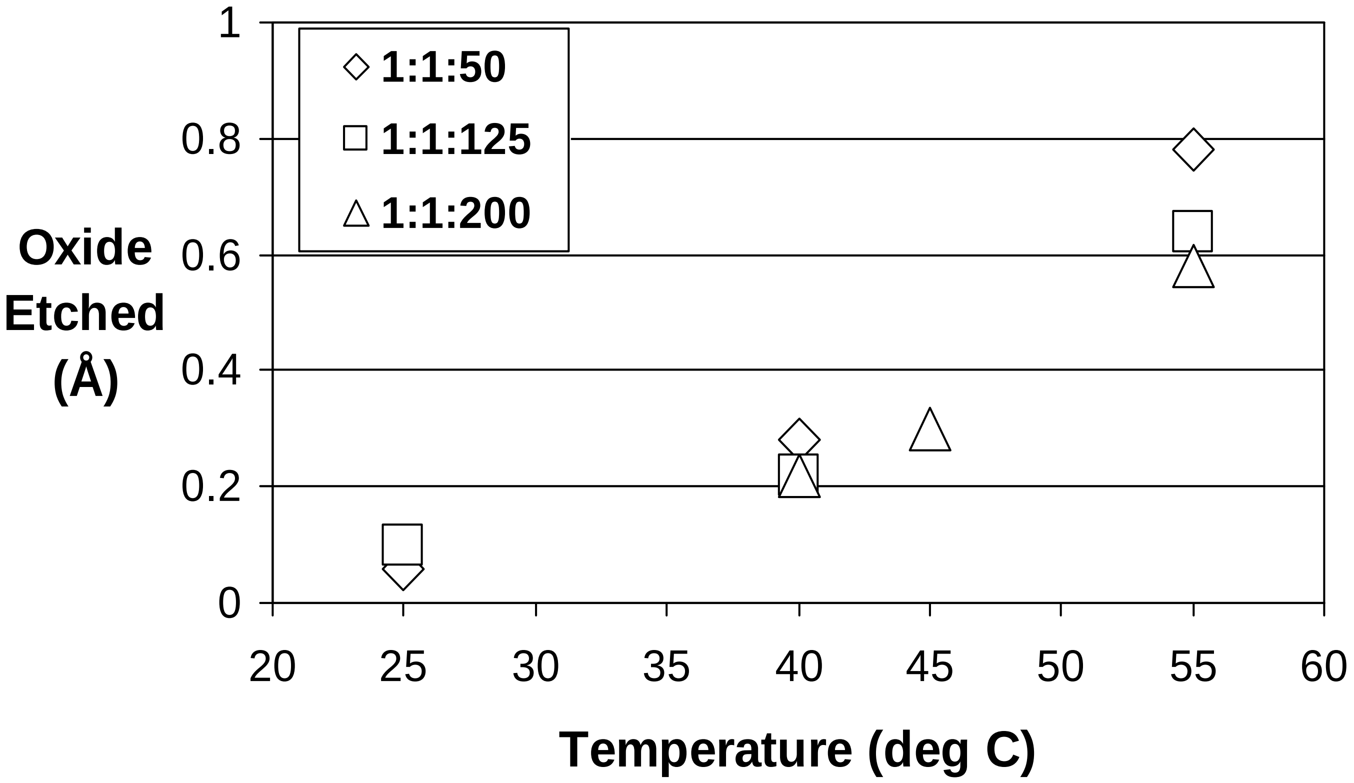
SC-2
HCl:H_2O
1:5 to 1:200

80 deg C
10 min

DI Water Rinse

25 deg C

Etching of Thermal Oxide in SC1 (time = 1 min)



Strong Etch Dependence on Temp

Courtesy: Dr. J. Butterbaugh, FSI

Wafer Cleaning Techniques

- **High Pressure Water Jet Cleaning**
- **Immersion Cleaning and Spray Cleaning without Megasonics**
- **Immersion Cleaning and Spray Cleaning with Megasonics**
  - Very simple and easy to use.
  - Great potential in removing sub – micron size particles in combination with dilute chemistries

Megasonic Cleaning

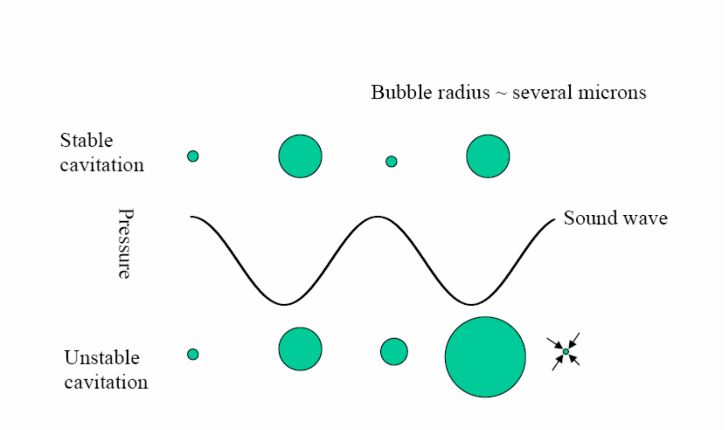
MHz frequency sound waves with different cleaning chemistries

Particle on wafer surface

- Hydrodynamic boundary layer thickness 400 - 1000 µm in DI water (viscosity = 10^{-3} Pa-s, density = 10^{3} kg/m^{3}, velocity = 0-10 m/s)
- Acoustic boundary layer at 1 MHz in DI water ~ 0.5 µm

Particle Removal Mechanisms:

- **Acoustic Streaming**: Drag forces and rolling moments @S/L interface to help particle removal.
- **Acoustic Cavitation**: High energy shock waves or fluid jet dislodging the particle.
- **Chemistry + Sonic field**



Physical Effect of Cavitation

Sonoluminescence (Photon emission)

- At collapse, the gas inside the cavity reaches extremely high temperatures (4300 K) and pressures (few hundred bars).
- Results in production of free radical species (excited hydroxyl radicals).
- Recombination of free radicals gives rise to photon emission.

$$H_2O + M \longrightarrow H_2O^*(\,^3B_1) + M$$

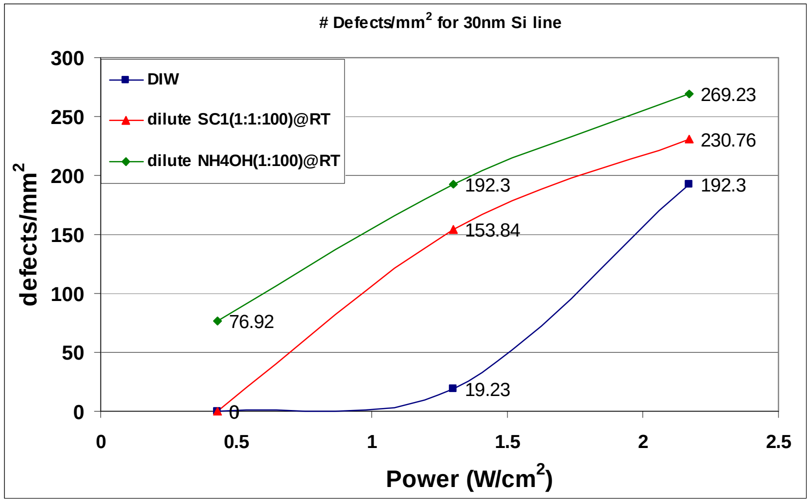
$$H_2O^*(\,^3B_1) + M \longrightarrow H_2O(\,^1A_1) + h\nu_0 \; (270 - 290\,nm)$$

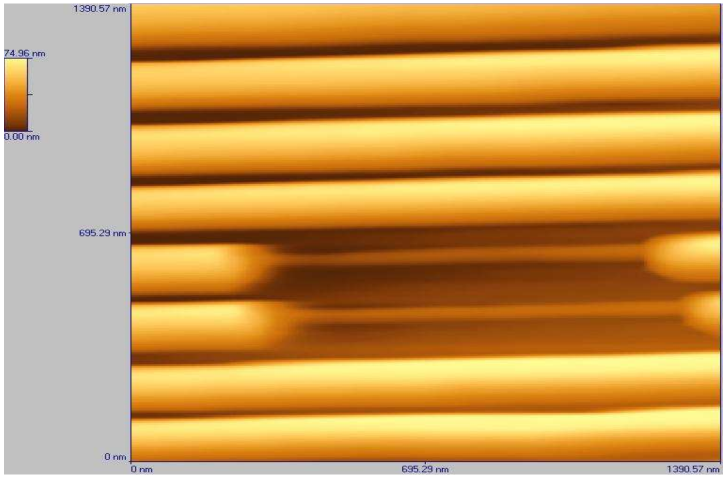
$$H_2O^*(\,^3B_1) + M \longrightarrow H + OH^* \longrightarrow OH + H + h\nu_1 \; (310\,nm)$$

Challenges Associated with Megasonic Cleaning

- Megasonic cleaning is typically done in alkaline pH condition (using SC1-1 solution) which causes loss of wafer surface due to etching

- Use of DI water instead of SC-1 requires much higher power density. A significant level of damage of features (in the case of patterned wafers) occurs at these power densities





Images from -H. Shende, MS Thesis, The University of Arizona, 2006

PROPOSED WORK

Need for Present Work

1) Identify a non-etching chemistry with advanced non-damaging megasonics

2) Focus of Past Work

- Acoustic Power
- Chemistry
- Gas content
- Surface tension
- Viscosity

- No literature on effect of Ionic Strength on Particle Removal Studies in Megasonics
- Industry uses cleaning solutions (eg SC1, SC2, TMAH, Piranha etc) which may have varying ionic strengths

Use of Electrolytes can achieve both objectives

Why Study KCl Solutions?

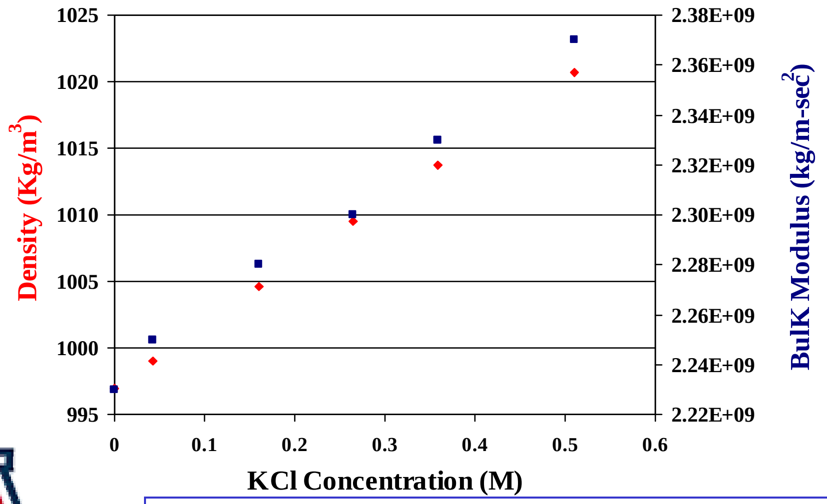
- Addition of KCl to water increases the bulk modulus (κ) and density (ρ_0) of solution and hence may modulate the pressure amplitude (*a*) of the propagating sound wave and affect Cavitation

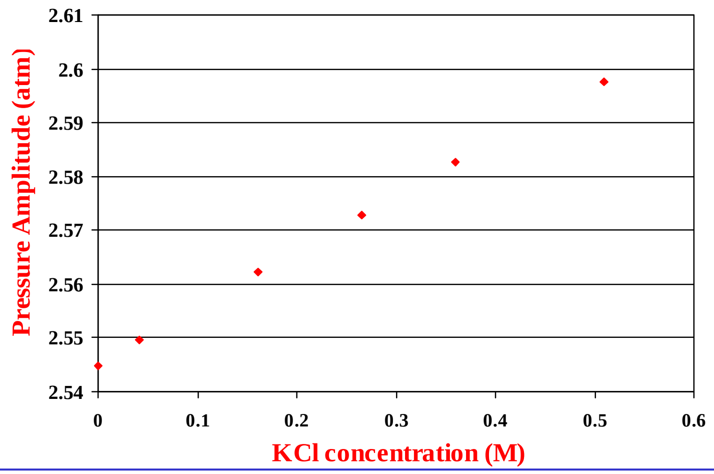
- The propagation of sound waves through an electrolyte solution containing particles is known to result in the generation of two types of oscillating electric potentials, namely, Ionic Vibration Potential (IVP) and Colloid Vibration Potential (CVP).

