Advanced Microsystems Laboratory

Design, Analysis and Fabrication of MEMS Thermal Micro-Actuators for Tactile Displays and Switches

Eniko T. Enikov
Aerospace and Mechanical Engineering
University of Arizona
1130 N. Mountain, Tucson AZ
Enikov@engr.arizona.edu

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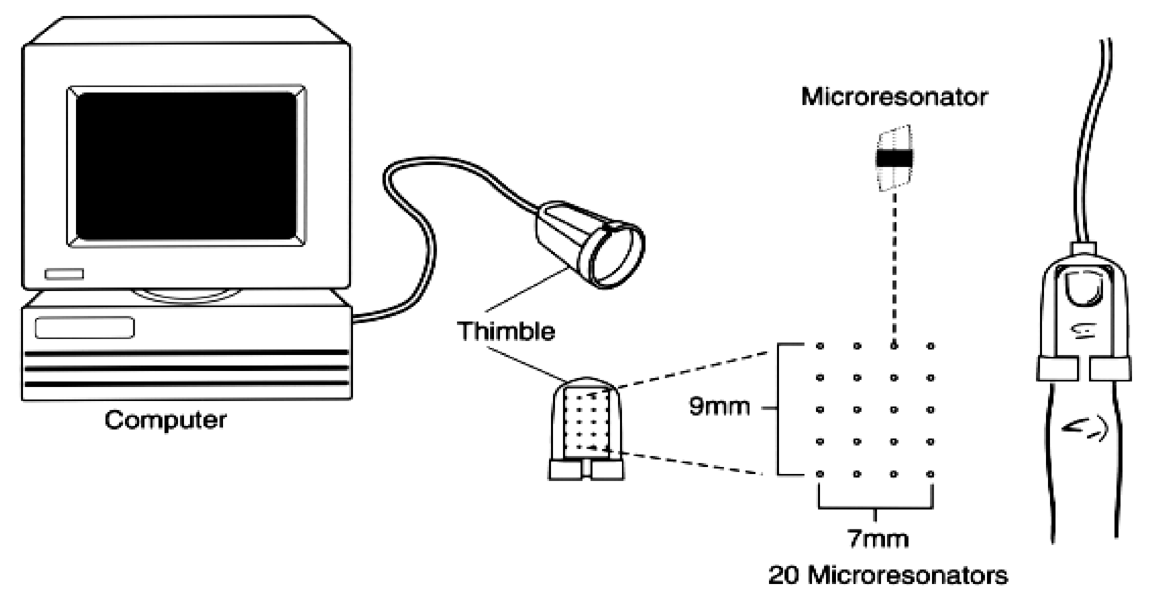
Motivation

