Micromachined Piezoelectrically Actuated Flextensional Transducers For High Resolution Fluid Ejection

or

Zero Waste Dispensing of Chemicals in Lithography and Backend Processing

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Outline

- Motivation
- Microsystems technology (MST) and inkjet printing markets
- Large scale prototype device
  - FEA of prototype device
  - Samples of ejection by using prototype device
  - Photoresist deposition
- Ejection simulation
- Micromachined device
  - Device configuration
  - Fabrication of micromachined device
- Theory and equivalent circuit
  - Input impedance, displacement, and mode shapes simulations
  - Electrical and optical measurements
- Samples of ejection by using micromachined device
- Conclusions and future work

Motivation

- Fluid ejection
  - Photoresist deposition without spinning
  - Controlled deposition of fluids and small solid particles
  - Inkjet printing
- Flextensional transducer
  - Air or immersion transducer
  - Piezoelectric actuation
    - Relatively small input and mechanical impedance mismatch
    - High sensitivity
- Micromachined into 2-D arrays
  - Individual addressing
  - High frequency response
  - Electronic integration with driving, receiving, and addressing circuitry
  - Fine tuning with DC bias
- Other applications are medical imaging and under water camera

Existing MST Products

Products	1996		2002	
	Units (millions)	US$ (millions)	Units (millions)	US$ (millions)
Hard disk drive heads	530	4500	1500	12000
Inkjet printer heads	100	4400	500	10000
Heart pace makers	0.2	1000	0.8	3700
In-vitro diagnostics	700	450	4000	2800
Hearing aids	4	1150	7	2000
Pressure sensors	115	600	309	1300
Chemical sensors	100	300	400	800
Infrared imagers	0.01	220	0.4	800
Accelerometers	24	240	90	430
Gyroscopes	6	150	30	360
Magnetoresistive sensors	15	20	60	60
Microspectrometers	0.006	3	0.15	40
Totals		**13033**		**34290**

Taken from MST News, November 1998, and Micromachine Devices, October 1998.

Emerging MST Products

Products	1996		2002	
	Units (millions)	US$ (millions)	Units (millions)	US$ (millions)
Drug delivery systems	1	10	100	1000
Optical switches	1	50	40	1000
Lab on chip (DNA, HPLC)	0	0	100	1000
Magneto optical heads	0.01	1	100	500
Projection valves	0.1	10	1	300
Coil on chip	20	10	600	100
Micro relays	-	0.1	50	100
Micromotors	0.1	5	2	80
Inclinometers	1	10	20	70
Injection nozzles	10	10	30	30
Anti-collision sensors	0.01	0.5	2	20
Electronic noses	0.001	0.1	0.05	5
Totals		**106.7**		**4205**

Taken from MST News, November 1998, and Micromachine Devices, October 1998.

Annual Cost of Dispensed Photoresist Per Track

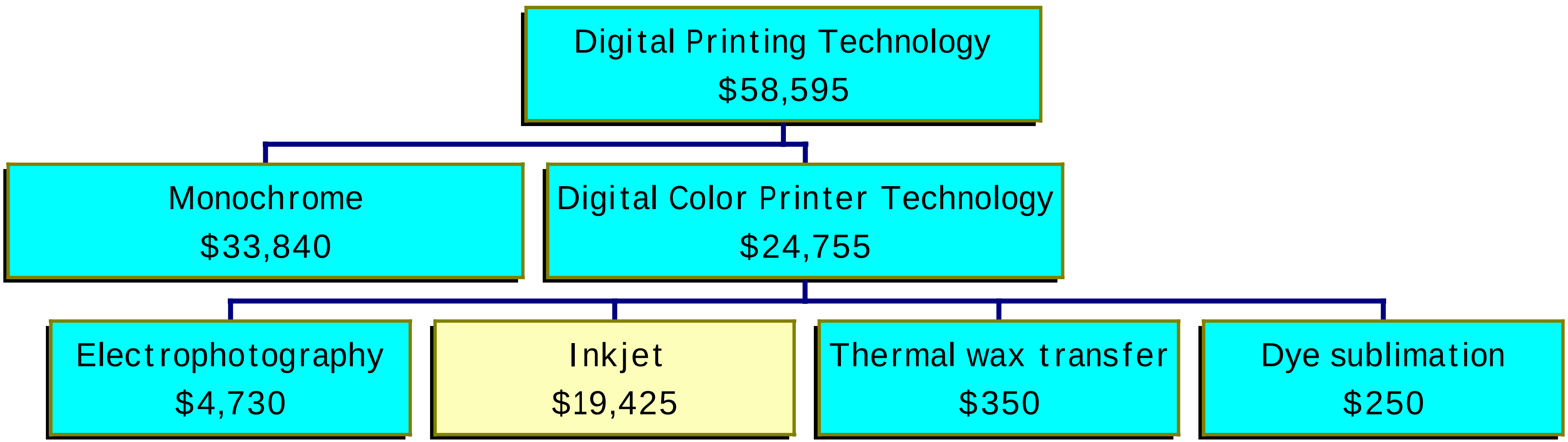
Photoresist	cost/gl	cost/cc	1cc/wafer	2cc/wafer	3cc/wafer	4cc/wafer
SPR 510	$560	$0.148	$69,021	$138,042	$207,064	$276,085
Apex E	$1,500	$0.396	$184,878	$369,757	$554,635	$739,513
DUV	$2,000	$0.528	$246,504	$493,009	$739,513	$986,017
DUV	$3,000	$0.793	$369,757	$739,513	$1,109,270	$1,479,026
DUV	$4,000	$1.057	$493,009	$986,017	$1,479,026	$1,972,035
DUV	$5,000	$1.321	$616,261	$1,232,522	$1,848,783	$2,465,043

Calculated for a wafer throughput per year for one track of (60 wafers/hr) (360 days/year)(0.90 track utilization)=466,560 wafers/year.

Photoresist	Viscosity (cSt)	Volume dispensed (cc)	Thickness (μm)	Final volume (cc)	Waste (%)
TOK	7.0	1.3	0.80	0.0251	98.1
AZ7511	10.1	2.1	1.08	0.0339	98.4
SPR505	8.2	1.4	0.60	0.0188	98.7
SPR507	12.3	1.9	0.84	0.0264	98.6
SPR508	13.9	2.1	1.00	0.0314	98.5
SPR510	18.6	2.1	1.20	0.0377	98.2
JSR061	18.0	2.1	1.06	0.0333	98.4
JSR300	55.0	2.4	3.20	0.1005	95.8

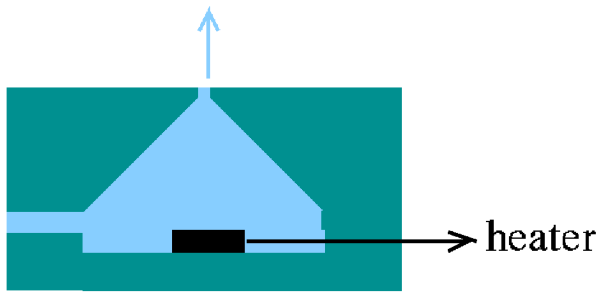
Taken from "How to minimize resist usage during spin coating," B. Lorefice *et al.*, SVG Photo Process Division, Semiconductor Intl., June 1998.

Printer Market in 1997

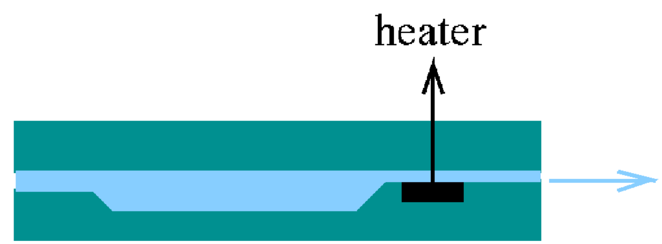


Dollar amounts in millions. Taken from InfoWorld, January 4, 1999. Data by IT Strategies.

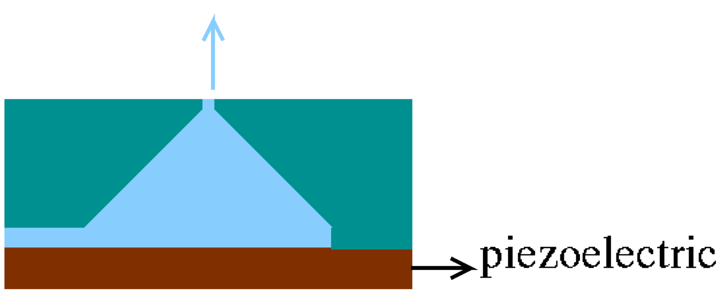
Common Inkjet Printheads



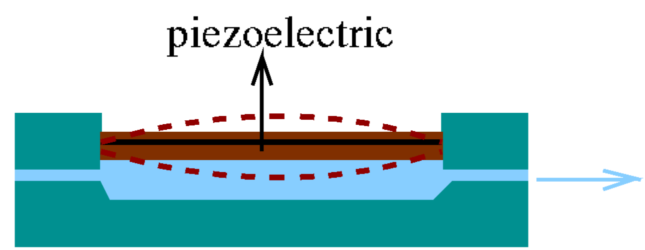
Bubble jet, roof shooter



Bubble jet, side shooter



Piezoelectric head, roof shooter



Piezoelectric head, side shooter

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- Ejection simulation
- Micromachined device
- Theory and equivalent circuit
- Samples of ejection by using MEMS device
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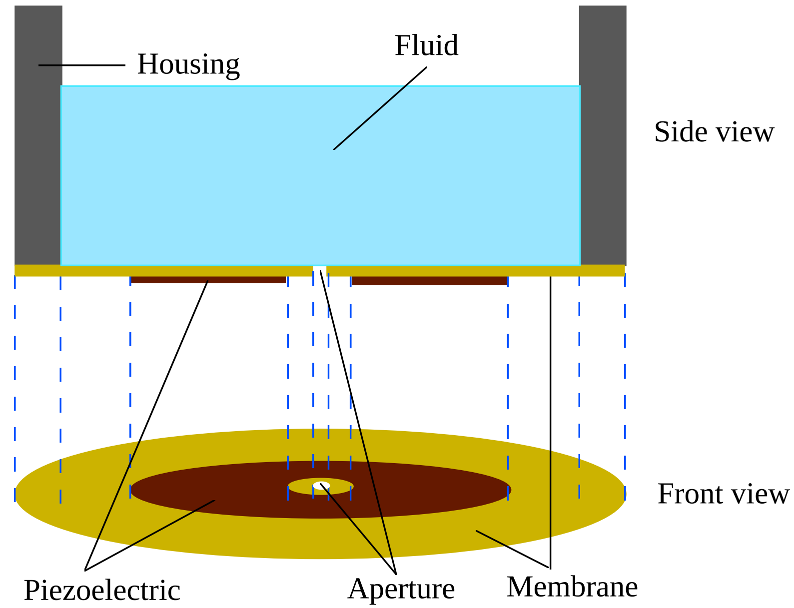
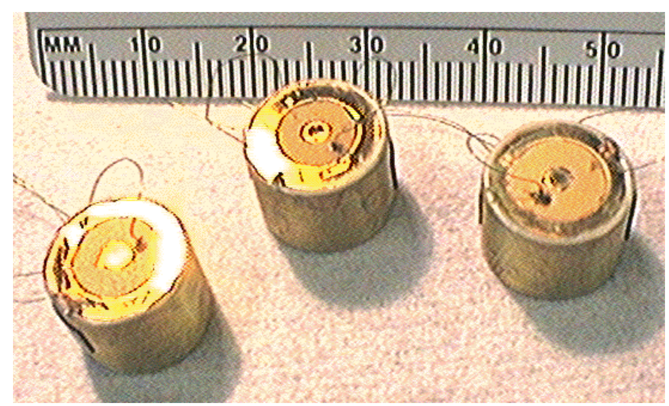
Large Scale Prototype

- Dimensions of demonstration device:
  - Diameter = 9 mm
  - Membrane thickness = 25 µm
  - Piezoelectric thickness = 15-25 µm
  - Piezoelectric inner diameter = 2 mm
  - Piezoelectric outer diameter = 6-7 mm
  - Orifice size = 50-200 µm
  - Operating frequencies: 9.5 kHz, 16.4 kHz, 19.0 kHz
  - Membrane material: brass, steel, silicon
  - Piezoelectric material: Murata SWM, Motorola PZT 3203HD, and lithium niobate
- Drop-on-demand and continuous modes of operation





Resonance Frequencies

- Resonance frequency is proportional to the thickness, and inversely proportional to the square of the radius.
- Average values for physical dimensions and material constants of the compound plate give a good approximation to the measured resonance frequencies.
- λ_0^2 values are well-tabulated. They correspond to the eigenvalues of the system under specific boundary conditions.