- These potentials and their associated electric fields can exert forces on particles adhered to a surface, resulting in their removal.

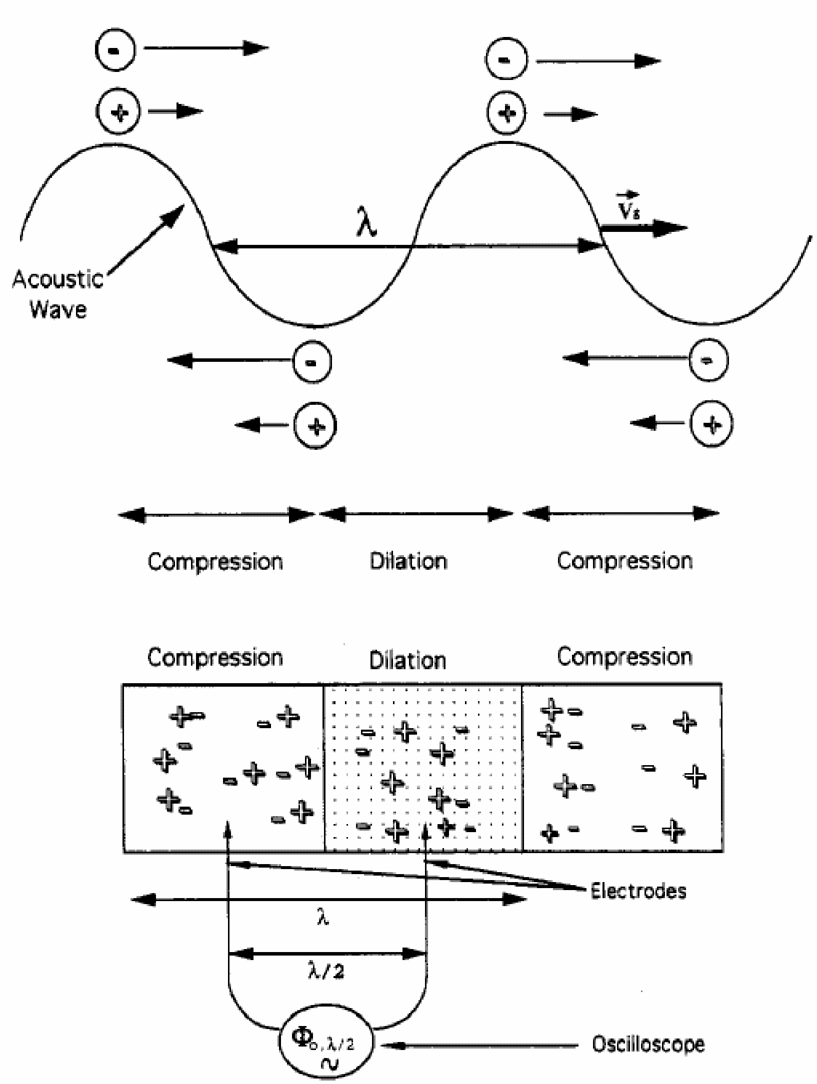
$$a = (2I)^{0.5} (\rho_0 \kappa)^{0.25}$$

I = Intensity of transducer=2.17 W/cm^2



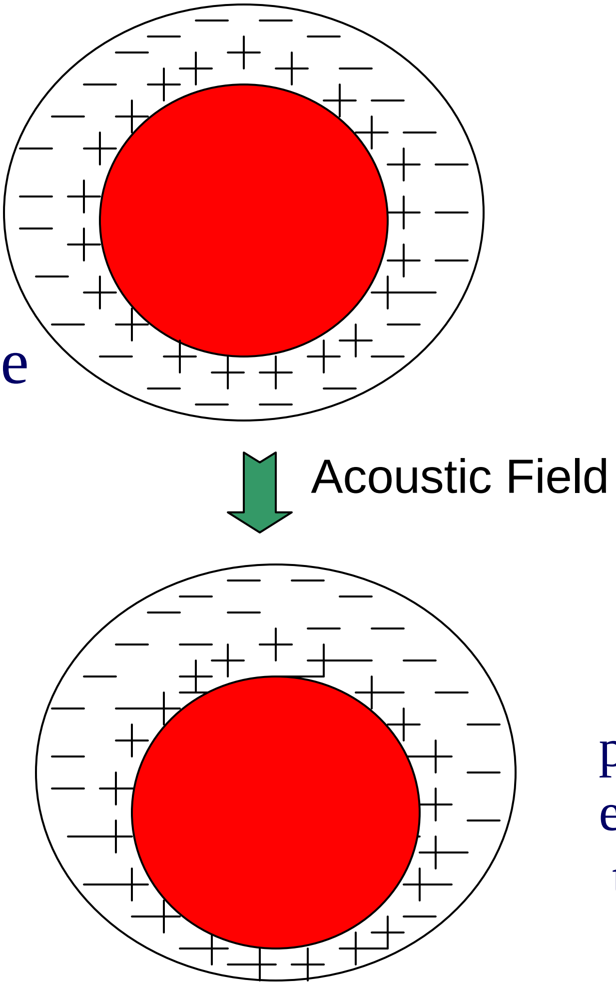


Debye Effect



S. D. Vidal et al., J. Phy. Chem., 99, pp.6733-6738 (1995)

Interaction of Sonic Field with Colloidal Particles: Colloid Vibration Potential (CVP)



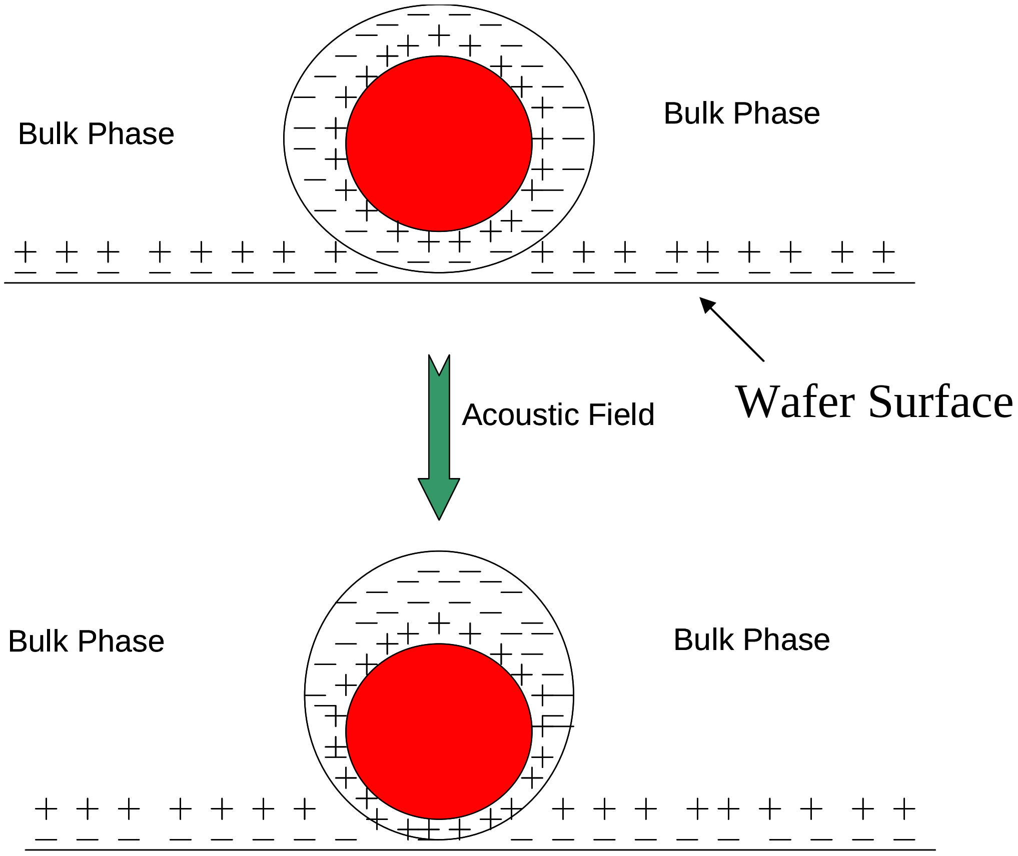
periodic polarization of the ionic atmosphere surrounding the particles.

periodic polarization causes each particle to act as a vibrating dipole

CVP ~ 5 to 10 mV for silica suspensions subjected to sound waves of 0.2 MHz at 0.22 W/cm^2 of power density

E. Yeager et al.,, The Journal of the Acoustical Society of America, 25, 3, 456-460 (1953)

Dipole Moment Formation Due to Asymmetry of Double Layer Around a Charged Particle Adhered on a Wafer Surface

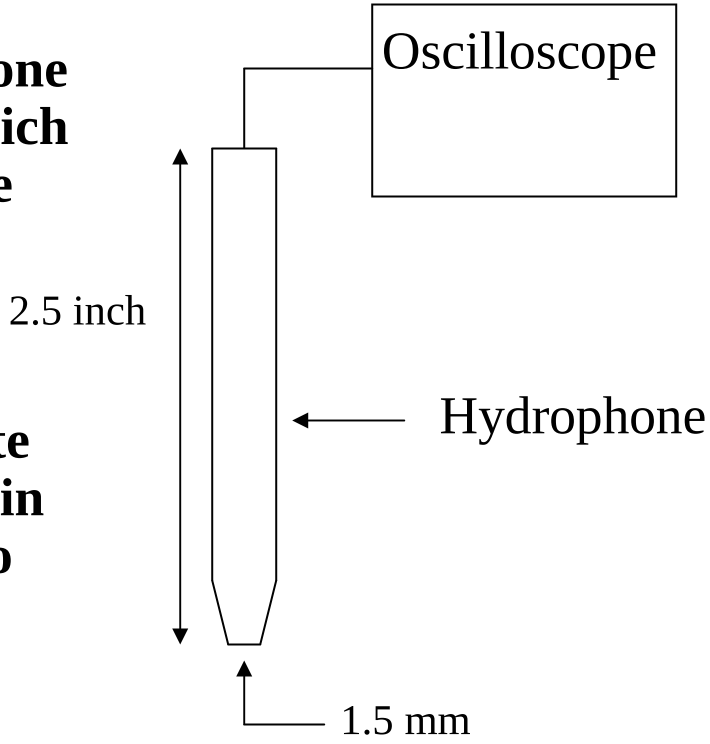


Can the electric field associated with CVP exert a force on charged particles adhered to a surface, resulting in their removal?