Motivation and Background

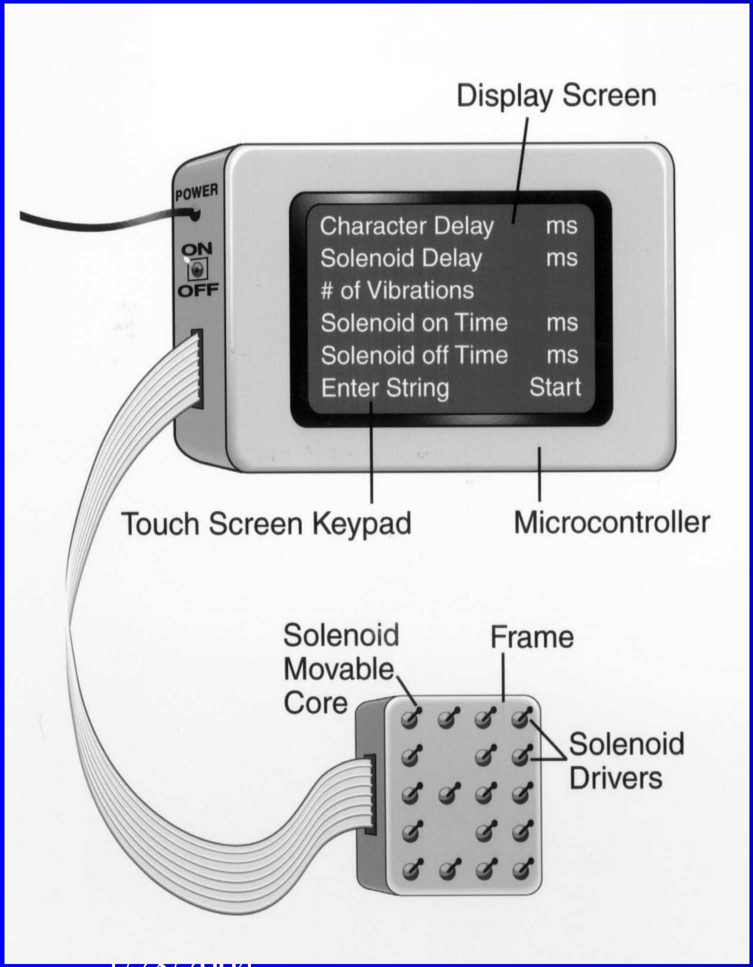


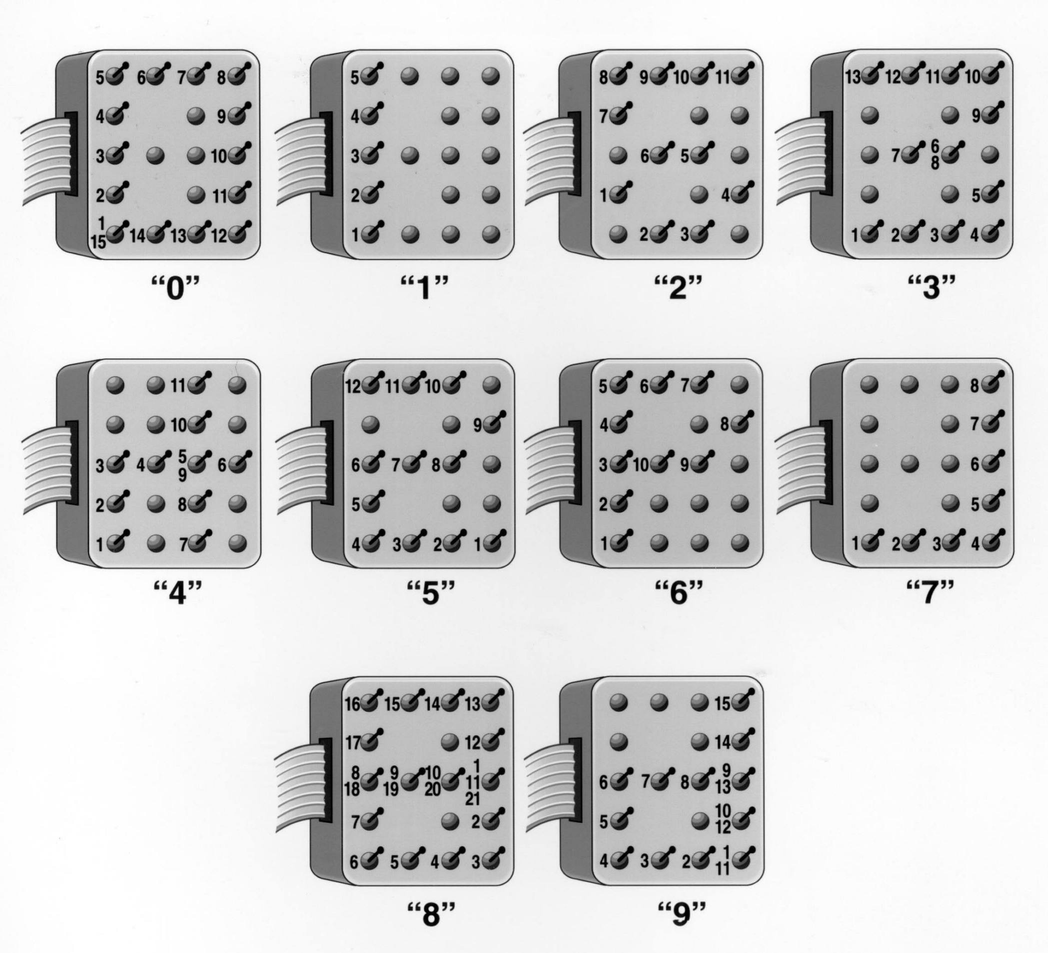
Possible Applications of Tactile MEMS:

- Communication device for divers, pilots, soldier, blind
- Diagnostic device for people with Central Nerve System Injury
- Applications: “quite pager”, “remote touch”