$$f = \frac{\lambda_0^2 h_{av}}{2\pi a^2} \sqrt{\frac{E_{av}}{12 \rho_{av} \left(1 - \nu_{av}^2\right)}}$$

a : the radius of the plate

h_{av} : the plate thickness

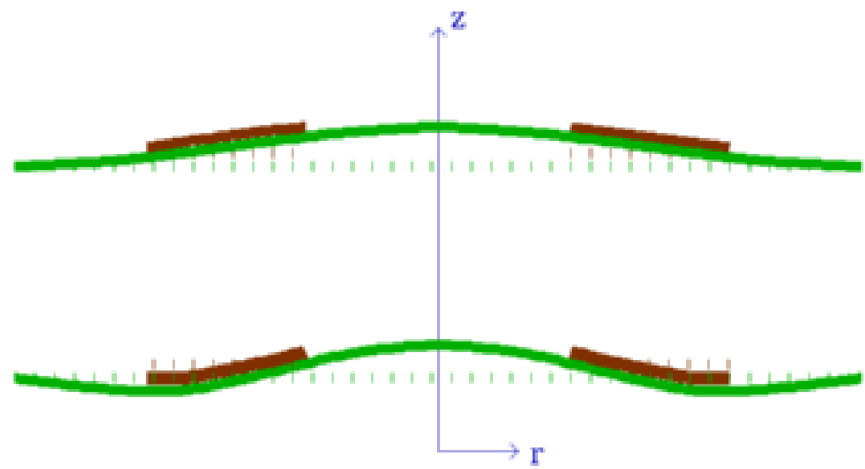
E_{av} : Young's modulus

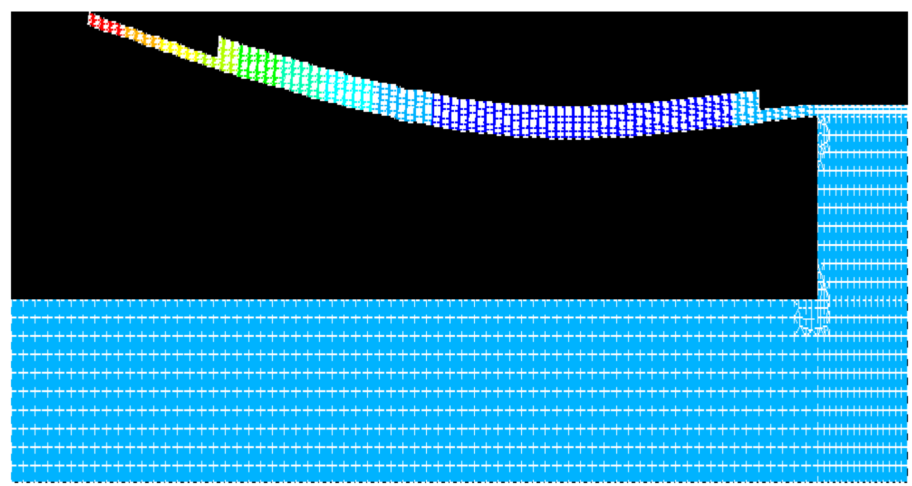
ν_{av} : Poisson's ratio

ρ_{av} : density

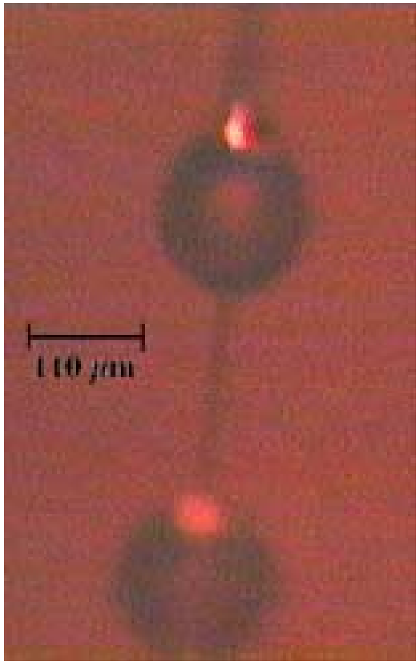
Large Scale Prototype

- Flexural mode of operation of composite membrane
- Large dynamic range, ie. 190 µm peak-to-peak measured displacement in air
- An ac voltage is applied to the membrane to set it into vibration
- Goal: maximum displacement at the center.
- Optimum dimensions for piezoelectric material and carrier plate material were obtained.

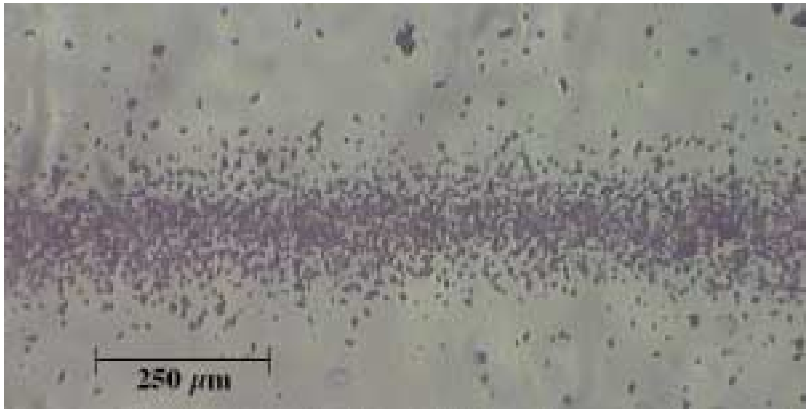




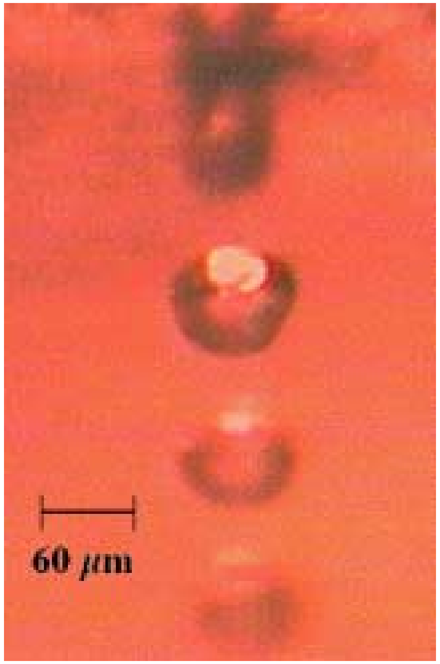
Samples of Ejection Using Prototype



Photoresist ejection at 7.15 kHz



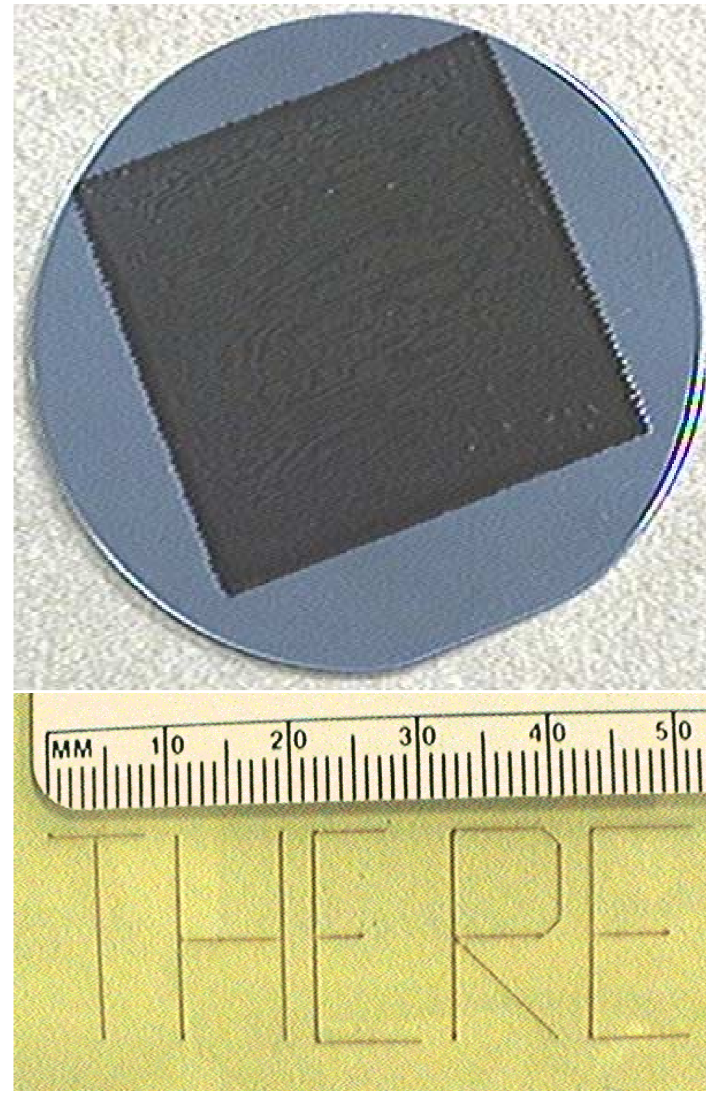
Talc powder ejection at 5.1 kHz



Water ejection at 19.0 kHz

Photoresist Coverage of A Wafer

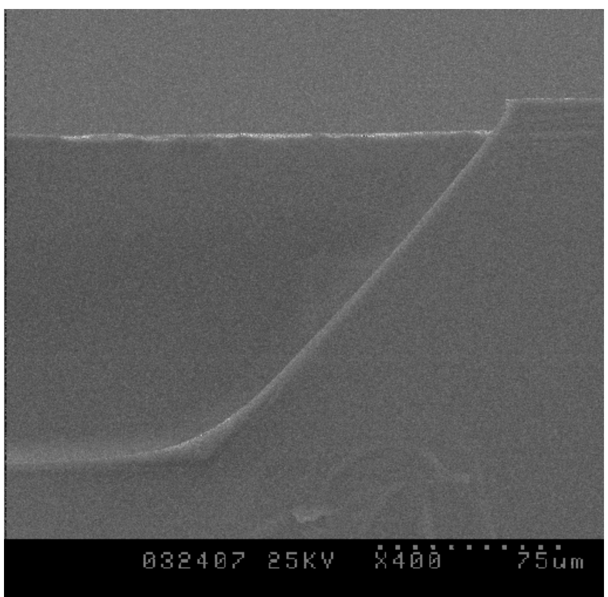
- Shipley Microposit® 1805, 1813, 1400-21, and 1400-27 photoresists which have dynamic viscosities of 5, 20, 8, and 18 cSt, respectively.
- 3.5 µm thickness, 0.15 µm variation in thickness
- Nonuniformity due to dust and dry lab environment
- Better results expected in solvent saturated chamber
- Direct write applications for MEMS
- Quick spinning after ejection may increase uniformity

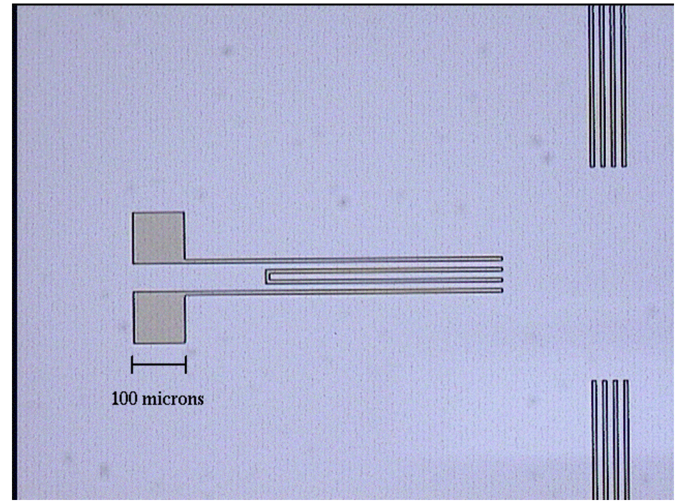


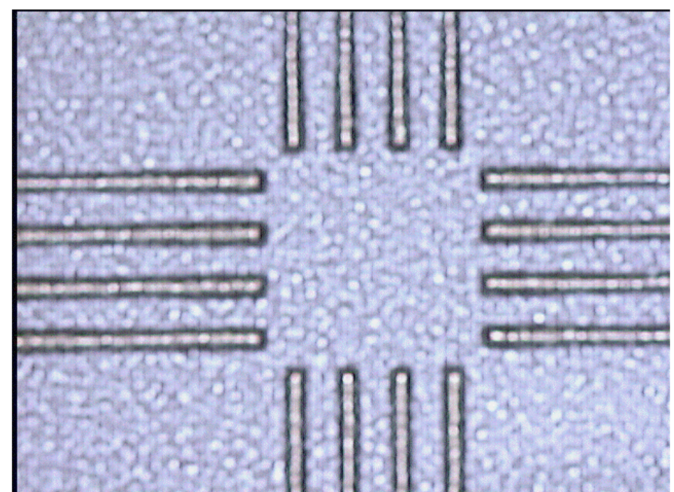
Direct write with photoresist, 350 µm-wide lines

Deposited and Patterned Photoresist

- Shipley Microposit® 1813 photoresist (20 cSt)
- 10 µm wide lines and spacings.
- Photoresist coverage of deep silicon trenches
- 2.5 µm thick photoresist