EXPERIMENTAL MATERIALS AND METHODS

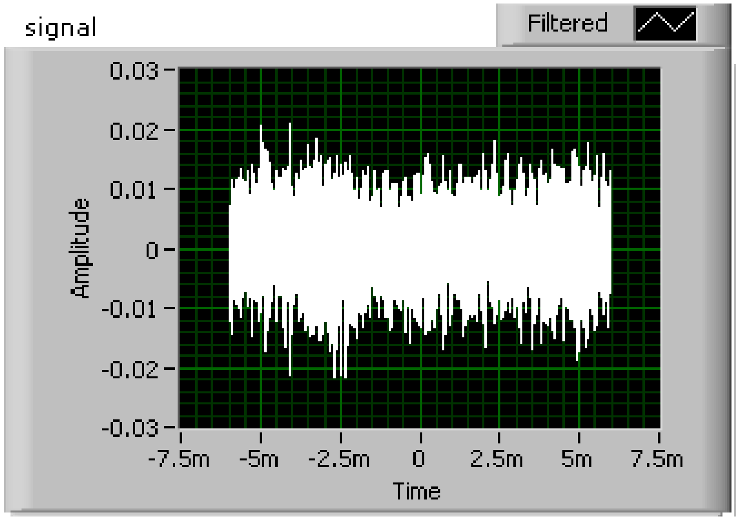
Hydrophone-Oscilloscope Experiments
Method and Analysis

- **Experiments were performed in a Prosys immersion megasonic system using a hydrophone (Onda Corporation/Specialty Engineering) which was positioned in the far field region to achieve consistency in results.**
- **The set up has a capacity to acquire 65000 continuous samples for each run. Sampling rate was 20 million samples/sec. The output signal, in volts, from the oscilloscope is then converted to the Root Mean Square value. Fast Fourier Transform of the raw output signal was performed to convert the data from time to frequency domain.**

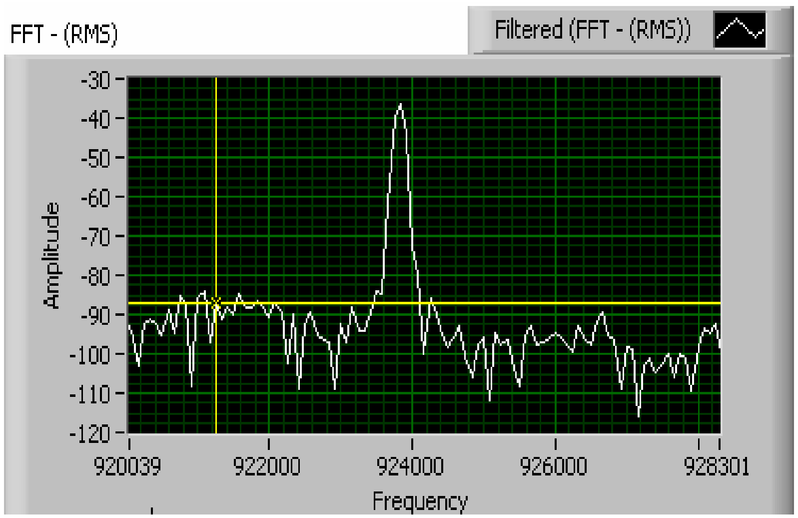


Hydrophone donated by Dr. Steven Verhaverbeke, Applied Materials

Spectral Analysis using Fast Fourier Transform



FFT

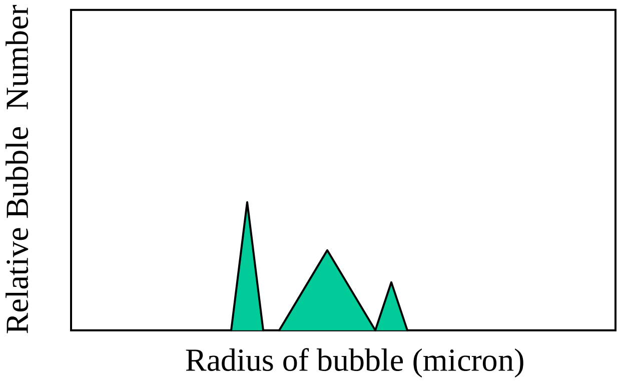


Linear Theory

$$\rho\, \omega_r^2\, R_r^2 = 3\, \gamma\, (P_0 + 2\sigma/R_r) - 2\, \sigma/R_r$$

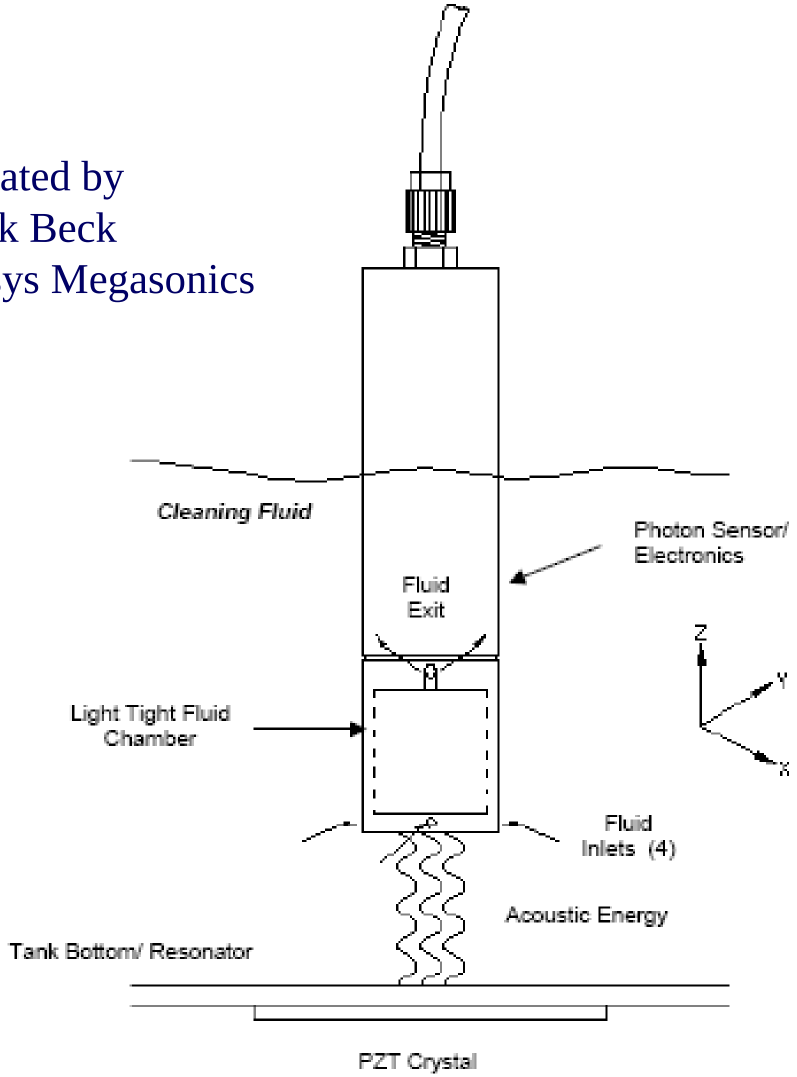
ρ is the density of the liquid
ω_r is the resonance frequency of the bubble
R_r is the radius of the resonating bubble
γ is the ratio of specific heats of the gas
P_0 is the steady pressure in the absence of the sound field

σ is the surface tension of liquid



How to measure cavitation???

Donated by
Mark Beck
Prosys Megasonics



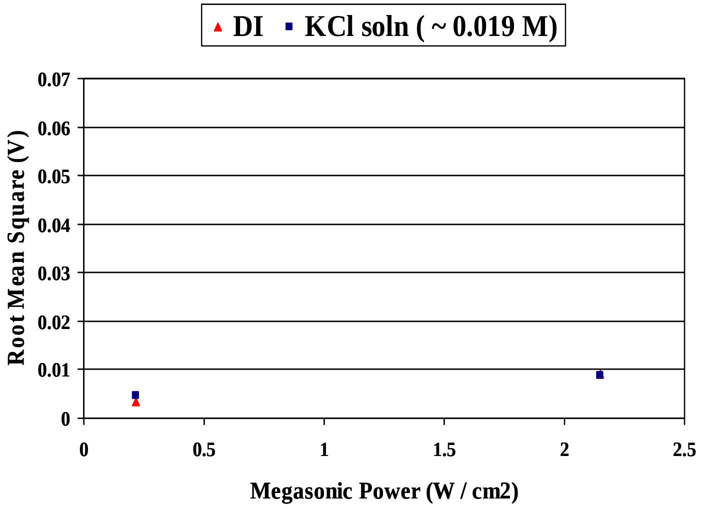
- Detects Sonoluminescence produced by Cavitation (Spectral Range 270 -650 nm)
- Real Time Monitoring of Cavitation Density
- Indicator of Feature Damage

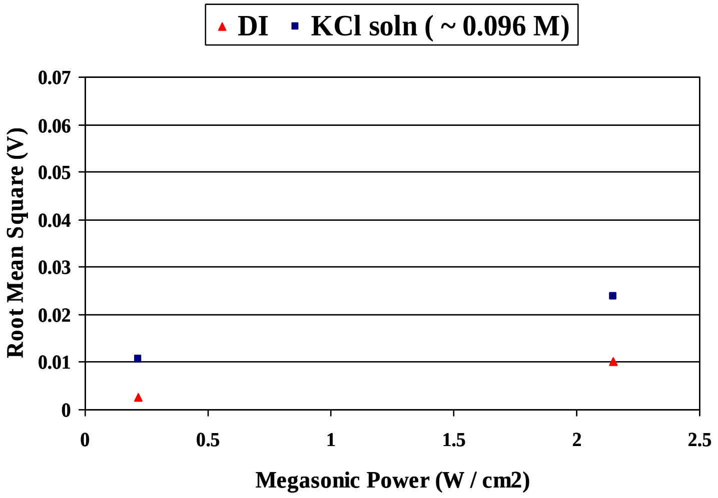
Wafer Pre-clean, Contamination and Cleaning Protocol

- **Pre-cleaning of 150-mm silicon wafers in 1:1:50 SC1 solution**
- **Aminated and Plain silica particles (Mean Size ~ 370 ± 20 nm purchased from Corpuscular Inc.) used for contamination. Typical particle count on wafers after deposition : ~ 2500**
- **Cleaning done in a Prosys immersion megasonic tank for one minute at 30 ^{0}C**
- **Surfscan 5500 used for particle counts**