Tactile Display

Motivation and Background



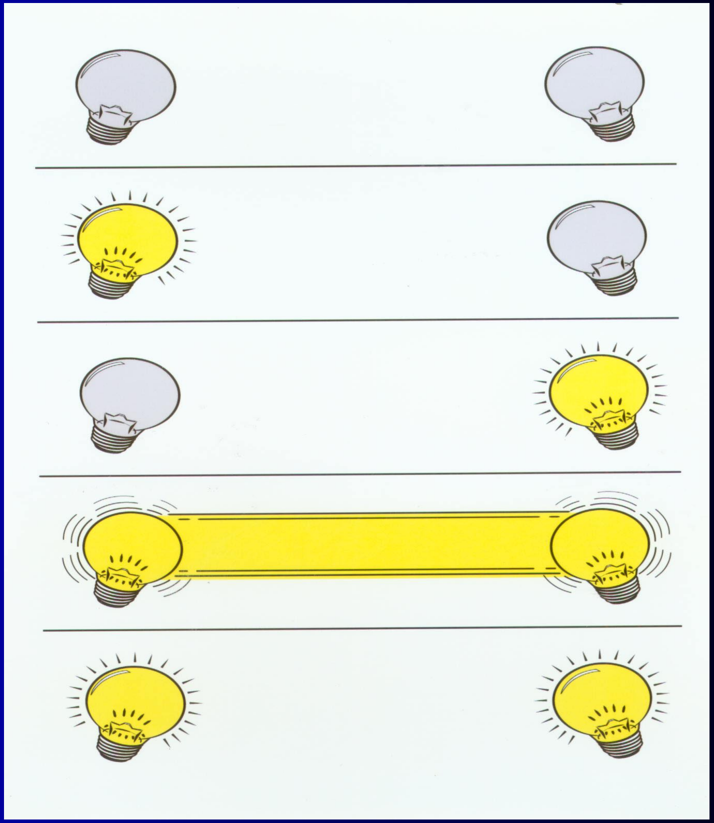


Sensory Illusion Phenomenon

Motivation and Background

Visual φ - phenomenon

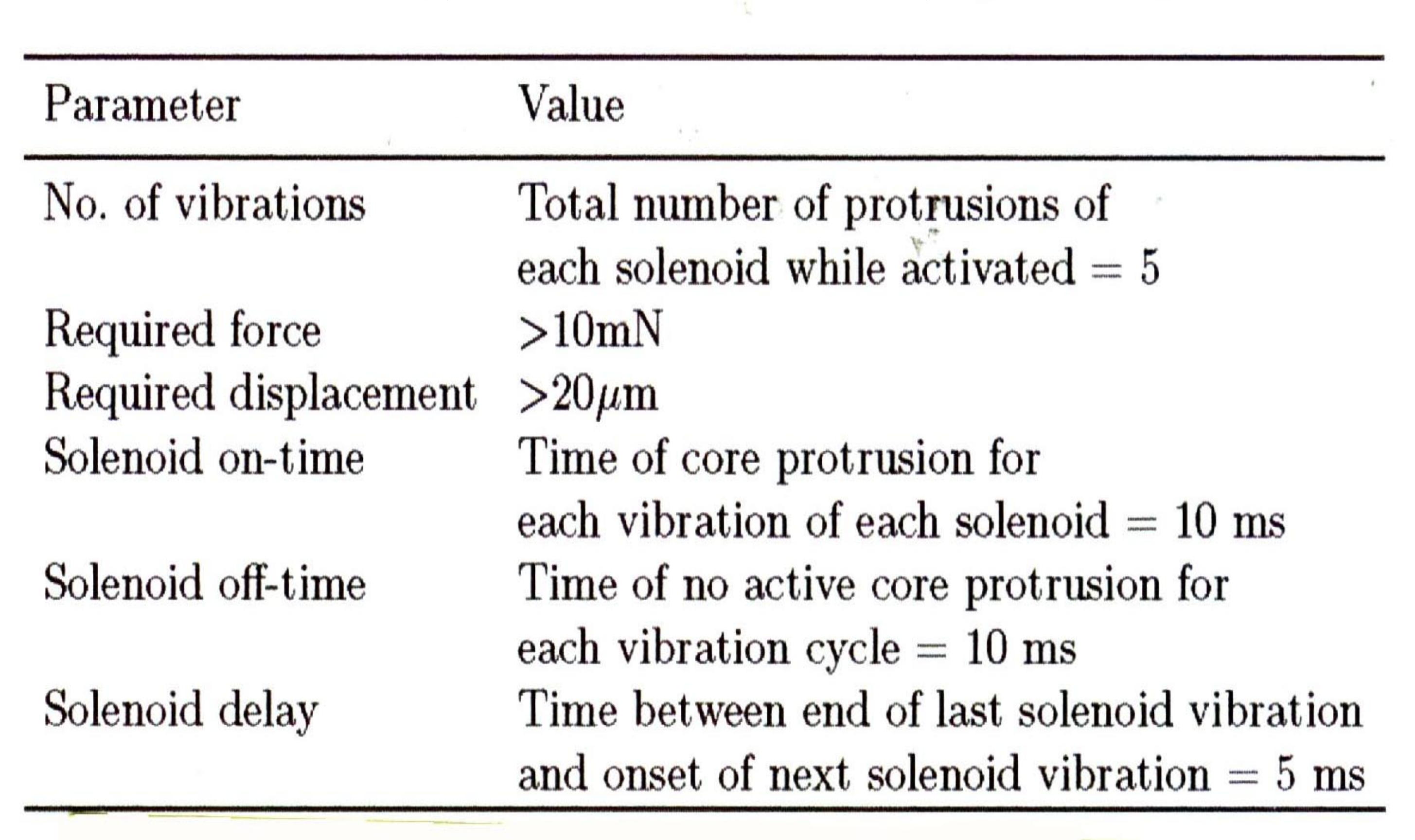
two separated lights flash sequentially using appropriate on-and-off sequences, the viewer perceives a single light moving smoothly from one light position to the other, rather than two lights flashing on-and-off, one after the other