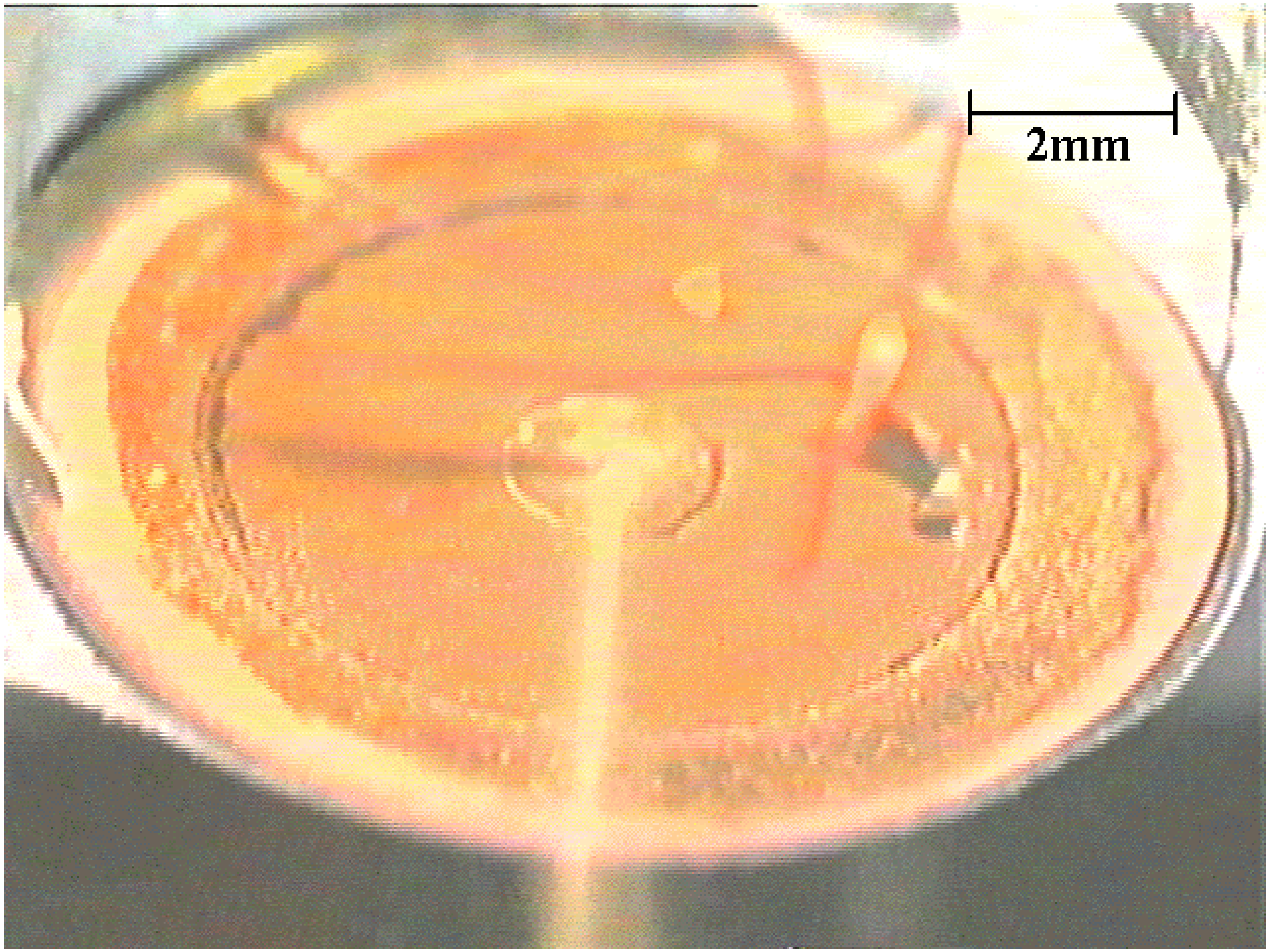




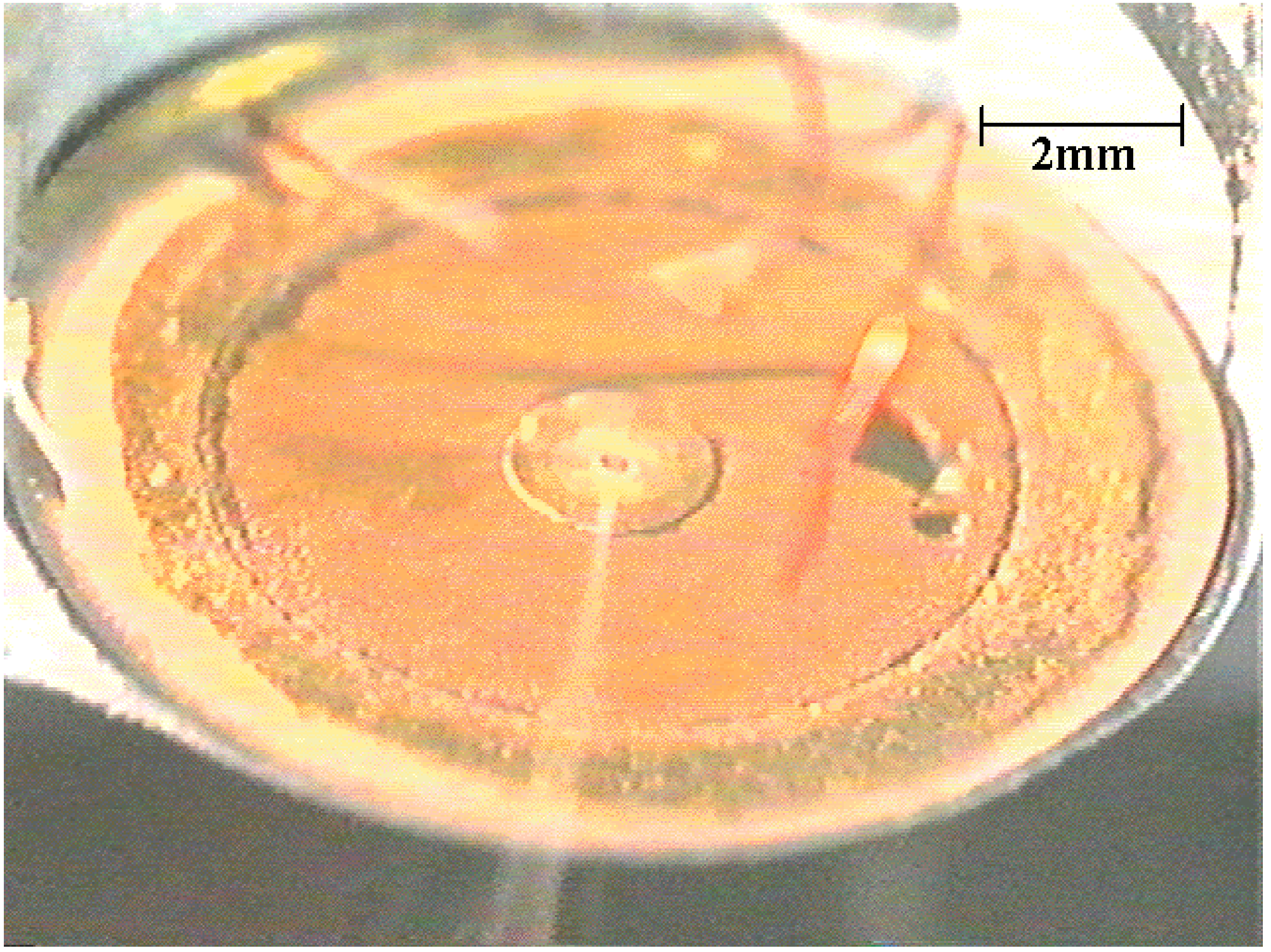


Patterned resist at 150 µm deep Si trench

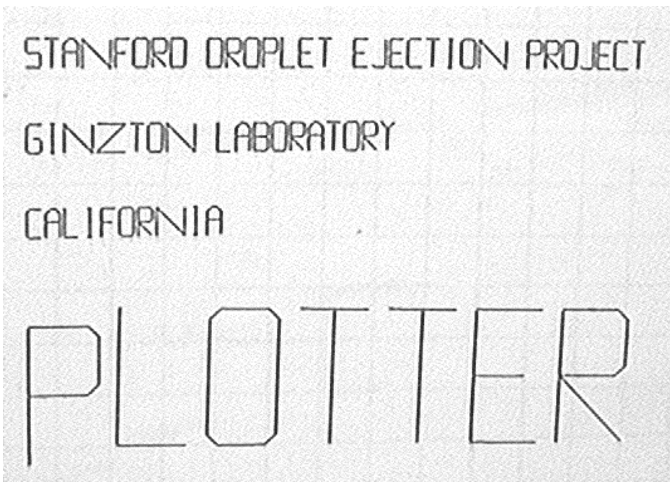
Solid Particle Ejection at 2.9 kHz



Solid Particle Ejection at 5.5 kHz



Outline



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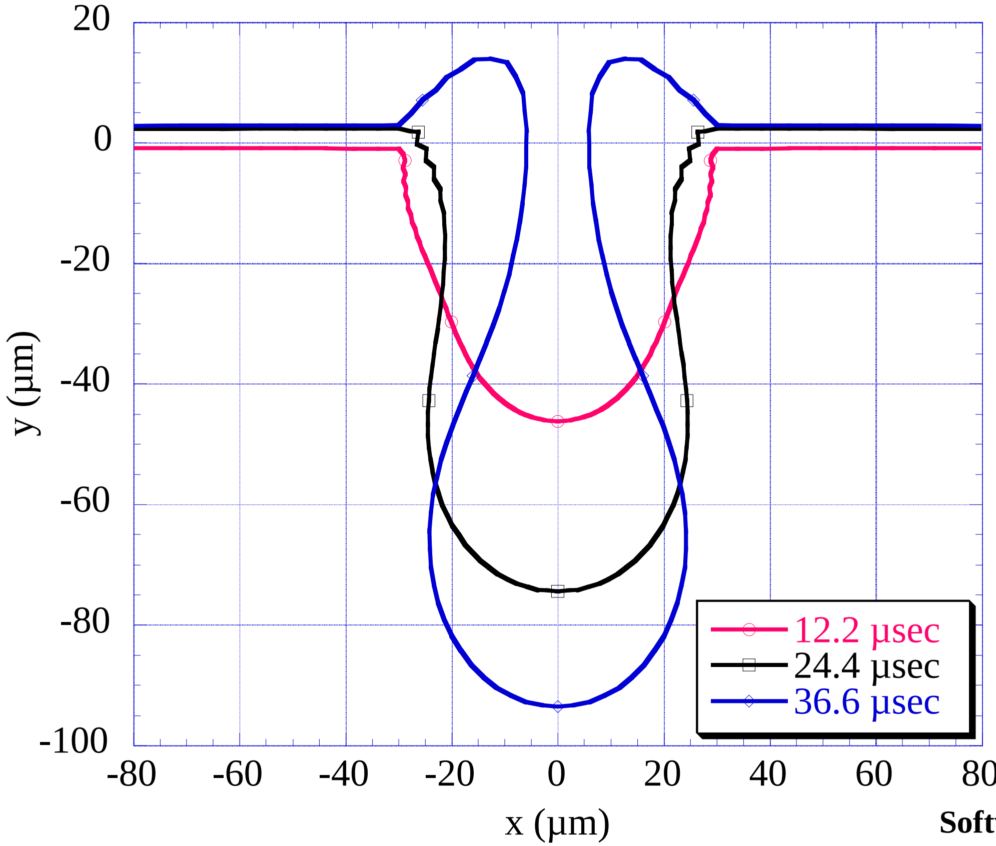
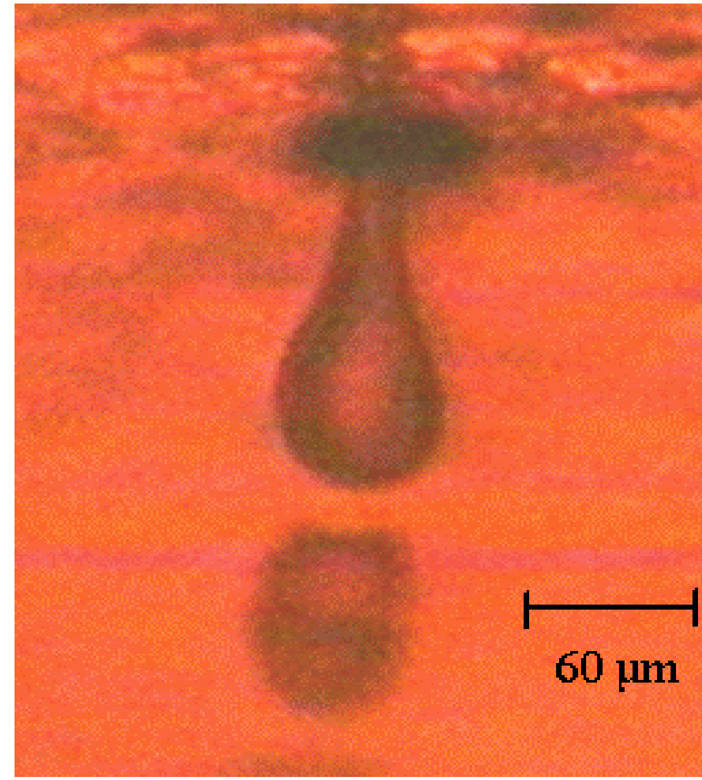
Ejection Simulation



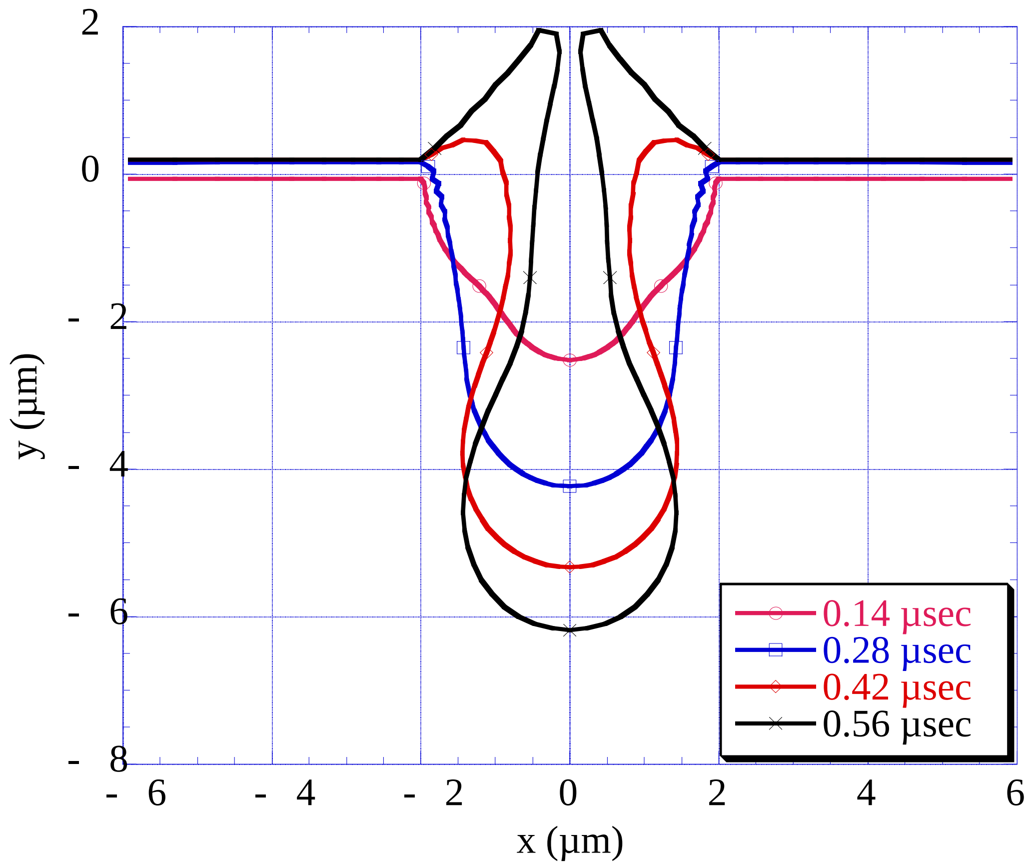


Software was developed by Prof. T. S. Lundgren, University of Minnesota, and N. M. Mansour, NASA Ames

- 9 mm-diameter prototype device , 60 µm orifice size, water ejection, *S* = 20
- 16.4 kHz 3 µm amplitude half cycle sinusoidal displacement, 2nd mode
- Velocity of the drop: 1.64 m/s simulated, 1.54 m/s measured
- 42.0 µsec pinch-off time, 1 µl/s flow rate, 62 pl volume of the drop

Ejection Simulation

- 4 µm orifice size
- 110 µm-diameter micromachined device
- 1.4 MHz 0.2 µm amplitude sinusoidal displacement, 1st mode
- Half cycle excitation
- 0.62 µsec pinch-off time
- Water ejection, $S = 9.3$
- Simulated velocity of the drop is 5.3 m/s.
- The diameter of the drop is 82% of the orifice diameter.
- 29 nl/s flow rate, 18.5 fl volume of the drop