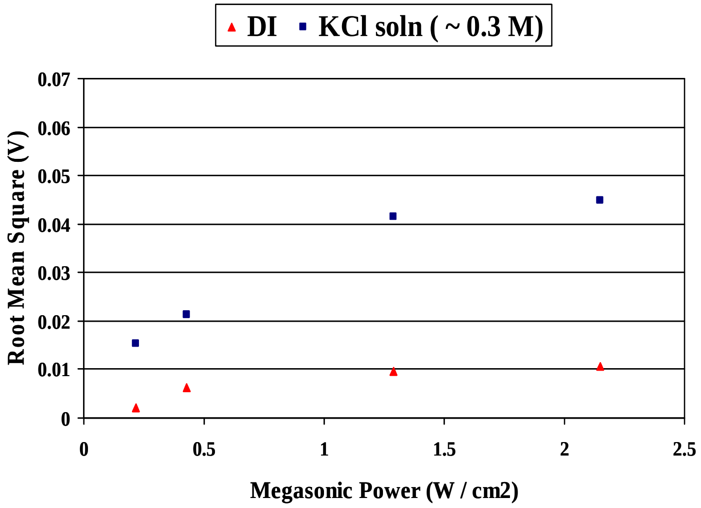
RESULTS AND DISCUSSION

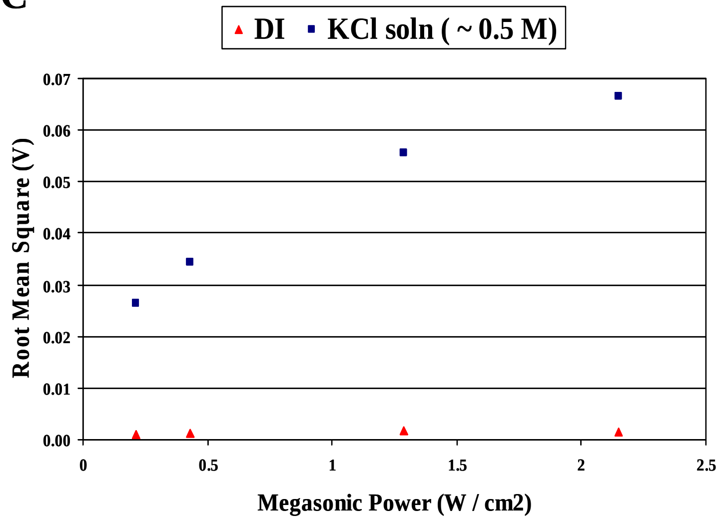
Role of KCl on Sound Wave Amplitude





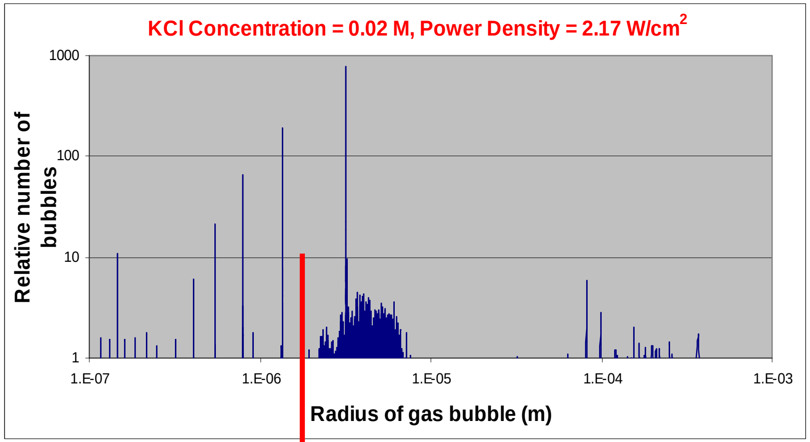
T = 33 C





Cavity Size Distribution from FFT and Energy Balance

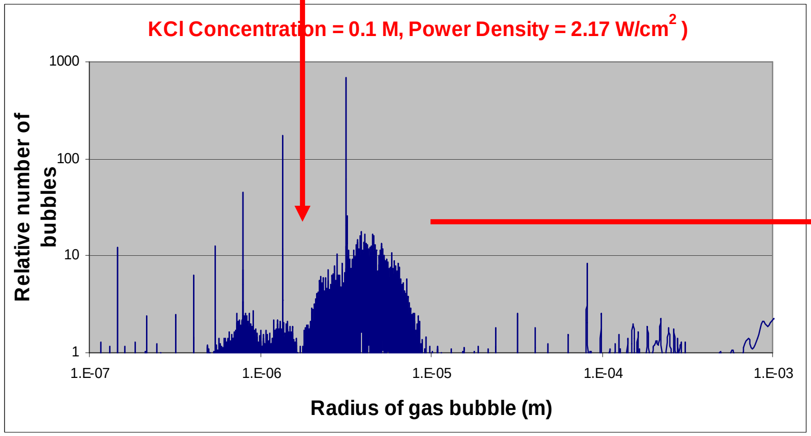
Correlating frequencies of oscillating bubbles with their sizes

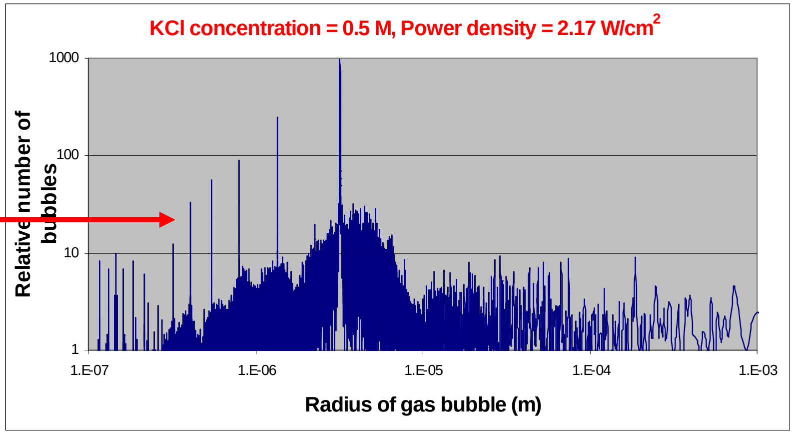

KCl Concentration = 0.02 M, Power Density = 2.17 W/cm^2

Increasing appearance of bubbles with increase In KCl concentration

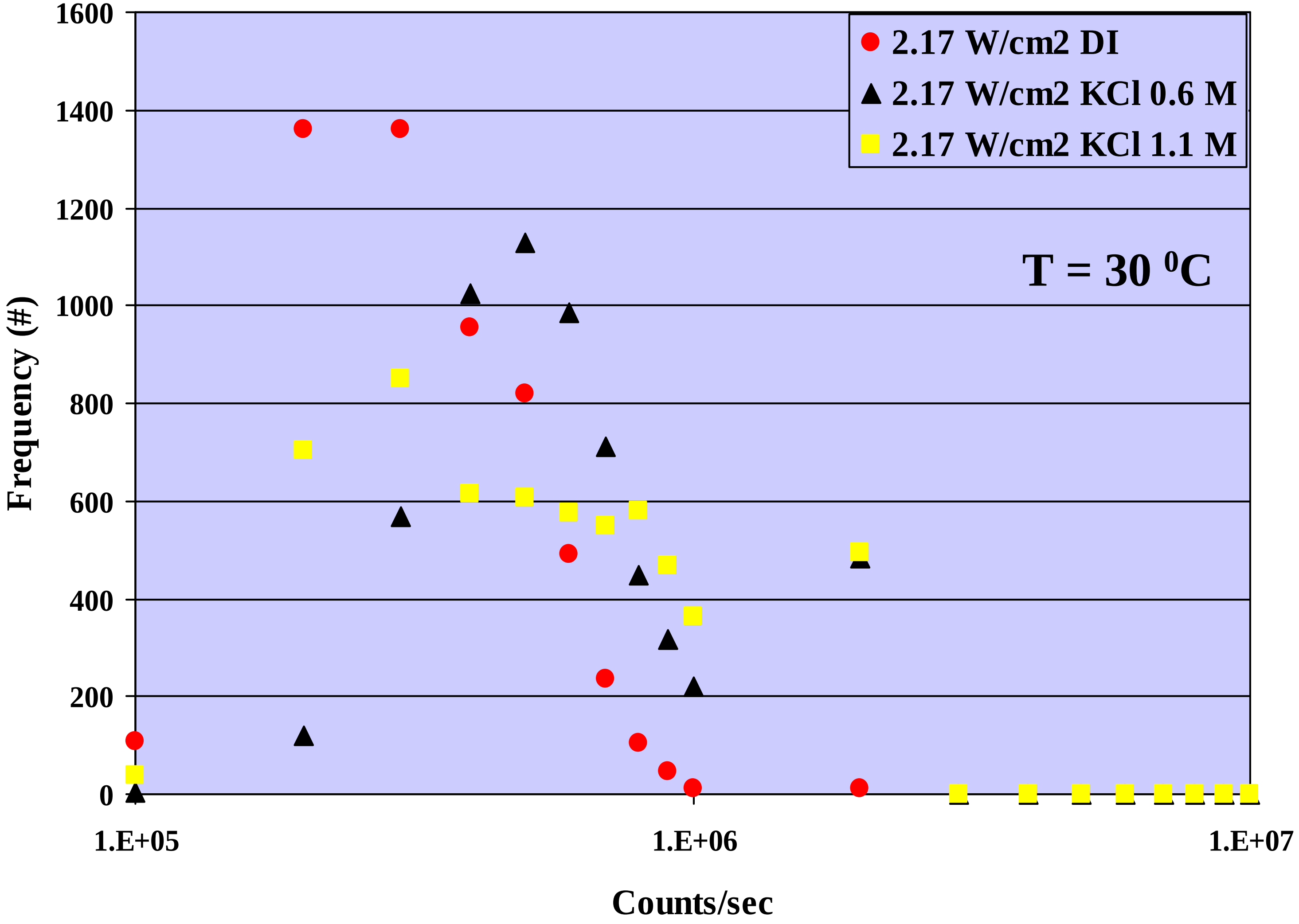
Distribution of bubbles between 1-1000 micron

Bubble size larger than about 1 mm can be ignored as such bubbles will be removed from the system due to buoyancy.

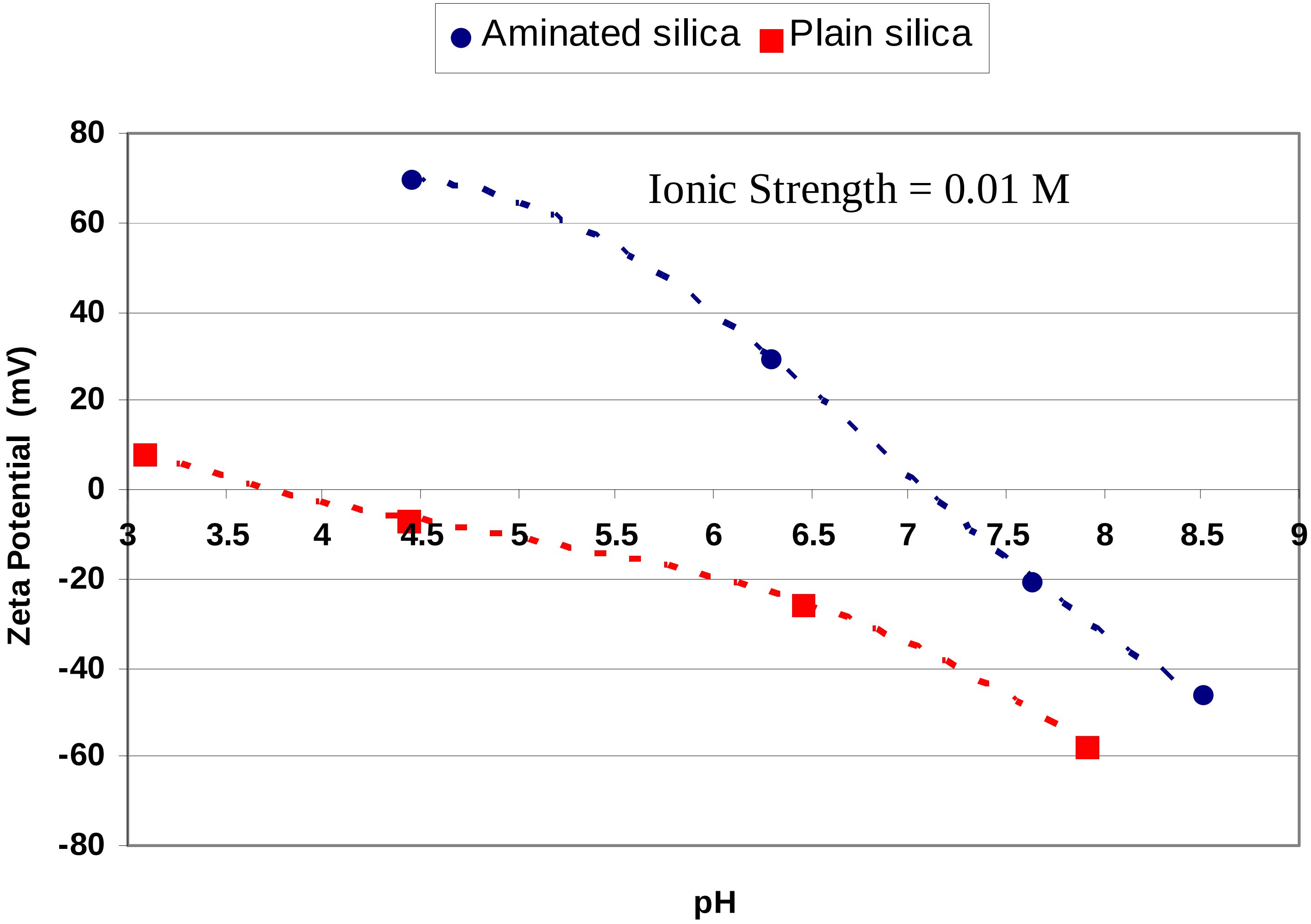

KCl Concentration = 0.1 M, Power Density = 2.17 W/cm^2)