Required Actuator Performance

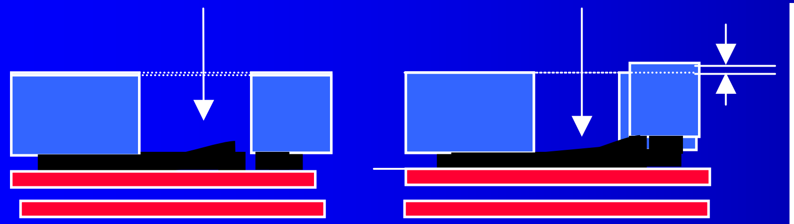
Settings on solenoid tactile illusion-producing device

(Data from Dr. Gonzales)



Parameter	Value
No. of vibrations	Total number of protrusions of each solenoid while activated = 5
Required force	>10mN
Required displacement	>20μm
Solenoid on-time	Time of core protrusion for each vibration of each solenoid = 10 ms
Solenoid off-time	Time of no active core protrusion for each vibration cycle = 10 ms
Solenoid delay	Time between end of last solenoid vibration and onset of next solenoid vibration = 5 ms

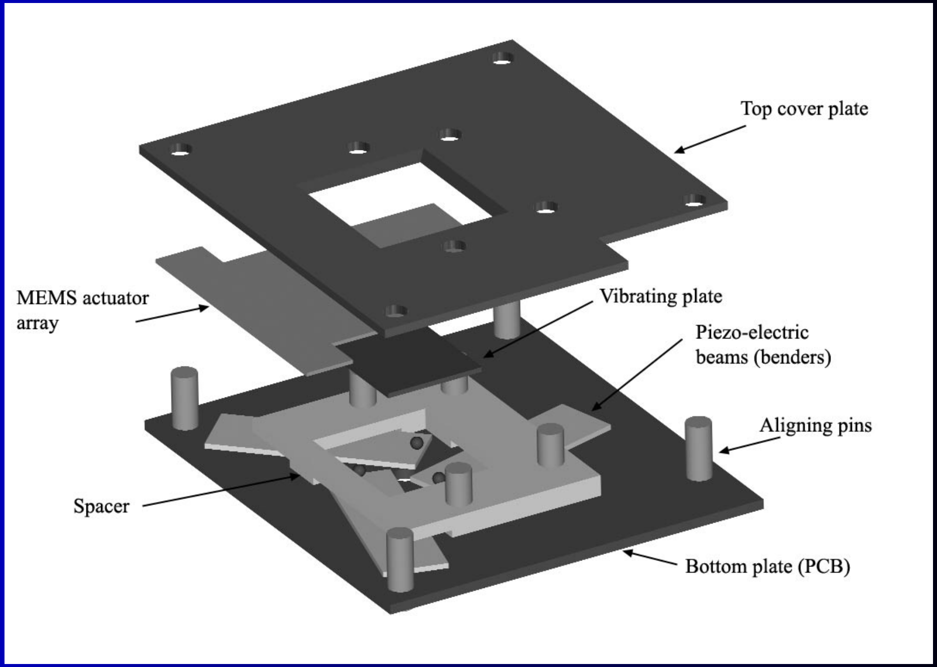
Micro-Mechanical Switch: Thermally Actuated Switch