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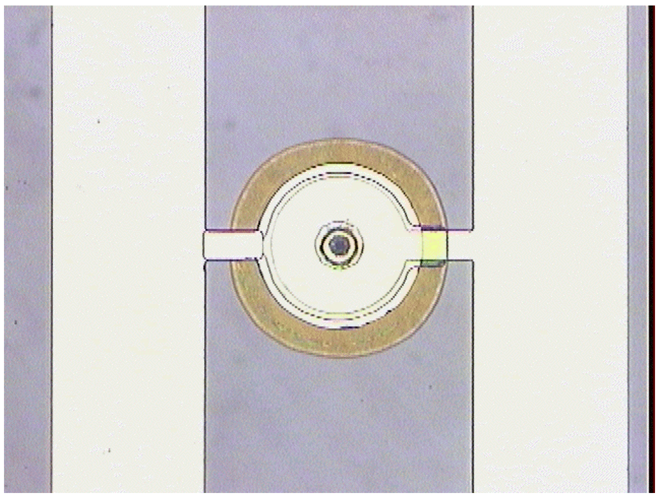

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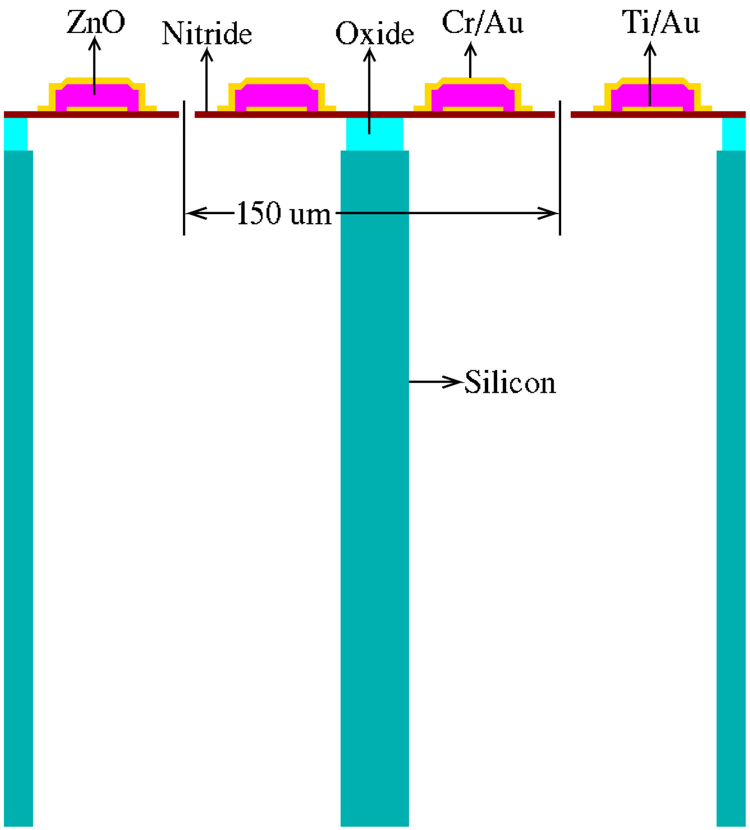
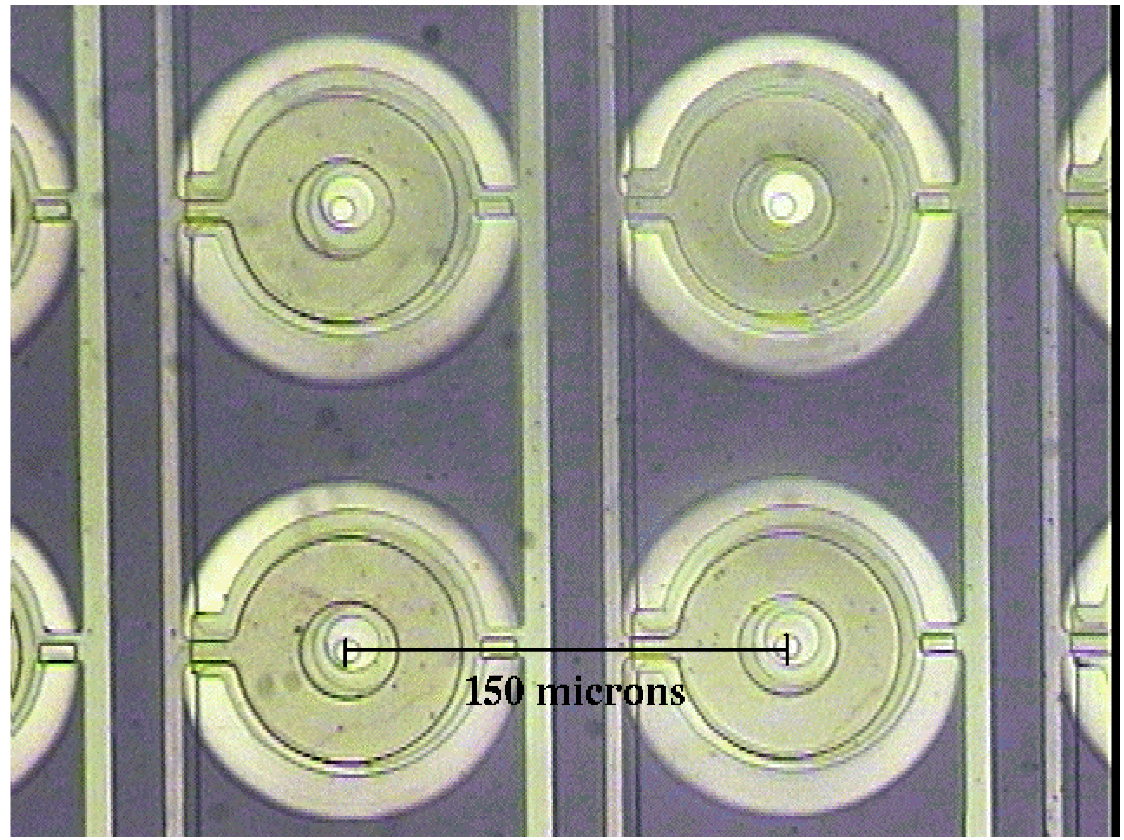
Micromachined Device

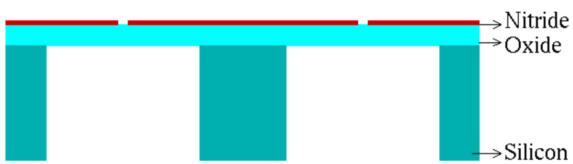




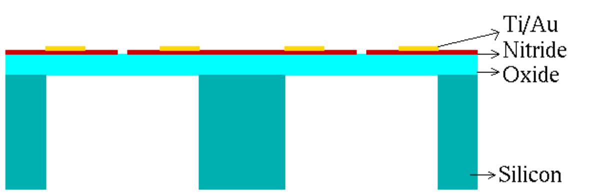
- 2-D array with individually addressed columns
- 4 - 8 μm orifice size
- 0.3 - 0.5 μm - thick zinc oxide actuator
- 0.25 - 0.4 μm - thick silicon nitride membrane
- Deep reactive ion etched 90 - 110 μm - diameter reservoir

Fabrication of Devices

Growing 2.2 microns LTO
Growing 0.25 microns LPCVD silicon nitride

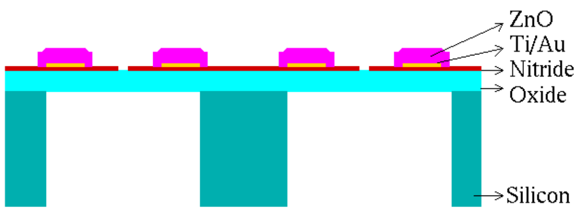


Patterning 8 microns ejection holes in the nitride by dry etch
Etching 100 microns fluid reservoir holes from the back side of the wafer by DRIE

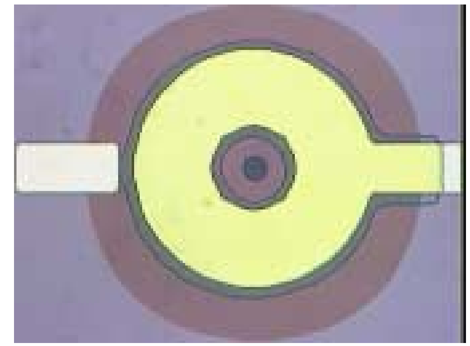


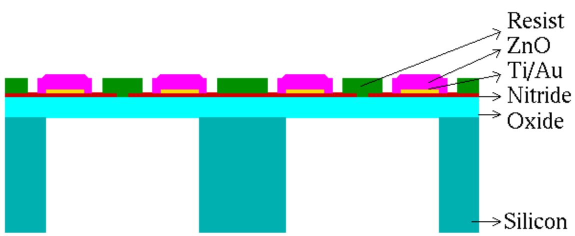
E−beam evaporation of 0.1 microns hot Ti/Au bottom electrode
Patterning Ti/Au bottom electrode by wet etch

Fabrication of Devices

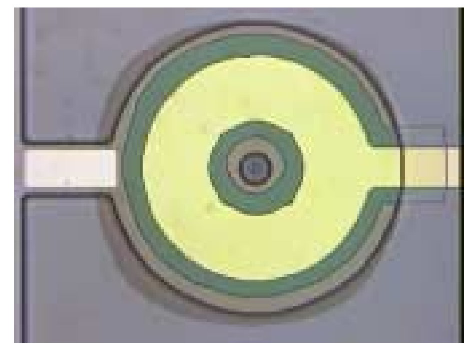


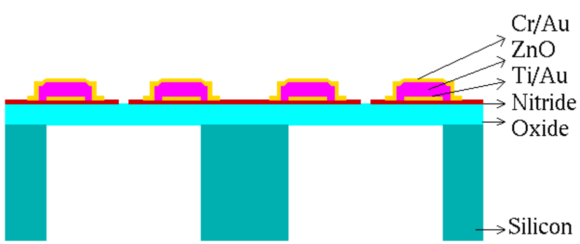
DC planar reactive magnetron sputtering of 0.4 microns ZnO
Patterning the ZnO layer with wet etch



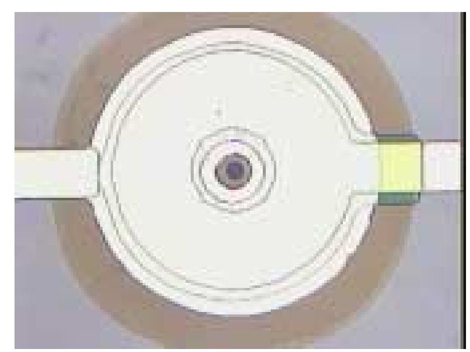


Patterning photoresist layer for top electrode layer liftoff

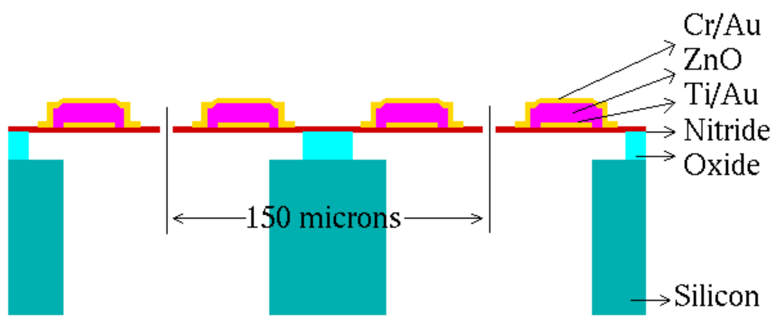




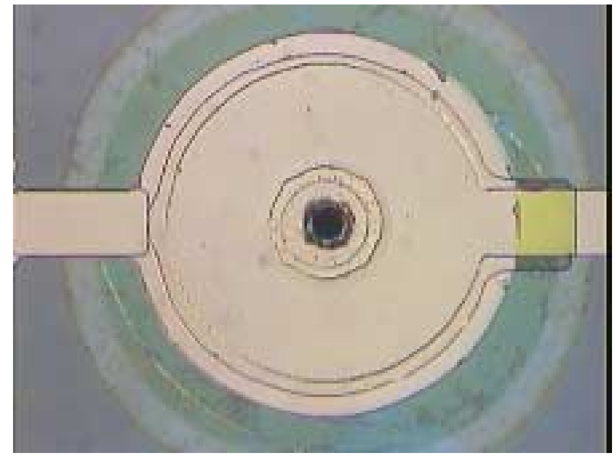
Patterning e−beam evaporated 0.1 microns Cr/Au top electrode layer by liftoff

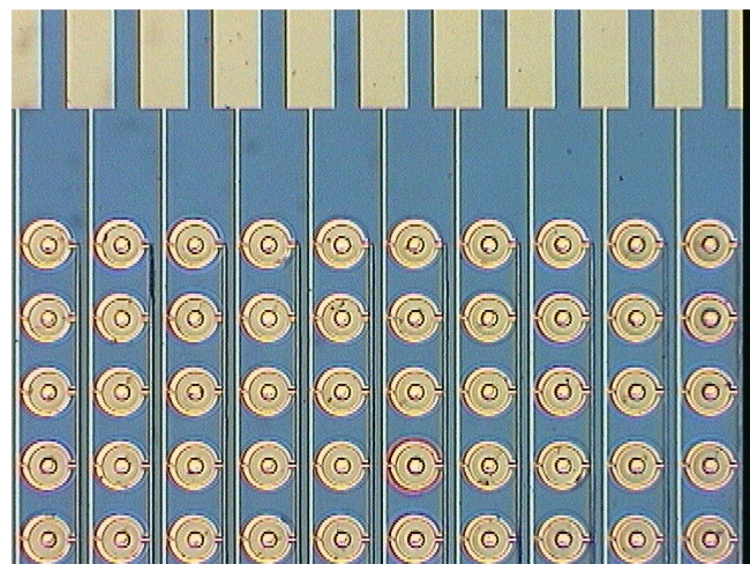


Fabrication of Devices



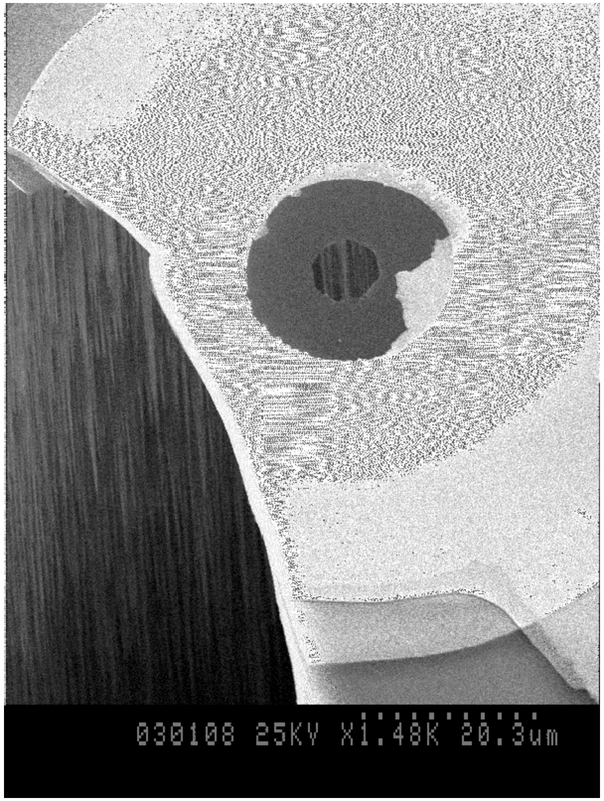
Etching the sacrificial LTO layer by wet etch





