Non Destructive Nanoparticle Removal from Submicron Structures Using Megasonic Cleaning

Ahmed Busnaina , Pegah Karimi and Jingoo Park
NSF Center for Microcontamination Control,
Northeastern University, Boston, MA 02115-5000
Email: a.busnaina@neu.edu
www.cmc.neu.edu

Outlines

- **Overview**
- **Introduction**
- **Ultrasonics**
- **Megasonics**
- **Why Damage Happens in Megasonics?**
- **Damage Experiments**
  - Frequency measurements
  - Cleaning performance
  - Damage free cleaning of polysilicon structures
- **Conclusions**

Overview

- A new novel damage-free megasonics cleaning techniques based on fundamental understanding of megasonics has been developed.
- The technique has been tested at low and high power and has been shown to be damage-free.
- The new technique is structure size independent and can be used to clean structures as small as a few nanometers without damage.
- Can be used with vendor's current set of tools (wet bench type, spin type, etc.) with minimum change in tool set and at minimum cost.

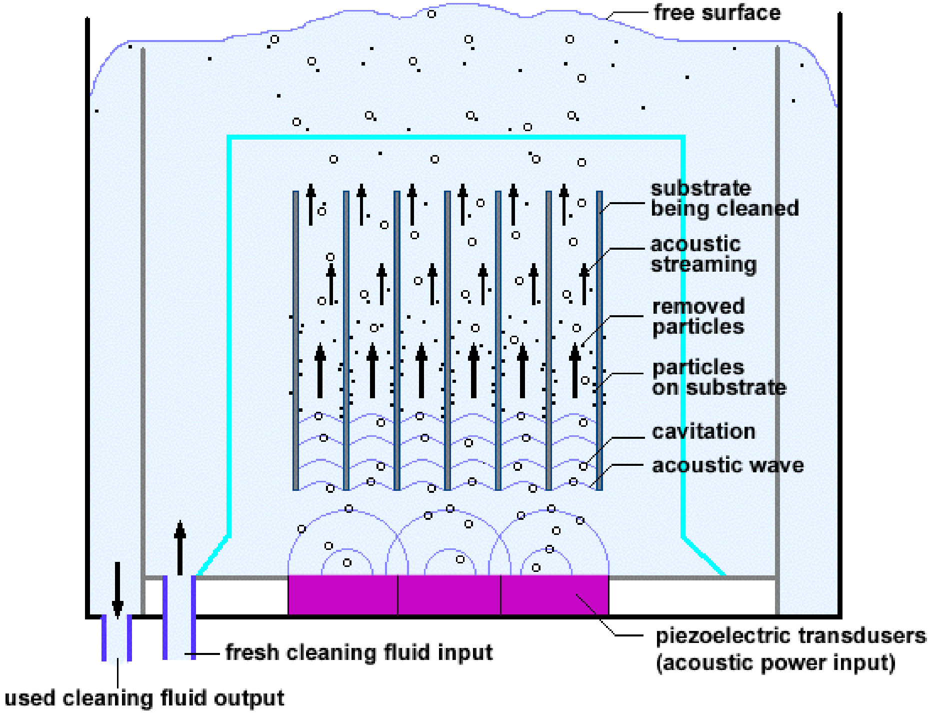
Introduction

- Particulate contamination is one of the most common defects resulting in low manufacturing yield
- particle may block an implant or locally disrupt pattern development during a lithography step
- Contaminate films prevent good adhesion of deposited films to the wafer surface
- Nanoparticle removal methods:
  - Brush cleaning
  - Chemical cleaning
  - Laser shock cleaning
  - Megasonic Cleaning

  However, among these techniques, only megasonics can clean structures such as via and trenches
- However, megasonics has been observed to cause damage in sub 200 nm structures

Introduction

TYPICAL MEGASONIC CLEANING SYSTEM



Ultrasonics

- **CLEANING MECHANISMS**
  - **CAVITATION**
  - **ACOUSTIC STREAMING**
  - **RADIATION (PRESSURE) FORCE**
    - **Not Significant Except At Very High Intensities**
- **CAVITATION**
  - **FORMATION OF GAS OR VAPOR BUBBLES BY ULTRASOUND**
  - **STABLE VS. TRANSIENT**
  - **“CREVICE MODEL” OF NUCLEATION (APFEL, 1970)**
    - **Growth By Rectified Diffusion**
  - **“CAVITATION THRESHOLD” PRESSURE AMPLITUDE**
    - **Cavitation Less Likely To Occur As Frequency Is Increased**

Ultrasonics

- **Sound energy is created within a liquid by means of transducers which convert electric energy into acoustic energy.**
- **High frequency sound waves passing through a liquid produces positive and negative pressures. In the regions of negative pressures, the liquid pulls apart creating micro/macro bubbles.**
- **Recent investigations indicate that these bubbles (upon collapse) may have sufficient energy to cause surface pitting.**
- **The acoustic streaming is defined as the flow of fluid induced by a sound field.**
- **Acoustic streaming can be implemented to play a major role in the removal of contaminants without substrate damage.**

Ultrasonics

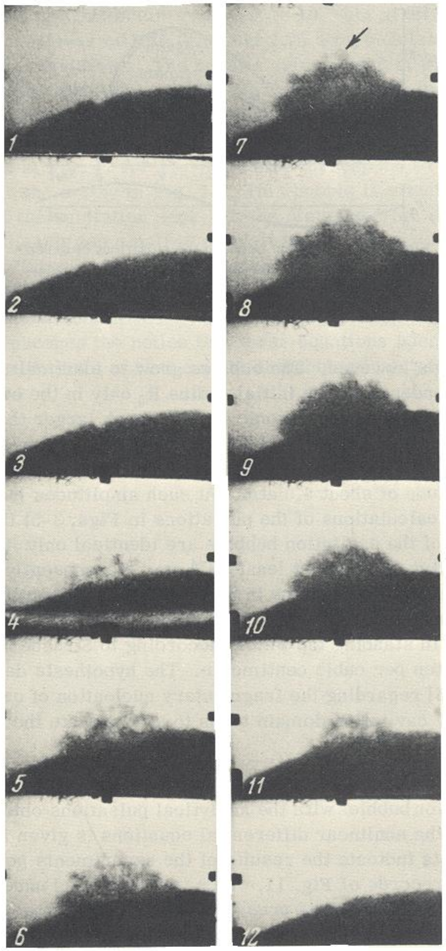
Cavitation Damage

SEM photograph of surface damage on a silicon wafer caused by ultrasonic cleaning

Ultrasonics

Cavitation Damage

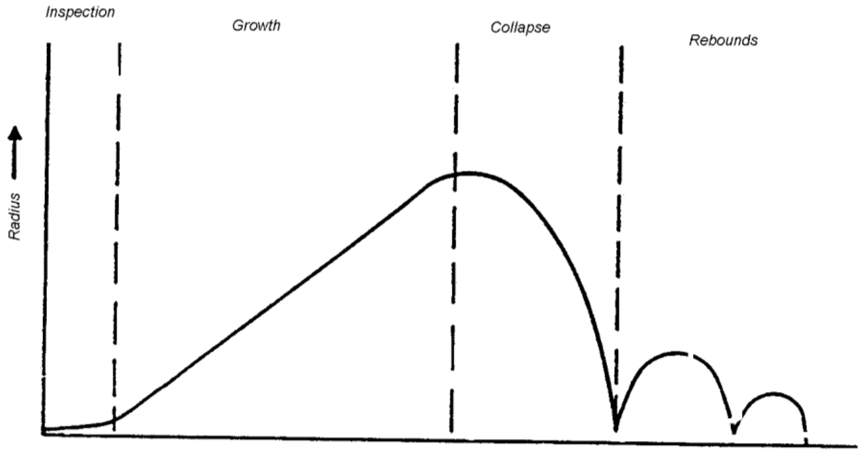
Magnification 20x
by V. A. Akulichev, (Rozenberg, Eds)



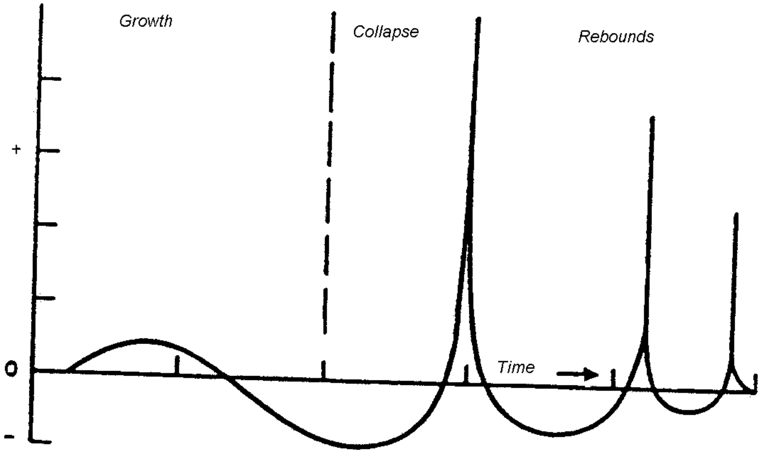
Photos of cavitation bubbles. The ultrasonic frequency is 15 kc, the film speed is 200,000 frames per second, and the ultrasonic pressure is about 2.0 atm. (Rozenberg, L.D.)

Ultrasonics

Growth and Collapse of Cavitation Bubbles



Growth and collapse of a cavitation bubble having finite gas content, (Ross, D.)

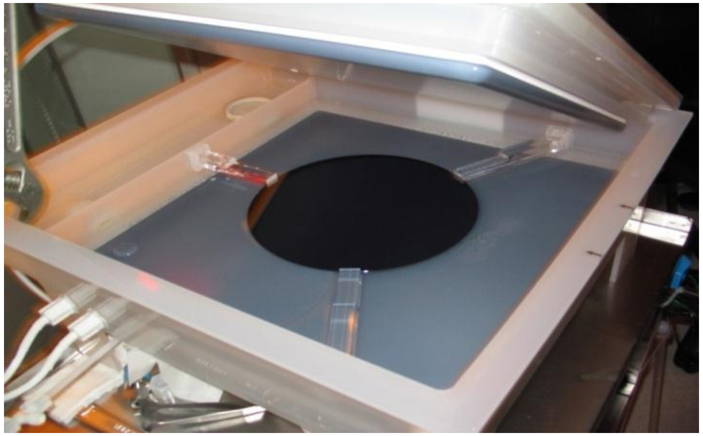


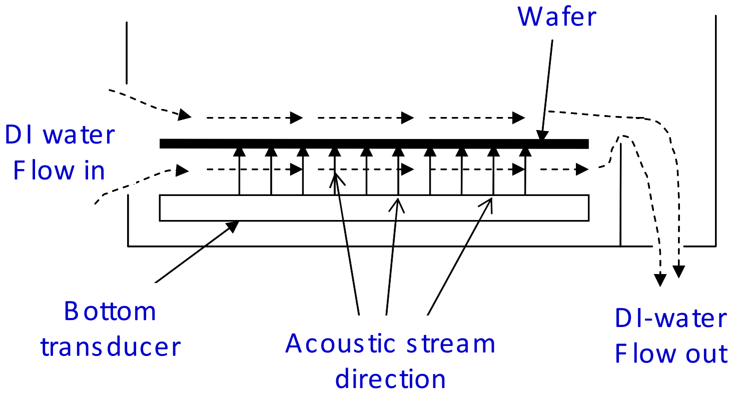
Pressure pulses from collapsing cavity, (Ross, D.)

