Micromachined Microdroplet Ejector Arrays

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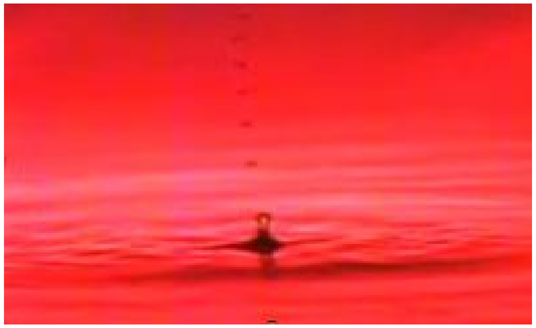
Micro-Droplets

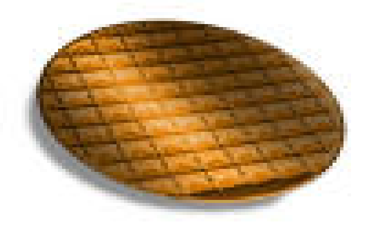
Mission:
To be the world leader in MEMS micro-droplet devices

Our Technology:

- 3-20μm drop size
- Acoustic drop ejection -> gentle for sensitive liquid
- Nozzle-less approach -> precise delivery
- Continuous delivery 100,000+ drops/second

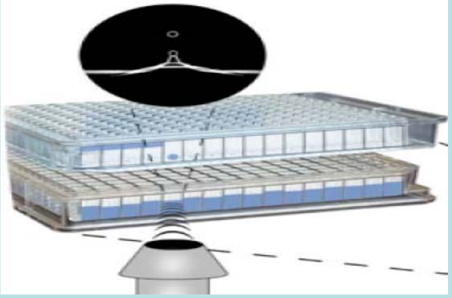


Small Drops ………… Big Opportunities



Semiconductor
Wafer Coating Application
Mask-less Lithography (Future)

OLED (Organic LED)
Direct circuit printing



Medical
Controlled drug delivery
Bio-array testing

Immediate Opportunity

Semiconductor Wafer Coating

MicroDroplet Value

Photoresist Cost Savings

- Huge amounts of waste
- $735M sold in 2003, up to 95% wasted

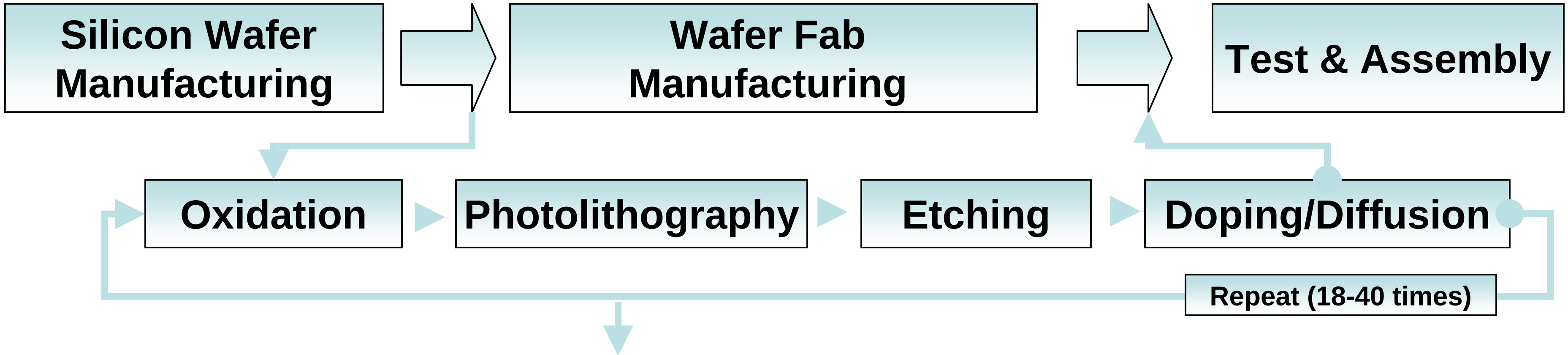
Enviromental Benefits

- Growing hazardous waste disposal costs
- Environmental regulations

Process Limitations

- Photo-mask technologies become smaller
- Eliminate EBR step
- Higher throughput
- Deep trenches coverage, 3D

Semiconductor Manufacturing Stages



Silicon Wafer Manufacturing

Wafer Fab Manufacturing

Test & Assembly

Oxidation

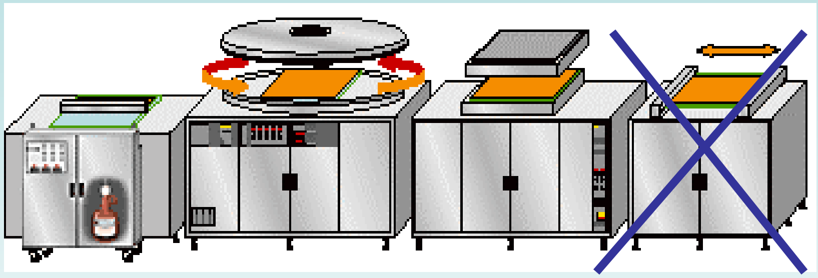
Photolithography

Etching

Doping/Diffusion

Repeat (18-40 times)

Front-end lithography



Replacement MEMS head

Coating component

Photoresist waste

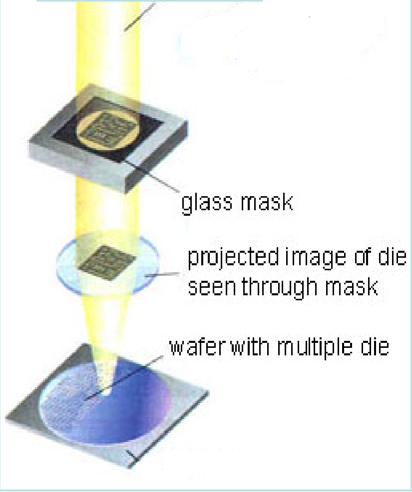
Coat & Spin

95%

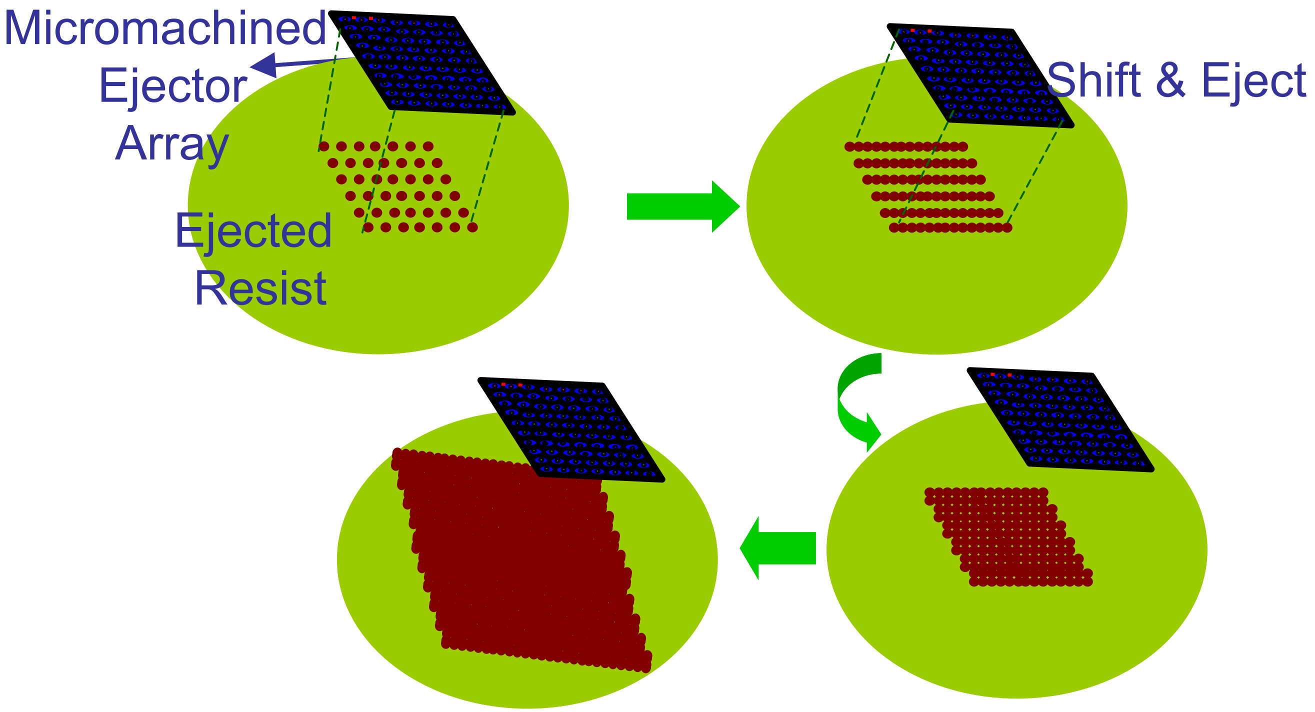
Spinless

5%

Patterning

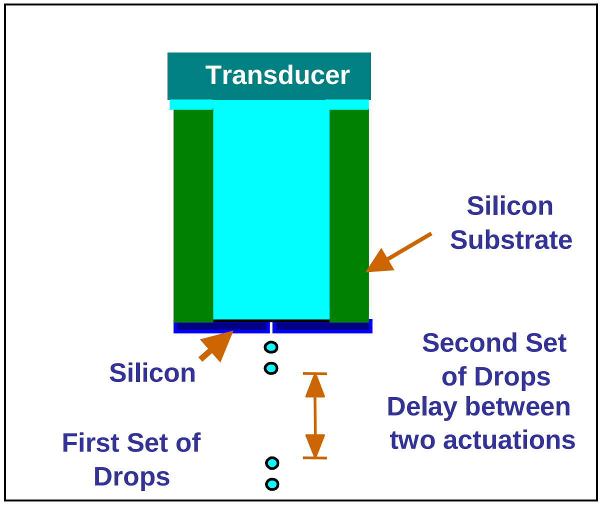


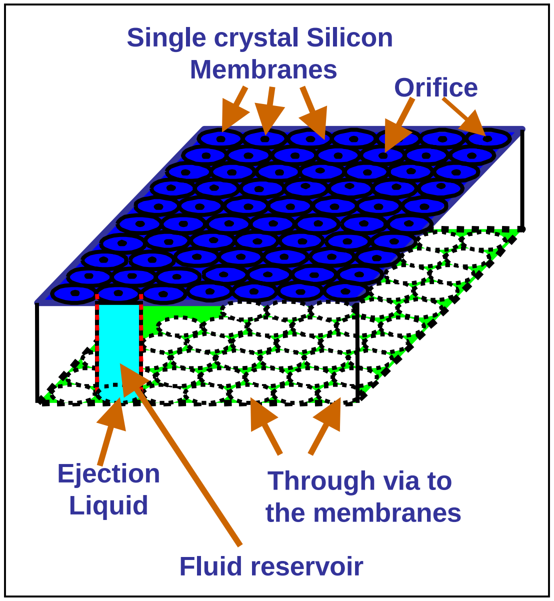
Ejection Approach

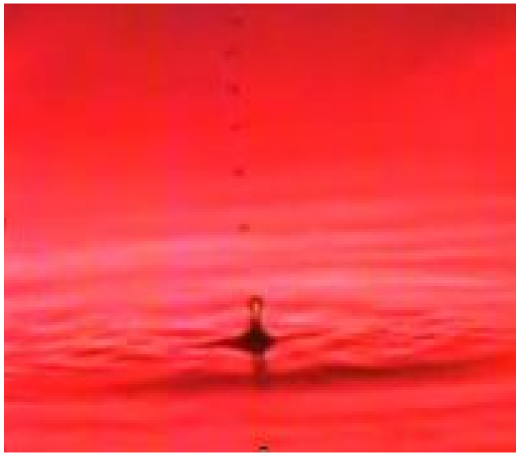


- Minimize chemical consumption, Environmentally Benign
- No edge bid removal necessary.
- Capability to cover deep trenches.

Technology



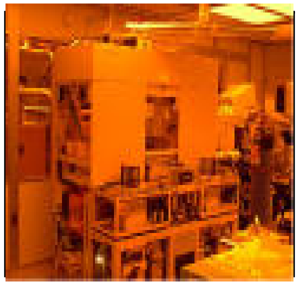


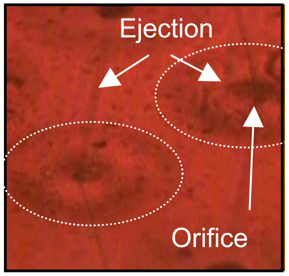


Key Differentiators:

- Acoustically-Driven Liquid Dispension
- Reduces liquid material waste and cleanup from improved measure of control
- Localized semiconductor lithography
- Materials are not heated or pressurized allowing a broad set of Liquids or Substrates
- Uniform thin film advantages
- Allows 3D Deposition-Deep Trench Coverage

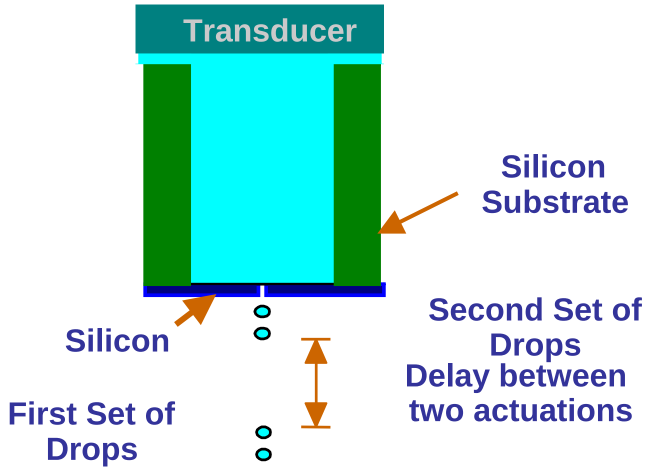
Competing Technologies

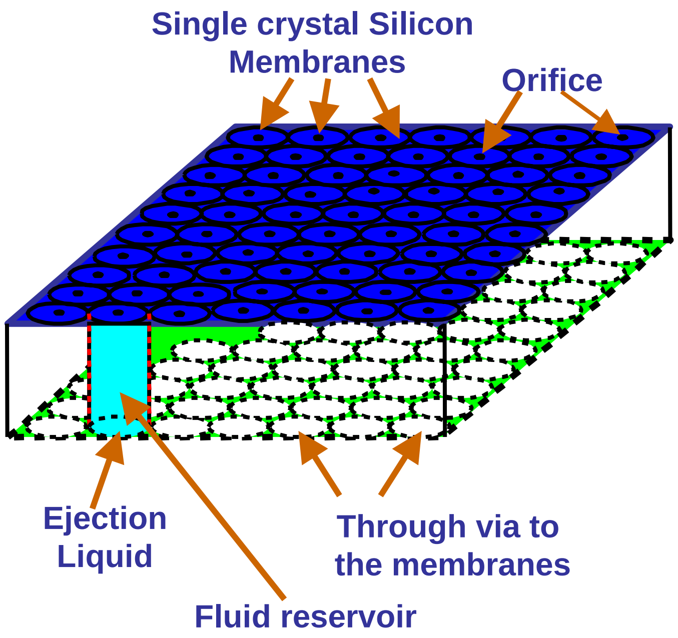




	Spin Coating	Spray Coating	Chemical Vapor Deposition	MicroDrop MEMS
Waste	95%	30%	5-10%	<5%
Droplet Size	N/A	20µm	Vapor	3-20µm
Complexity	Low	Low	Very High	Low
Edge Bead	Prominent	Minimal	None	None
Liquid Limits	Current Resist	Pressurized	Special Resists	No heat or pressure
Pattern Printing	N/A	N/A	N/A	Yes
Deep Trench 3D	N/A	Yes	Yes	Yes

Membrane Based 2D Ejector Array





- 2D array of ejectors
- Membrane actuation by a transducer through the fluid reservoir
- Thin single crystal silicon uniform membrane
- Deep reactive ion etched reservoir
- High frequency operation for high flow rate (MHz)
- Drop-on-demand and continuous modes of operation