- 60x60 or 22x22 array of ejectors per 1 cm^2
- Individually addressed columns

Outline



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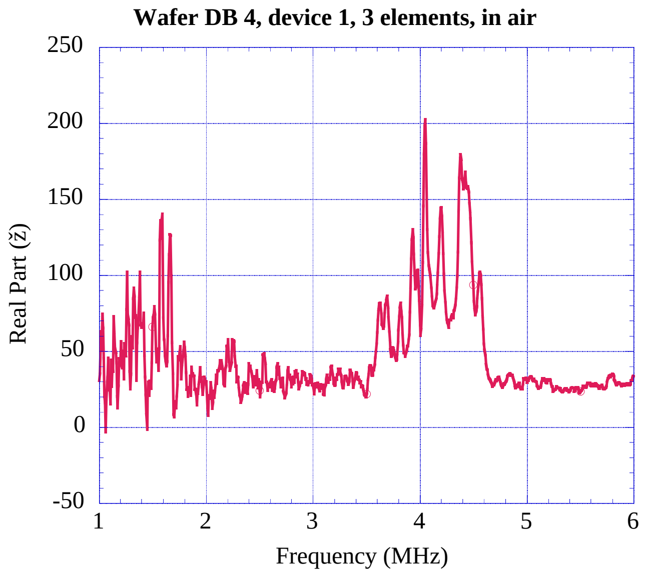
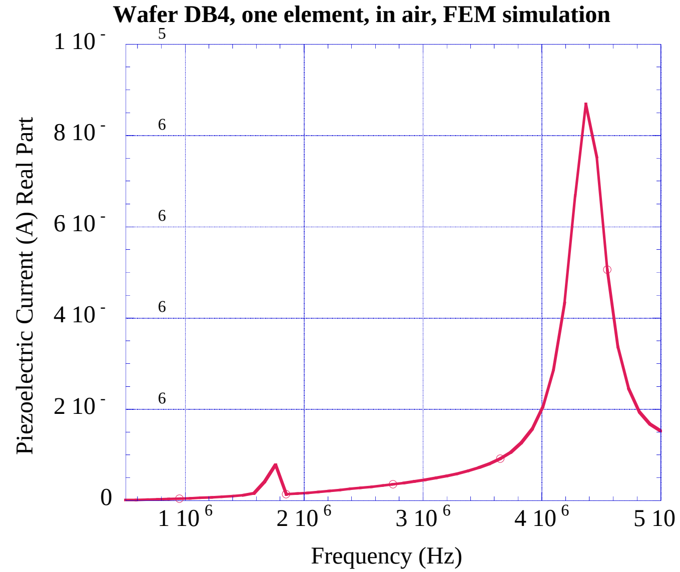
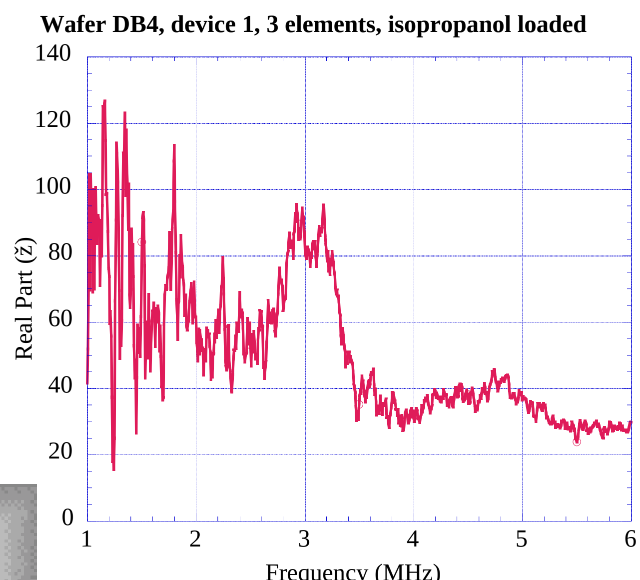
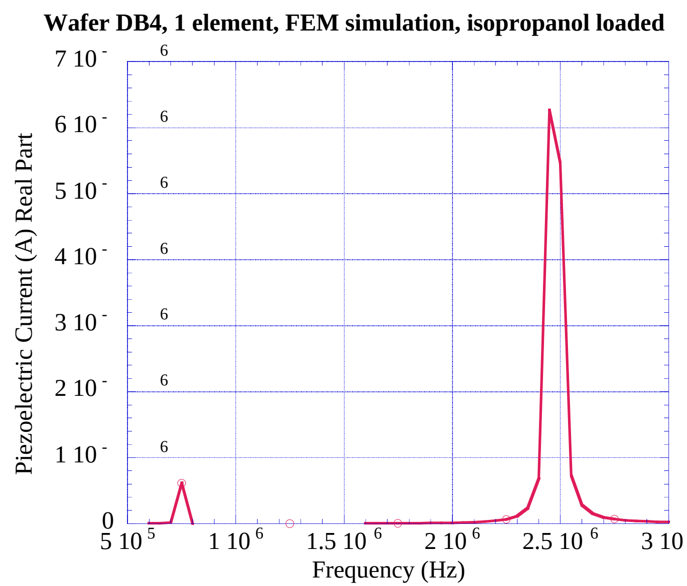
Finite Element Analysis

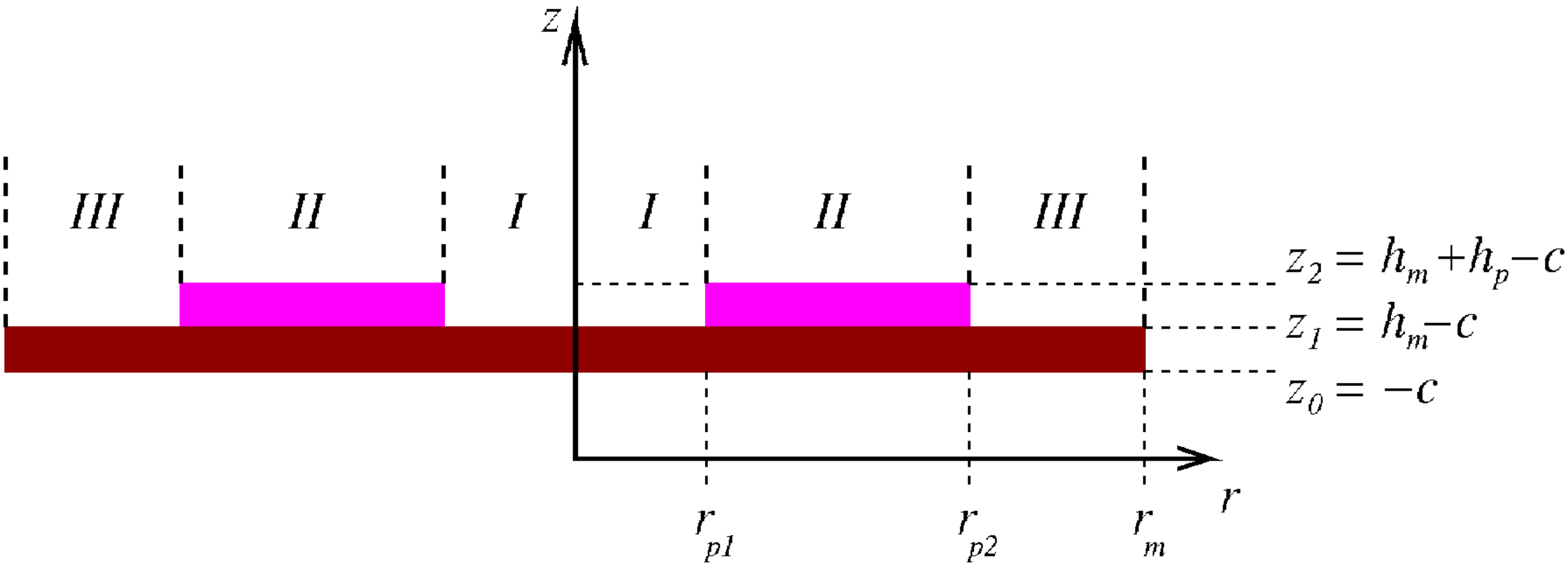






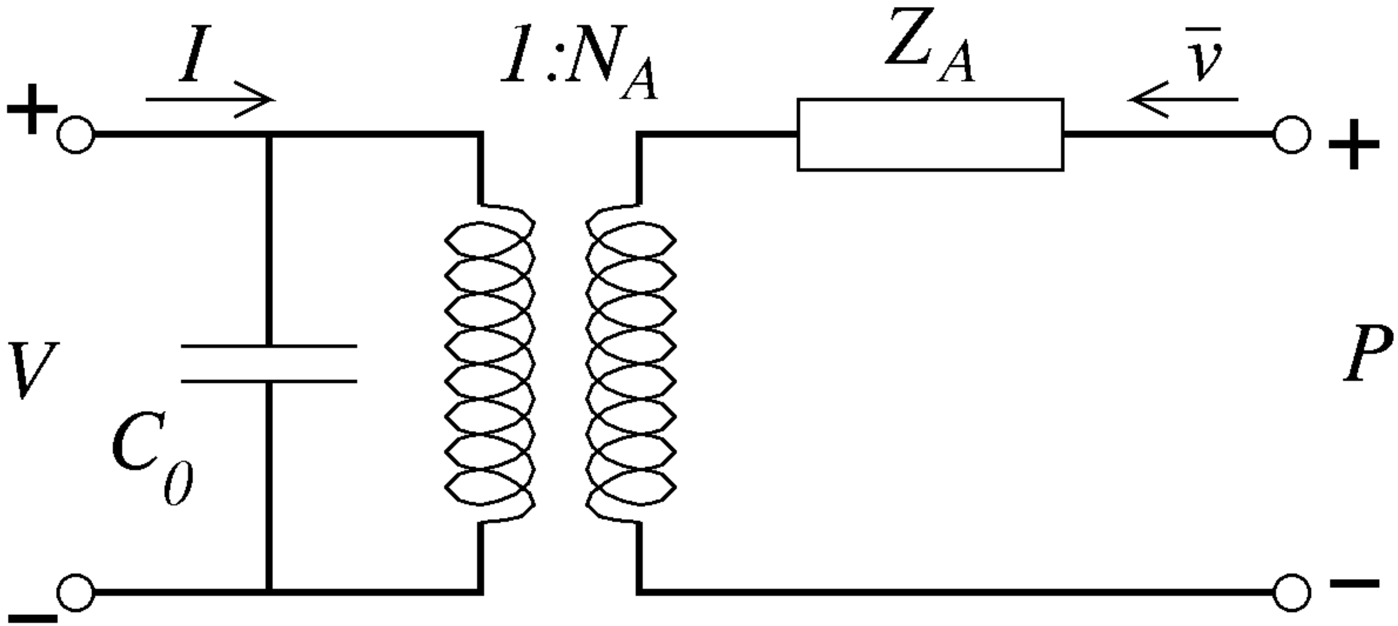


Step-Wise Laminated Plate



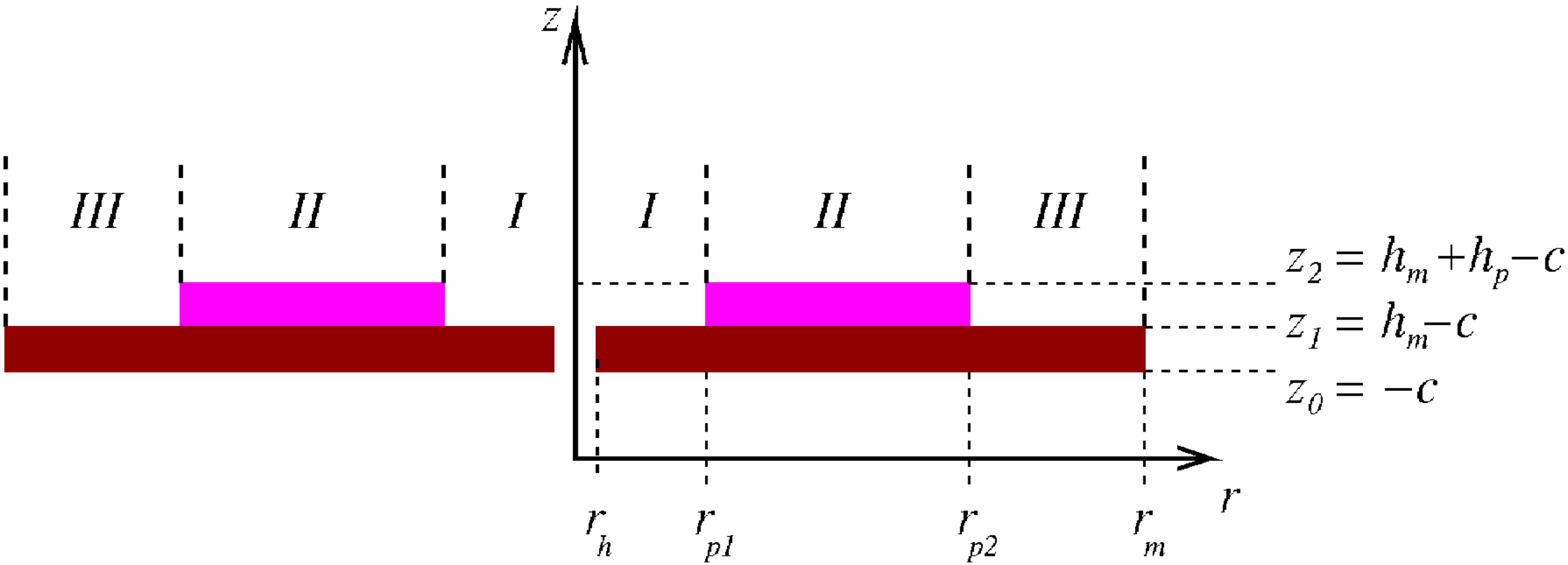
- Classical thin (Kirchoff) plate theory, Mindlin plate theory, and variational methods are used to obtain two dimensional plate equations from three dimensional coupled electromechanical equations.
- In the mentioned methods, the variations across the thickness direction vanish by using the bending moments per unit length (or stress resultants). Thus, two dimensional plate equations for a step-wise laminated circular plate are obtained.