Megasonic Cleaning

- Piezoelectric transducers
- Piezoelectric substance become electrically polarized when mechanically stressed and mechanically deform when electrically polarized
- Produce sound wave
- Megasonic sound wave

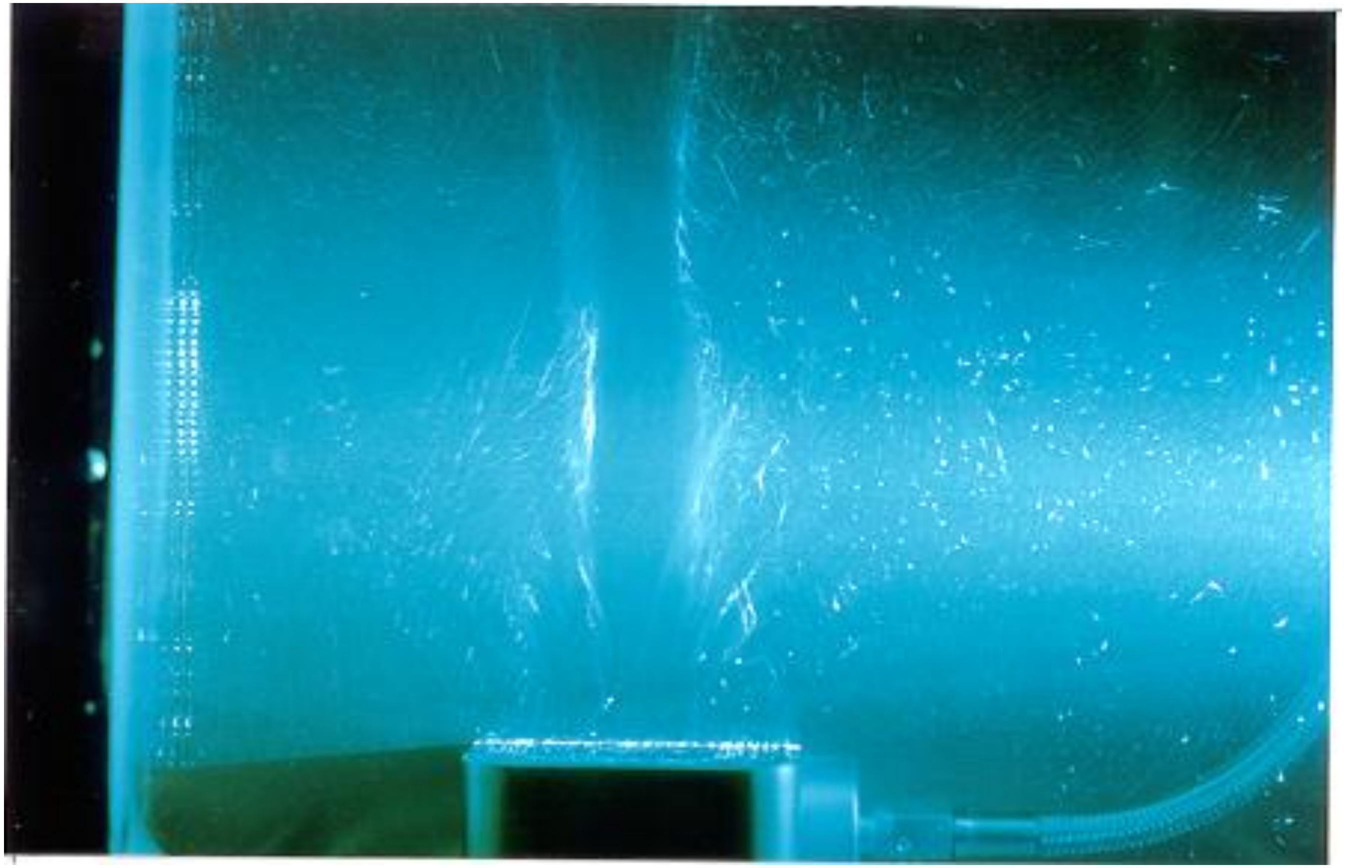
$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$





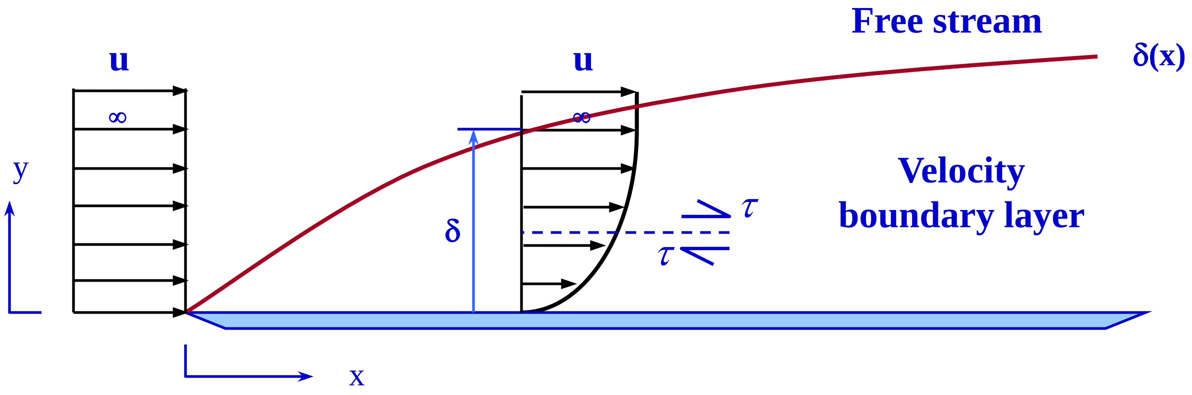
Megasonic Cleaning

Acoustic Streaming



Eckart-type streaming (360 kHz)

Acoustic Boundary Layer Thickness



Velocity boundary layer on a flat plate

- **Acoustic boundary layer thickness**:

$$\delta_{ac} = \left(\frac{2\nu}{\omega} \right)^{\frac{1}{2}}$$

in water, f=850KHz, δ_{ac}=0.61μm

f=760KHz, δ_{ac}=0.65μm

f=360KHz, δ_{ac}=0.94μm

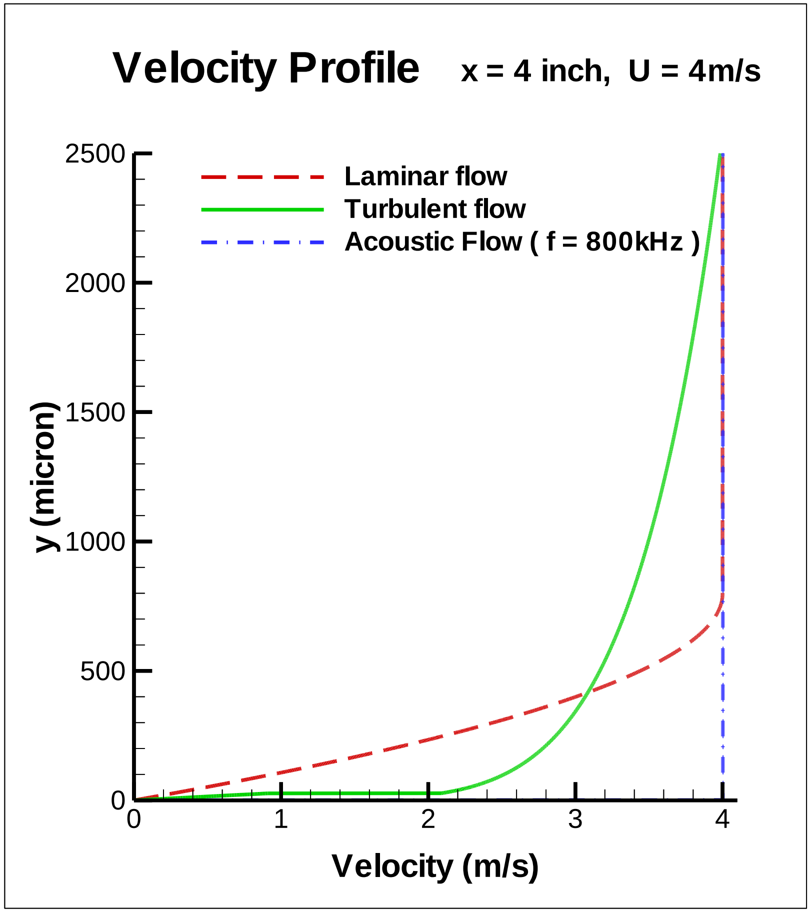
- **The hydrodynamic boundary layer thickness**:

$$\delta_H = 0.16 \left(\frac{\nu}{Ux} \right)^{\frac{1}{7}} \cdot x$$

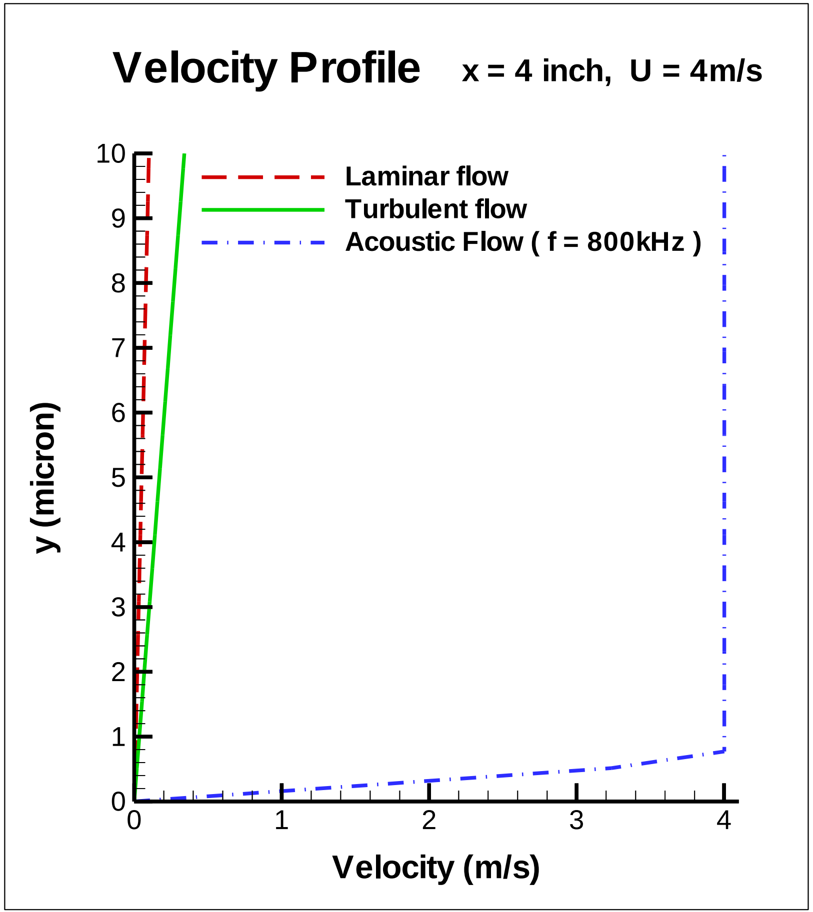
in water, u=4m/s, at center of the wafer, δ_H=2570 μm