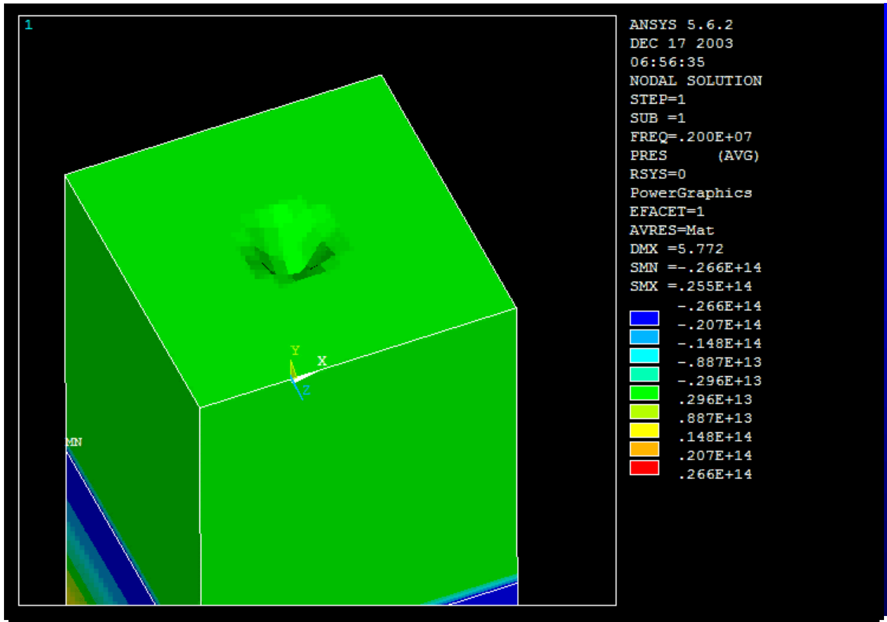
Finite Element Method (FEM) Simulations

FEM is utilized to fully characterize membrane based ejector arrays

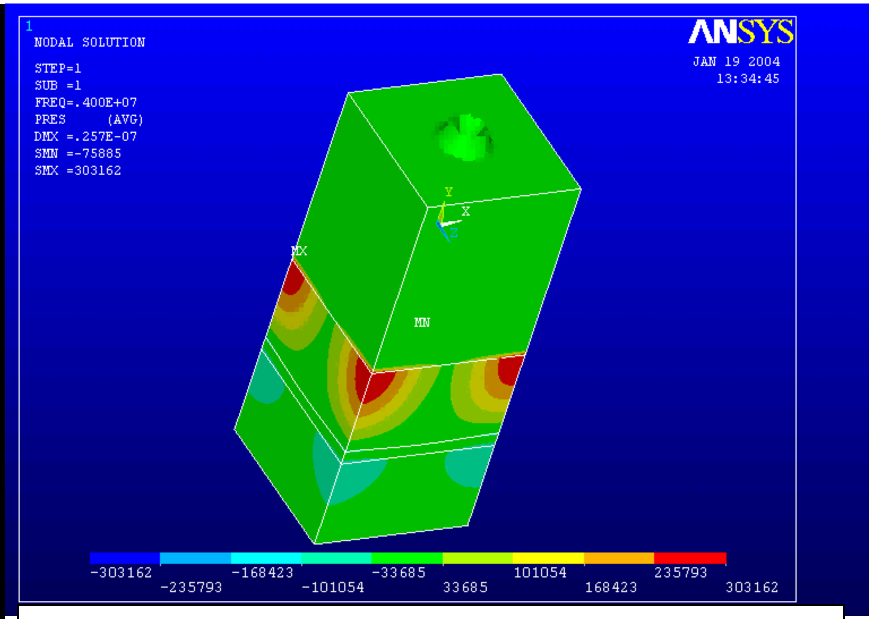
- Single membrane
  - Resonance frequencies and mode shapes
  - Displacement of the orifice
- Array simulation
  - Crosstalk

ANSYS and Coventorware were used in the simulations.

Theory and Experiments

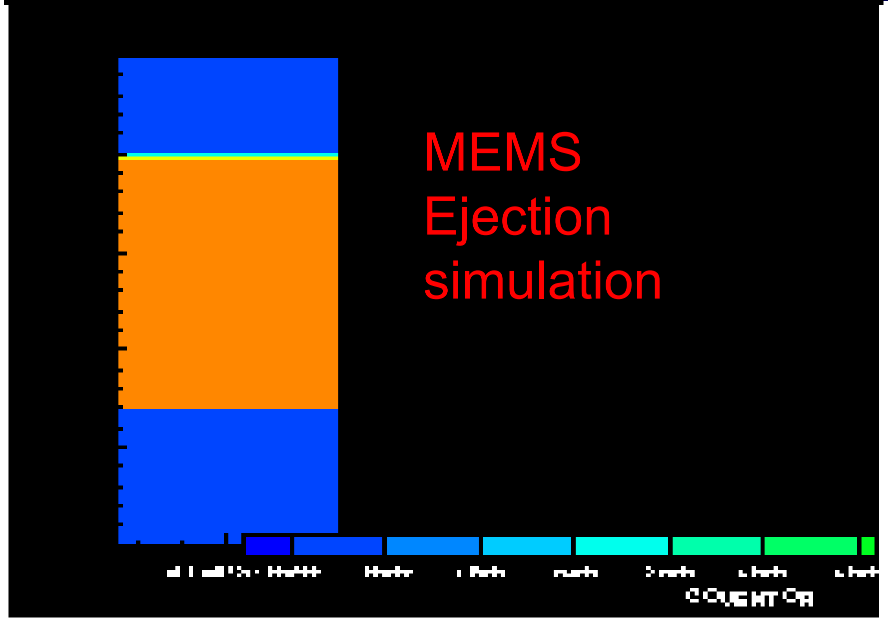


```
ANSYS 5.6.2
DEC 17 2003
06:56:35
NODAL SOLUTION
STEP=1
SUB =1
FREQ=.200E+07
PRES      (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =5.772
SMN =-.266E+14
SMX =.255E+14
```

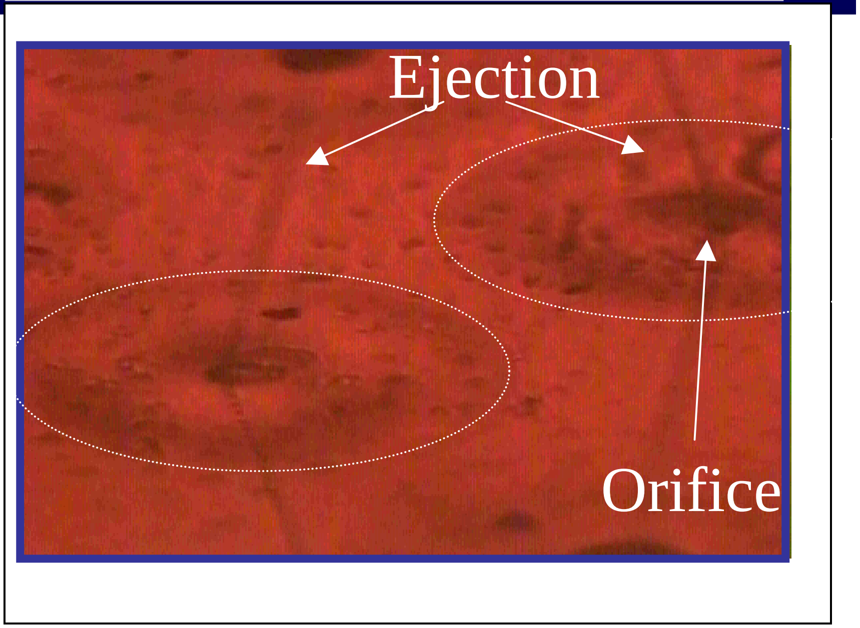


```
NODAL SOLUTION

STEP=1
SUB =1
FREQ=.400E+07
PRES      (AVG)
DMX =.257E-07
SMN =-75885
SMX =303162
```



MEMS
Ejection
simulation



Challenges with Membrane Ejectors

(i) Non-uniform membrane properties

- ✓ Solved by utilizing SOI wafer to wafer bonding technology
  - Achieved uniform resonance frequency

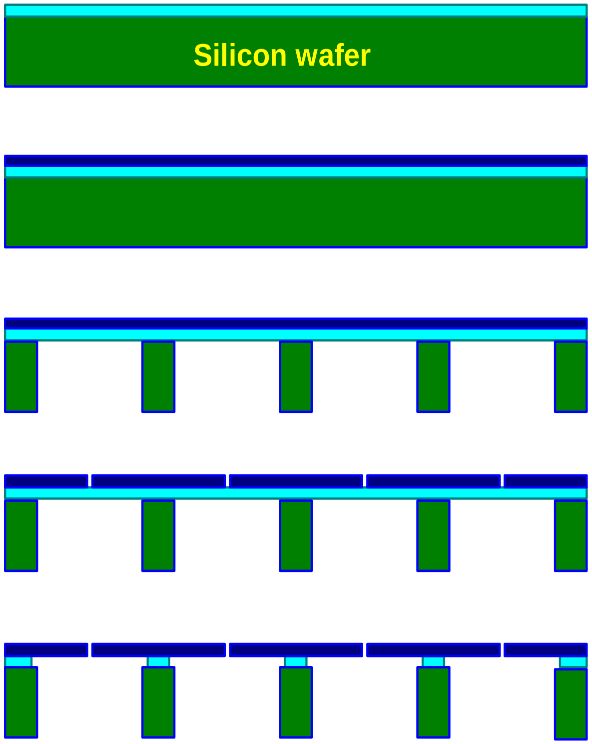
(ii) Reduction of coupled acoustic power by the reservoir

- ✓ Solved by reversing the geometry
  - Capability to eject high viscosity fluids (photoresist, etc.)

(iii) Non-uniform membrane actuation

Fabrication Processes

Previous



Oxide film deposition

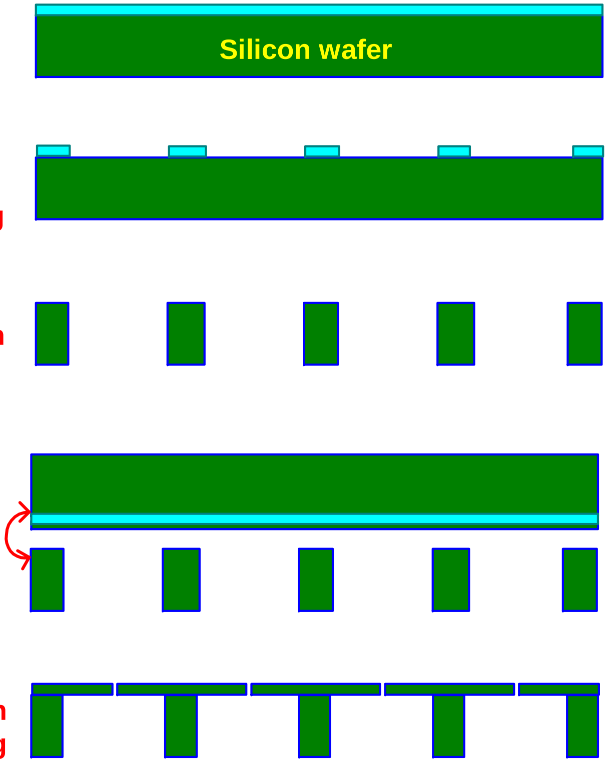
Nitride film deposition

Silicon bulk etch

Orifice formation with dry etching

Oxide etching

New



Oxide film deposition

Oxide film patterning

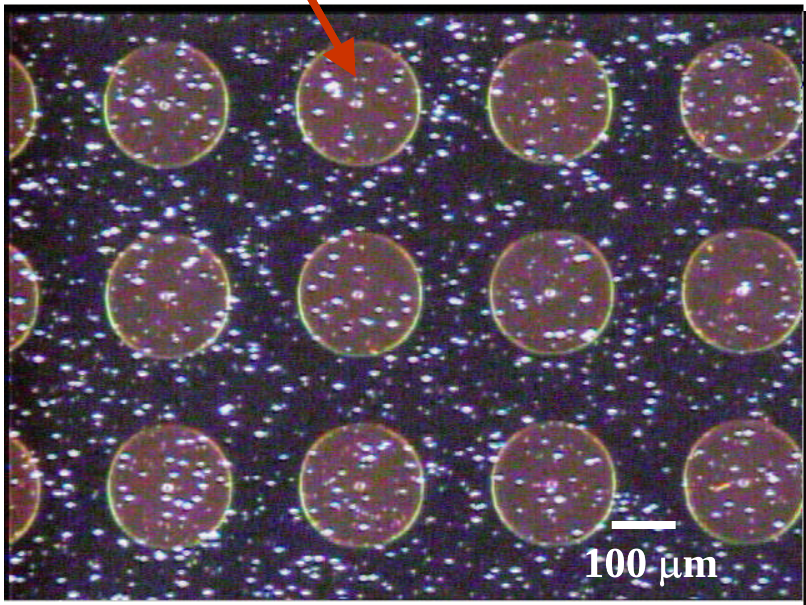
Silicon bulk etch
Oxide removal

SOI wafer bonding

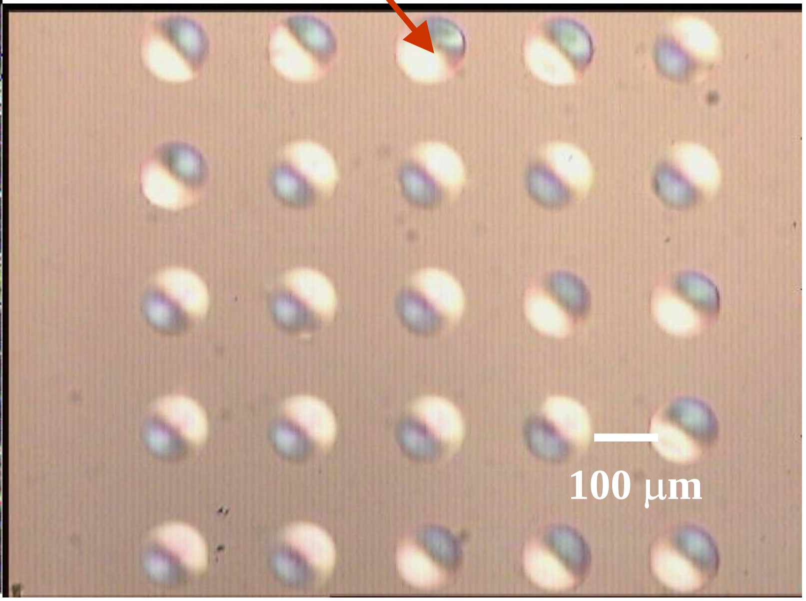
Wet Oxide etch
Orifice formation with dry etching

(i) Si_xN_y and Single Crystal Silicon Ejector Arrays

Silicon nitride membrane



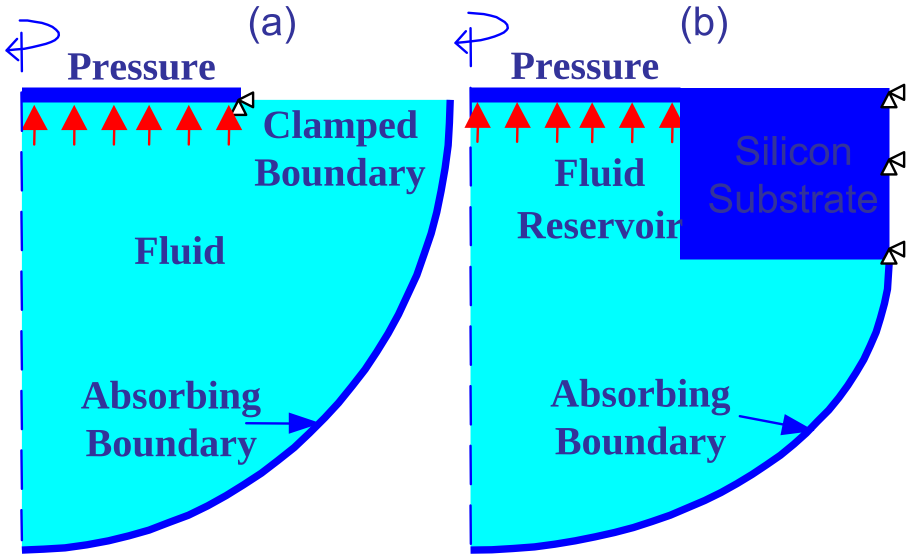
Single Crystal Si membrane



Membrane diameter : 160 μm
Orifice diameter : 10 μm

Membrane diameter : 100 μm
Orifice diameter : 14 μm

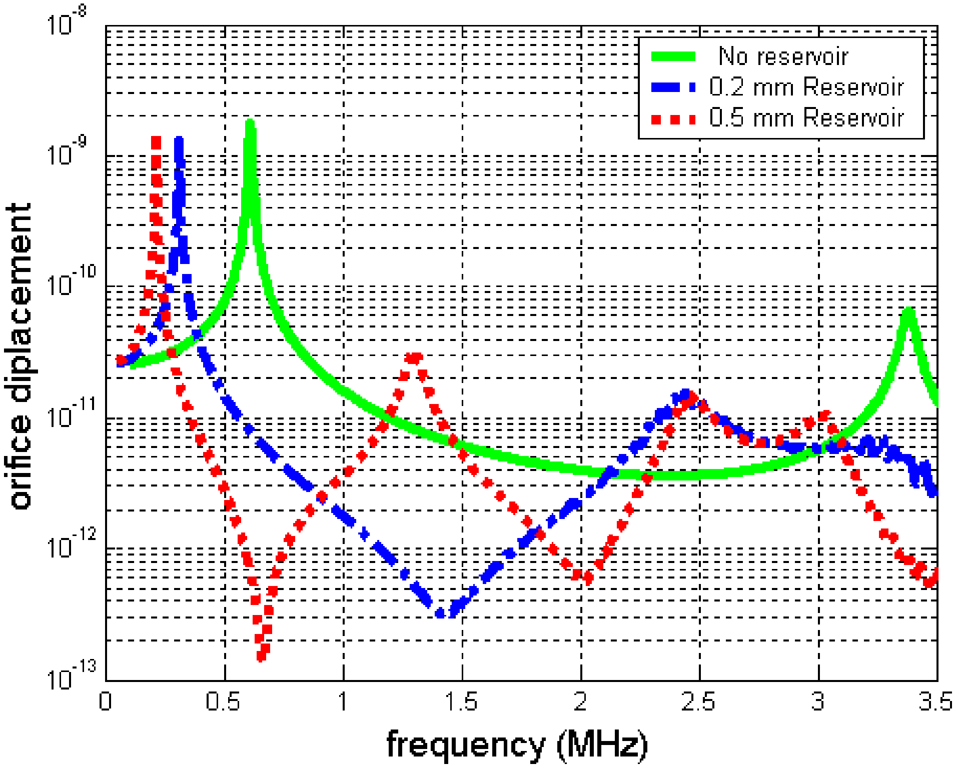
(ii) Reservoir Effect: FEM Simulations



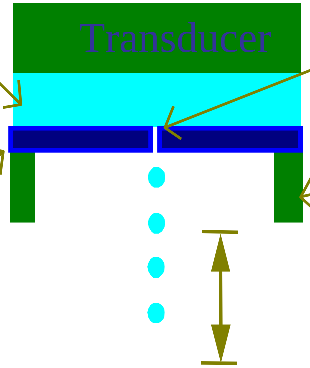
The reservoir effects the displacement spectrum