Equivalent Circuit



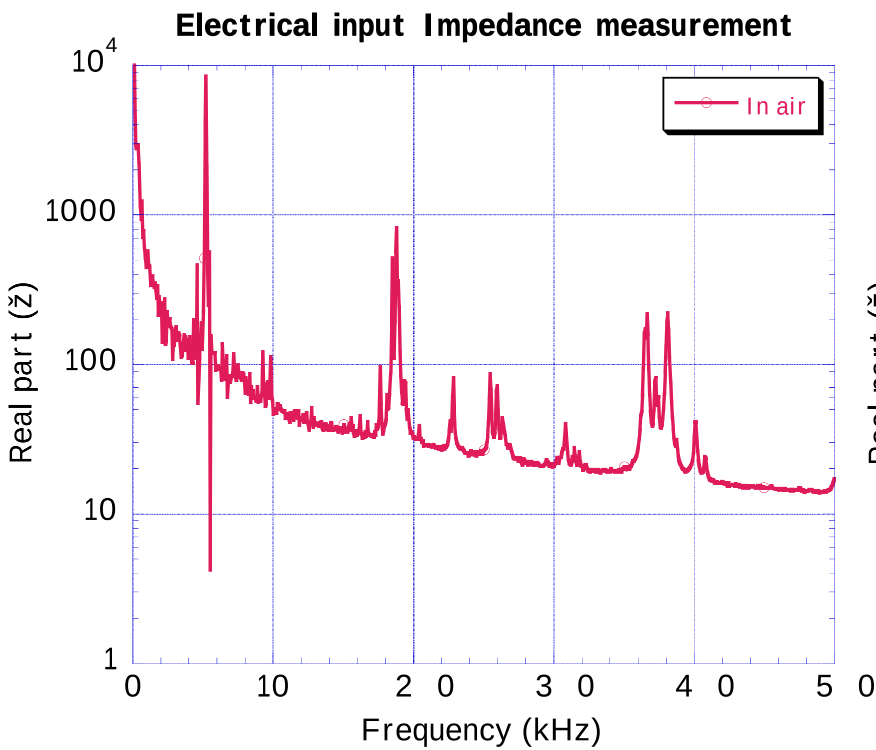
- Classical thin (Kirchoff) plate theory, Mindlin plate theory, and variational methods are used to obtain an equivalent circuit that consists of electrical and mechanical ports.
- The equivalent circuit is used to calculate important design parameters (ie. the electrical input impedance, the received signal, and the output displacement) when the device is loaded with a fluid.

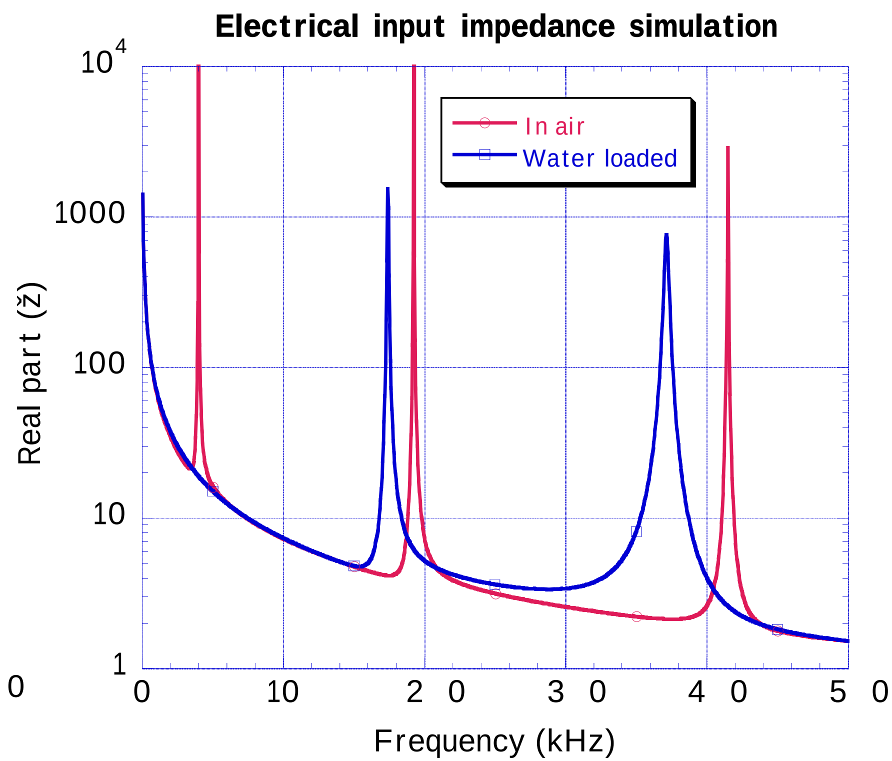
Solutions of Equations



- The solutions for each region are expressed in terms of Bessel functions.
- The unknown coefficients for these solutions are obtained by imposing the boundary conditions in radial direction.
- Depending on the method and geometry used, the number of the boundary conditions and the unknown coefficients are 10, 12 or 14.
- Transcendental matrix has dimensions of 10x10, 12x12, and 14x14.

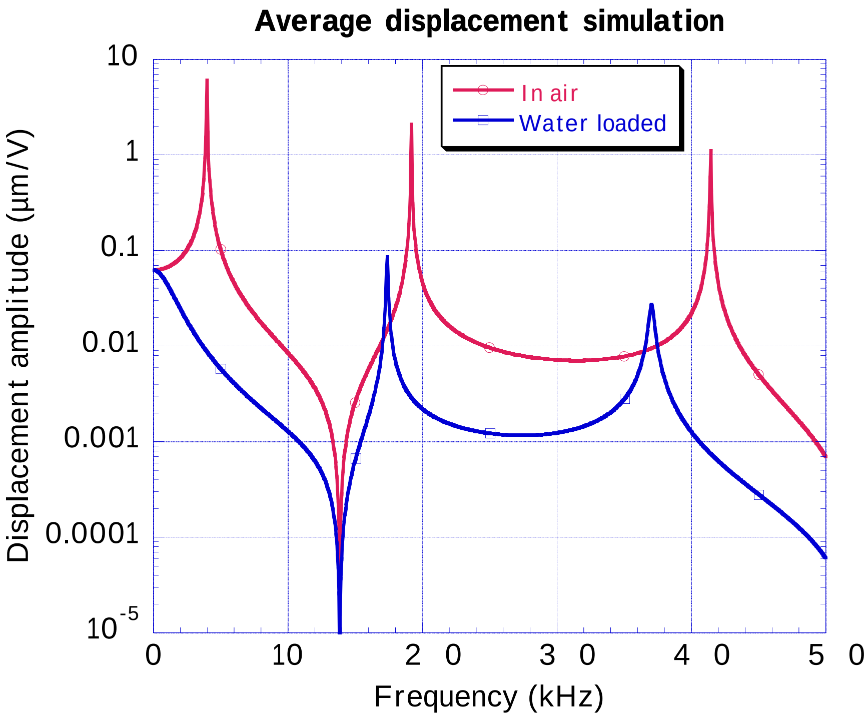
Large Scale Prototype

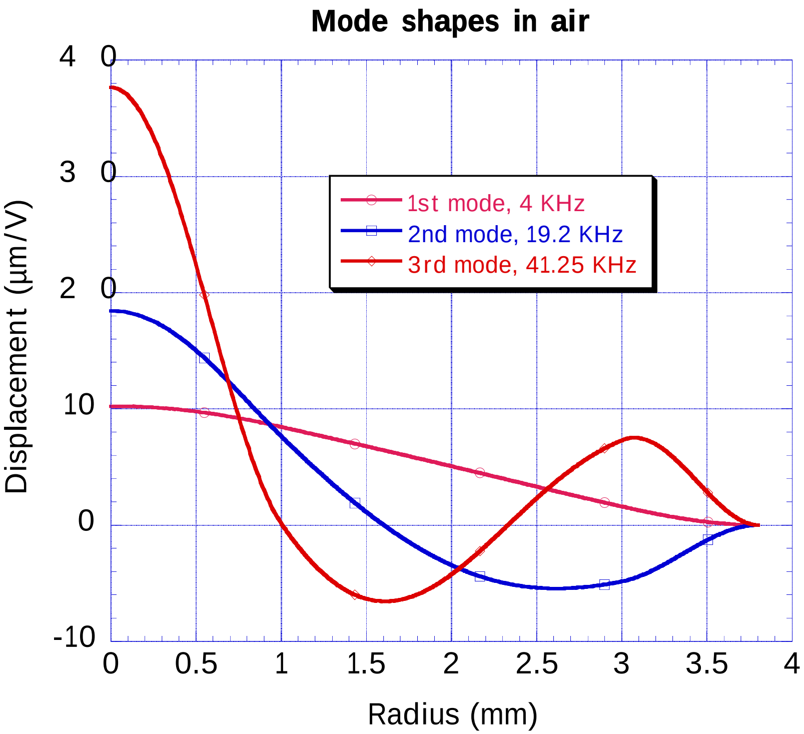




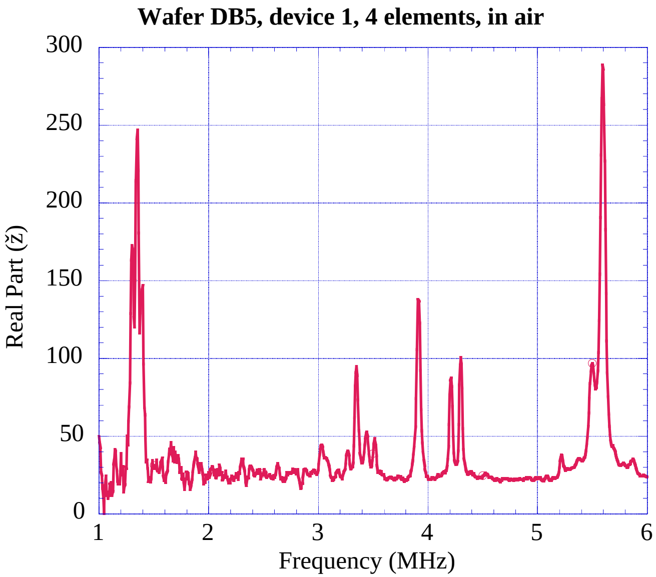
r_h = 30 µm, r_{p1} = 1 mm, r_{p2} = 3 mm, r_m = 3.8 mm, t_m = 25 µm, and t_p = 20 µm.