Velocity Profile in a Boundary Layer

y = 0~2500 micron



y = 0~10 micron



Acoustic Flow Properties

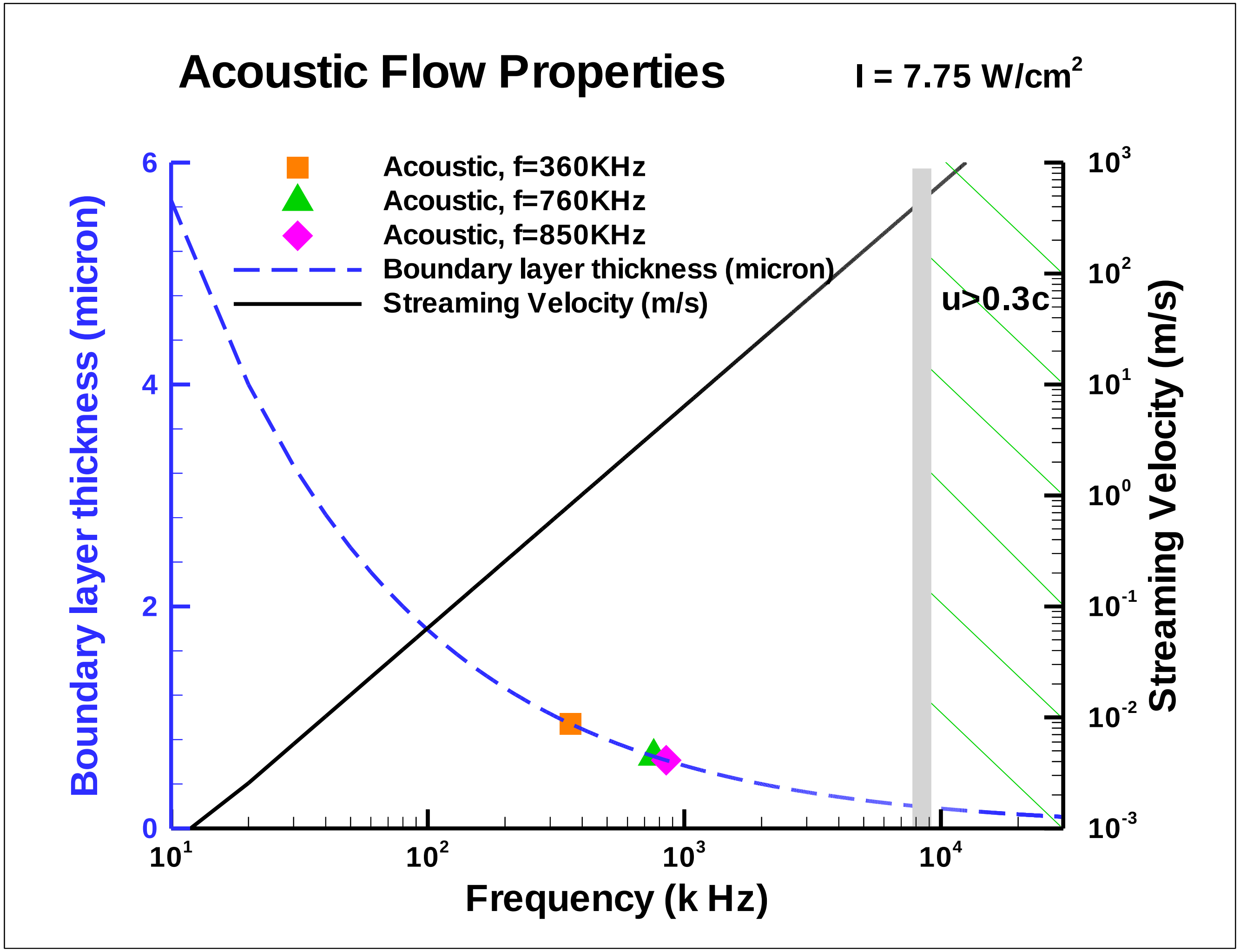
- Acoustic boundary layer thickness:

$$\delta_{ac} = \left(\frac{2\nu}{\omega}\right)^{\frac{1}{2}}$$

- Acoustic streaming velocity (at center of tank):

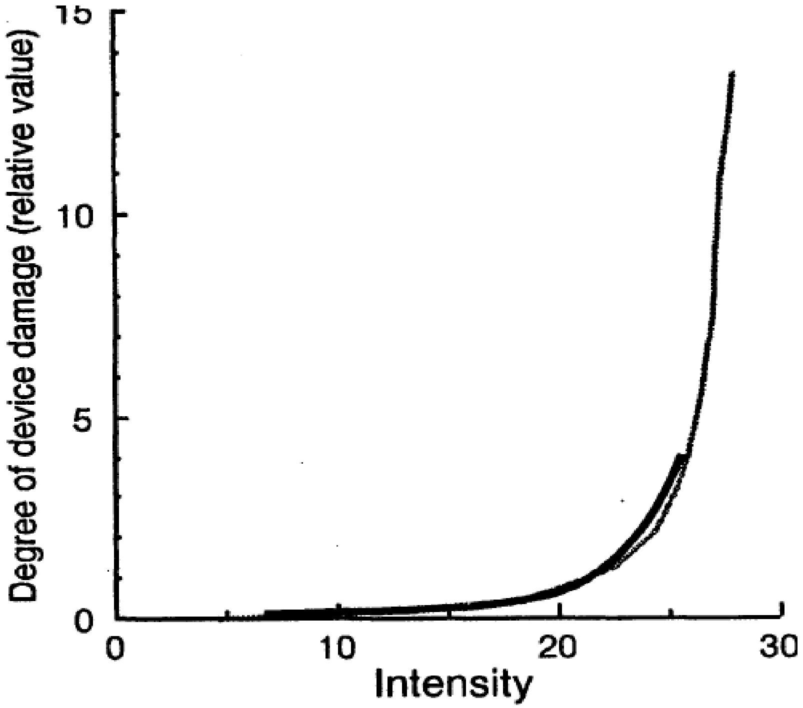
$$u = \frac{8\pi^2}{3\rho c^4} \cdot If^2 \left(\frac{h^2}{4} - z_1^2\right)$$

$$u \propto If^2$$



Device Damage

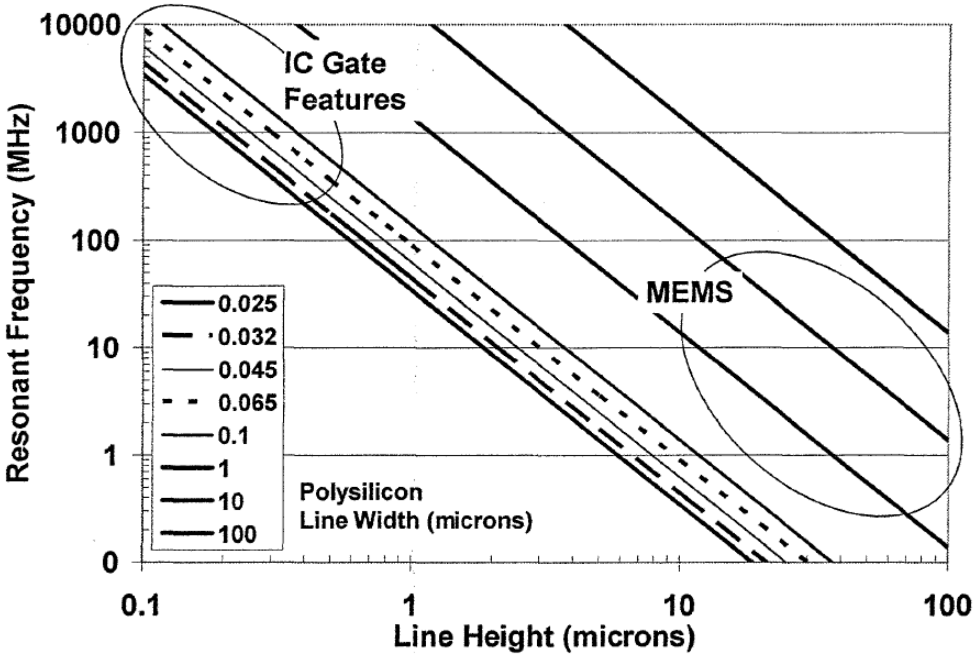
The degree of device damage depends on the maximum ultrasonic intensity



Intensity vs. device damage

Resonant Excitation Theory

- **The destruction of a feature by acoustically driving the feature at a natural vibration mode.**
- **Damage by acoustic resonant can occur when a mechanical structure is exposed to the vibration which is close to its resonant frequency.**
- **The lowest resonant frequency is 700 MHz.**
- **Therefore it’s highly unlikely that resonant excitation can be the cause of damage to sub-micron structures.**

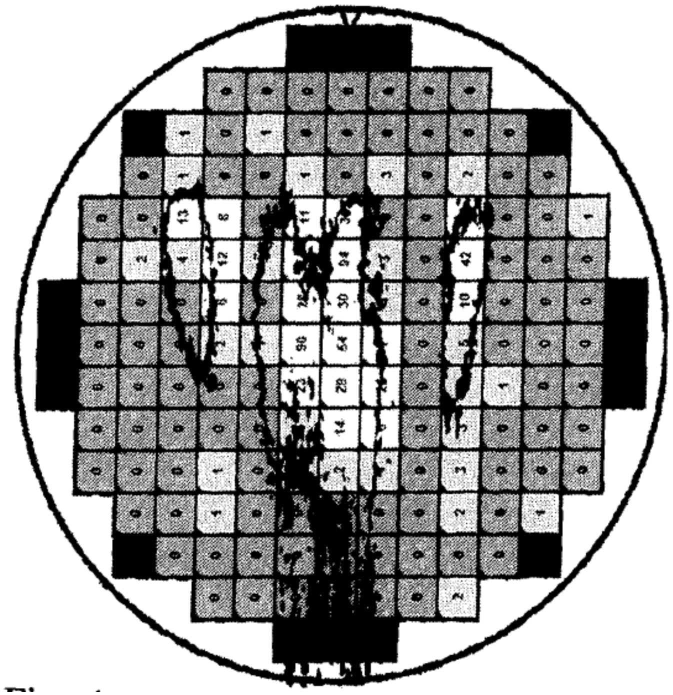


Resonant frequencies of the first order vibrational mode for polysilicon line

Vereecke G., et. al., Electrochemical Society Proceedings, vol. 03-26, 145 (2003).