- Dips in the spectrum
- Shifts the resonances
- Changes the Quality factor

Reservoir	With	Without
Q of 1st resonance	35	47
Q of 2nd resonance	8	33
Energy per Drop	7.9 nJ	3.7 nJ



Photoresist Ejection



Photoresist

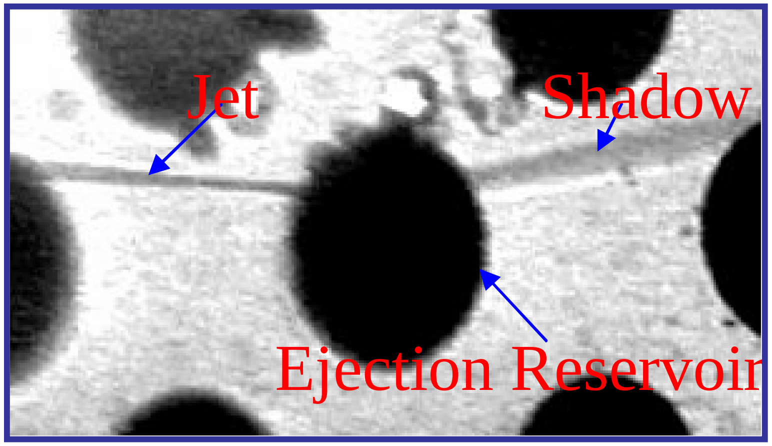
Transducer

Orifice

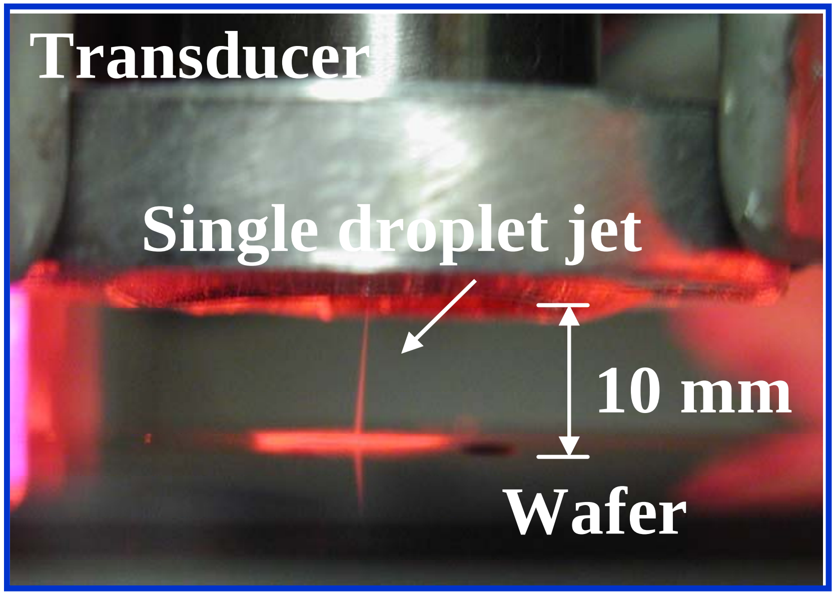
Silicon Substrate

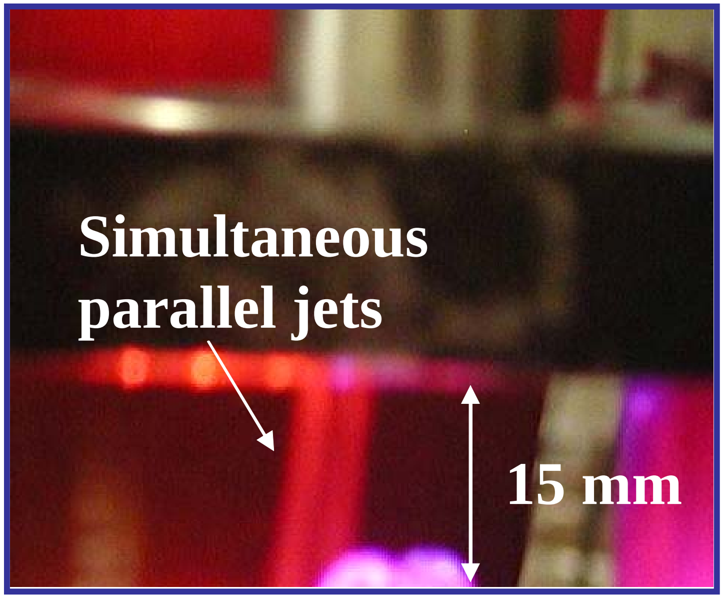
Membrane

Delay between two actuations

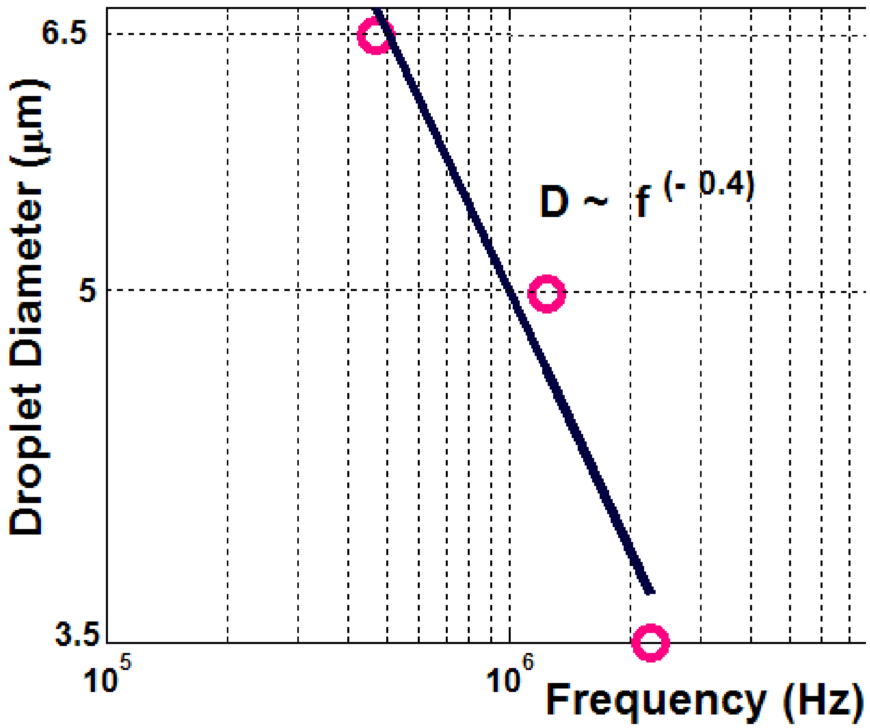


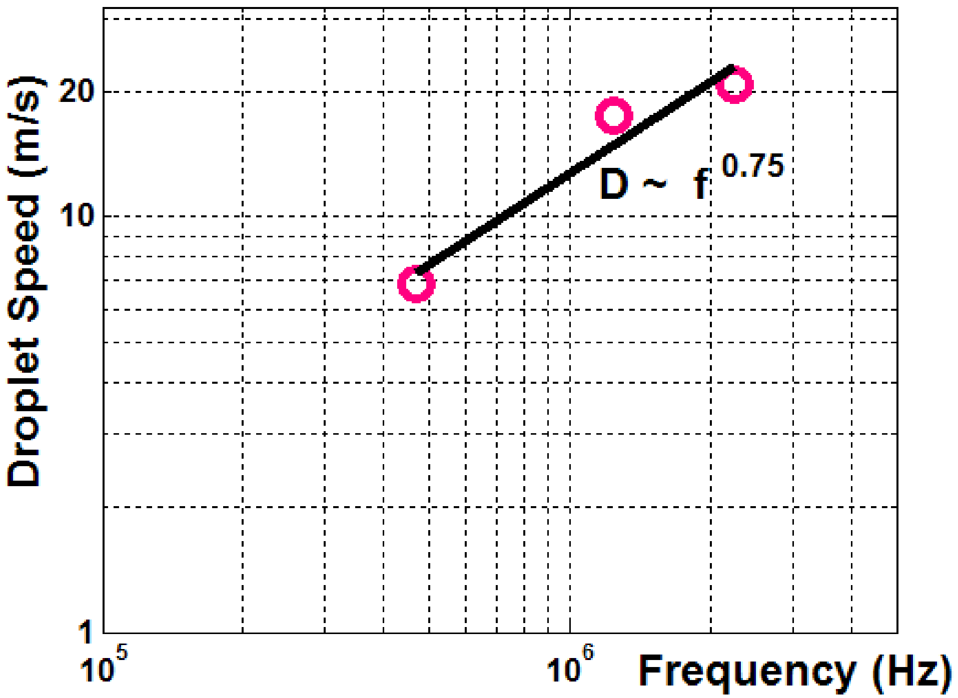
Water droplet jet and its shadow at 1.06 MHz from 160 µm in diameter Silicon membranes with 10 µm in diameter orifices. Droplets travel through a 500 µm long open-ended cylinder.





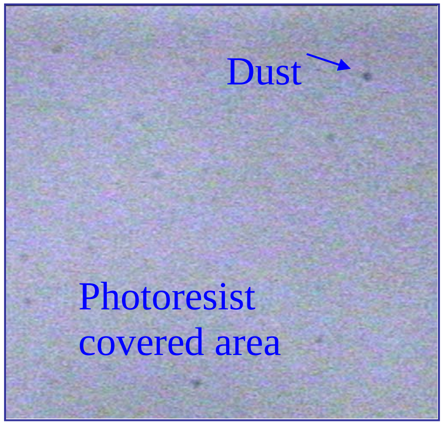
Experimental Droplet Data



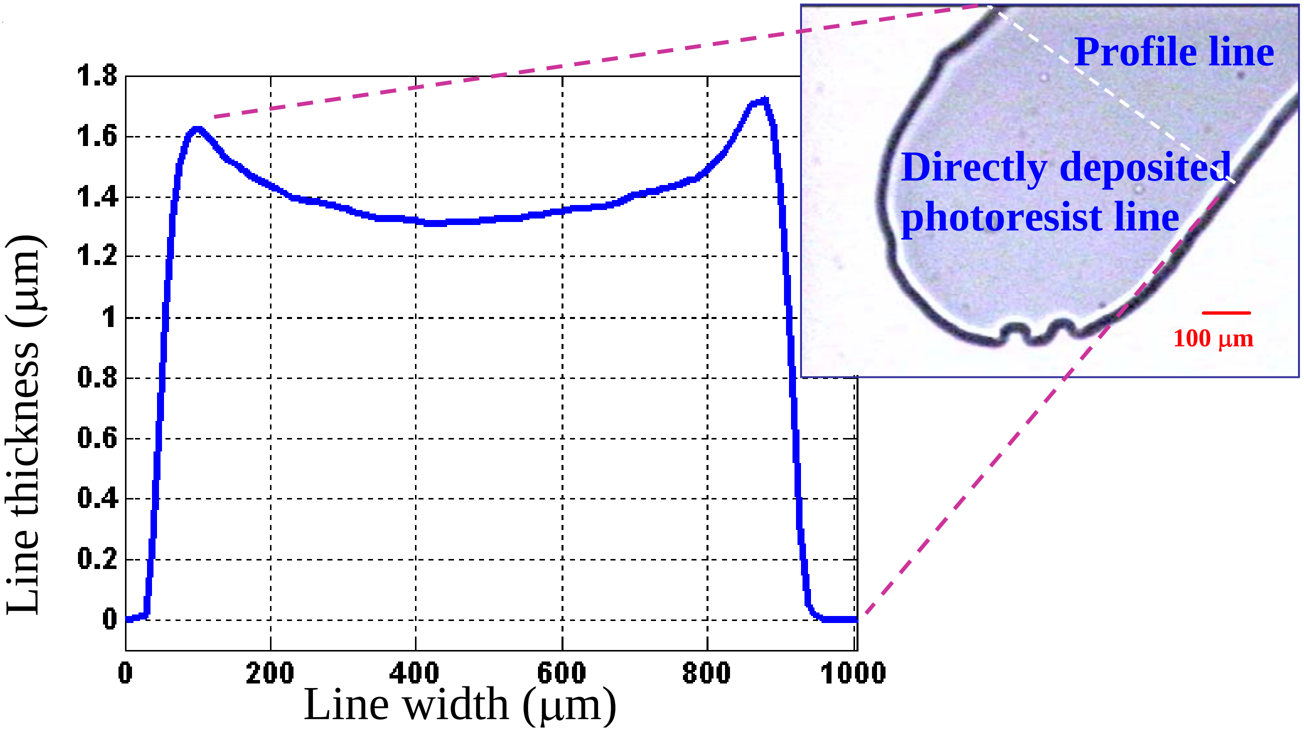


Droplet diameter decreases with frequency
Droplet ejection speed increases with frequency

Photoresist covered area and a drawn line



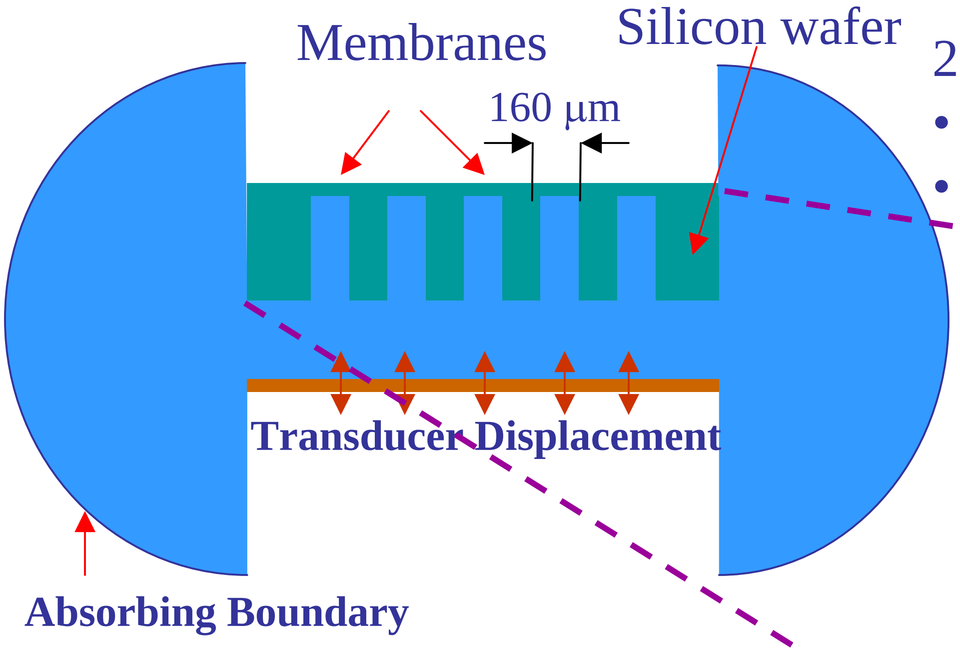
2mm x 2mm



(a) Coverage of a 2mm x 2mm area on a silicon wafer with a 5.5 µm thick layer of resist. The maximum thickness variation was 0.4 µm over the area. Dust particles can be seen on the photoresist covered area.