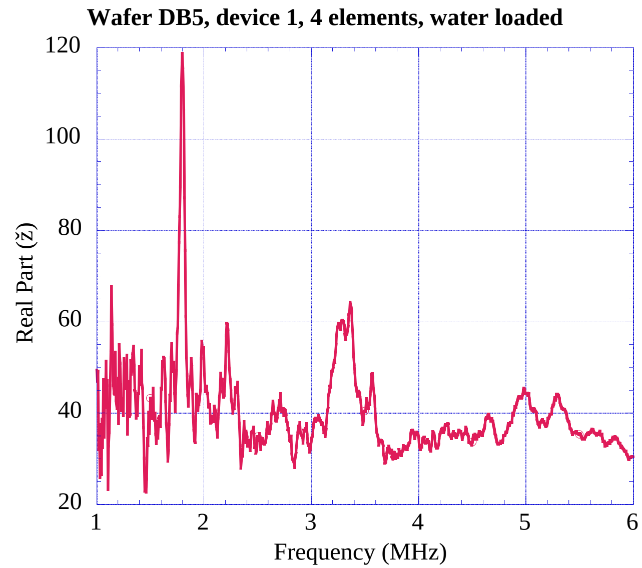
Large Scale Prototype

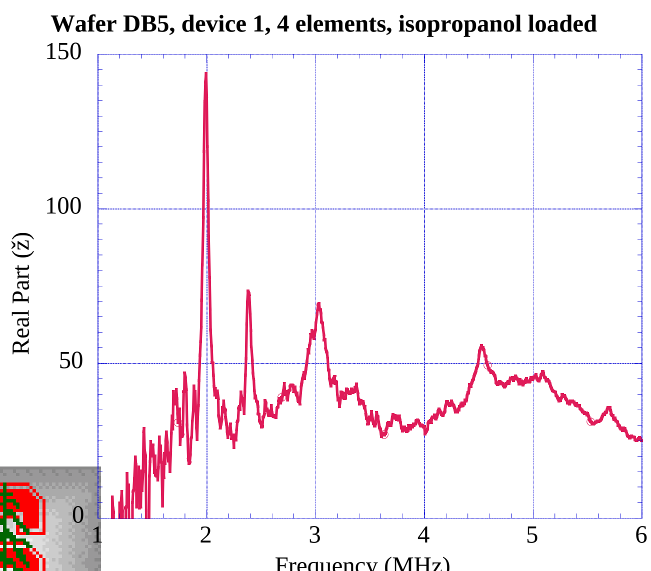


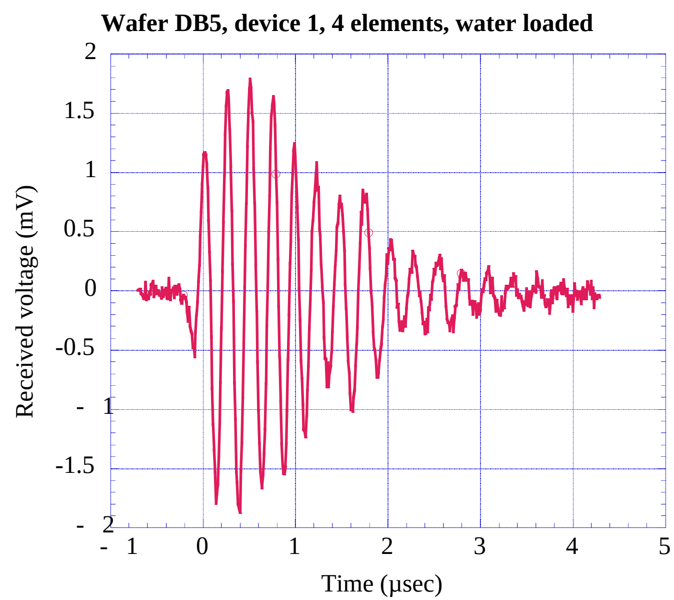


MEMS Device Measurements

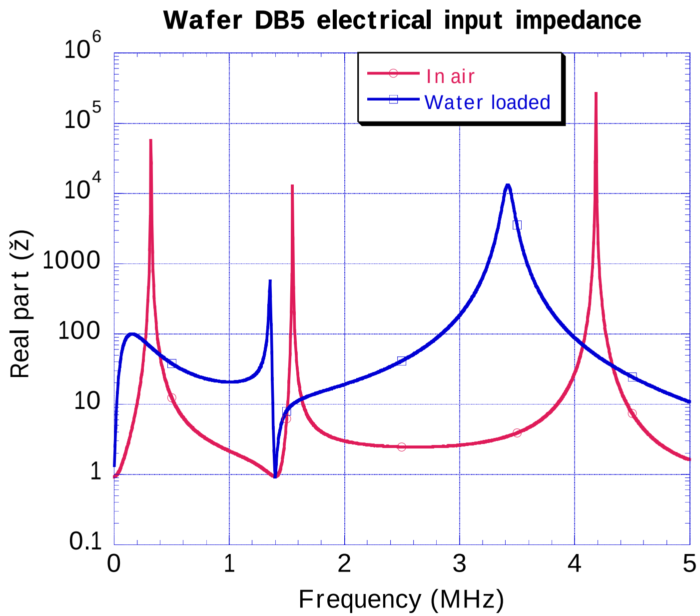


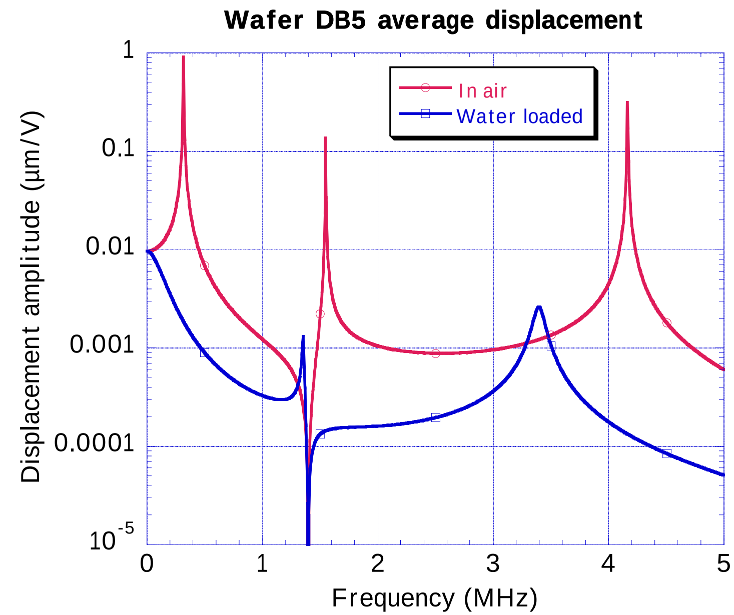




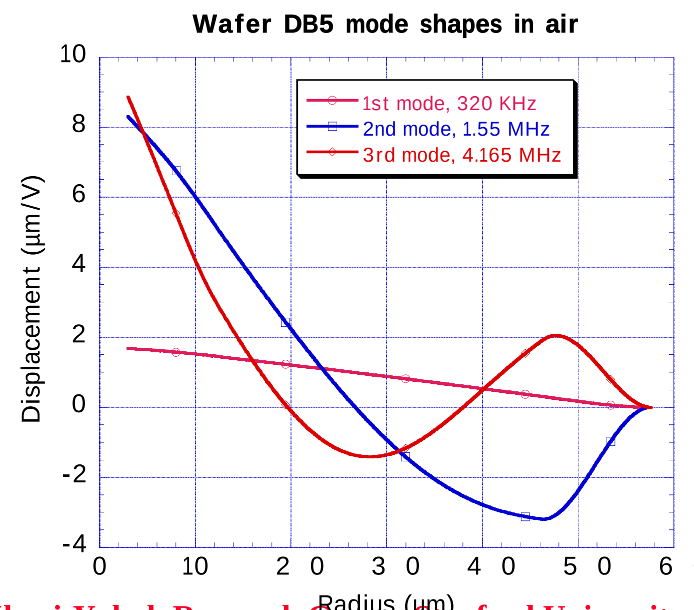


MEMS Device Simulations

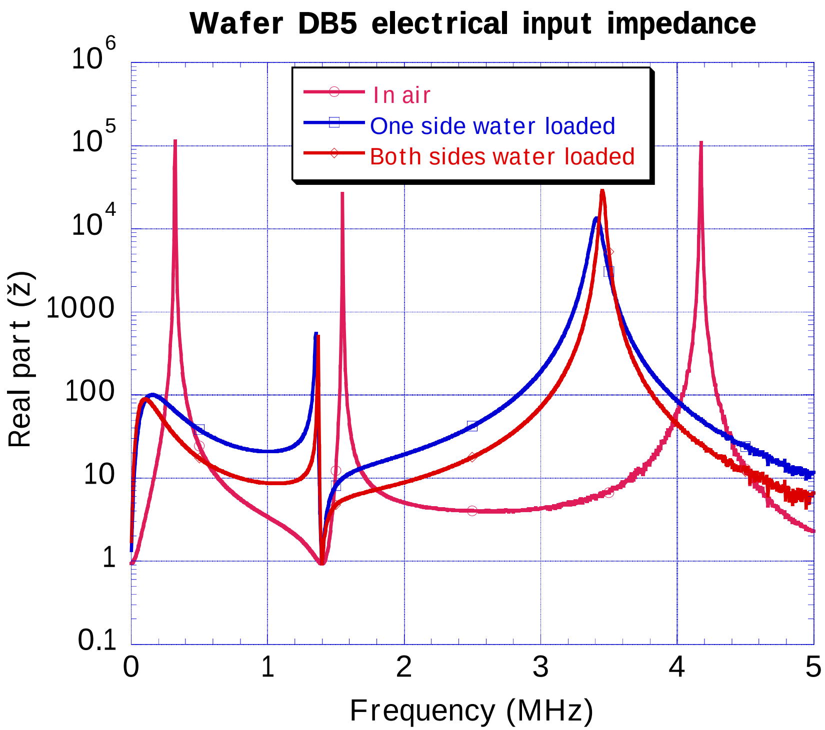


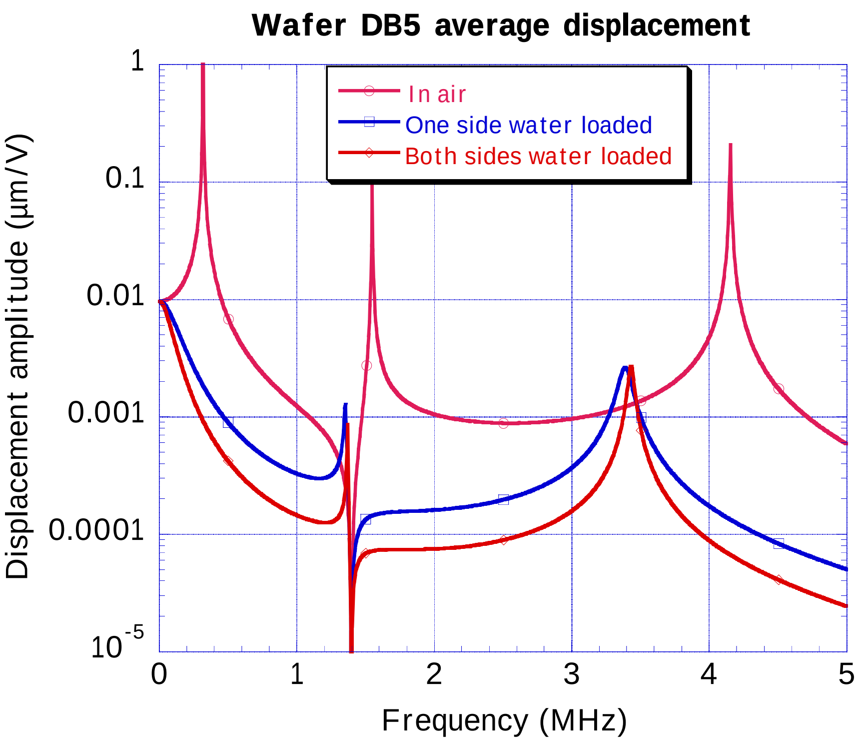


- Devices have multiple resonance frequencies.
- Measured resonance frequencies at 380 kHz, 1.4 MHz, and 3.9 MHz in air.
- Resonance frequencies are predicted by the theory.
- r_h = 3 µm, r_{p1} = 12 µm, r_{p2} = 46 µm, r_m = 58 µm, t_g = 0.1 µm, t_m = 0.25 µm, and t_p = 0.4 µm.



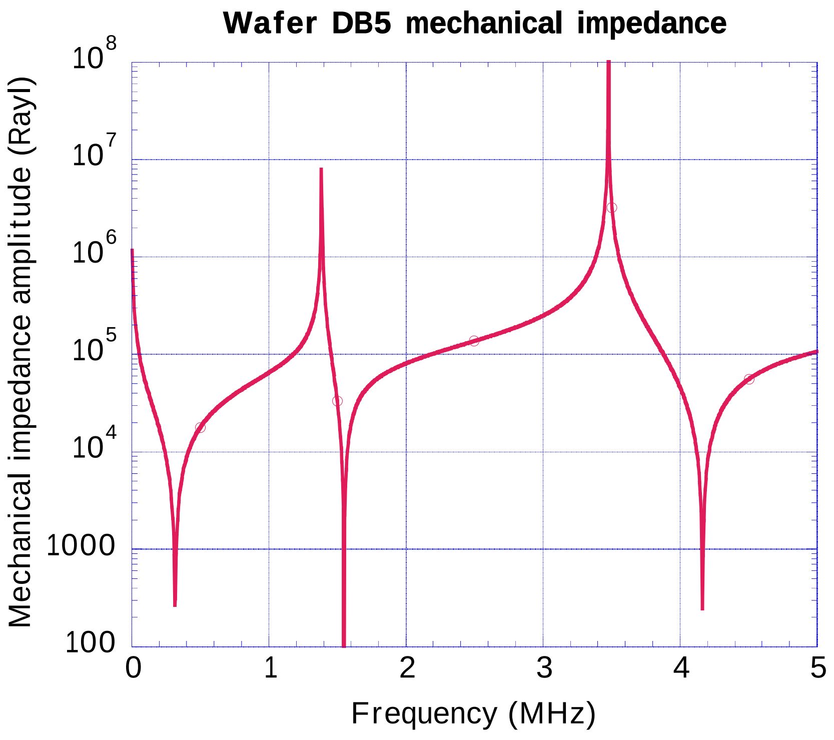
MEMS Device Simulations

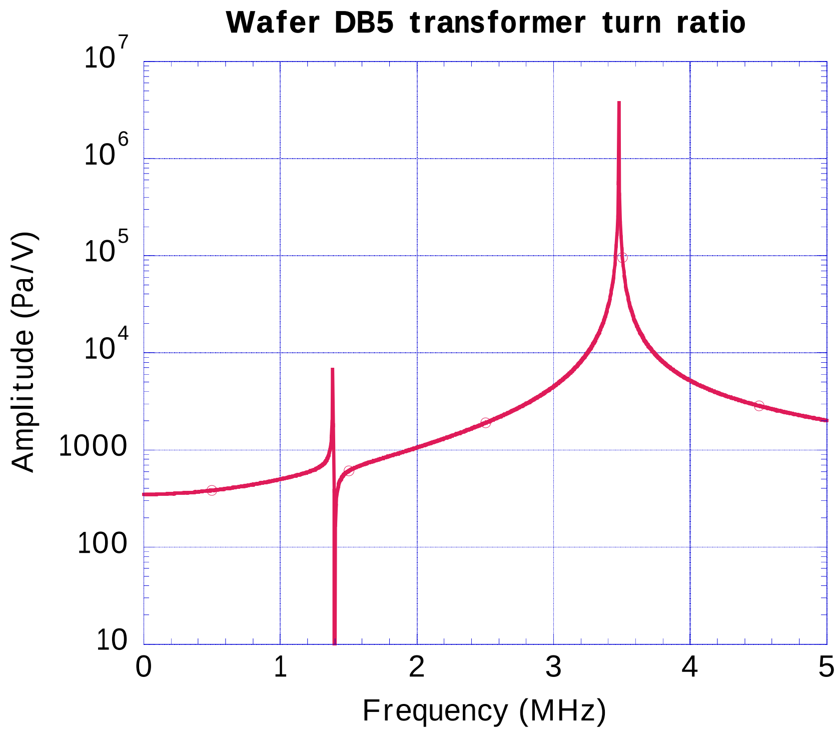




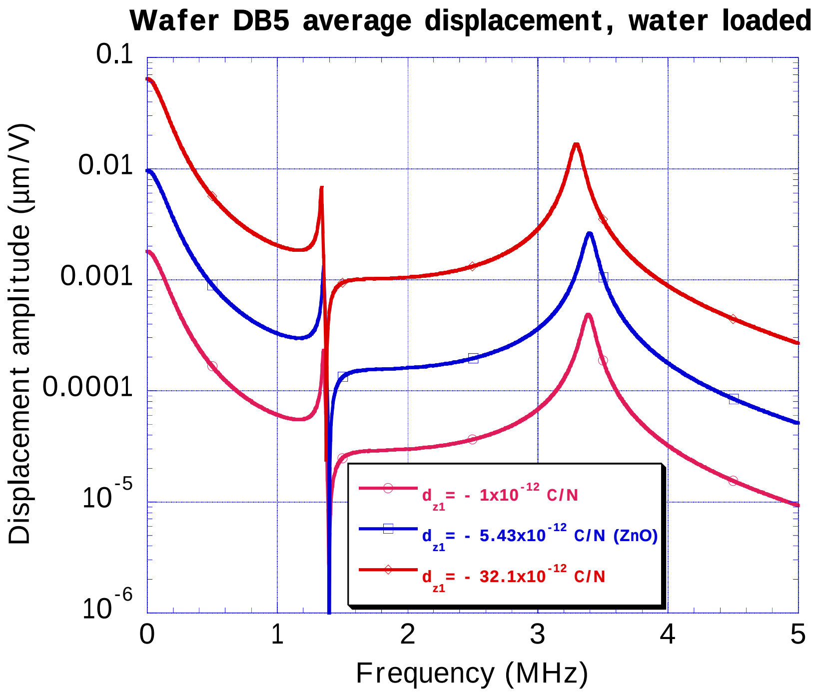
3-ports equivalent network is obtained by using modified Mindlin plate theory.