Damage on Polysilicon Lines

- Damage events on sub 90nm polys-line structures in megasonic cleaning at 1 MHz frequency
- The most significant influences on the cleaning and damage process happens from the bubble distribution and the size distribution of stimulated gas bubbles.
- Sonoluminescence is a weak glow arising in a liquid in response to acoustic vibration.

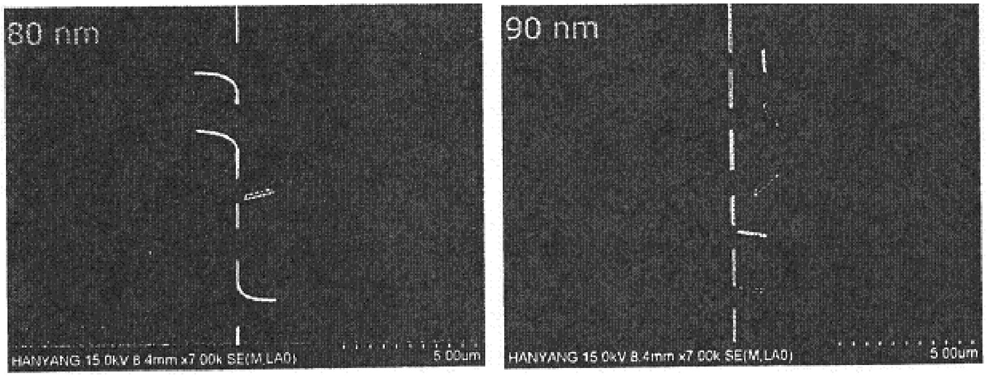


Correlation between MBSL(multi bubble sonoluminescence) and damage on a polysilicon structure

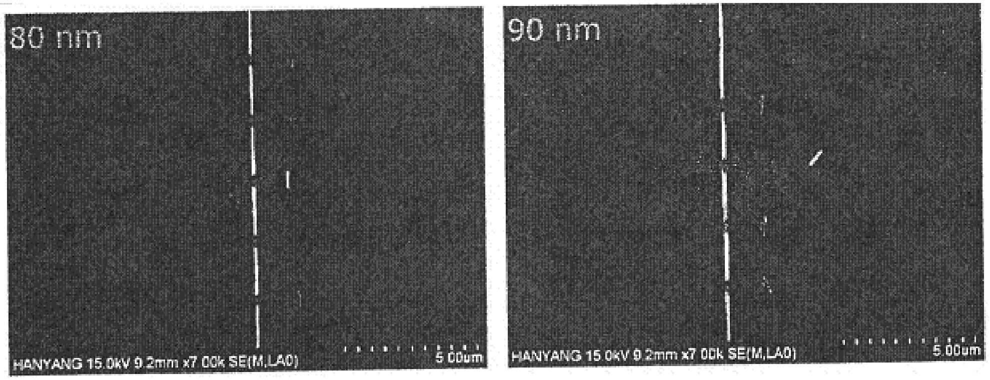
Vereecke G., et. al., Electrochemical Society Proceedings, vol. 03-26, 145 (2003).

Pattern Collapse using AFM

- Mechanical property and line width of structures
- Softer pattern, larger length of fragment and less force
- Harder pattern, smaller length of fragment and larger force



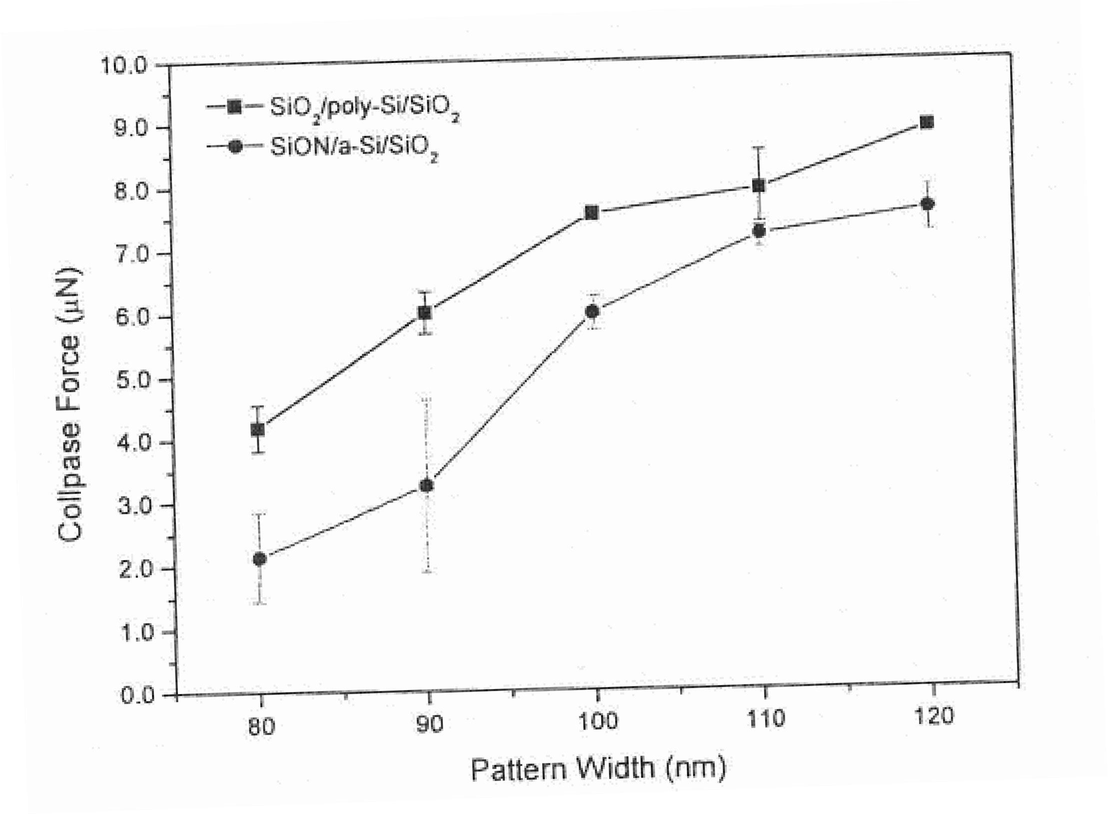
$SiON$/a-Si/SiO_2 pattern collapse (T.G. Kim)



SiO_2/poly-Si/SiO_2 pattern collapse (T.G. Kim)

88 Kim T.G., Wostyn K., Park J.G., Mertens P.W.,and Busnaina A.A. , Solid State Phenomena. 145-146 (2009) pp 47-50.

Pattern Collapse Force using AFM



Collapse force of the SiO2/poly-Si/SiO2 line pattern
and SiON/a-Si/SiO2 line pattern.

88 Kim T.G., Wostyn K., Park J.G., Mertens P.W.,and Busnaina A.A. , Solid State Phenomena. 145-146 (2009) pp 47-50.

Why Damage happens in Megasonic Cleaning?

- It is known that in present megasonic cleaning, there is a tradeoff between cleaning efficiency and possible damage to structures as power (intensity) is increased.

- However, it’s expected, based upon previous work, that cleaning efficiency will continue to improve as intensity is increased.

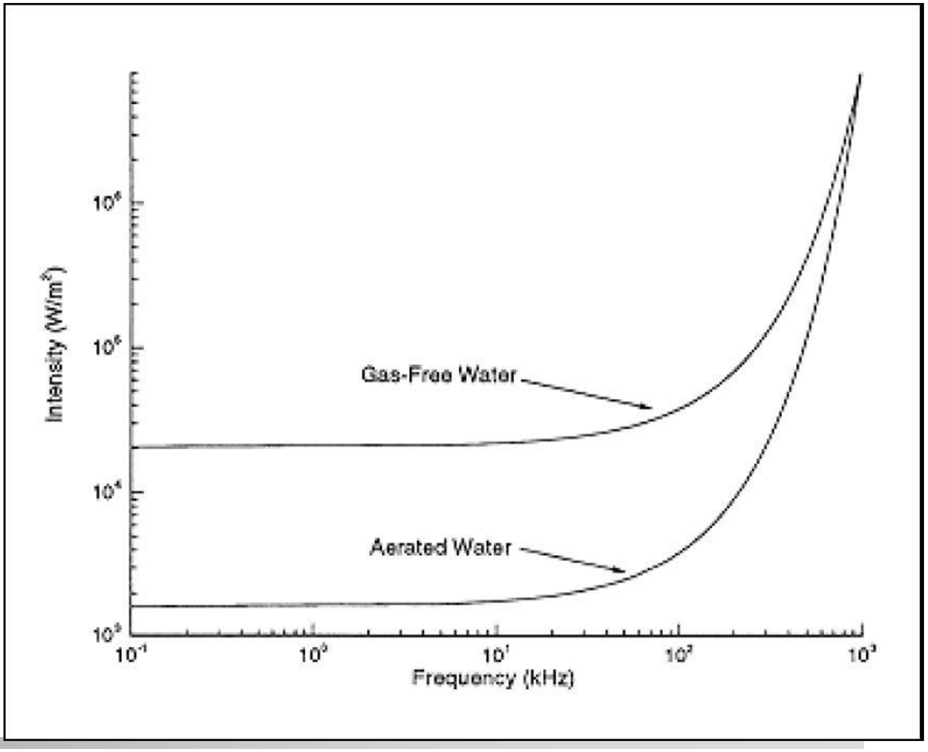
- This damage at low frequencies has been shown by many to be caused by cavitation.

- The cavitation threshold, defined as the minimum pressure amplitude to induce cavitation, has been extensively studied as a function of various liquid properties.

Why Damage happens in Megasonic Cleaning?

- A lower cavitation threshold indicates that the cavitation occurs more readily, this suggests that conditions at which cavitation would occur would be at low surface tension, high hydrostatic pressure, and low temperature.

- At megasonic frequencies, the cavitation threshold is very high showing that it's unlikely to have cavitation at high (megasonic) frequencies.



High-Intensity Ultrasonic Fields, Edited by Rozenberg, L. D., Plenum Press. New York-London (1971).

Why Damage happens in Megasonic Cleaning?

- Many researchers have clearly shown that cavitation damage does occur at megasonic frequencies. We have also observed damage at megasonic frequencies in our own experiments using commercial megasonic equipment.