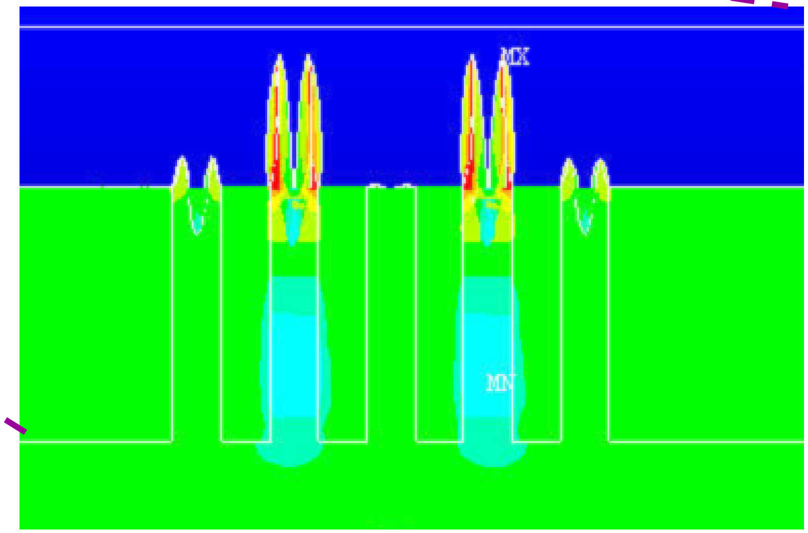
(b) Directly deposited 1.6 µm thick, 900 µm wide and 8 mm long photoresist line. The maximum photoresist thickness variation on the line was 0.2 µm and 0.4 µm in vertical and horizontal directions, respectively. 20% photoresist solvent was added to the photoresist to compensate for the fast evaporation.

CURRENT WORK:
How to make all the membranes eject?



2D analysis of 160 µm membrane 1x5 array.

- Reservoirs are infinitely long into the plane
- Transducer is modeled as a an ideal piston



f=1.78 MHz

NEW RESEARCH AREA

Non-uniform pressure distribution over the array membranes due to

- Cross-talk among the membrane
- Waves propagating on the fluid/silicon interface
- **Acoustic periodic crystal effect**
- Currently running Vibrometer measurements on each membrane of the array to understand these effects more into detail.

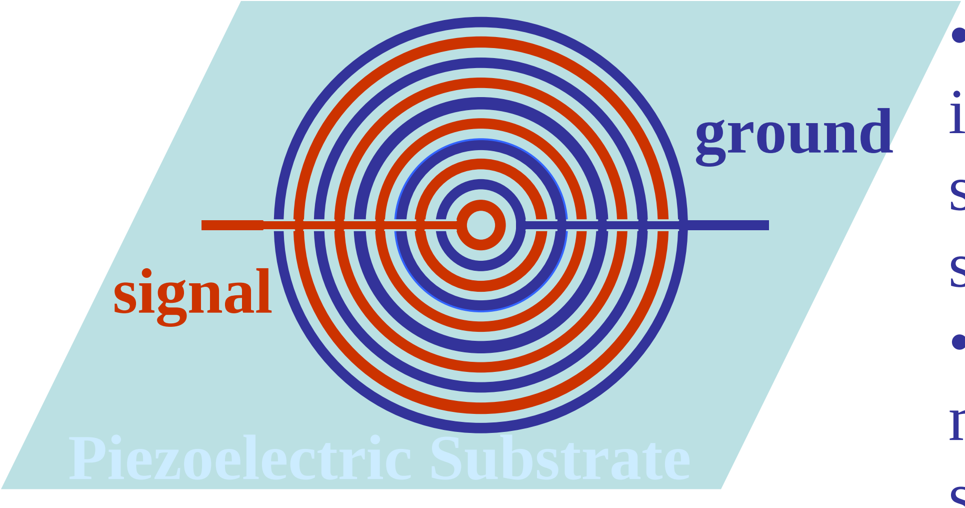
Alternative Ejection Method

- Membrane arrays can be utilized for covering wafers with photoresist.
  - Due to relatively high resonance quality factor of membranes drop on demand is difficult.
- For direct write applications drop demand is desirable.
  - A new ejection method that utilizes acoustic radiation pressure is developed.

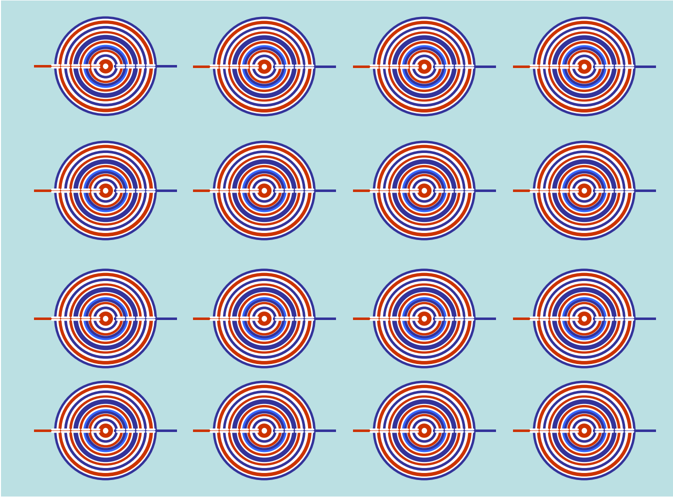
Alternative Ejection Method

- A new ejector array based on surface acoustic waves (SAW)
  - SAW generation using interdigital electrodes on a piezoelectric substrate
  - This device satisfies all our needs
    - Easy fabrication process
    - Capabilities
      - Drop on demand
      - Fast coverage
      - Ejection of high viscosity fluids (water 1 cp, ethylene glycol 16 cp, photoresist viscosity is 2-8 cp)

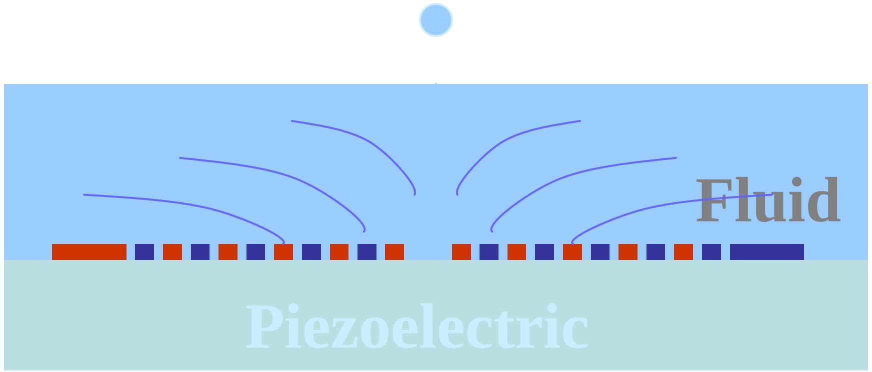
Interdigital Ring Ejectors



Top View

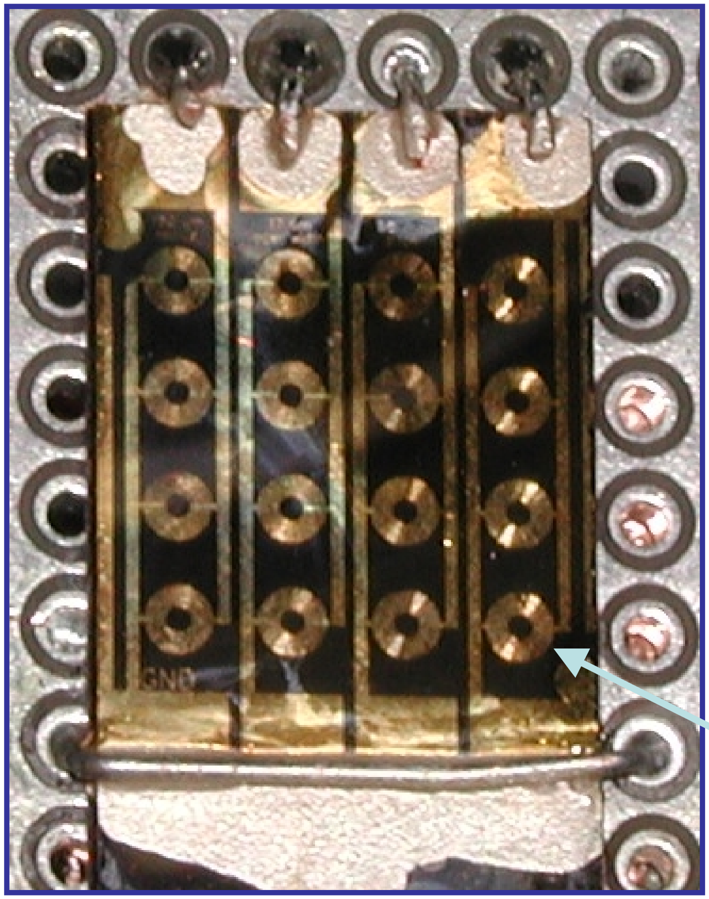


- Sinusoidal voltage on the interdigital electrodes generates surface waves on the piezoelectric substrate.
- These waves couple to the fluid medium and focus at the fluid surface.
- Radiation pressure breaks a droplet off the fluid surface.

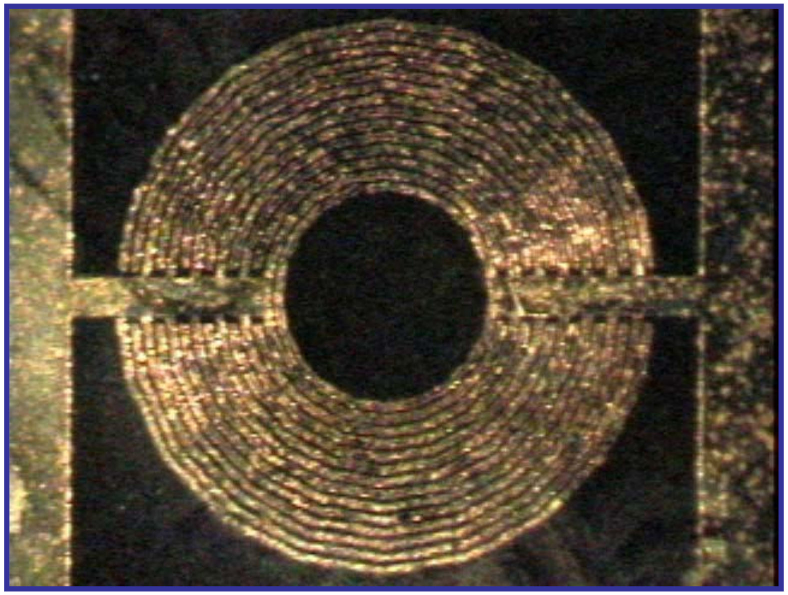


Side View

Fabricated Devices



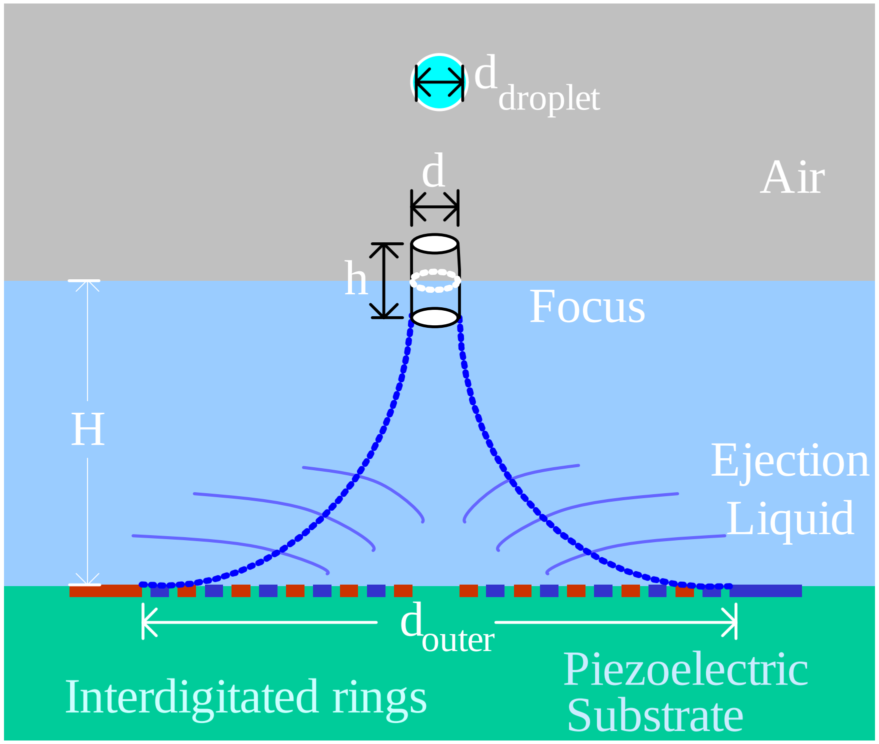
4x4 2D ejector array



OD=1.5mm
ID=0.5mm

- We fabricated these arrays at Stanford Nanofabrication Facility.
- SAW velocity on PZT= 2312 m/s , f_0=34 MHz ➔ ID w=17 μm
- Leak angle, asin(1500/2312) = 40^o

Simple Model of Ejection: Radiation Pressure



$$d = 1.02\lambda F$$

$$h = 7.1\lambda F^2$$

$$\Phi = \arcsin\left(\frac{v_{water}}{v_{piezo}}\right)$$

$$H = \frac{d_{outer}}{2}\tan\Phi = \frac{d_{outer}}{2}\tan\left[\arcsin\left(\frac{v_{water}}{v_{piezo}}\right)\right]$$

$$F = \frac{H}{d_{outer}} = \frac{\frac{d_{outer}}{2}\tan\Phi}{d_{outer}} = \frac{1}{2}\tan\left[\arcsin\left(\frac{v_{water}}{v_{piezo}}\right)\right]$$

Initial Momentum to the cylinder of fluid

$$P_{initial} = \Psi_{initial} A = \aleph T A = \frac{2 I_{initial} A T}{c} = \frac{2E}{c}$$

Droplet Radius

$$V_{cylinder} = \pi\left(\frac{h}{2}\right)\left(\frac{d}{2}\right)^2 = V_{droplet} = \frac{4}{3}\pi\left(\frac{d_{droplet}}{2}\right)^3$$