Micro switch open

Micro switch closed

- ⬛ Thermal actuator
- 🟦 Silicon
- 🟥 Main moving plate



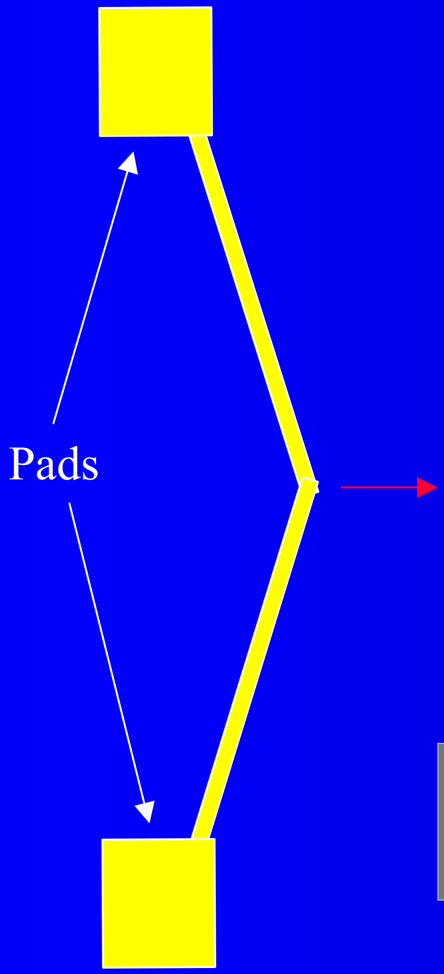
Need

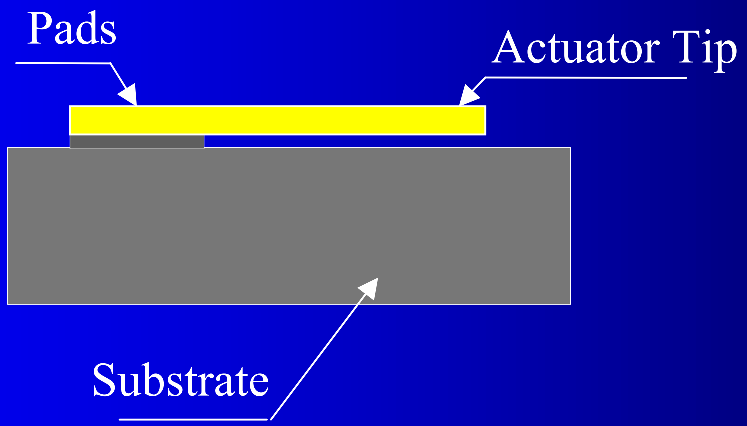
- Robust, low cost actuators
- Simple fabrication process
- Ability to integrate with polymers
- Large displacement needed