- The question is how could one reconcile the theory stating that damage should not occur at megasonic frequencies and experiments that show it does?

- Are these differences irreconcilable? Or is there a reason for damage to occur at megasonic frequencies even if theory says that it should not?

Why Damage happens in Megasonic Cleaning?

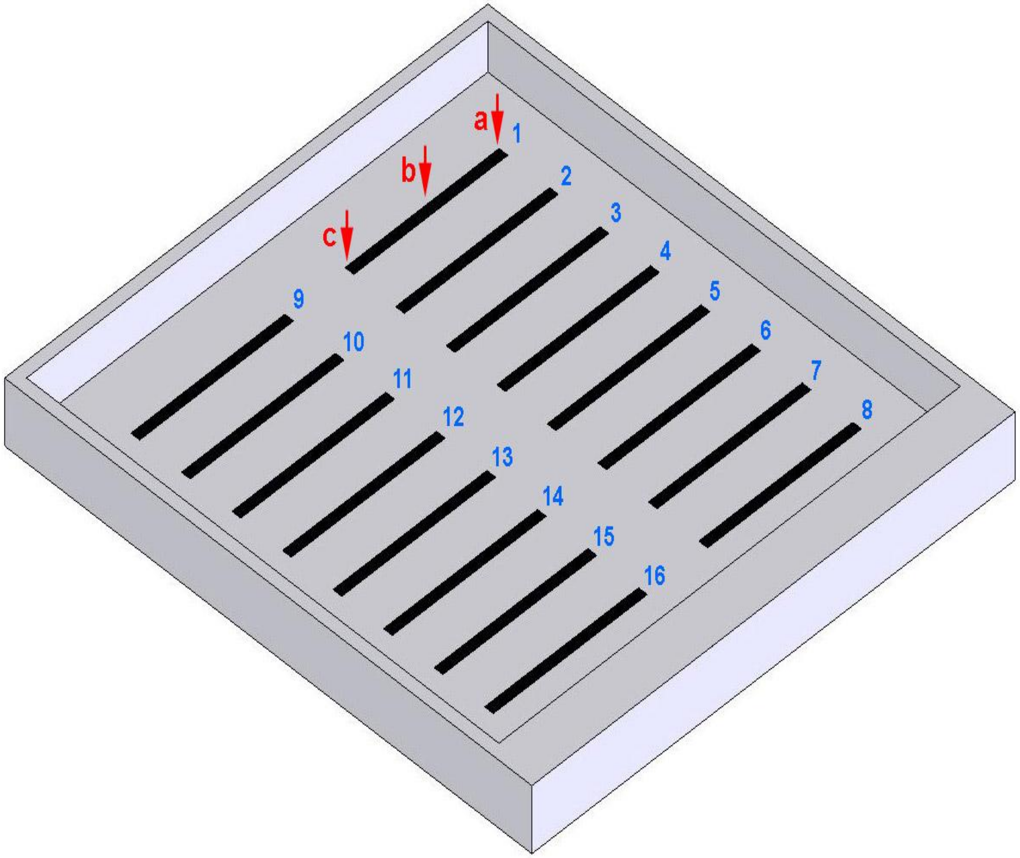
- The answer depends on what *frequencies* was damage observed (in the experiments and all of the megasonic cleaning currently being used).
- Was damage observed at megasonic frequencies only?
- Or was there a spectrum of frequencies that included low frequencies (ultrasonic between 40 and 100 kHz) as well as megasonic frequencies?
- For damage to happen at Megasonic frequencies only (typically above 400 kHz), the amplitude (or acoustic pressure) has to be sufficiently large for this to happen.
- This indicates that possible damage at megasonic frequencies only occurs because of the existence of low frequencies (below 100 KHz) at amplitude to megasonic frequencies.

Why Damage happens in Megasonic Cleaning?

- We have observed damage of small structures of polysilicon lines (less than 200nm) in our all of the commercial megasonic tanks at high and low powers.

- A direct measurement of the frequency and power in these tanks reveals that all megasonic tanks used in the experiments (including those in use by industry today) had significant powers at much lower frequencies in many cases as low as 40 kHz.

Experimental Procedure

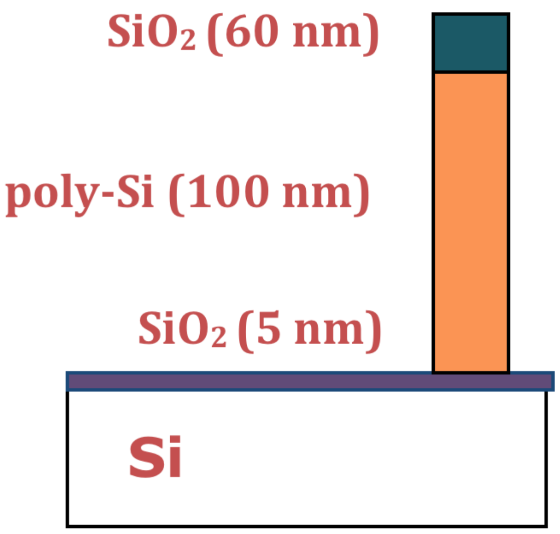


Frequency probe measurements for all the 16 transducers

- Different places on transducer
  - a, b and c
- Different heights from the bottom of the tank
  - ½ inch
  - 1 inch
- On top of the active transducer
- Away from the active transducer