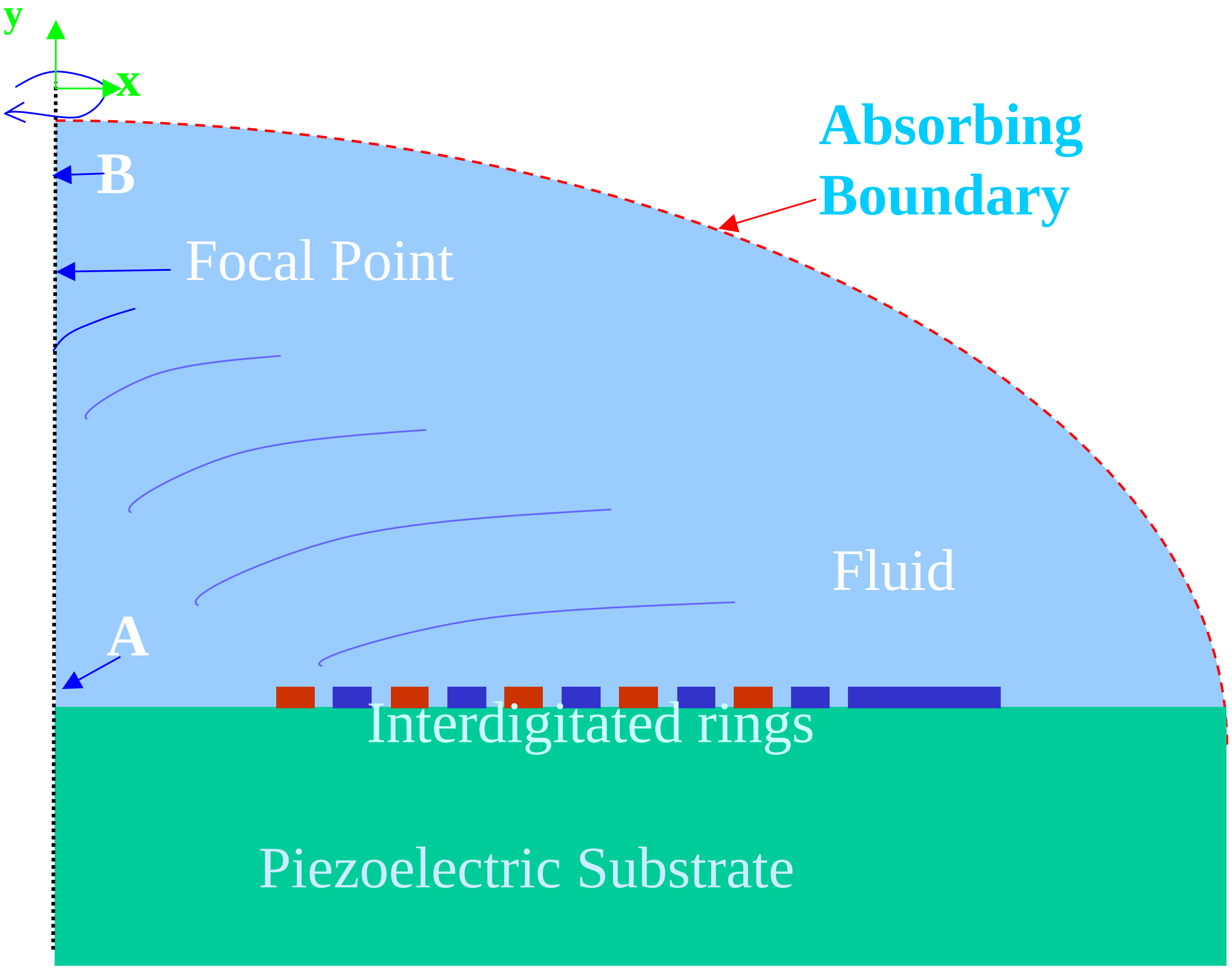
$$\boxed{d_{droplet} = \sqrt[3]{\frac{3}{4} h d^2} \quad \alpha \quad \left(\frac{1}{f}\right)}$$

Conservation of Momentum

$$P_{initial} = m_{droplet}\, v_{initial} \qquad m_{droplet} = \rho_{bulk}\, V_{cylinder}$$

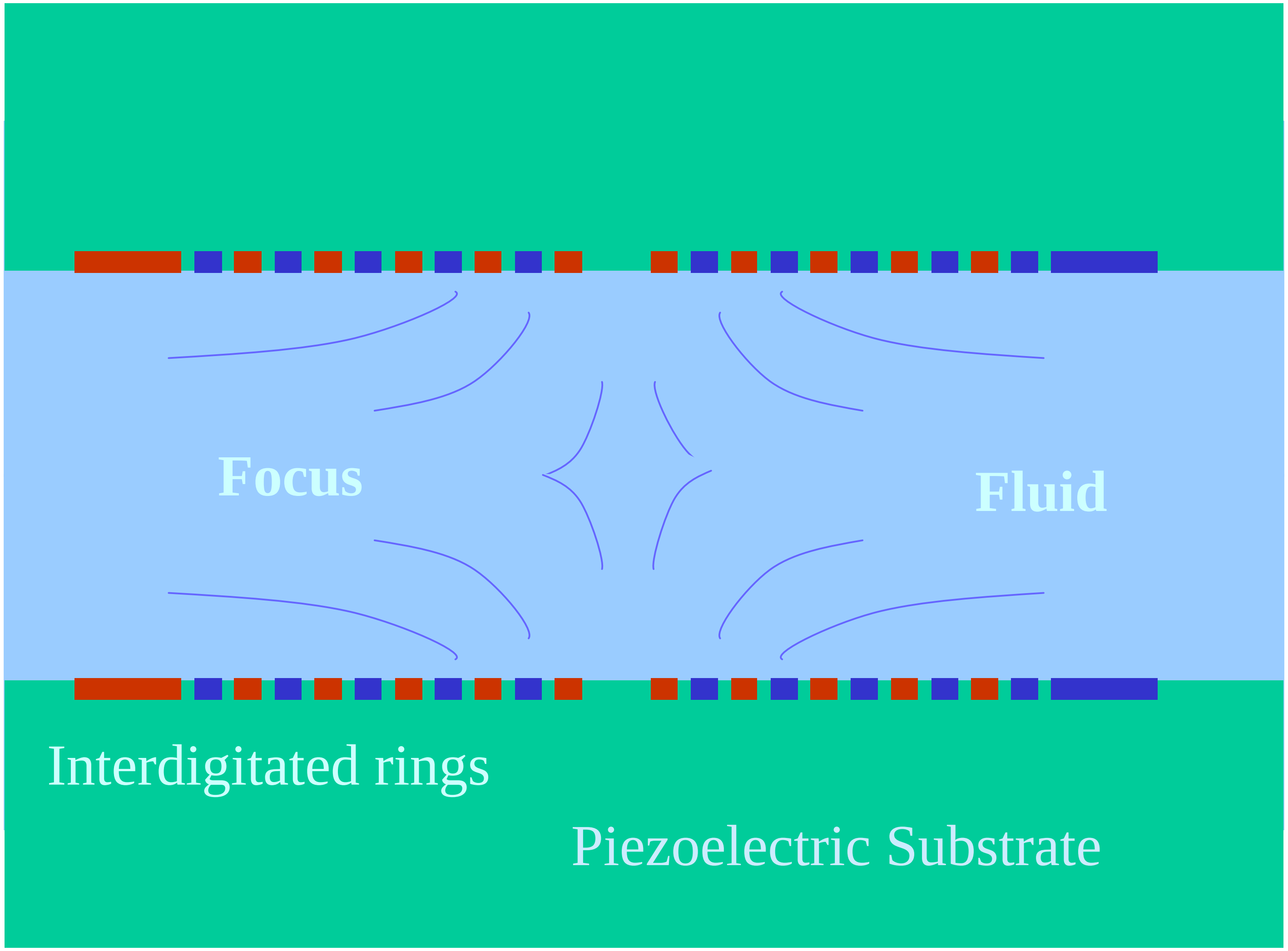
$$\boxed{v_{initial} = \frac{P_{initial}}{m_{droplet}} \quad \alpha \quad E f^3}$$

Finite Element Analysis (FEA)



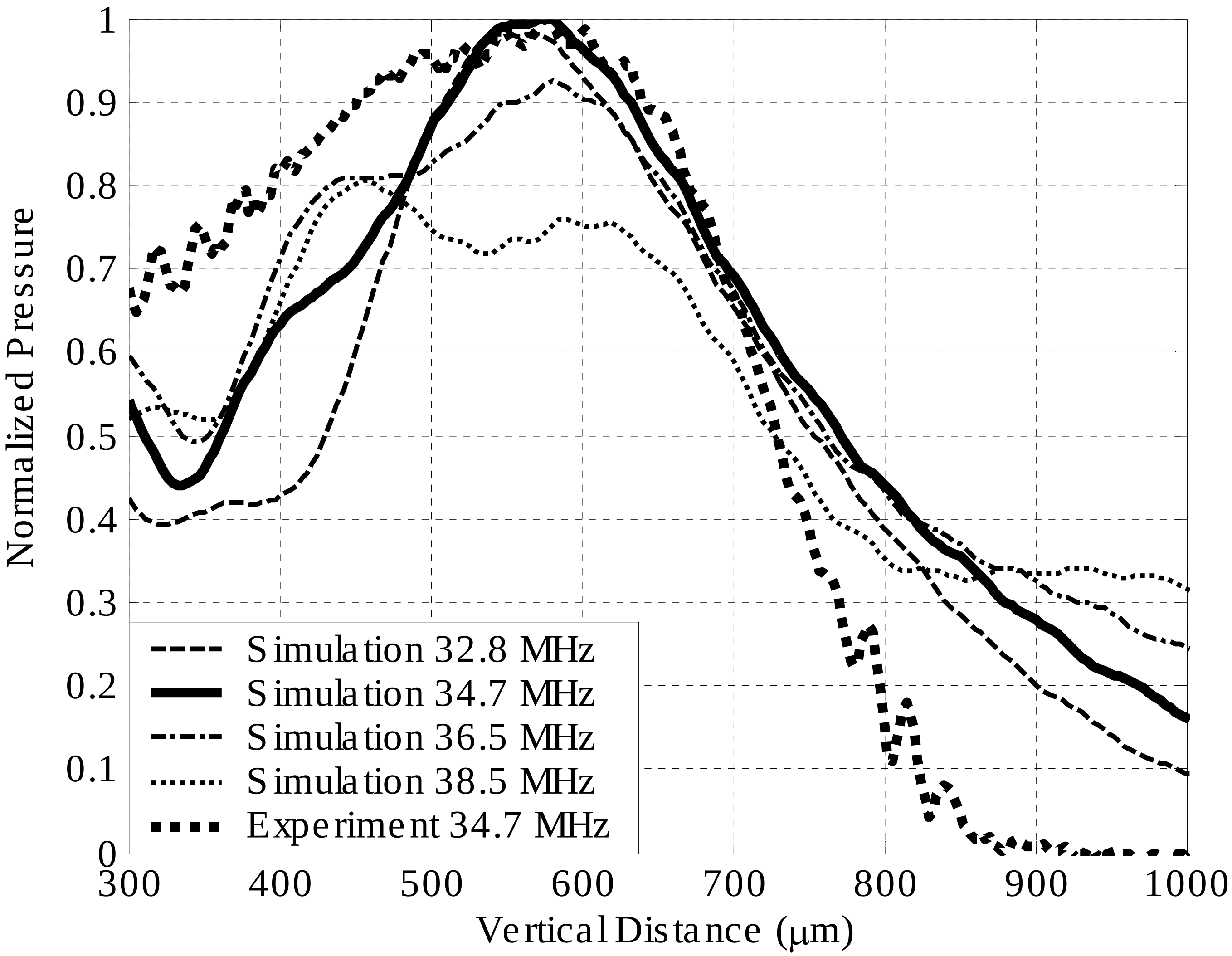
Axisymmetric FEA around y axis.

Pitch Catch Experiments with Single Devices

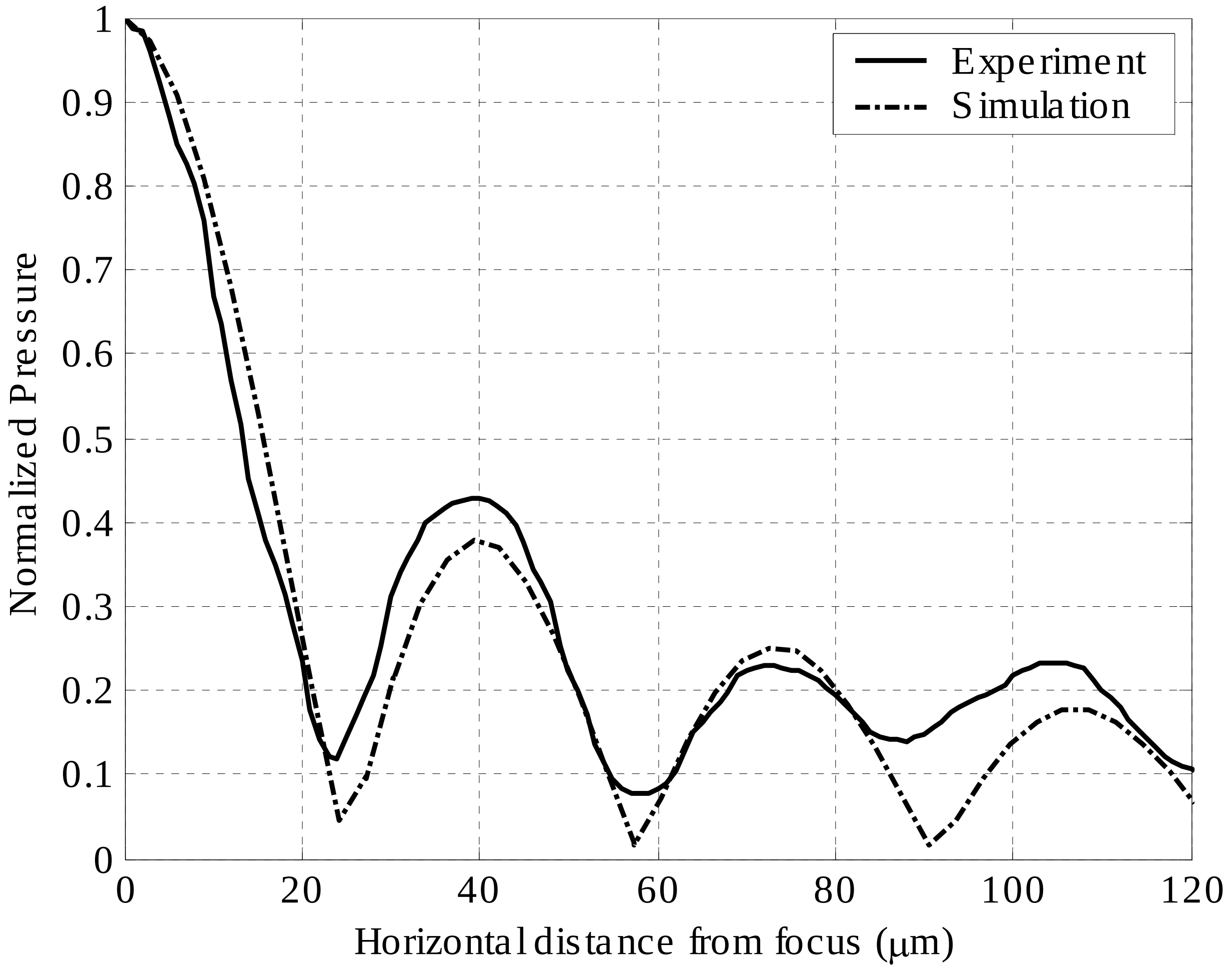


We have two micromachined ejectors facing each other.