KCl concentration = 0.5 M, Power density = 2.17 W/cm^2

Sonoluminescence in KCl Solution

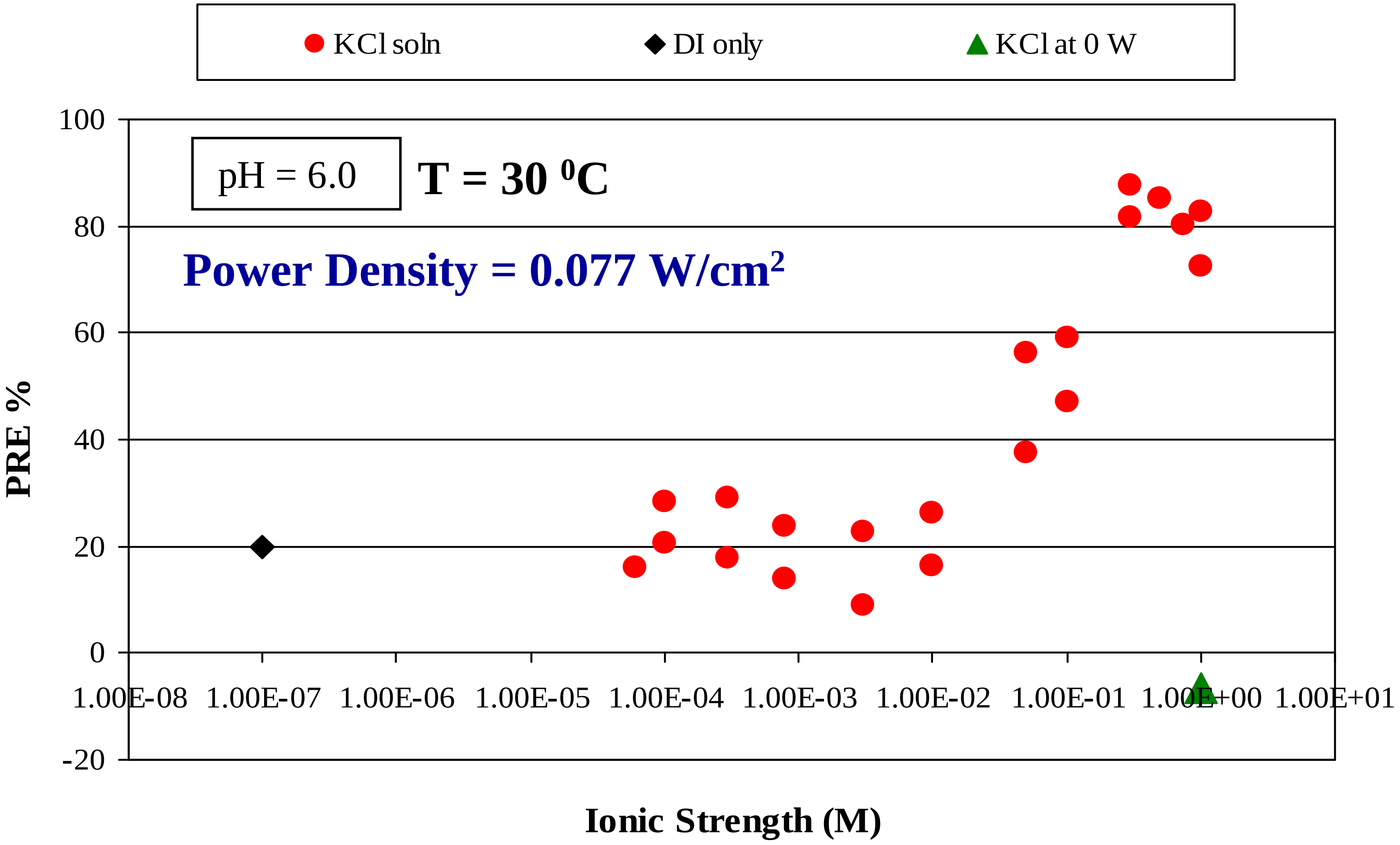


Zeta Potential of Aminated and Plain Silica Particles

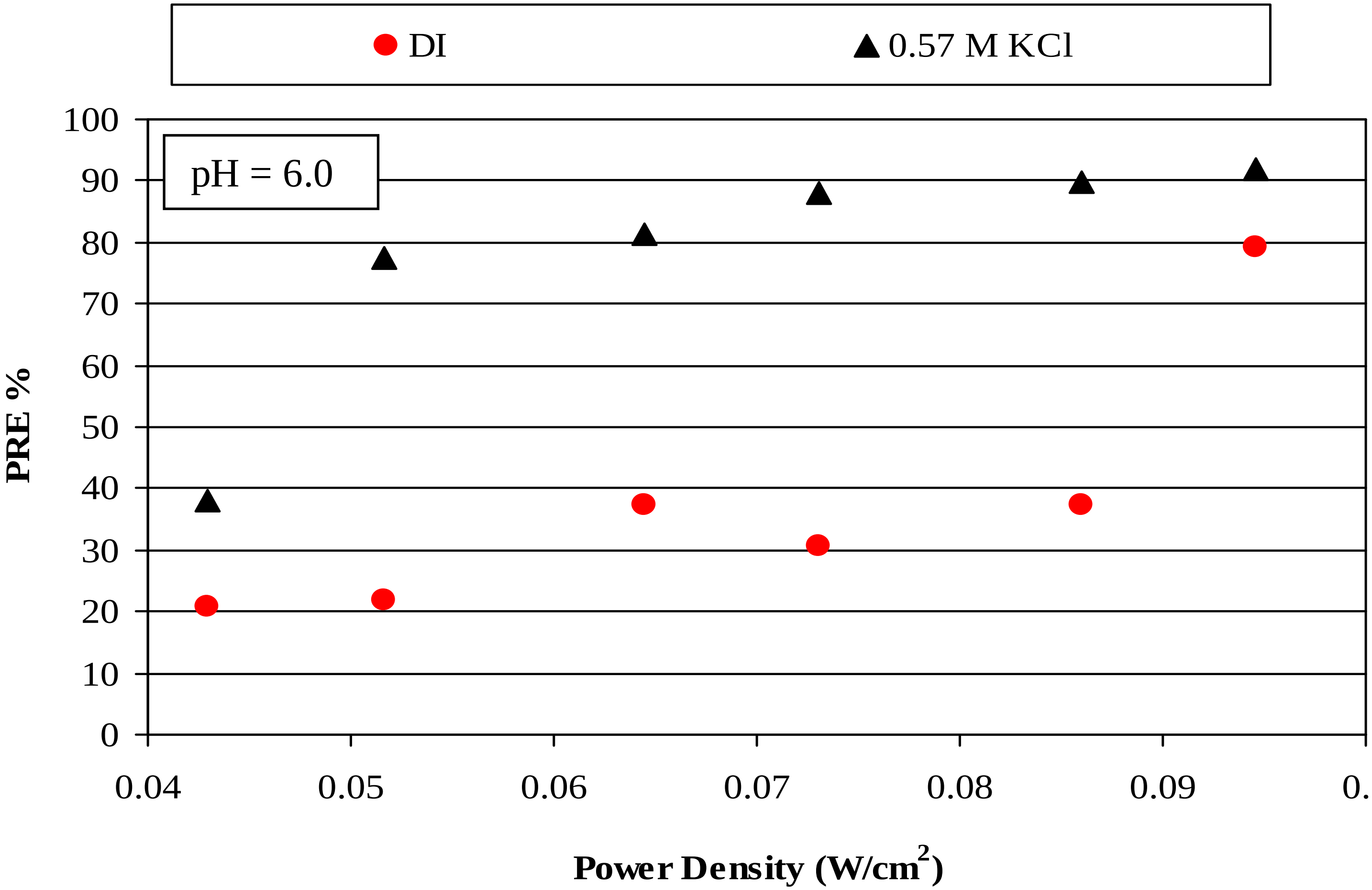


The isoelectric point (IEP) of aminated silica and plain silica particles was found to occur at pH values of 7.1 and 3.9 respectively.

Megasonic Removal of Plain Silica Particles in KCl Solutions of Different Concentration

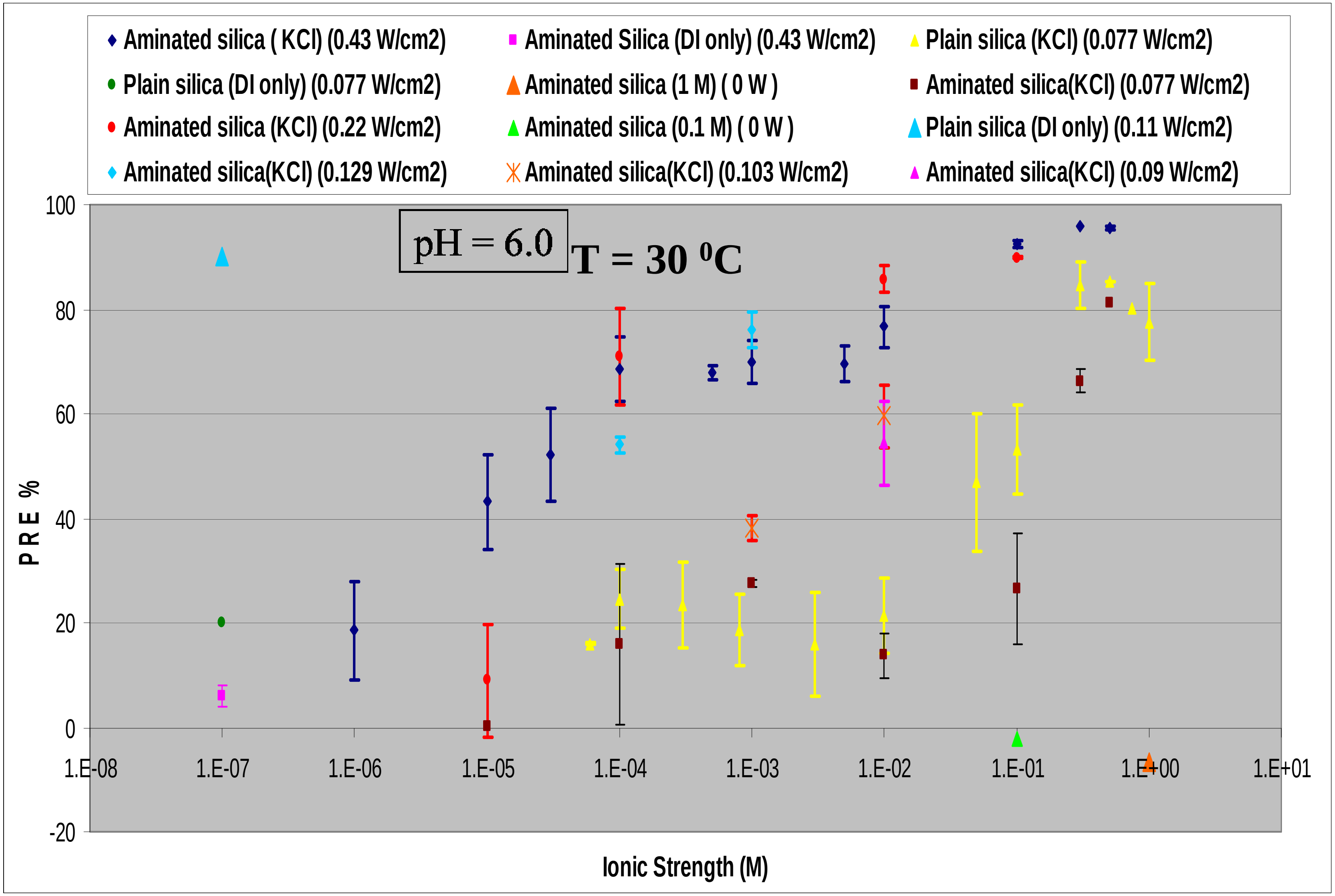


Megasonic Removal of Plain Silica Particles in 0.57 M KCl Solution at Different Power Densities