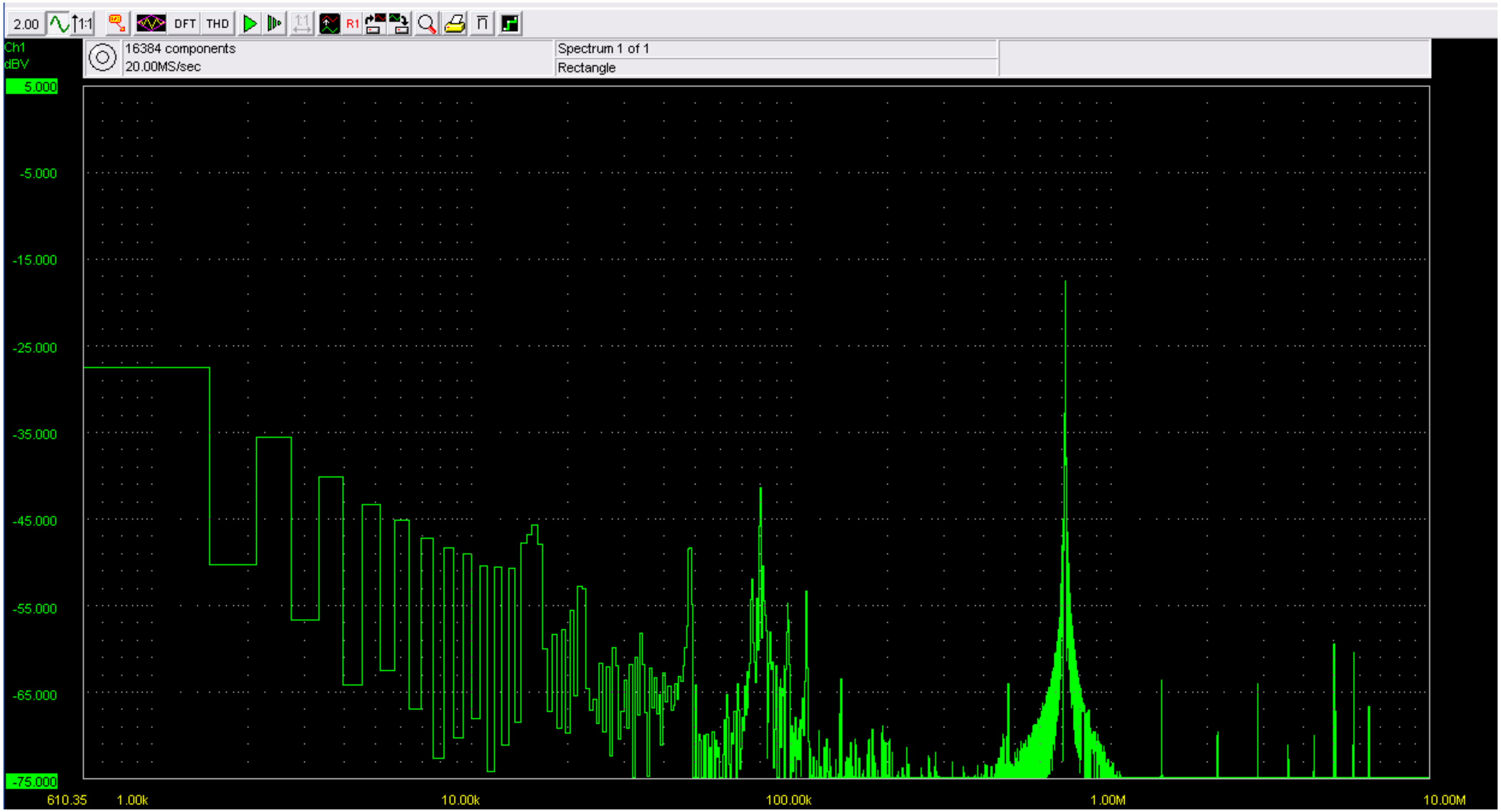
All the area in the tank was mapped

Experimental Procedure



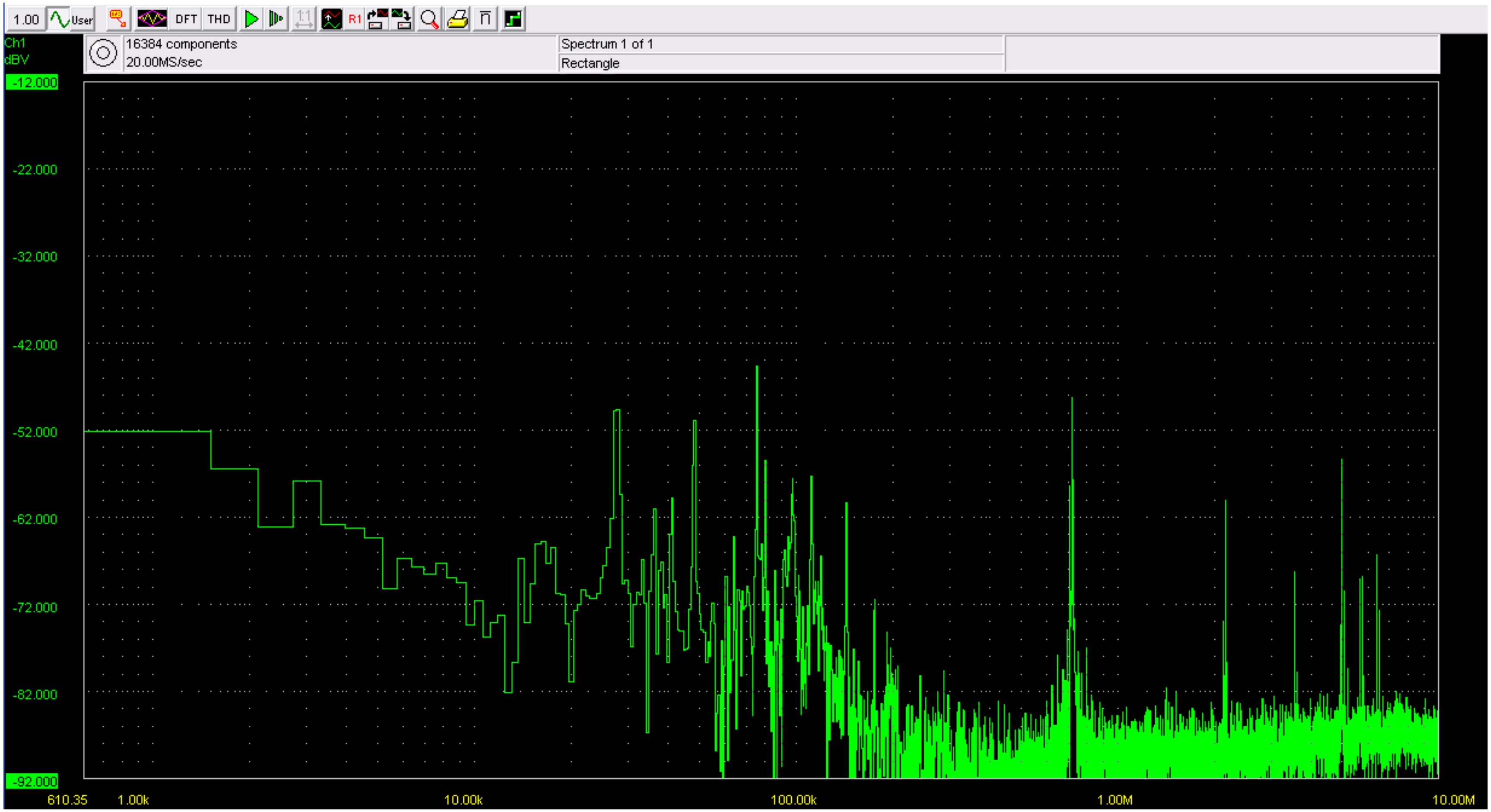
- The structures are walls with widths that vary between 50nm to 30 micron and the ratio of walls to pitch varies from 1:1 to 1:5.
- The experiments were conducted at 100%,70%,50% and 30% power for both tanks. 1cm x 2cm chips were used with multi-scale structures.
- Samples were cleaned in both tanks for 5 minutes for each power setting. Samples were then inspected using a field emission scanning electron microscope (FESEM) before and after each cleaning experiment.

Frequency Measurement for Traditional Megasonic Tank


16384 components
20.00MS/sec
Spectrum 1 of 1
Rectangle

Power vs. frequency; probe is placed ½ inch above the bottom of the tank and on top of transducer which is active (transducer #4)

Frequency Measurement for Traditional Megasonic Tank

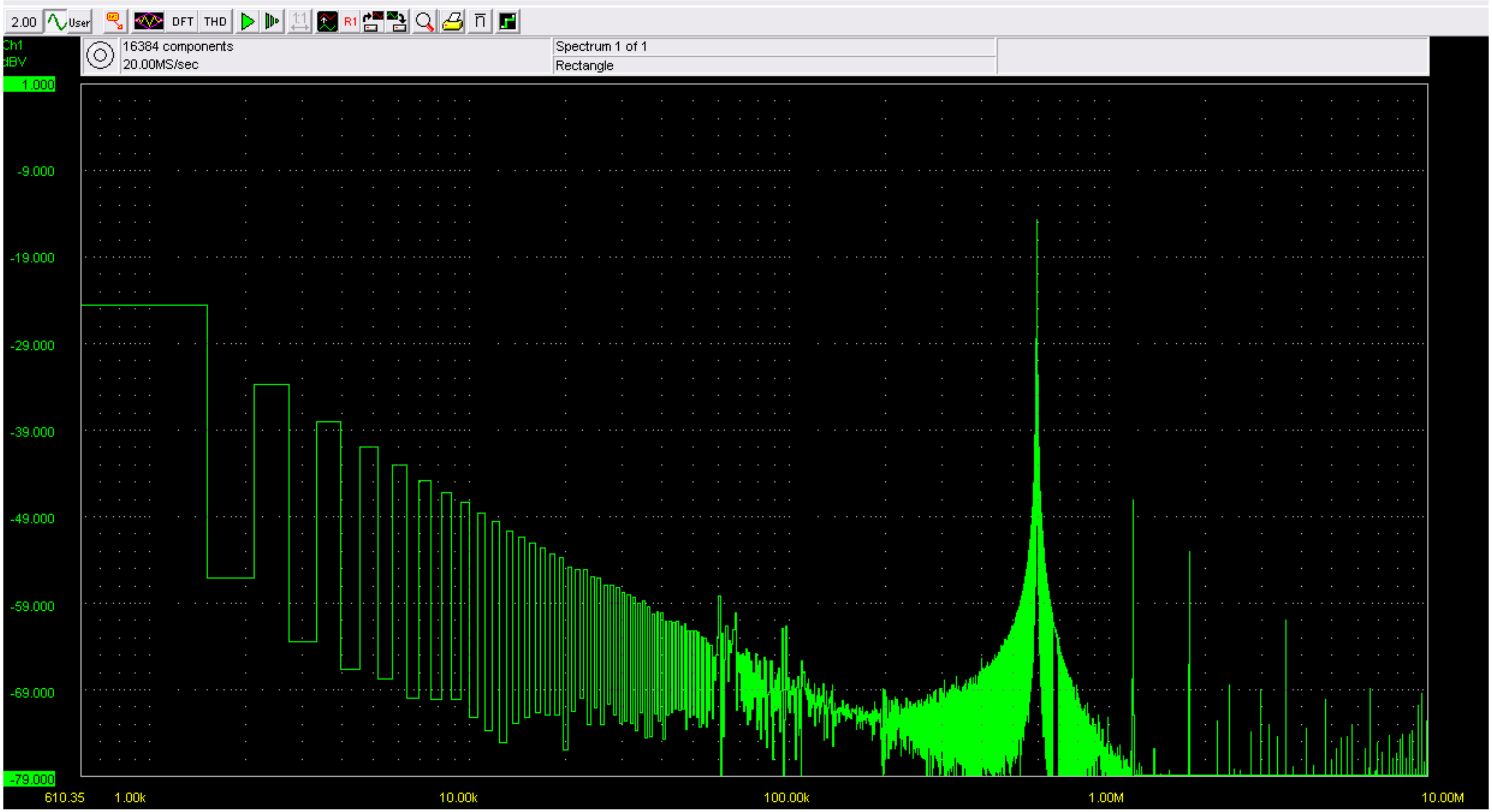


16384 components
20.00MS/sec

Spectrum 1 of 1
Rectangle

Power vs. frequency; probe is placed ½ inch above the bottom of the tank and 6 inches far from the active transducer

Frequency Measurement for Narrow Bandwidth Megasonic Tank



16384 components

20.00MS/sec

Spectrum 1 of 1

Rectangle

Power vs. frequency; Narrow bandwidth transducer

Damage in Megasonic Cleaning

- Our investigation has shown that elimination of all the low frequencies (using a narrow bandwidth transducer) will eliminate damage even at high power once the low ultrasonic frequencies (with high amplitude) are eliminated.

- Effective damage free removal of nanoscale particles can be accomplished at low or high power.

- Our data verified that cavitation implosion does not occur at high megasonic frequencies because the threshold pressure required at these frequencies is very high (this pressure requirement is not met by any of the current megasonic tanks).

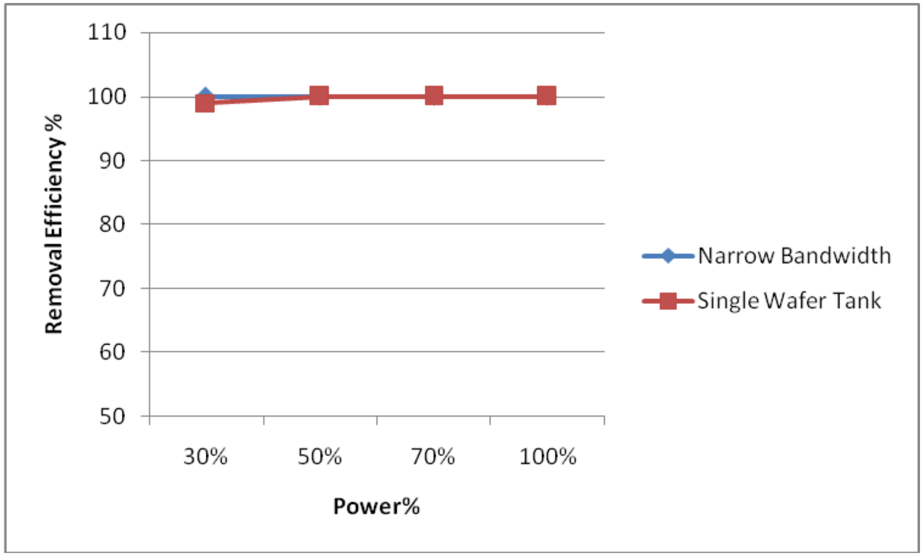
Damage in Megasonic Cleaning

- **Since it has been shown that using high power in megasonics cause damage but it is also required to achieve high removal efficiency, there is need to show that the cleaning efficiency is not due to the low frequency and that the cleaning is the same at single frequency as the traditional tanks when using narrow band frequency megasonics.**

- **The cleaning is matched between two tanks (one single narrow band frequency and one traditional) to insure that we have high removal efficiency without any structural damage.**

Investigation of Cleaning Performance

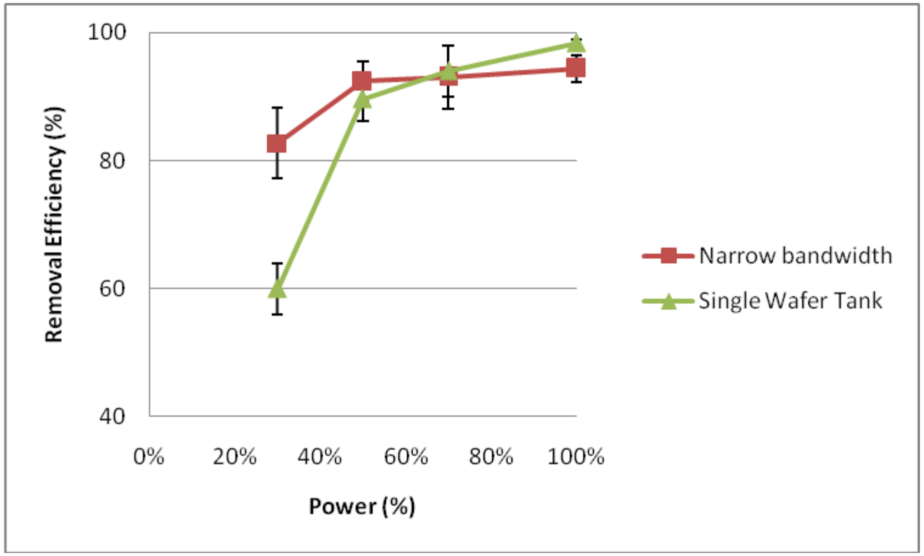
- 100nm PSL particles deposited on silicon chips
- Samples cleaned immediately both in traditional and narrow bandwidth megasonic for different powers (100%, 70%, 50% and 30%)