Vertical Pressure Distribution

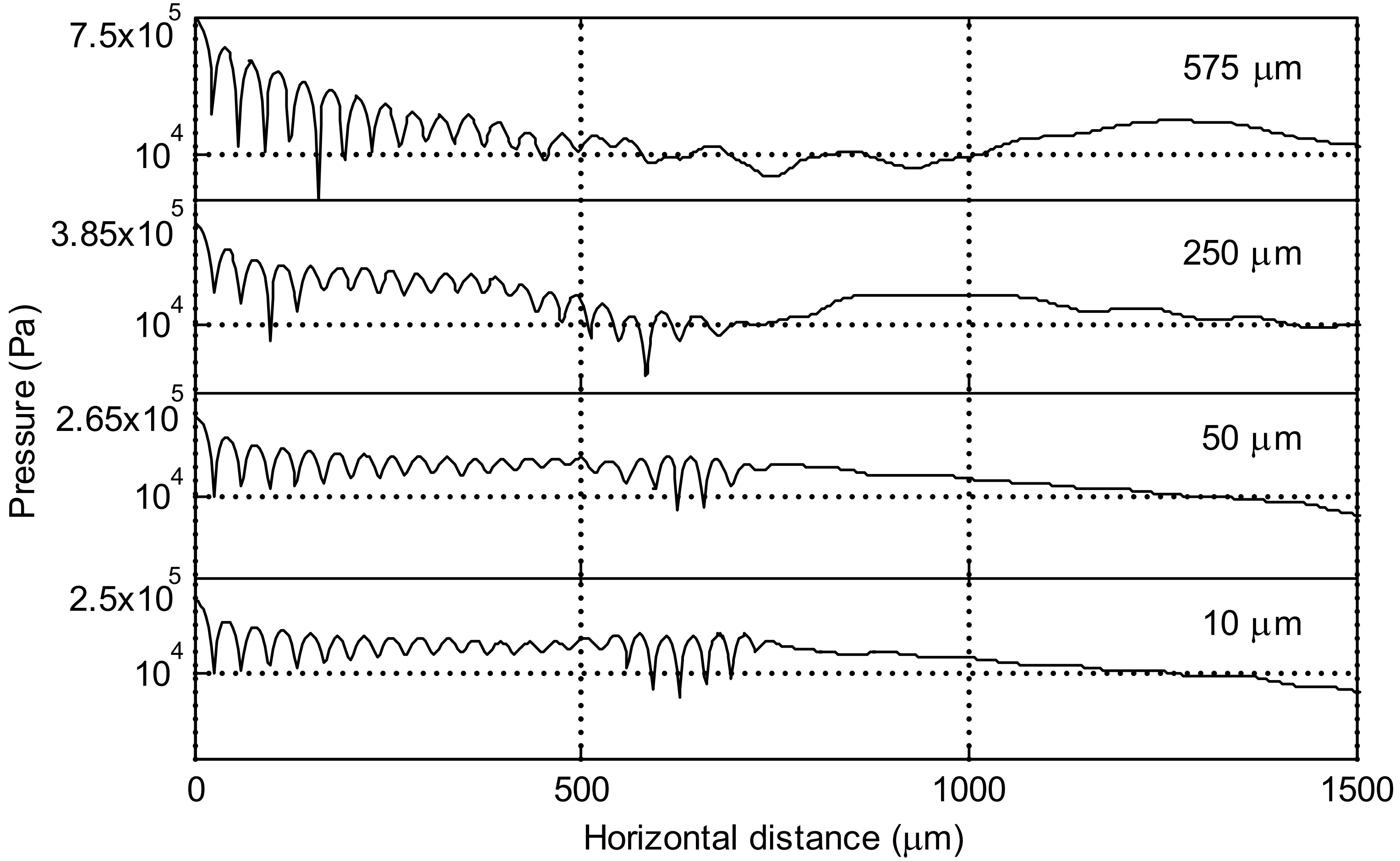


Focal Point



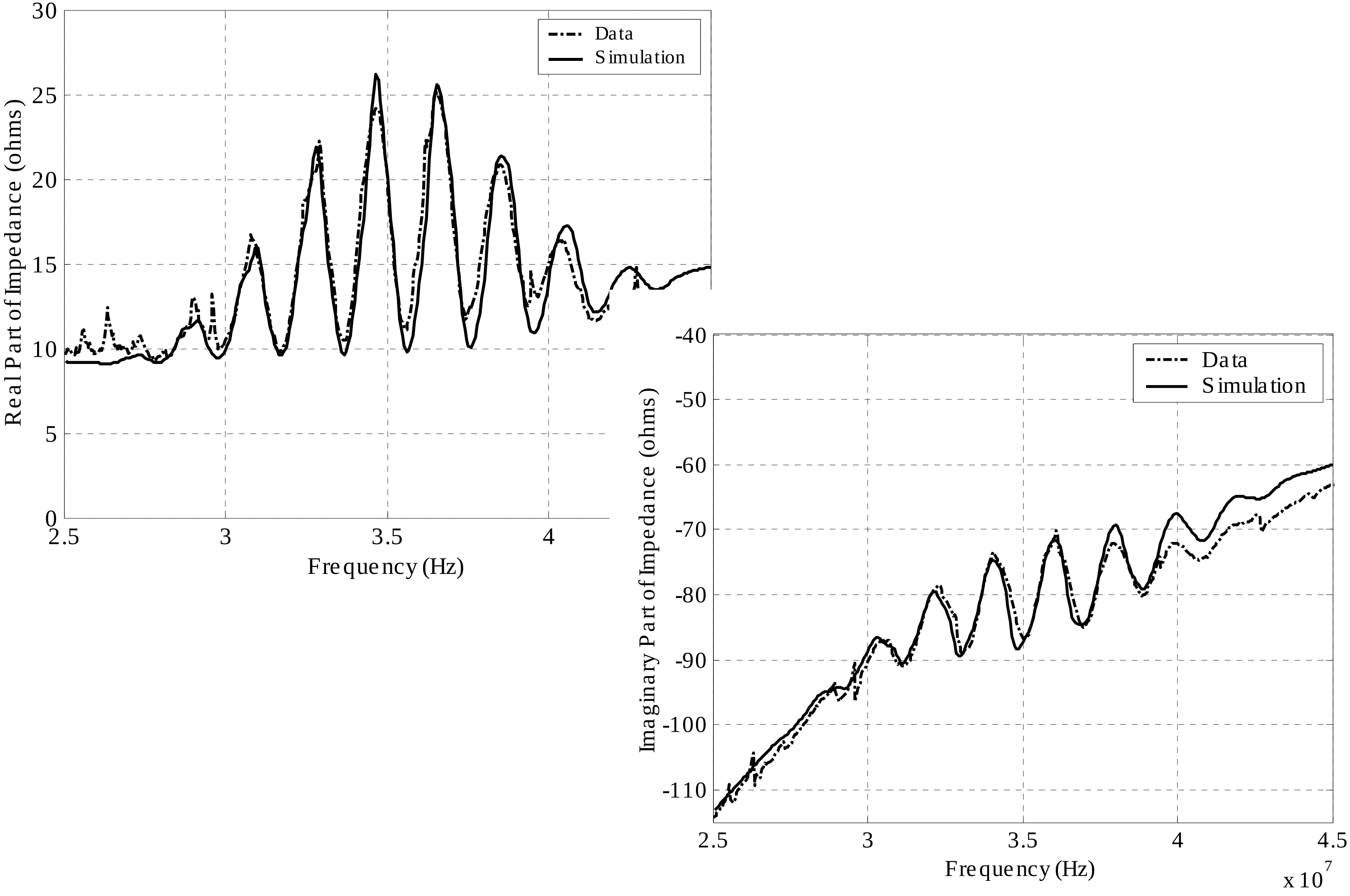
Lateral pressure distribution at the focal point.

Focal Point



Lateral pressure distributions at various heights.

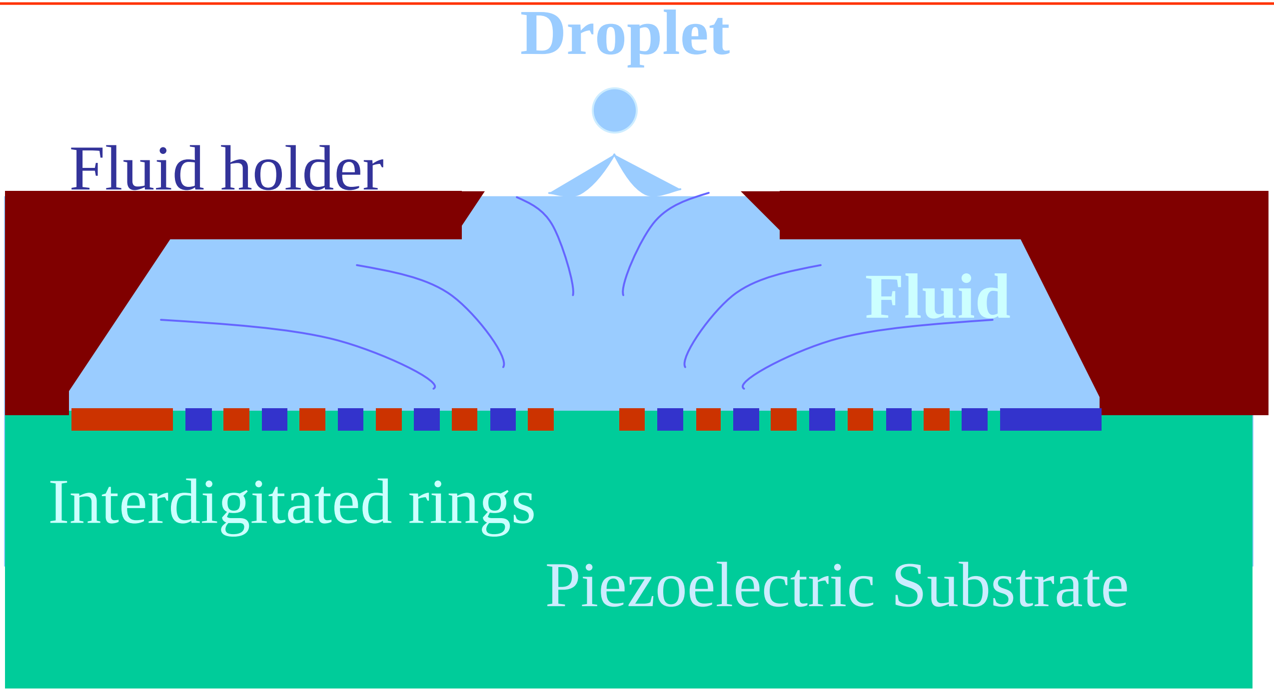
Real and Imaginary part of electrical input Impedance



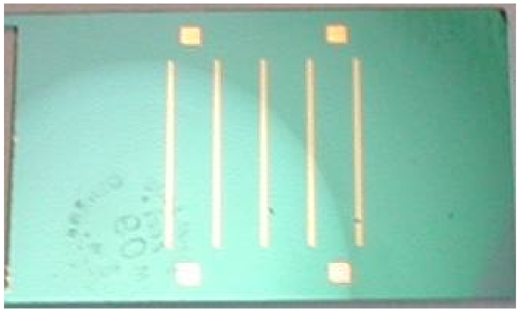
Open Pool Ejection from Ring Ejector Arrays

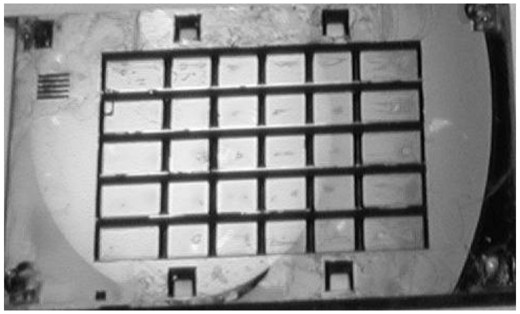
Droplet size: 28 µm, Repetition frequency: 1 kHz
RF frequency: 34 MHz, Pulse width: 10 µs

Fabricated Spacers

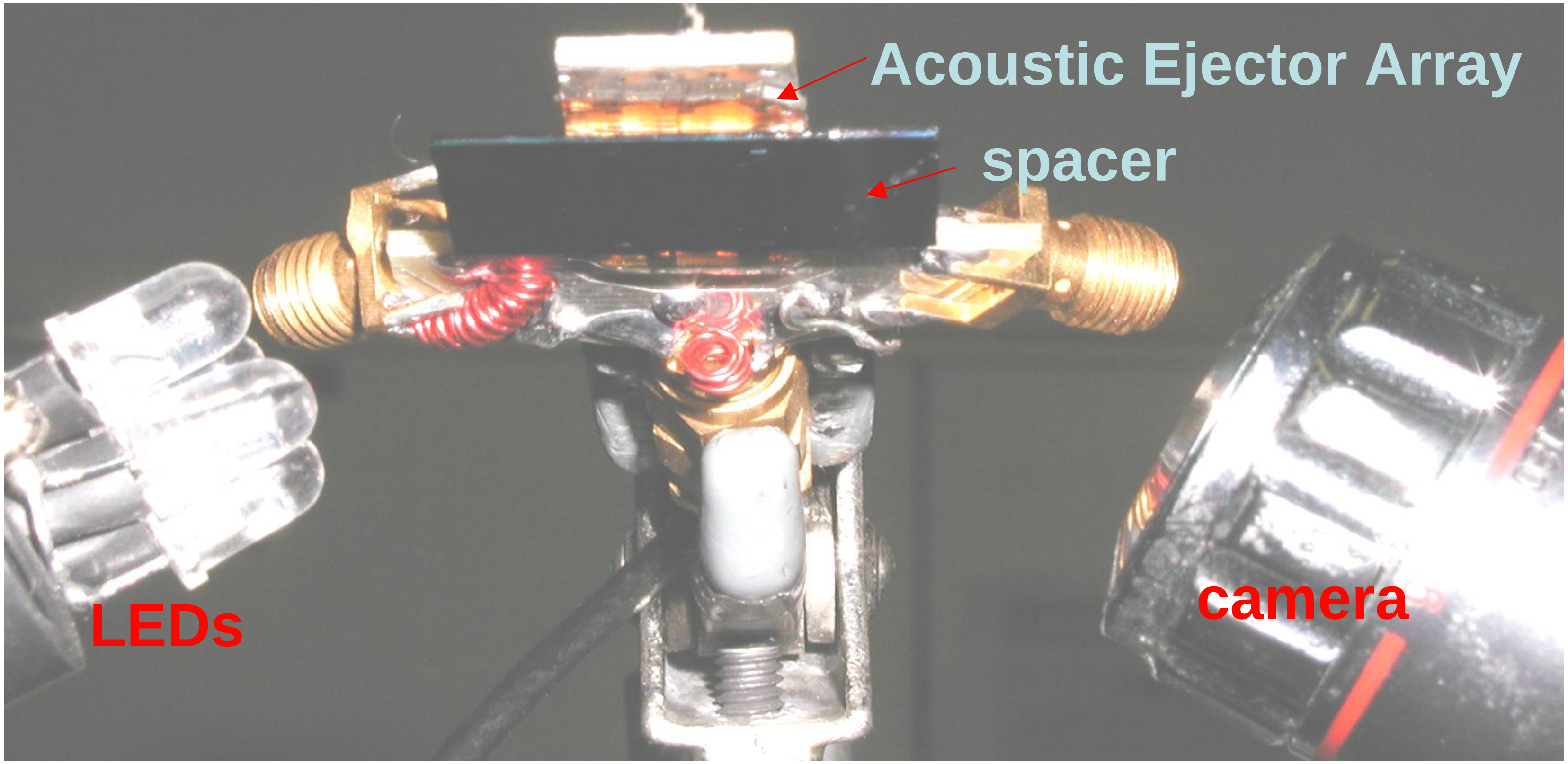


We have two micromachined spacers aligned on top of each other.
300 µm and 500 µm thick wafers; 50,100,200 µm wide ejection pools



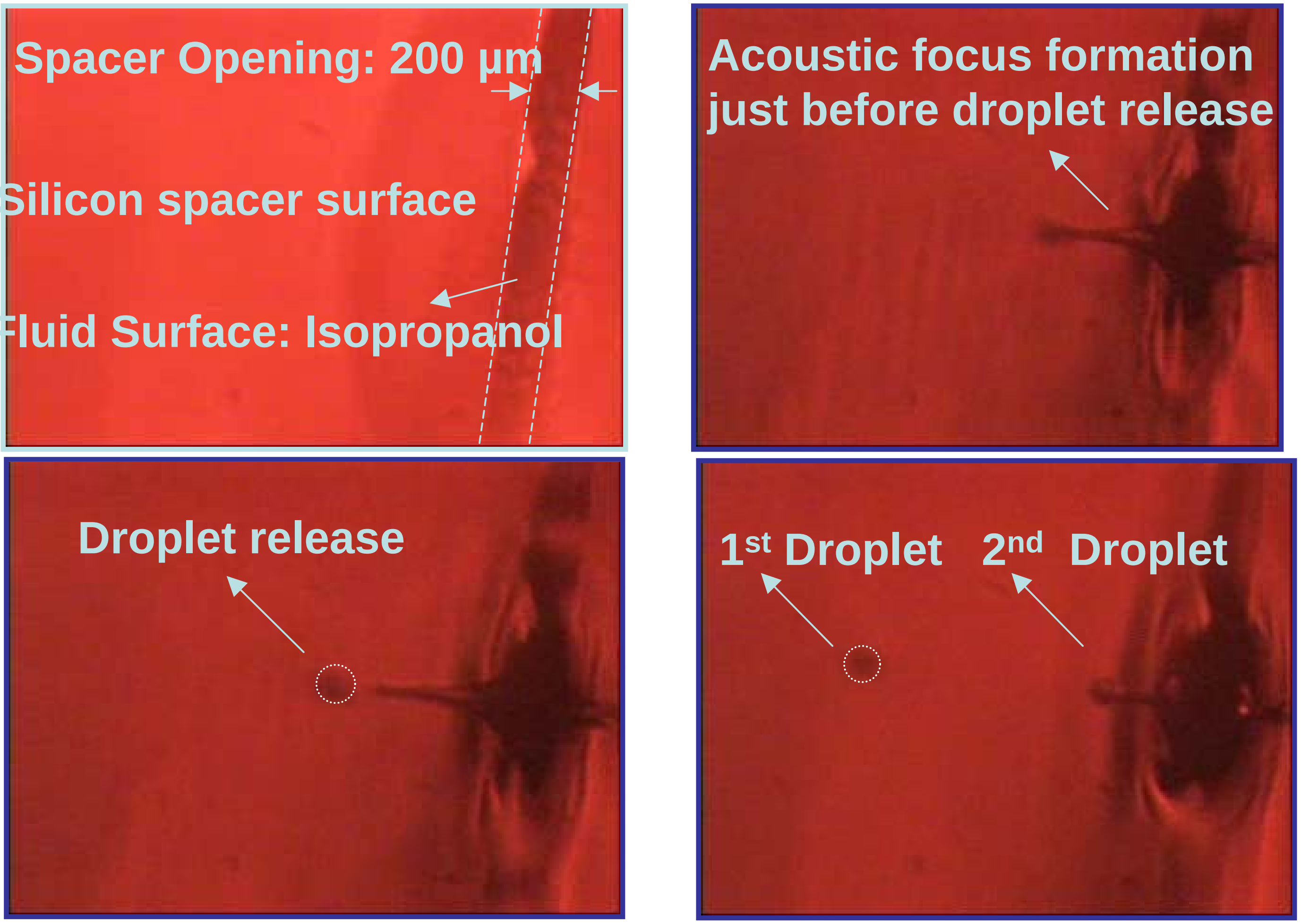


Open Pool Downwards Ejection Setup



The stroboscopic imaging setup for a 3x3 Droplet Ejector Array.
Spacers are aligned on top of the ejectors.
This spacer design allows ejection in all directions.
The picture shows ejection downwards to the ground.
The fluid holds with surface tension at the spacer edges.