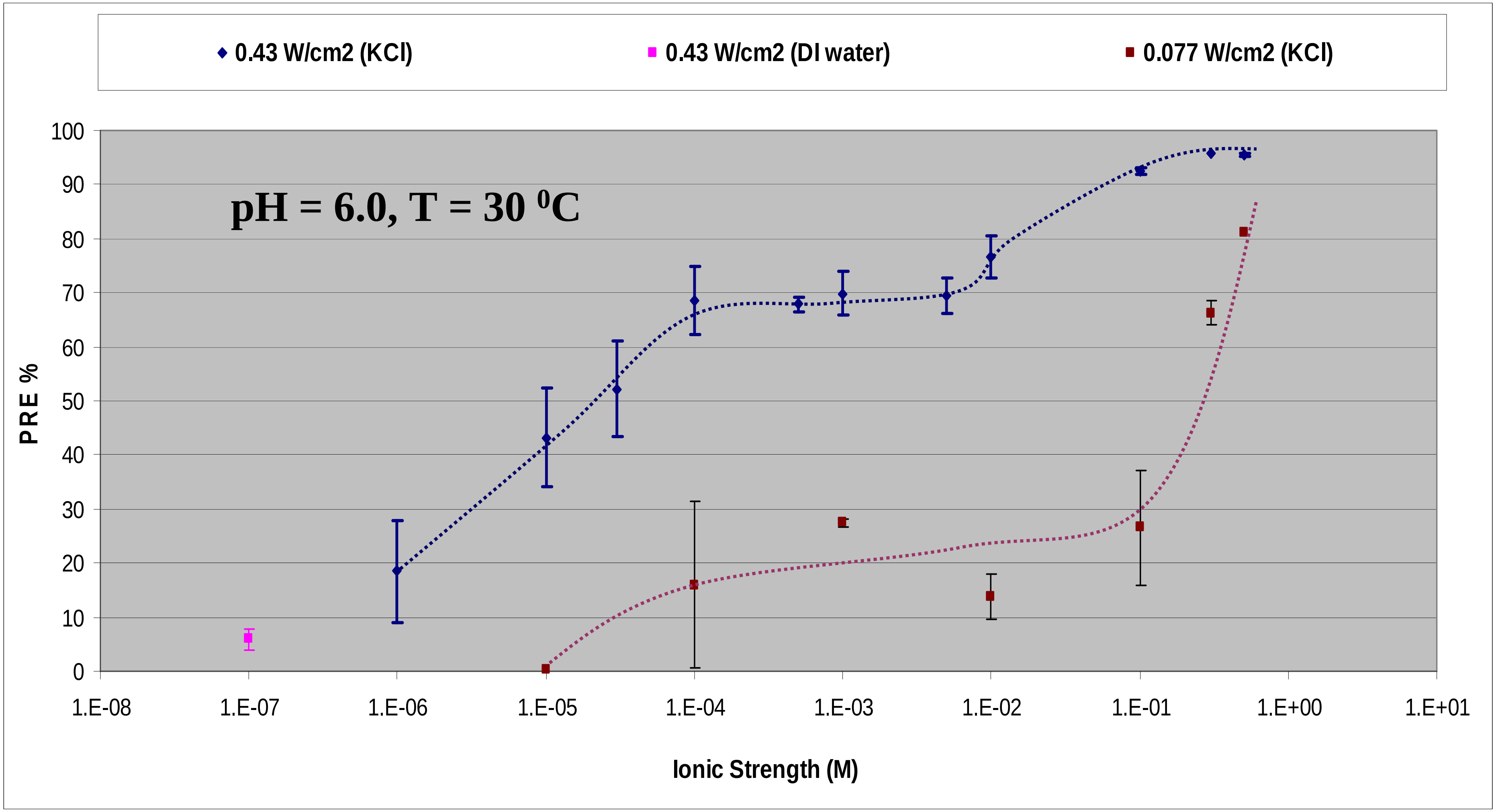
T = 30 ^{0}C

Megasonic Removal of Aminated Silica Particles in KCl Solutions of Different Concentration at Different Power Densities

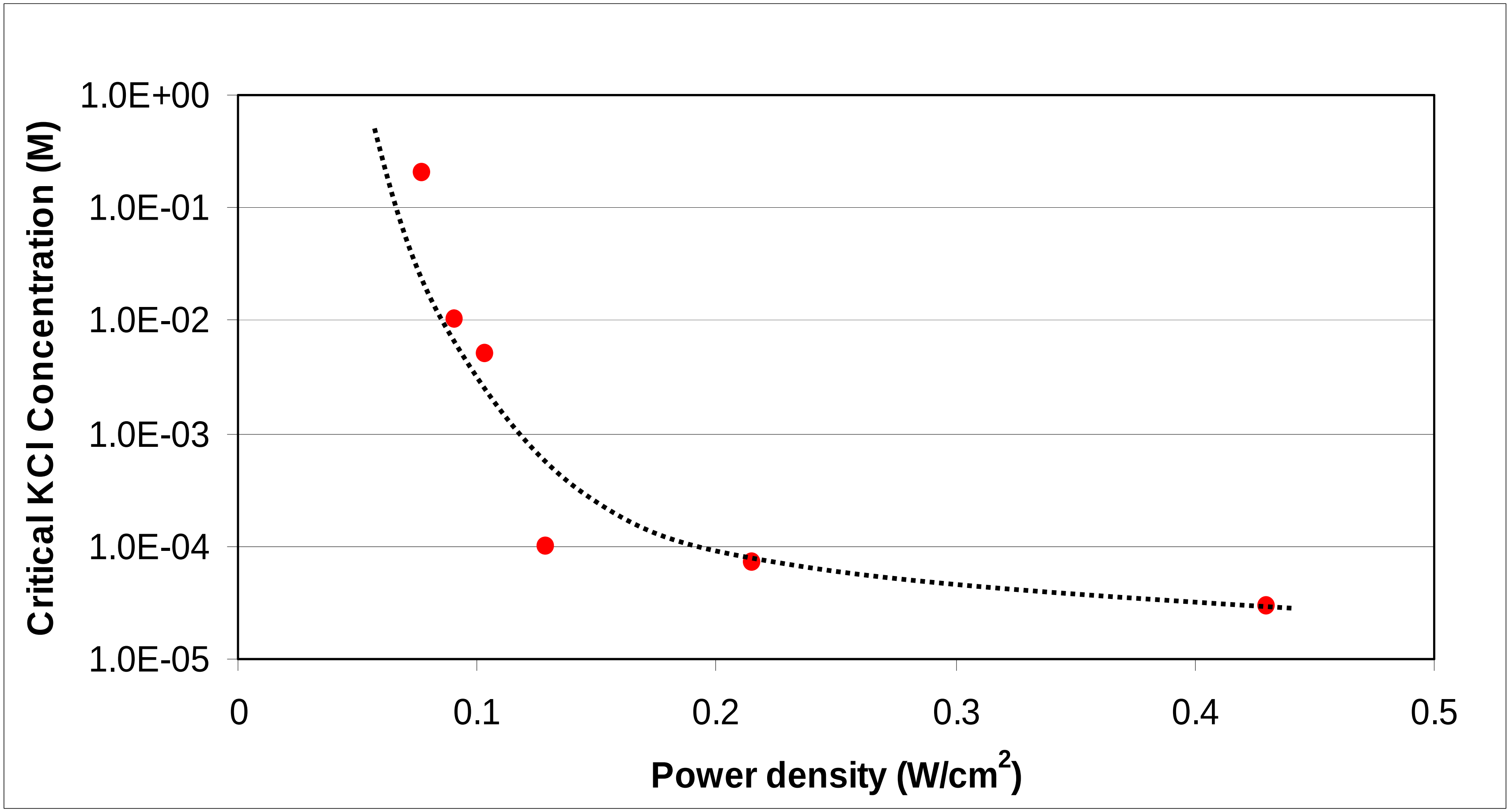


SRC/Sematech Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

Megasonic Removal of Aminated Silica Particles in KCl Solutions of Different Concentration at Different Power Densities