Removal Efficiency vs. power for 100nm PSL particles

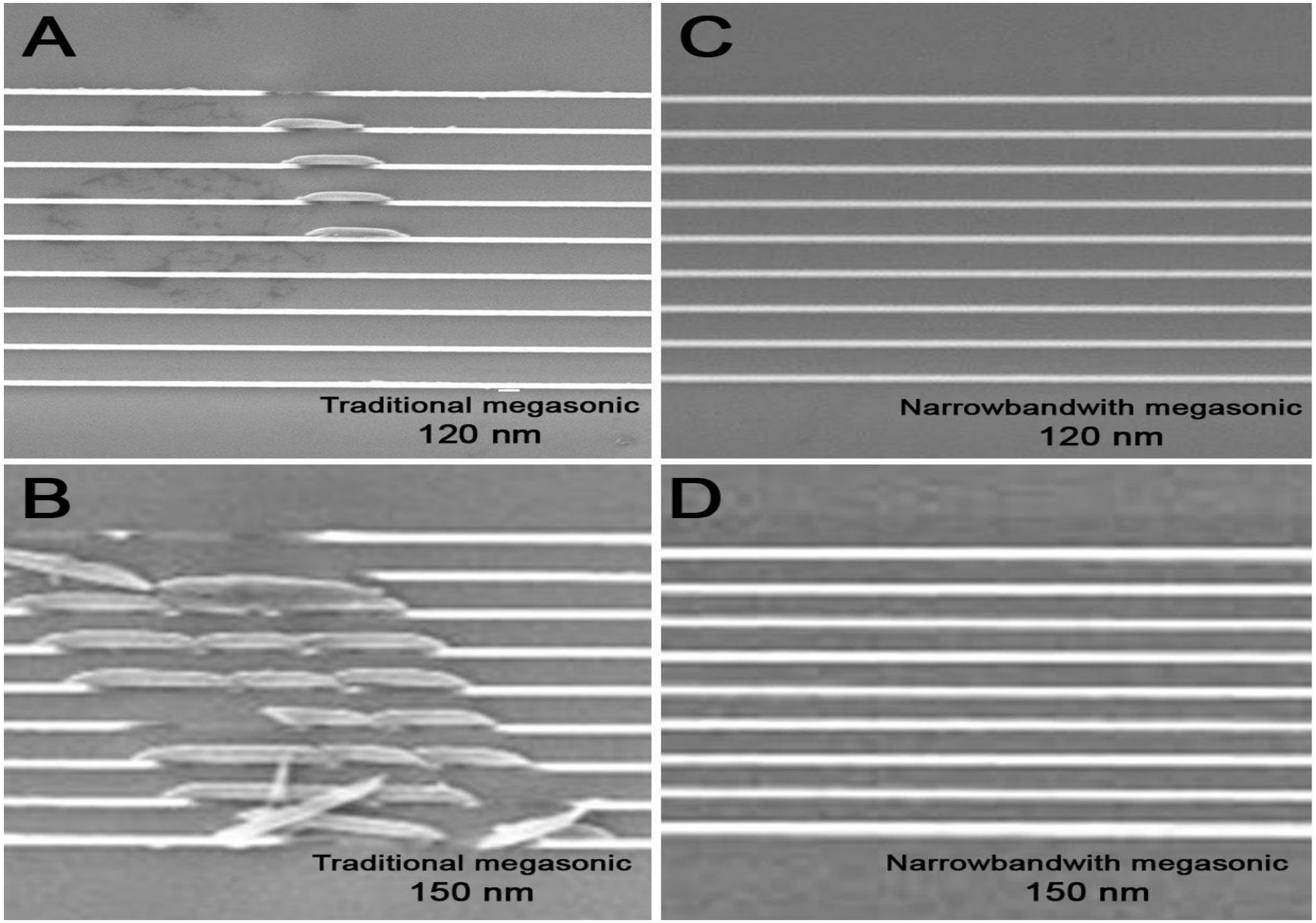
Cleaning without Damage

- 100nm PSL particles deposited on silicon chips
- Samples were left in the clean room for 7 hours
- Samples cleaned both in traditional and narrow bandwidth megasonic for different powers (100%, 70%, 50% and 30%)



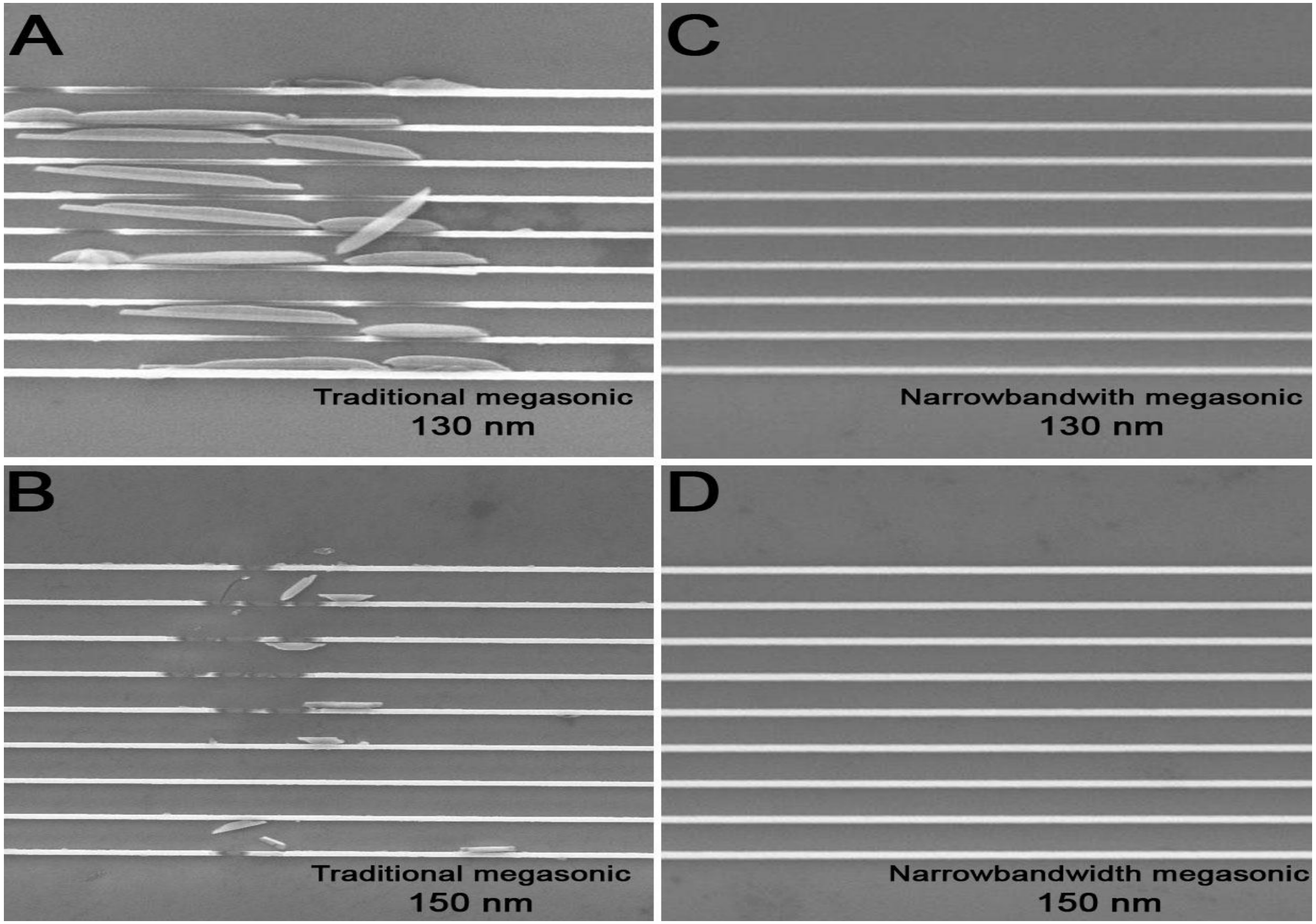
Removal Efficiency vs. power for 100nm aged PSL particles

Damage Results for 30% Power



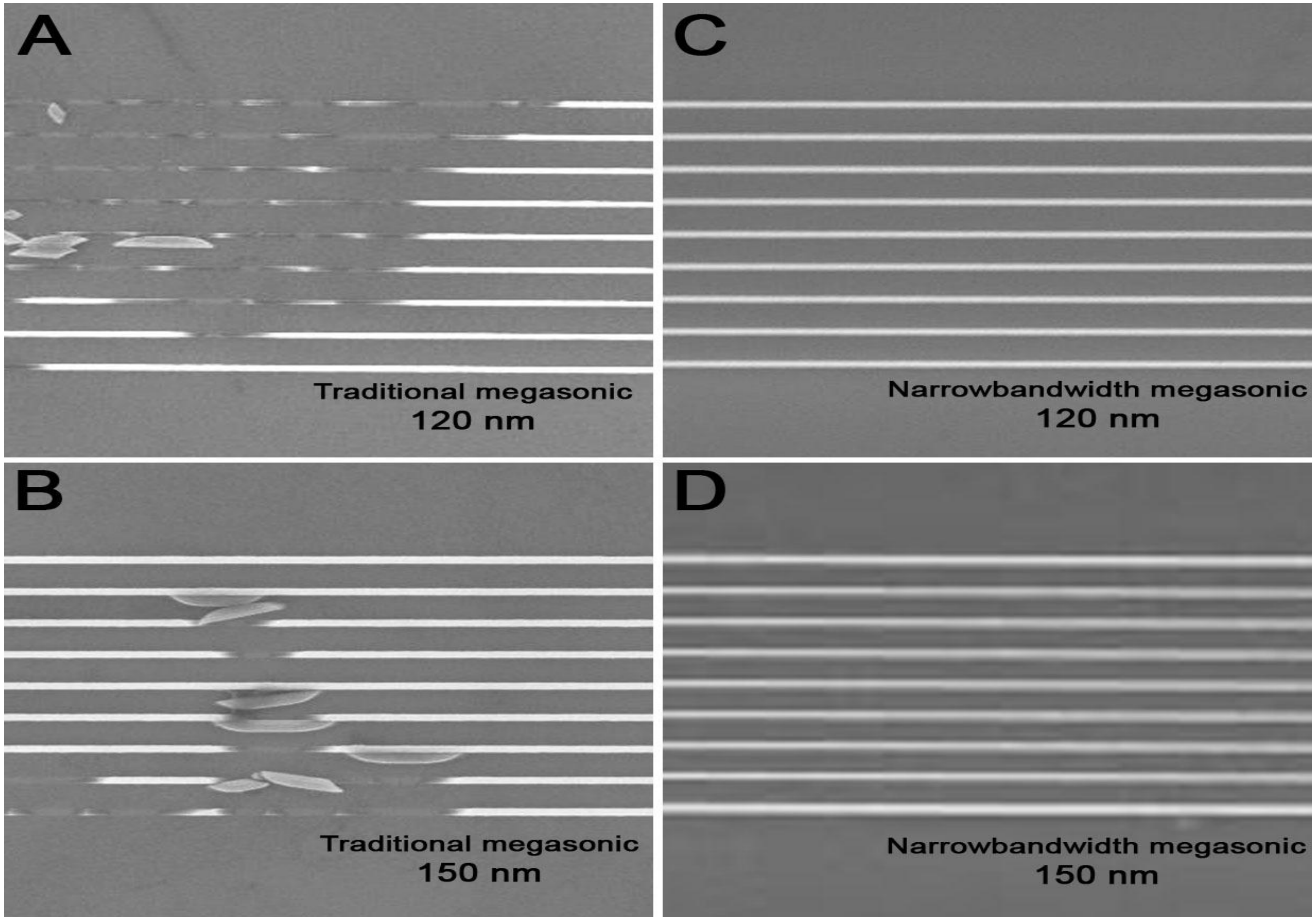
SEM images of 120nm (A and C) and 150nm (B and D) lines after cleaning with 30% power for 5 minutes. While the single wafer megasonic tank damages the structures the narrow bandwidth transducer preserves the patterns.