Step by Step Droplet Ejection with Spacers

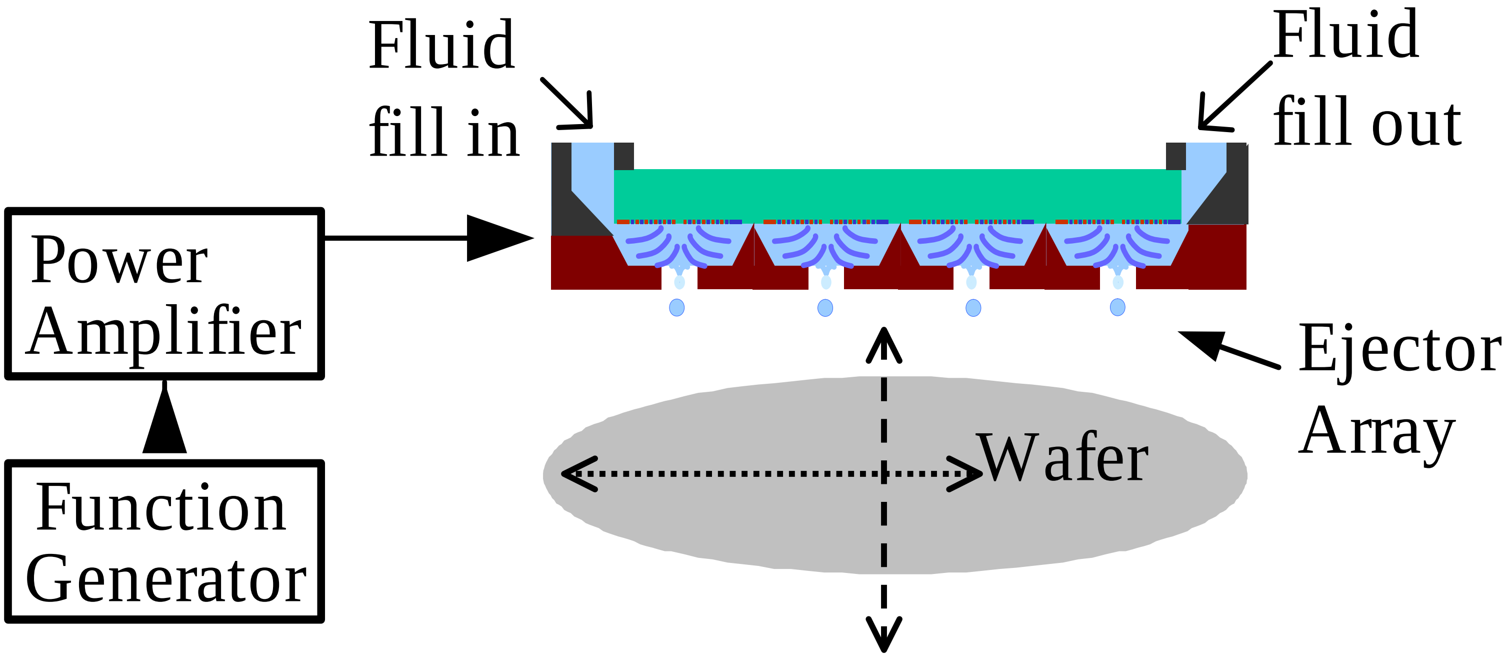


-Droplet sizes and directionality are uniform.

-Drop on Demand and Continuous modes of operation are easy to control.

-All the array elements eject, addressing can be done.

Experimental Setup for Wafer Coverage



X Y stage control on the wafer

Droplet Wafer Interaction

The droplet has a spherical form in air before it lands onto the surface. The spreading of photoresist drops on the wafers has been researched, Mundo et al. presents a simple relation between the ejected drop radius in air and the spread radius on the substrate by the following equation.

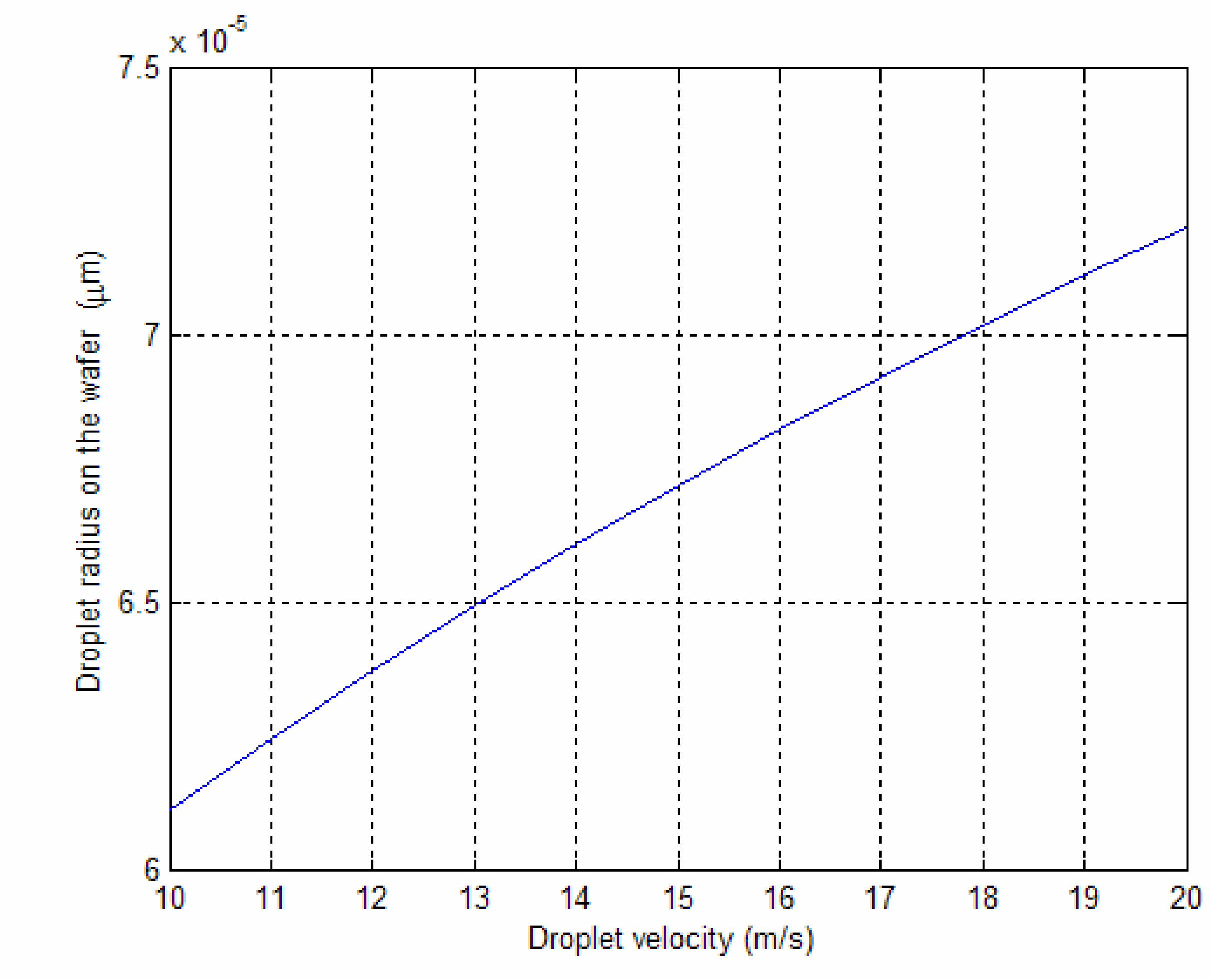
$$r_{substrate} = r_{air}\sqrt{\frac{-1+\cos\Theta+\sqrt{(1-\cos\Theta)^2+\frac{6\,W_e}{R_e}\left(\frac{W_e}{3}+4\right)}}{\frac{3\,W_e}{R_e}}},$$

$$R_e = \frac{2\rho\upsilon_D r_D}{\eta}$$

$$W_e = \frac{2\rho\upsilon_D^2 r_D}{\sigma}$$

, where
‘r_{air}’ is the radius of the ejected drop,
‘$r_{substrate}$’ is the radius of the spot on the substrate,
‘ϴ’ is the contact angle,
‘Re’ is Reynolds number,
‘We’ is Weber number,
‘v_D’ is the ejected drop velocity,
‘η’ is dynamic viscosity of the liquid .

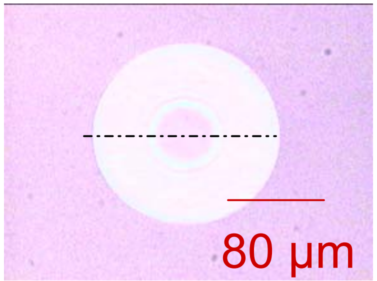
Droplet Wafer Interaction



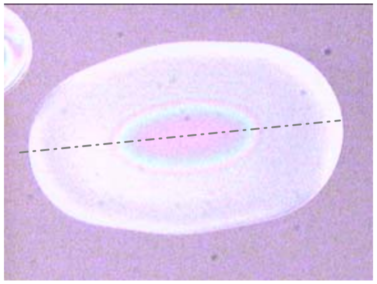
In the computations, we have used:
r_D = 22 µm, σ = 30 x 10-3 N/m, η = 4 mPa.sec, ρ = 1.01 g/cm, ϴ = 38º
The droplet spread is shown for vD varying from 10 m/s to 20 m/s in the figure.