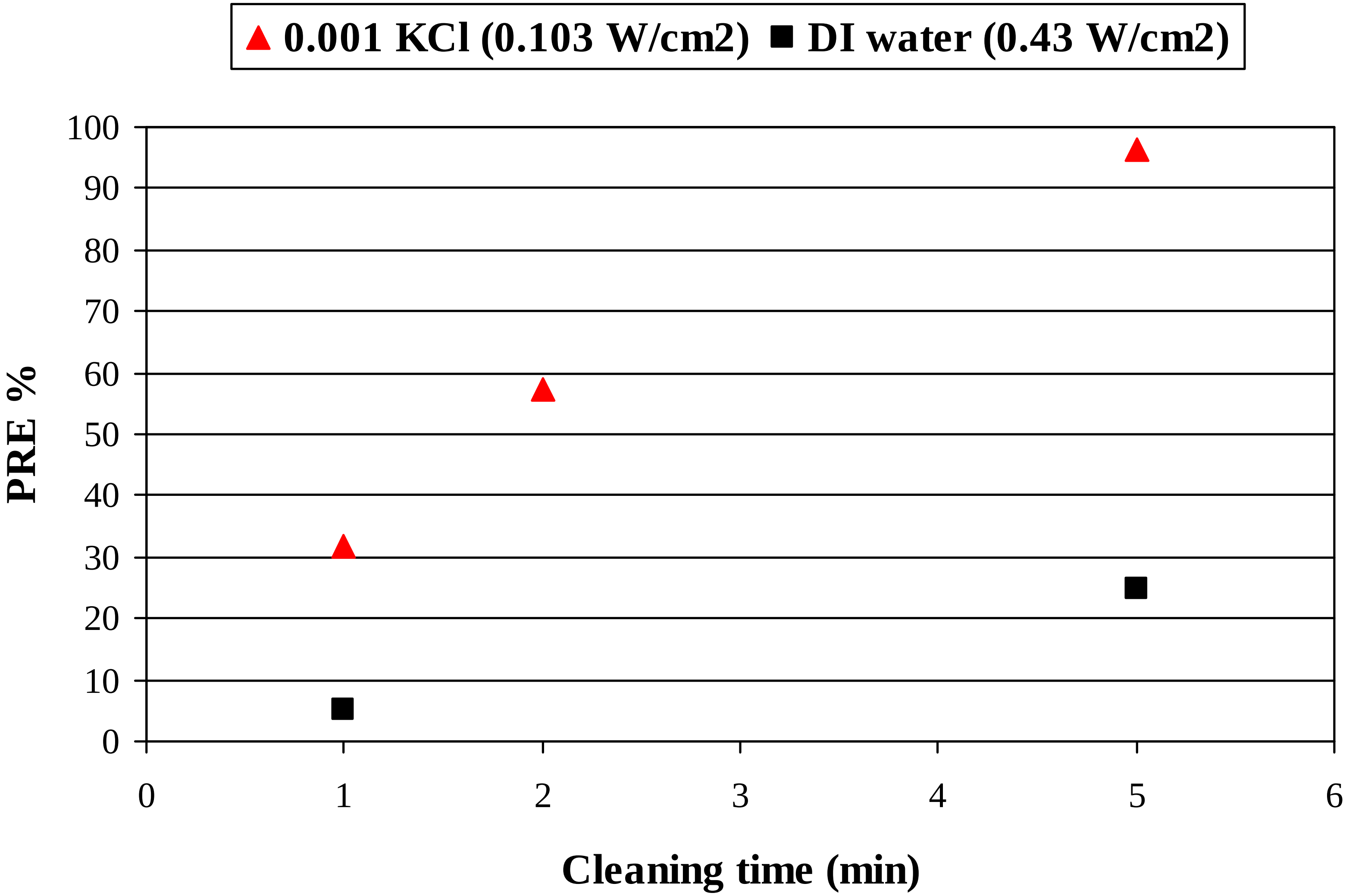


Critical Concentration of KCl for Removal of Aminated Silica at Different Power Densities

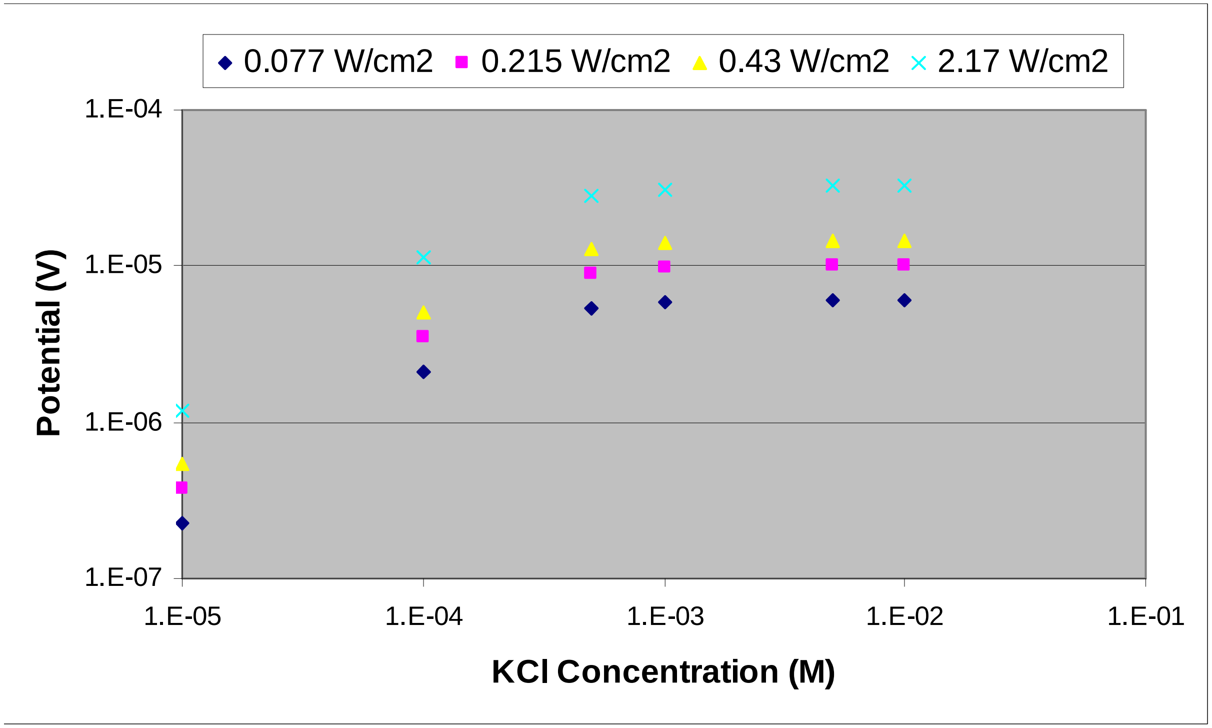


Critical concentration (Cc) is defined as the concentration at which 50 % particle removal efficiency (PRE) is achieved

Effect of Cleaning Time on Removal of Aminated Silica Particles



Effect of KCl Concentration on Debye Potential



$$\phi_0 = c u_0 \frac{(4\Pi / D w)\sum(\overline{n_j}\, m_j\, e_j / f_j)}{[1+((4\Pi / D w)\sum(\overline{n_j}\; e_j^{\,2} / f_j))^2]^{0.5}}$$

Removal Force (10^{-3} M KCl and 2.17 W/cm^2) = 10^{-15} N

Van der Waals Force = 3 * 10^{-10} N

$e_i X - f_i (v_i - v_0) = m_i (dv_i/dt)$ Force Balance (1)

$(\delta n_i/ \delta t) + \delta(n_i v_i)/ \delta t = 0$ Continuity Equation (2)

$D (\delta X/ \delta x) = 4\Pi\, \Sigma\, (n_j e_j)$ Poisson’s Equation (3)

e_i is the charge on the ion, m_i is the mass of the ion, f_i is the friction coefficient, X is the electric field strength
v_i and v_0 are velocities of ion and solvent molecules, n_i is the number of ions in a given volume
D is the dielectric constant of the solvent

Computation of Force Due to Dipole Moment
CVP Effect

v = solvent velocity

$$v = \left(\frac{2I}{\rho_1 c}\right)^{0.5}$$

Transducer Intensity

Zeta Potential

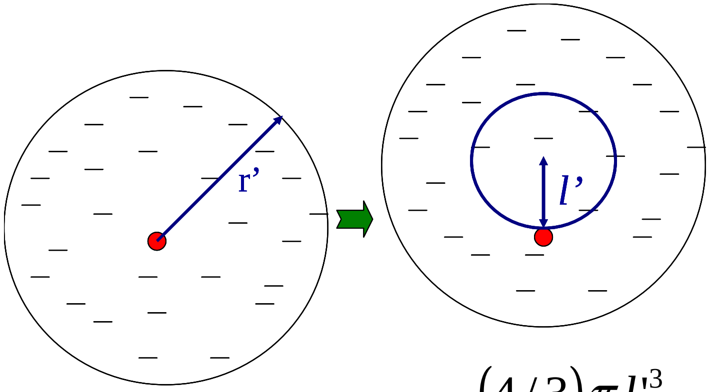
$$m = \frac{6\pi v a \varsigma \varepsilon_0 D}{w}$$

Net charge displaced due to asymmetry of double layer

Force on particle due to dipole moment

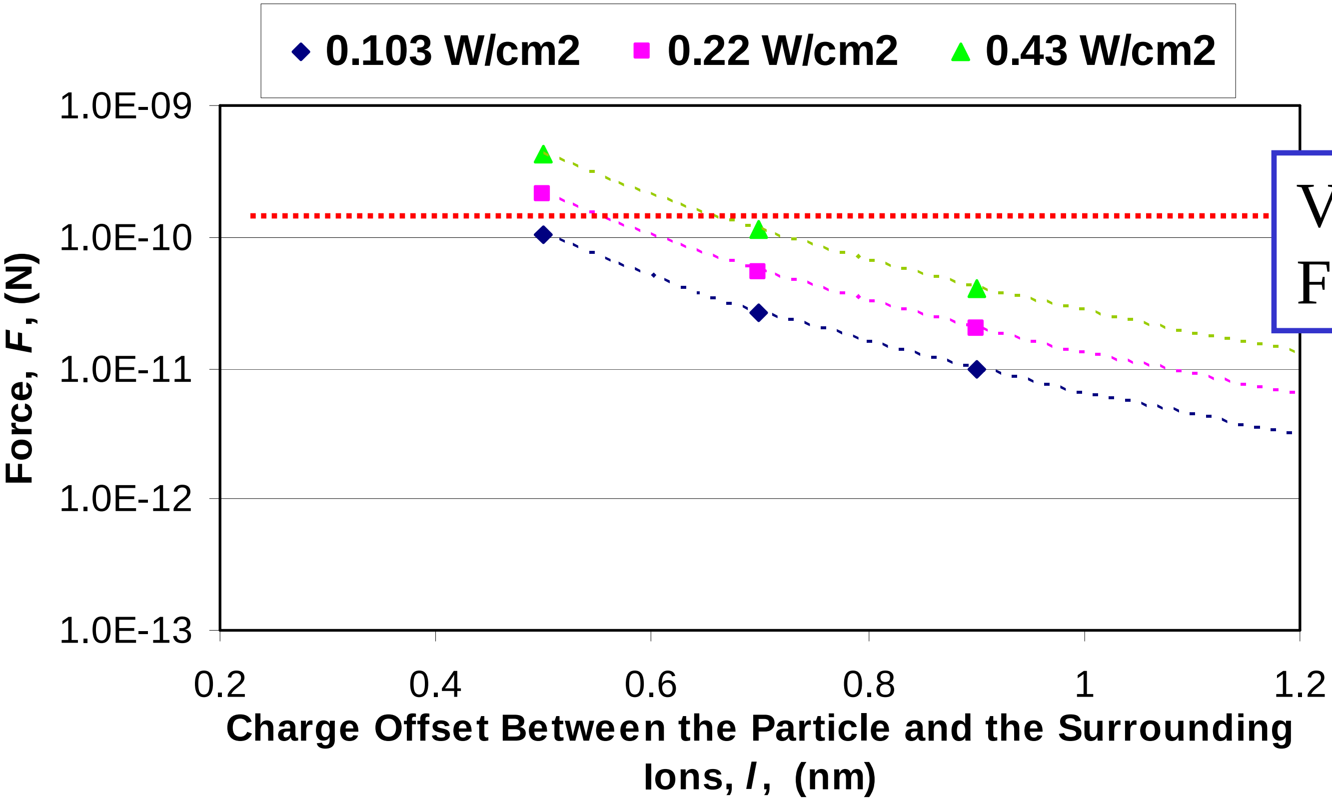
$$F = \frac{mQ'}{l^3} = \frac{Q'^2}{l^2}$$

Offset between the center of particle and the double layer



$$Q' = Q\frac{(4/3)\pi l'^3}{(4/3)\pi r'^3}$$

Magnitude of removal force, *F*, as a function of transducer power density for solution ionic strength of 10^{-4} M