Damage Results for 50% Power



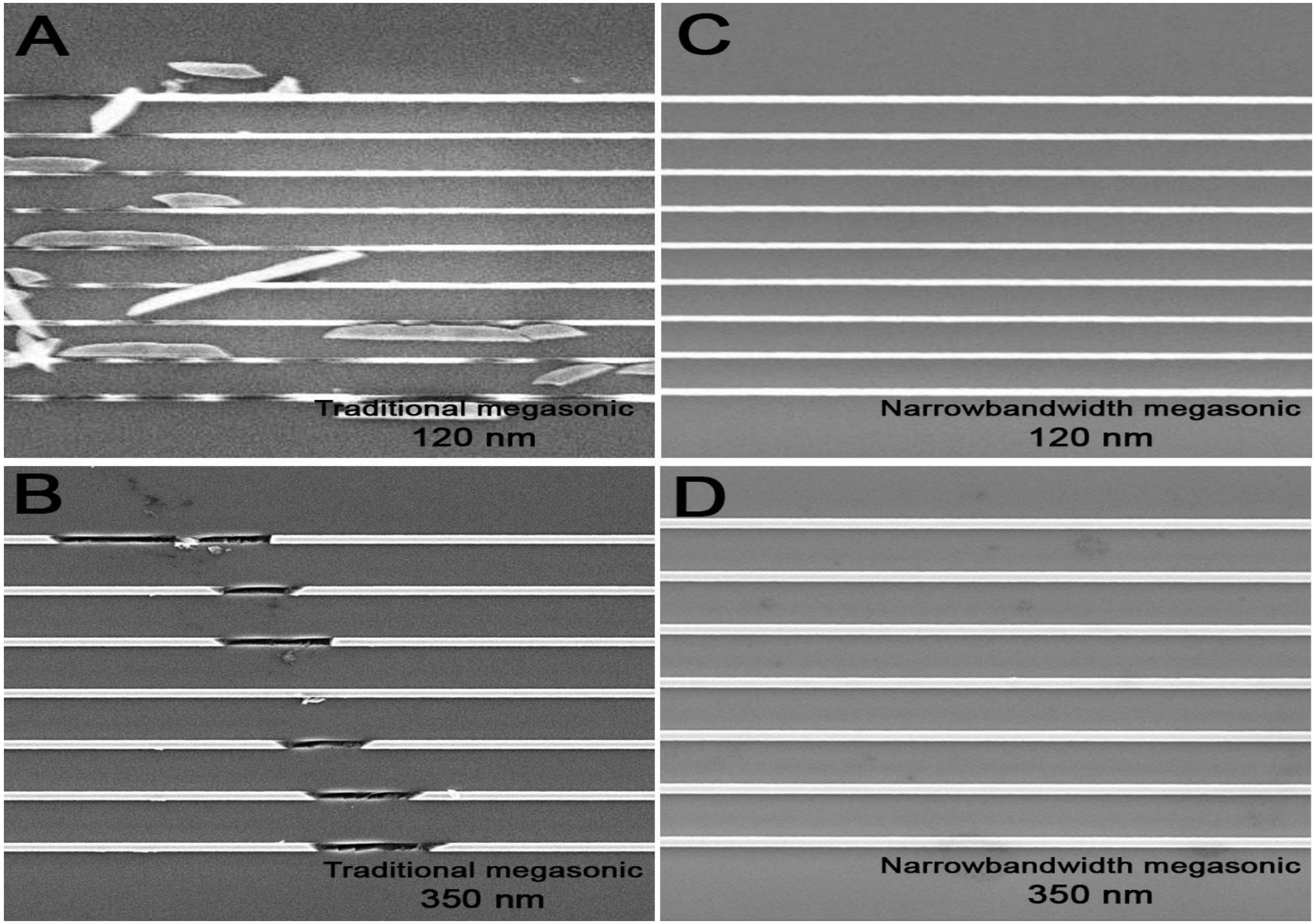
SEM images of 130nm (A and C) and 150nm (B and D) lines after cleaning with 50% power for 5 minutes. While the single wafer megasonic tank damages the structures the narrow bandwidth transducer preserves the patterns.

Damage Results for 70% Power



SEM images of 120nm (A and C) and 150nm (B and D) lines after cleaning with 70% power for 5 minutes. While the single wafer megasonic tank damages the structures the narrow bandwidth transducer preserves the patterns.

Damage Results for 100% Power



SEM images of 120nm (A and C) and 350nm (B and D) lines after cleaning with 100% power for 5 minutes. While the single wafer megasonic tank damages the structures the narrow bandwidth transducer preserves the patterns.

Damage Results for 100% Power

FESEM images of 120nm (A from last figure after cleaning with 100% power for 5 minutes.

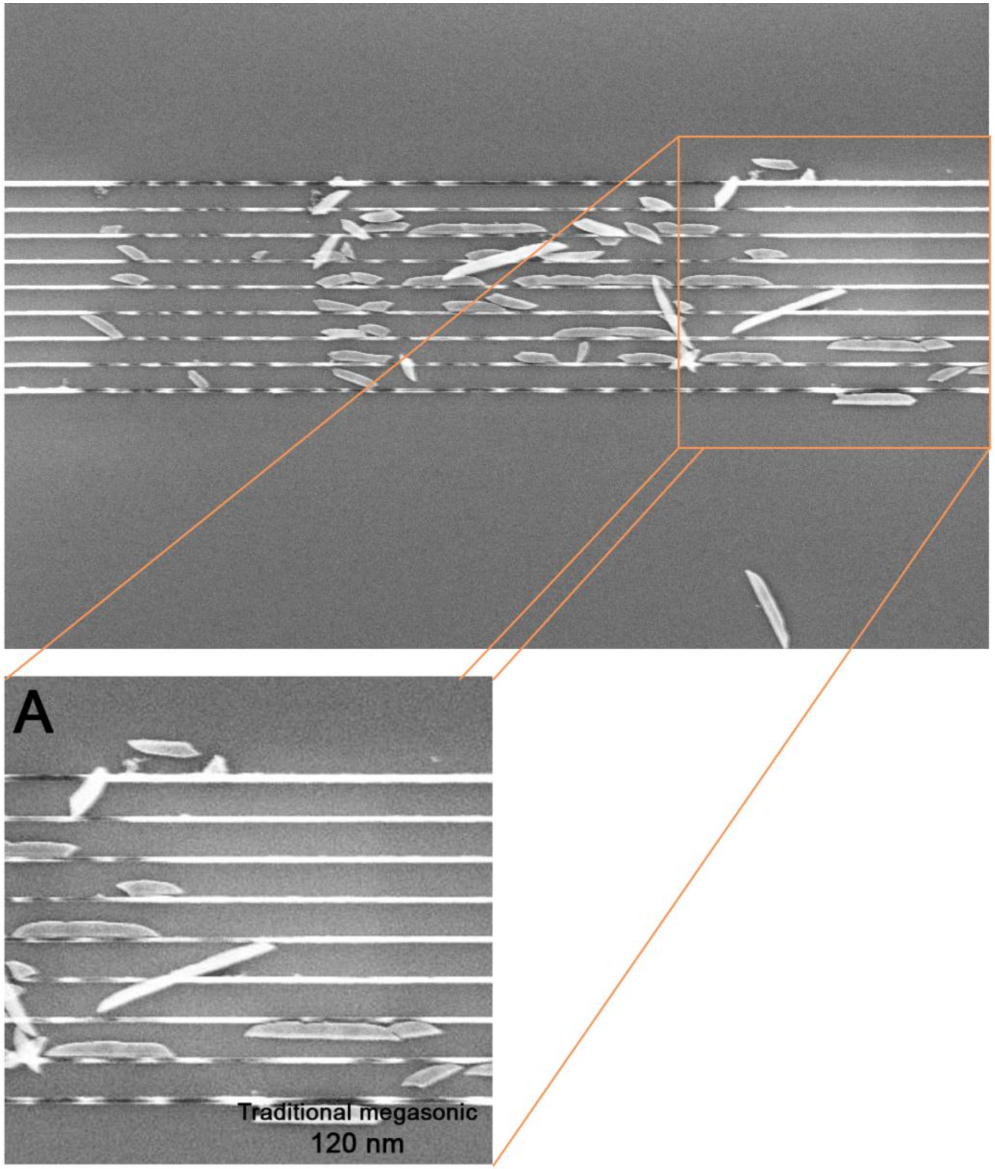


Figure 4-20: low magnification picture for 120nm lines in figure 4-18

Conclusion

- The existence of high amplitude low frequencies in a traditional megasonic has been shown.
- Low frequencies in a traditional megasonics can have a large amplitude compared to high frequencies.
- Narrow bandwidth megasonics almost eliminated the low frequencies and has a comparable removal performance as traditional megasonic.
- There was no damage to polysilicon lines that were cleaned in narrow bandwidth megasonics