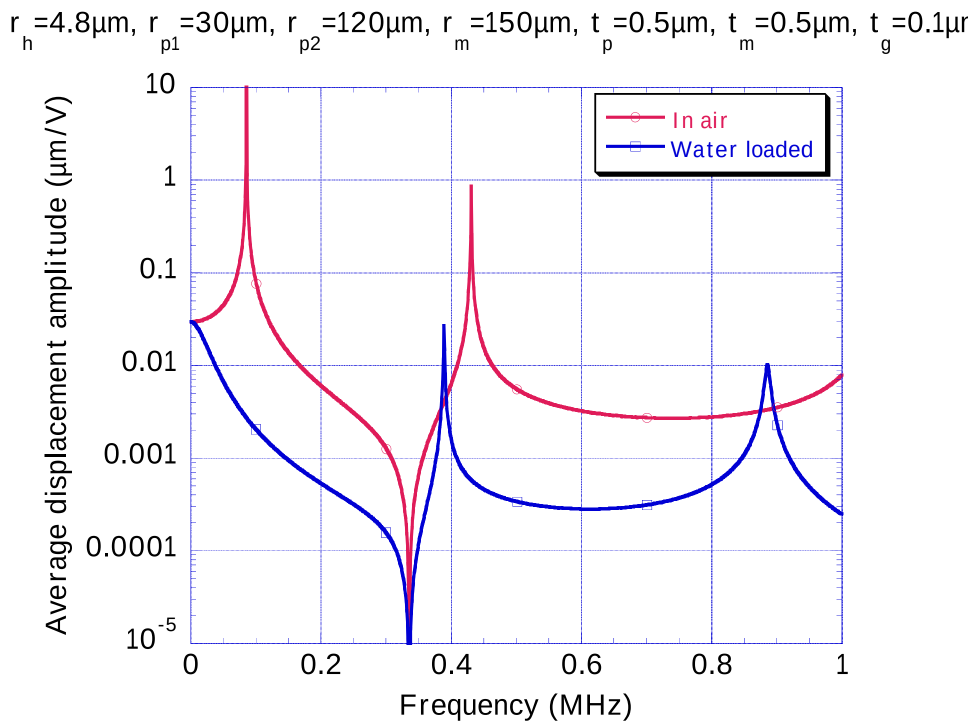
MEMS Device Simulations





MEMS Device Simulations

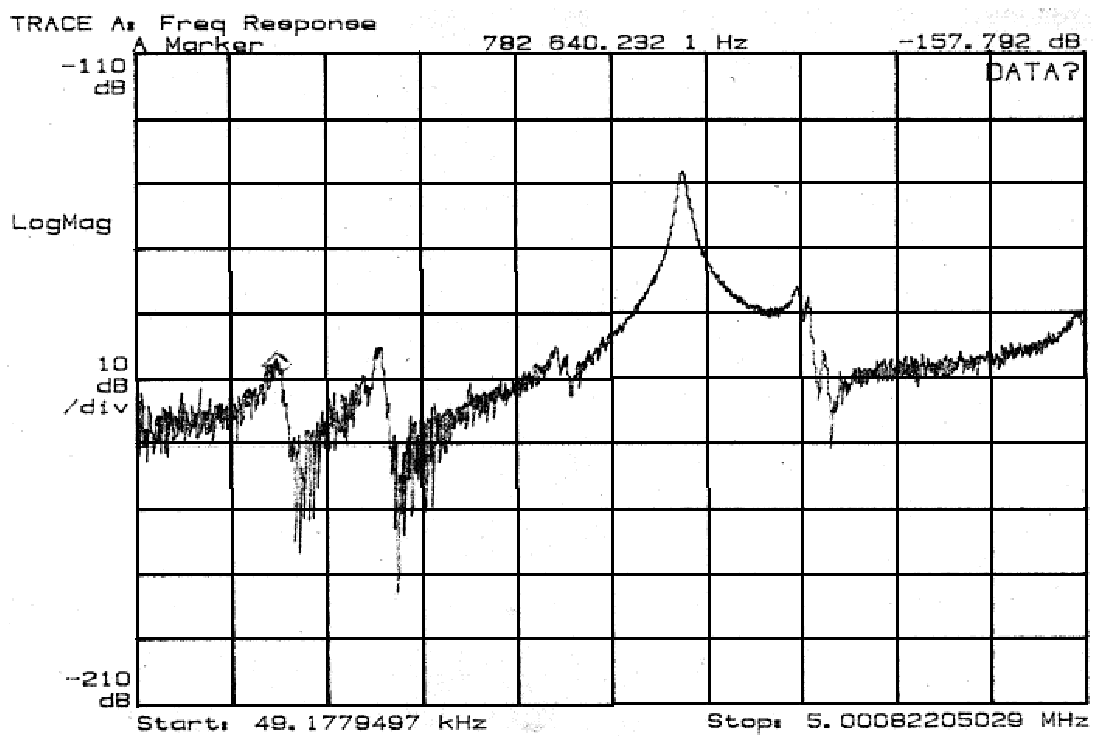




Using different piezoelectric materials or larger diameter devices results in obtaining the required displacement to eject fluids.

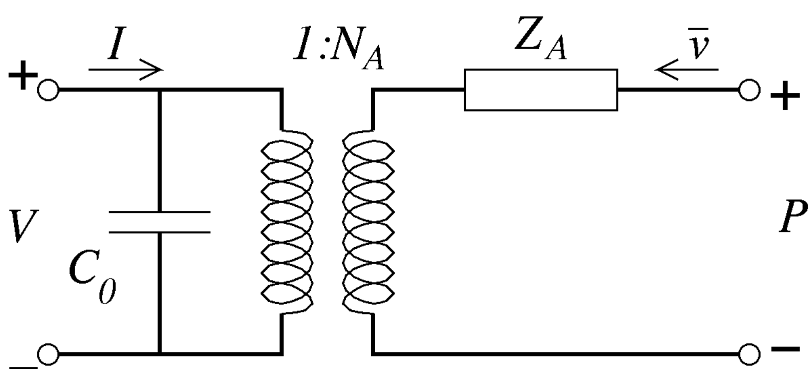
MEMS Device Interferometer Measurements

- In air. 0 dB = 0.5 m/V
- 90 µm diameter device
- 0.0053 µm/V @ 0.75 MHz 0.0070 µm/V @ 1.25 MHz 0.0090 µm/V @ 2.30 MHz 0.1500 µm/V @ 2.90 MHz 0.0175 µm/V @ 3.52 MHz
- 0.15 µm/V at 2.9 MHz is scaled from 0.003 µm/0.02 V.
- 1.2 nm/V at 900 KHz when oil loaded



Flextensional vs. Thickness Mode Transducers

	Longitudinal Mode Transducer			Flexural Mode Transducer		
Piezoelectric		PZT 5H Vernitron			Zinc oxide	
Relative permittivity		1470			11.1	
Area		0.0104 mm^2			0.0104 mm^2	
Thickness	6.35 mm	1.31 mm	488 μm		0.4 μm	
Capacitance (zero strain)	0.02 pF	0.10 pF	0.28 pF		2.56 pF	
Frequency	320 kHz	1.55 MHz	4.17 MHz	320 kHz	1.55 MHz	4.17 MHz
Displacement/Volt (in air)	81 nm/V	17 nm/V	6.5 nm/V	370 nm/V	160 nm/V	320 nm/V
Pressure/Volt (in air)	68 Pa/V	70 Pa/V	70 Pa/V	303 Pa/V	645 Pa/V	3478 Pa/V
Volt/Pressure (in air 50Ω)	87 nV/Pa	88 nV/Pa	87 nV/Pa	380 nV/Pa	810 nV/Pa	4.3 μV/Pa
y_{21} (velocity/V when P=0)	0.17 m/s/V	0.17 m/s/V	0.17 m/s/V	1.3 m/s/V	8.3 m/s/V	16.4 m/s/V



$$I = y_{11}V + y_{12}P$$

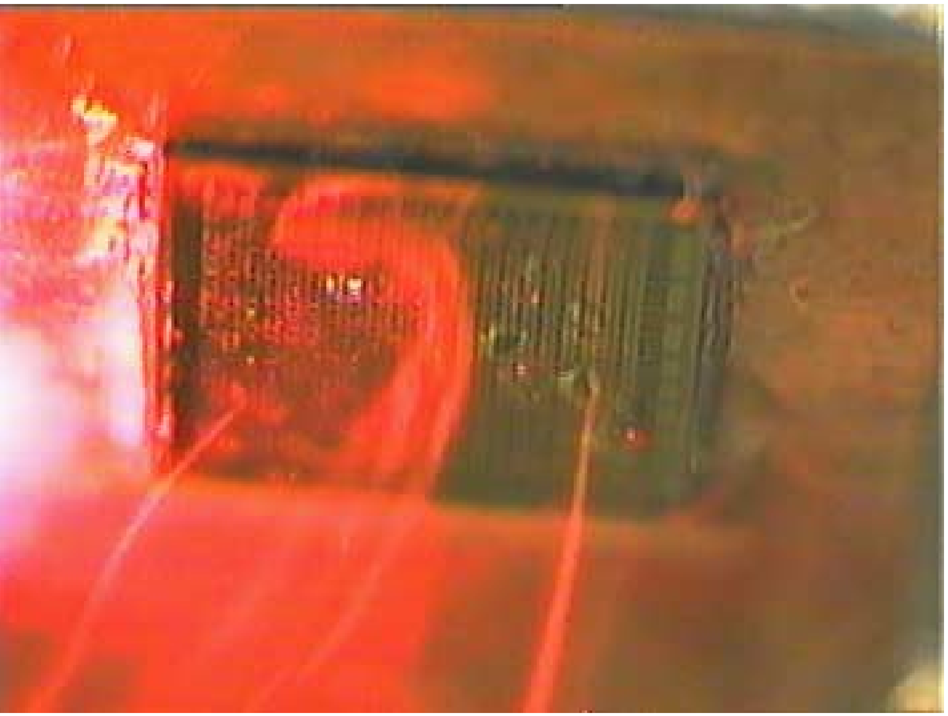
$$\tilde{v} = y_{21}V + y_{22}P$$

$$y_{21} = \left.\frac{\tilde{v}}{V}\right|_{P=0} = -\frac{N_A}{Z_A}$$

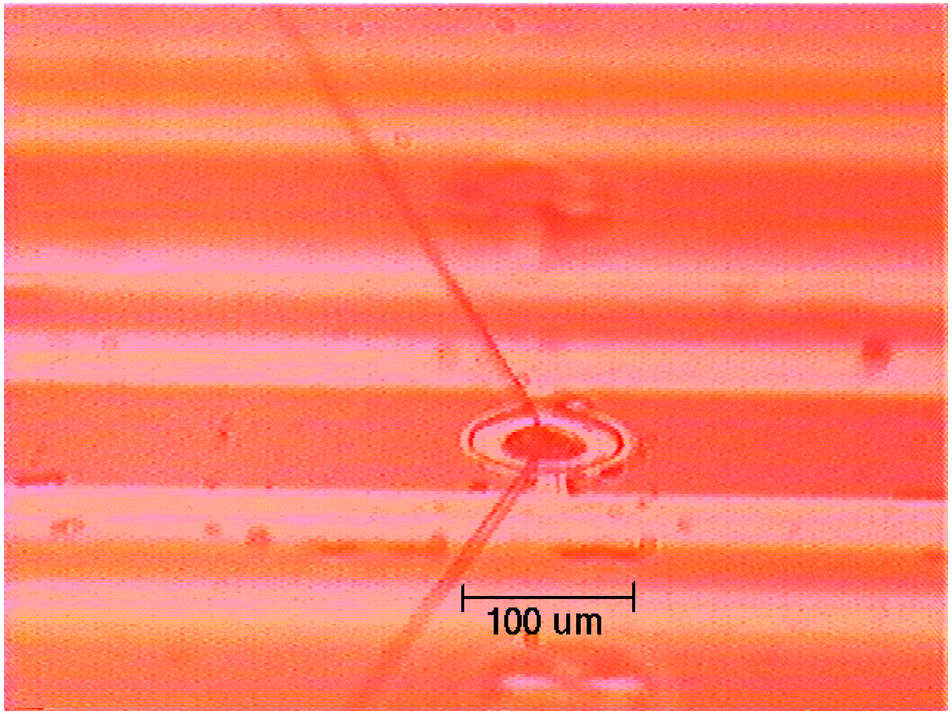
Outline

- Motivation
- MST and inkjet printing markets
- Large scale prototype device
- Ejection simulation
- Micromachined device
- Theory and equivalent circuit
- Samples of ejection by using MEMS device
- Conclusions and future work

Samples of Ejection by Using Micromachined Device

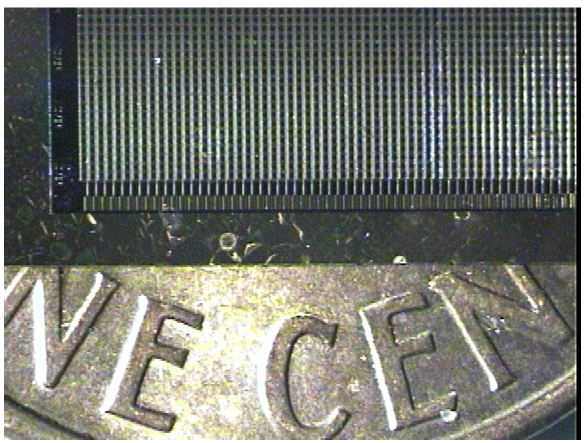


Water ejection from 22 x 22 (1 cm^2) array



Water ejection thru 5 µm diameter orifice at 3.48 MHz

Conclusion and Future Work



- Proof of principle with large scale device.
- Micromachined transducers can be used in medical imaging and under water camera applications.
- The micromachined ejectors and ultrasonic transducers can be integrated with driving, receiving, and addressing circuits.
- Complete theory for vibrations of step-wise laminated plate in contact with a fluid can be developed.
- Different materials and geometry can be used to optimize the devices for either as an ejector or an ultrasonic transducer.