Profiles: Photoresist Droplets Interacting on the Wafer

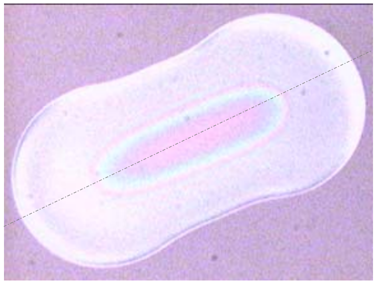
Single Droplet

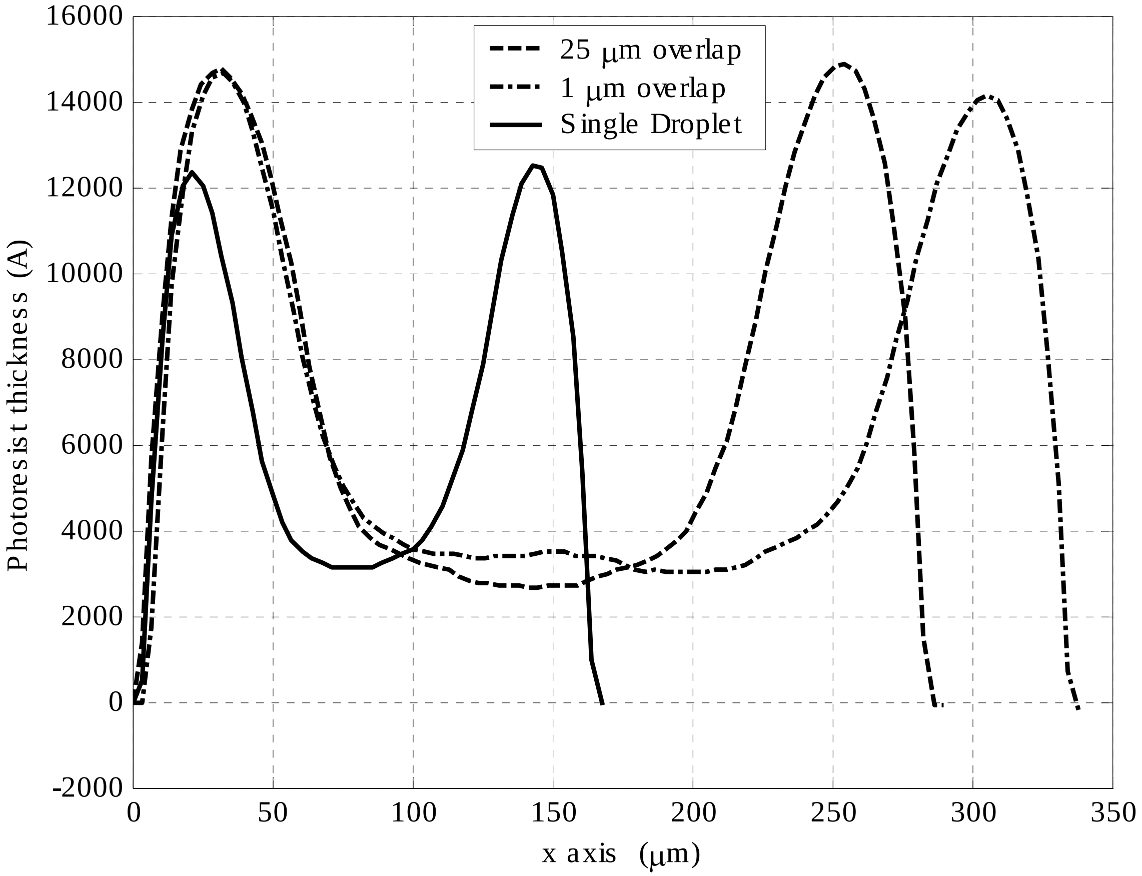


25 µm overlap



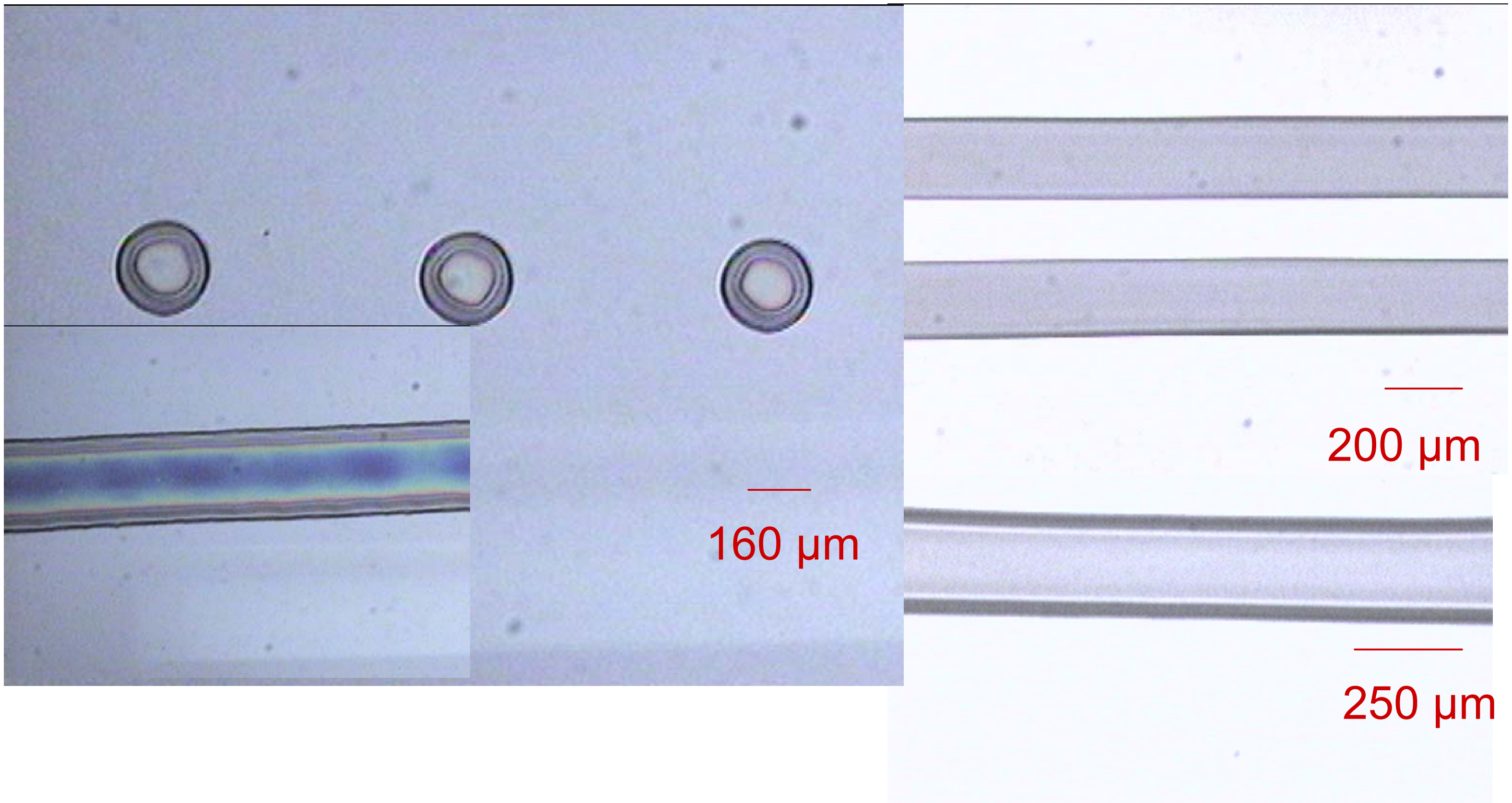
1 µm overlap





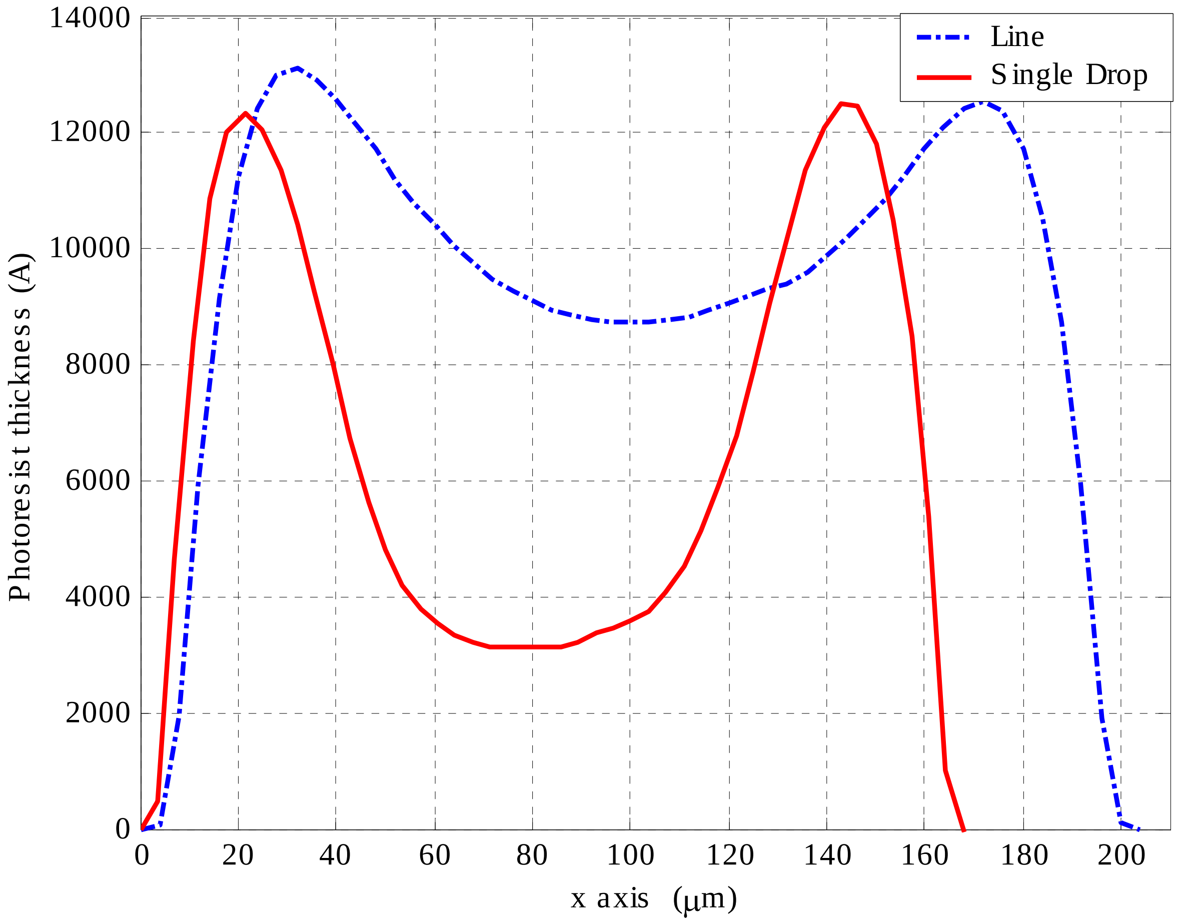
Single droplets overlap and surface tension forces reshape the final topography on the silicon wafer surface.

Picoliter Photoresist Drops Deposited onto the Wafer



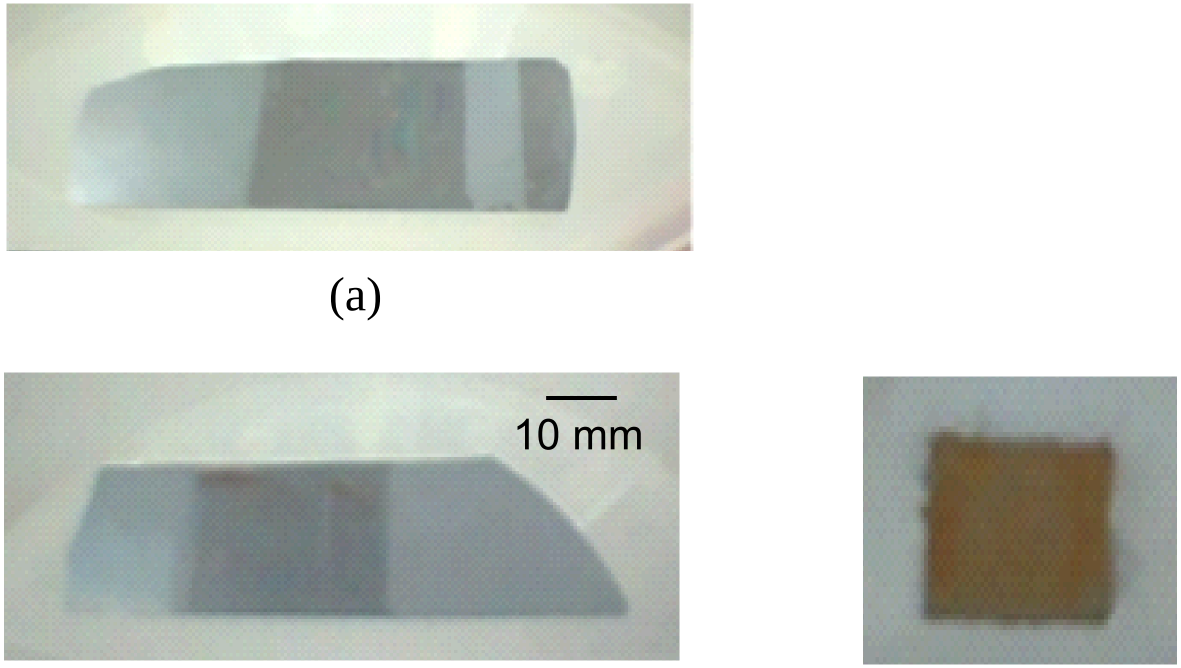
Single droplets of photoresist can be written on the silicon wafer surface.
A photoresist line can be drawn, and a wafer can be covered.
Two photoresist lines written simultaneously: non-overlapping and overlapping with eachother.

Profile of the Photoresist Drops and Lines



Profile of a single droplet and a line of photoresist on the wafer .

Coverage Experiments



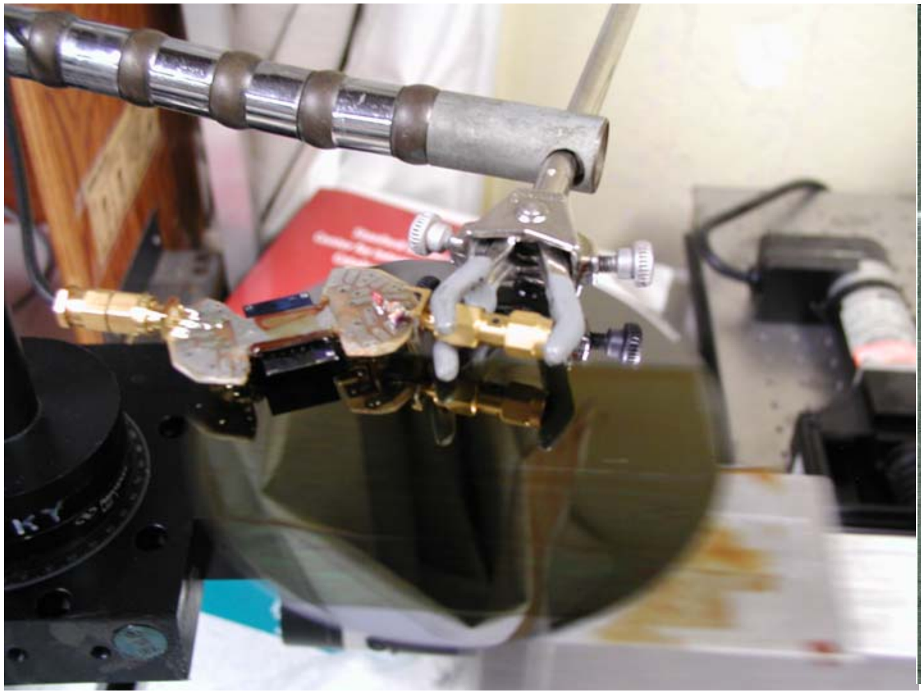
(a)

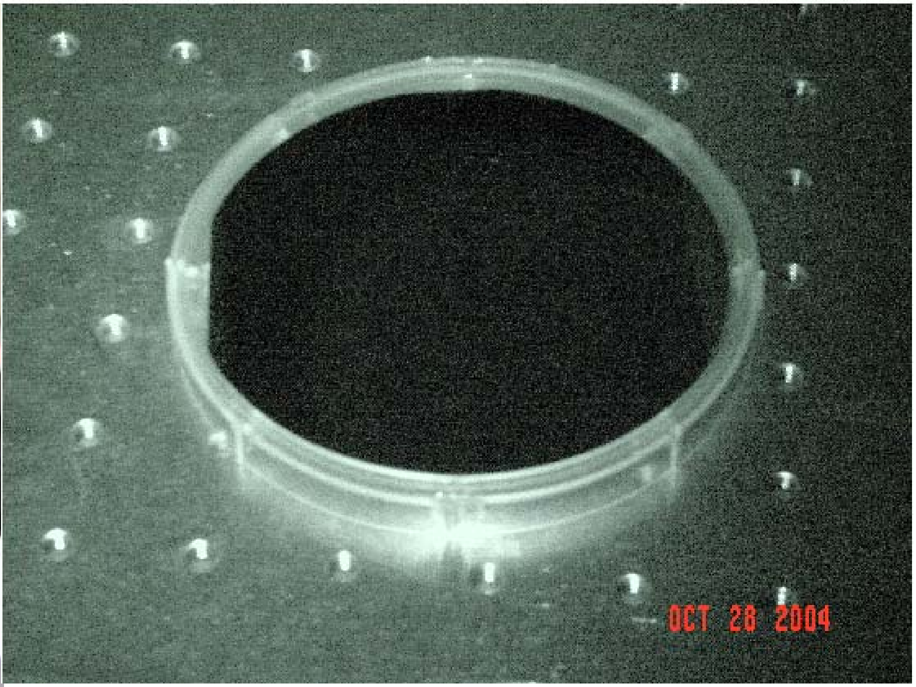
(b)

(c)

Coverage experiments:
(a) Selective photoresist coverage of a wafer pieces 20 mm x 30 mm in area,
(b) 20 mm x 20 mm in area,
(c) coverage of a 10 mm x 10 mm in area on a silicon wafer.

Full Wafer Coverage Experiments





4” wafer coated with photoresist in dry laboratory environment.
Surface roughness: best 68 A, worst 500A.
Thickness uniformity 2.8 ± 0.02 µm.

Summary

- Ejected high viscosity fluids.

Ejected Fluids	Water	Isopropanol	Photoresist	Ethylene glycol
Viscosity (cP)	1	5	5-8	16

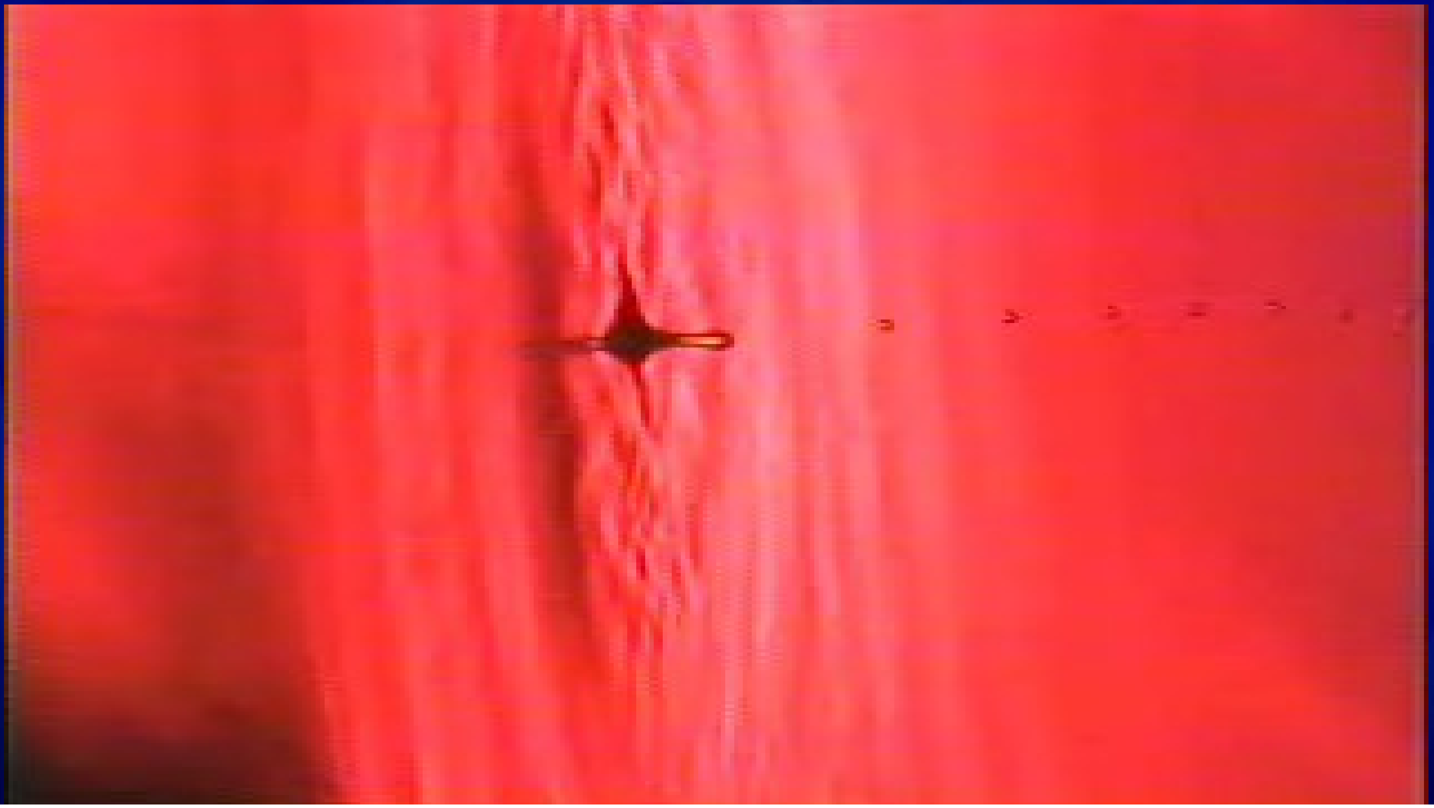
- Drop on demand and Continuous mode of operation.
- Each element is easily addressable.
- Easily cover surfaces with fluids and reduce waste.
- Single lithography step. Easy to fabricate as arrays.
- Easy to make the each array element eject.
- Cross-talk is no longer a serious problem, does not impede ejection.
- FEA predicts device characteristics.
- All the 2D array elements ejected droplets.

Conclusions and Future Work

FEM Simulations and experiments show that

- We need to determine the location of the focal point for each type of fluid (especially for photoresist).
- We have a wide vertical range focal point, which is helpful in spacer design.
- The spacers hold fluid by surface tension, and will allow us to eject in any angle.
- We could eject from all the elements of 2D ejector arrays.
- Demonstrated coverage with photoresist using 2D Ring Ejector Arrays.
- More work has to be done to improve thickness uniformity and increase coverage speed.

Huge Potential Market
Proven Technology
More than $ 1 Billion of Savings
Genuine Interest from the Industry
Significant Environmental Advantages
Huge Opportunity for Innovation



Thank you.

Questions?