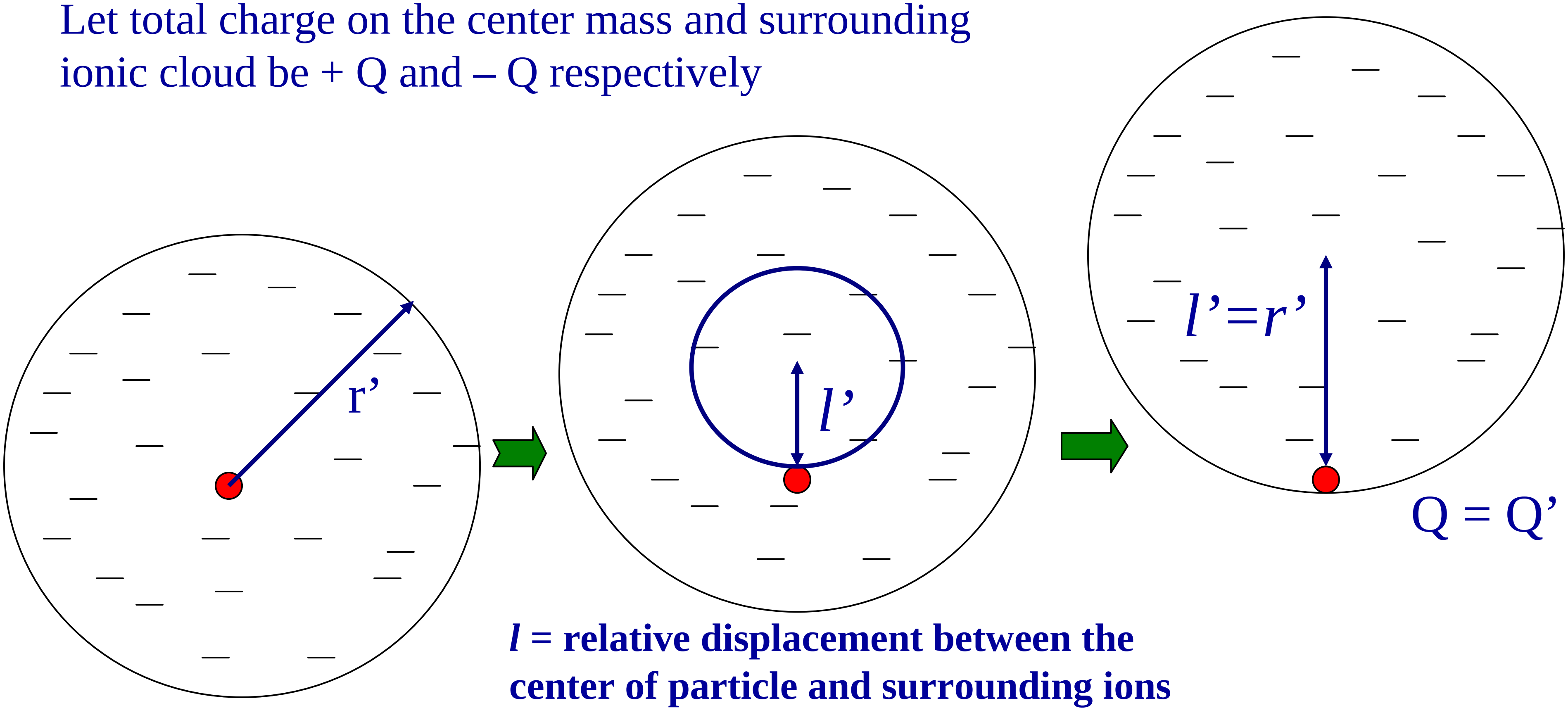
Van der waals Force

Hamaker constant for SiO_2 and water taken as 6.2 $*10^{-20}$ J and 4.4$*10^{-20}$ J respectively

Separation Distance between particle and wafer = 4 Å

HOW TO EXPLAIN THE EFFECT OF IONIC STRENGTH?

Let total charge on the center mass and surrounding ionic cloud be + Q and – Q respectively

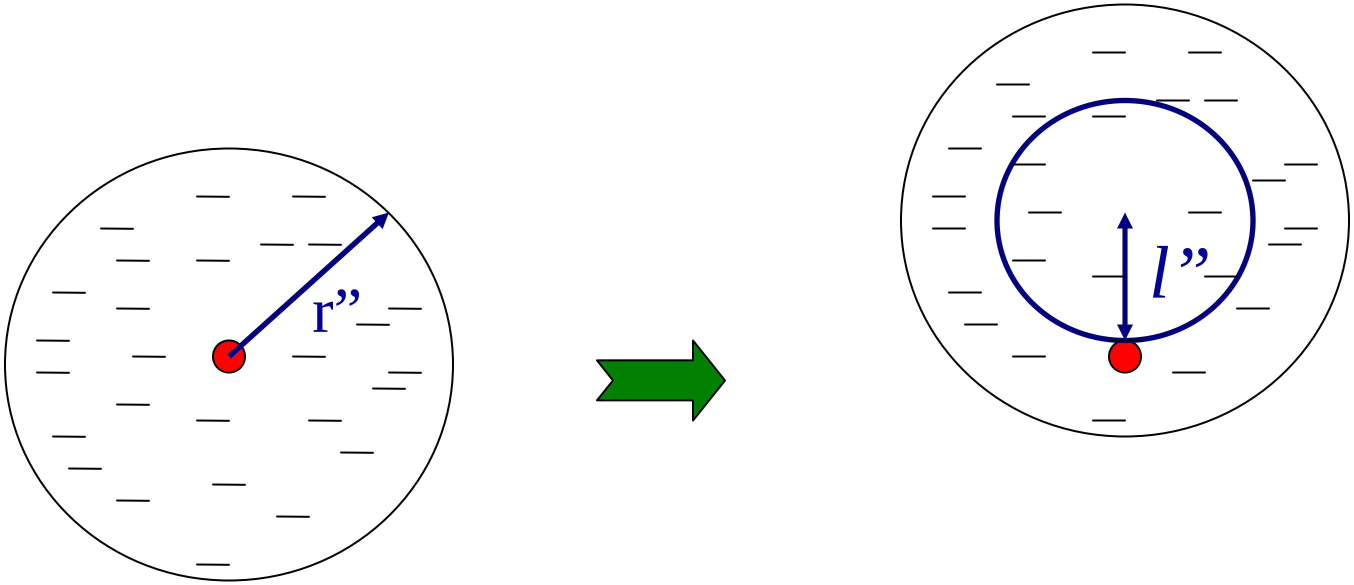


***l* = relative displacement between the center of particle and surrounding ions**

Force, $F' = Q'^2 / l'^2$ where $Q' = Q\frac{(4/3)\pi l'^3}{(4/3)\pi r'^3}$

$$\boxed{F' = \frac{Q'^2}{l'^2} = \frac{Q^2 l'^4}{r'^6}}$$

Now, if the outer ionic cloud is compressed due to increase in solution ionic strength

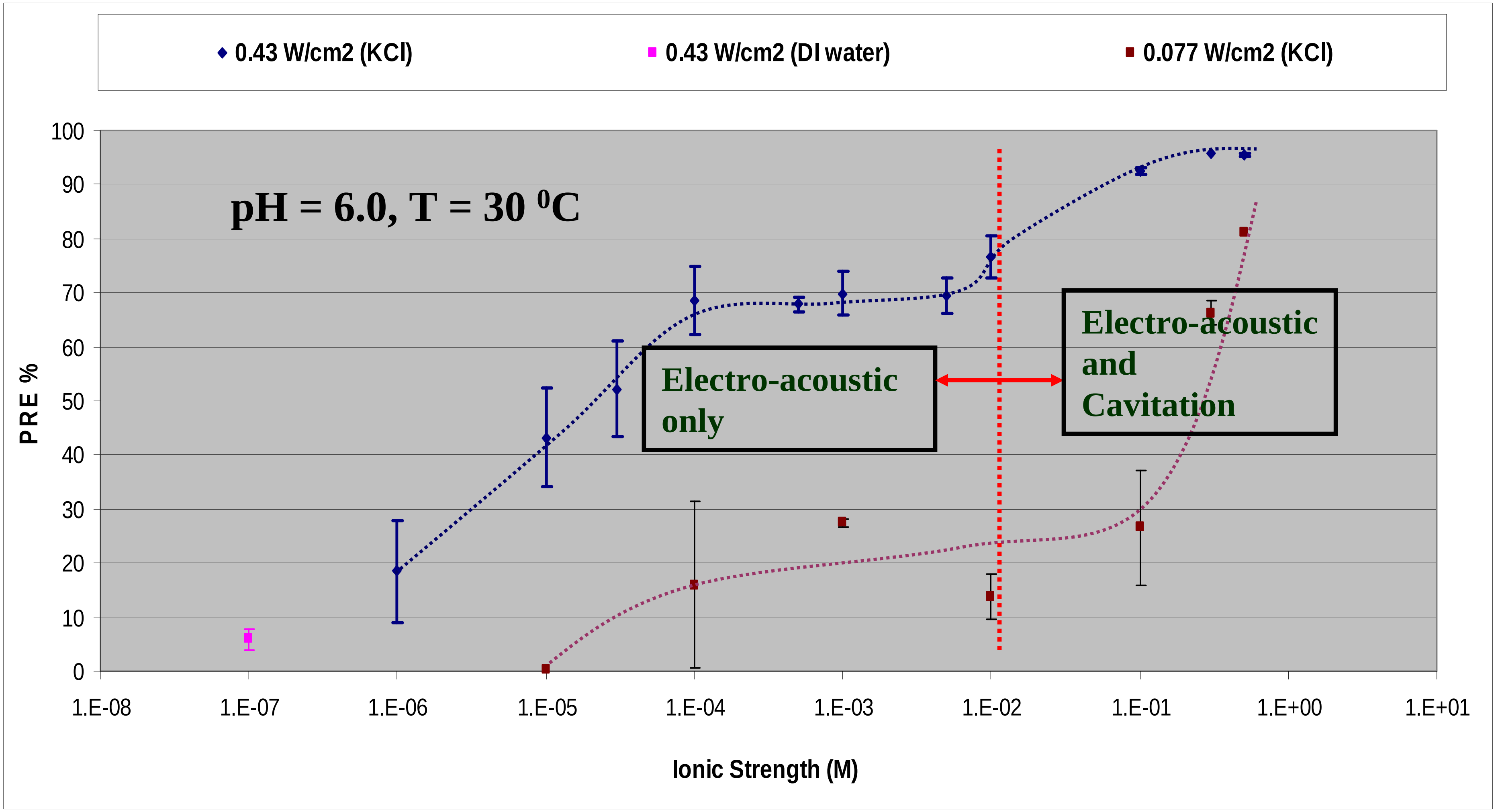


Force, F ” = Q”^{2}/ *l*”^{2} where $$Q'' = Q\frac{(4/3)\pi l''^3}{(4/3)\pi r''^3}$$

$$\boxed{F'' = \frac{Q''^2}{l''^2} = \frac{Q^2\, l''^4}{r''^6}}$$

Removal force increases with increase of ionic strength

Separation of Electro-acoustic and Cavitation Effects



Summary

- Using simple electrolyte solutions, removal of positively charged silica particles from native oxide wafers in a megasonic field can be significantly improved by increasing solution ionic strength.
- Simple calculations have shown that depending on ionic strength and power density, CVP can exert a removal force that is equal to adhesive force on the particles.
- Hydrophone and sonoluminescence studies revealed that pressure amplitude of the sound wave can be increased in KCl solutions of concentration greater than 0.01 M. This higher pressure amplitude leads to more intense cavitation which could provide additional force for removal of particles.

Future Work

- Attempt to deconvolute the effect of cavitation from electro-acoustic effect. This can be done using CO_2 that is known to suppress cavitation. The ionic strength of the solution can be modulated by controlling the amount of CO_2 dissolved.
- Carry out particle removal studies on patterned test structures. Relate particle removal to damage of structures.
- Study the effect of electrolytes for particles with varying degree of adhesion to surface. Investigate the degree of adhesion by atomic force microscopy measurements.

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