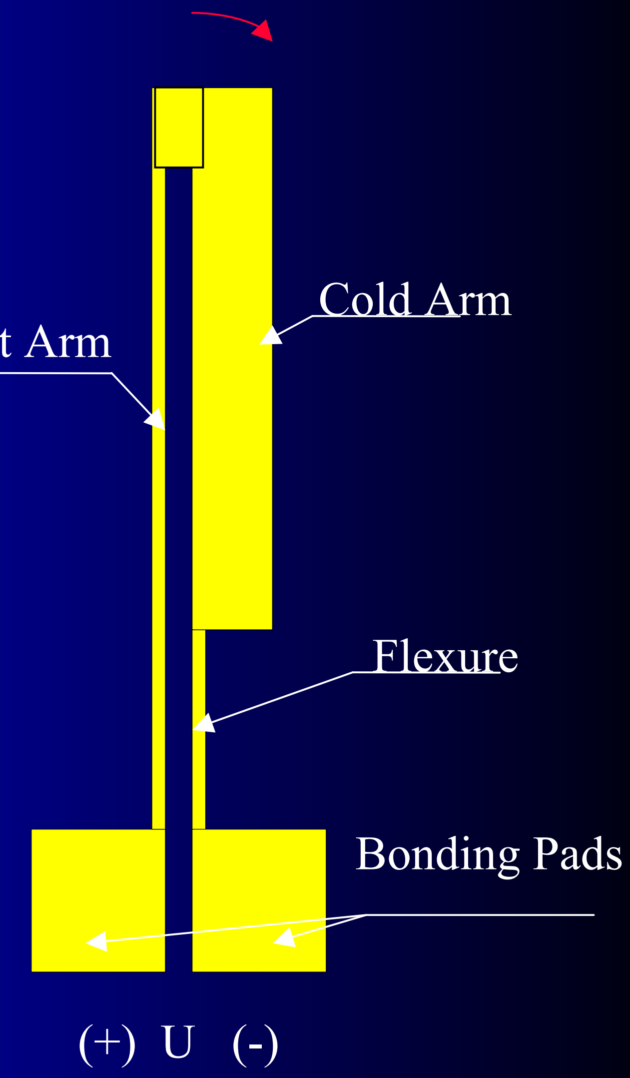
Other Applications

- Switches
- RF MEMS
- Optical MEMS, Aligners

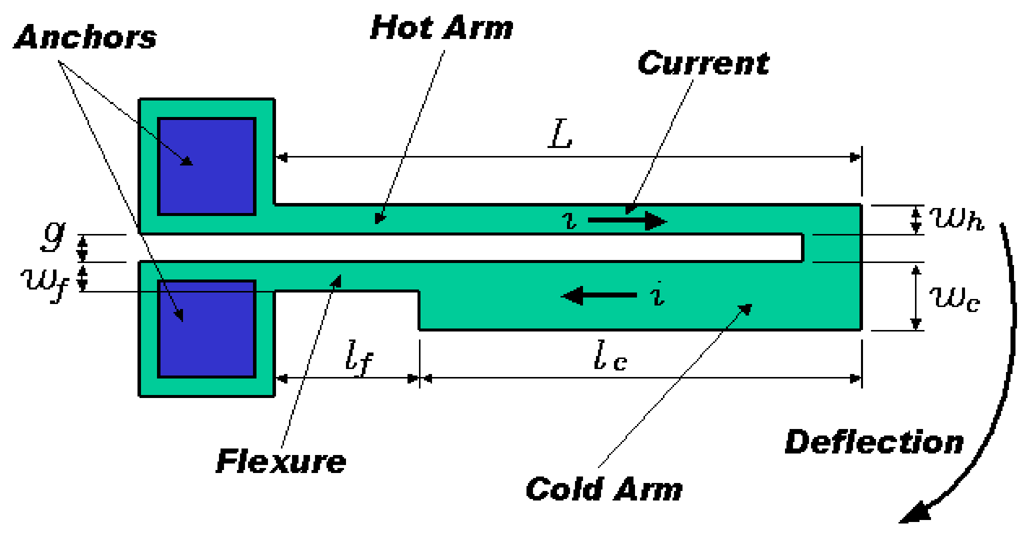
Conventional Thermal Actuators







Design of Thermal Actuators



$$L = 600\mu m$$
$$l_c = 400\mu m$$
$$l_f = 200\mu m$$
$$w_f = w_h = 15\mu m$$
$$w_c = 25\mu m$$

$$\delta \approx \frac{(\alpha\Delta T)(l_f + l_c)hw(w+g)(2l_f l_c + l_f^2)}{2(2l_f + l_c)I}; \quad I = \frac{2}{3}h\left[\left(w+\frac{g}{2}\right)^3 - \left(\frac{g}{2}\right)^3\right]$$

Transient Response

Mechanical Response

$$v(x,t) = \sum_i \left(a_i S(\lambda_i x) + b_i T(\lambda_i x) + c_i U(\lambda_i x) + d_i V(\lambda_i x)\right)\sin(\omega_i t + \varphi_i),$$

$$S(x) = \left(\cosh x + \cos x\right)/2 \qquad T(x) = \left(\sinh x + \sin x\right)/2 \qquad U(x) = \left(\cosh x - \cos x\right)/2$$

$$V(x) = \left(\sinh x - \sin x\right)/2$$

$$f = \omega/2\pi = 37.89 \ \text{kHz} \qquad \tau_{mech} \approx \underline{7.5\mu s}$$

Thermal Response

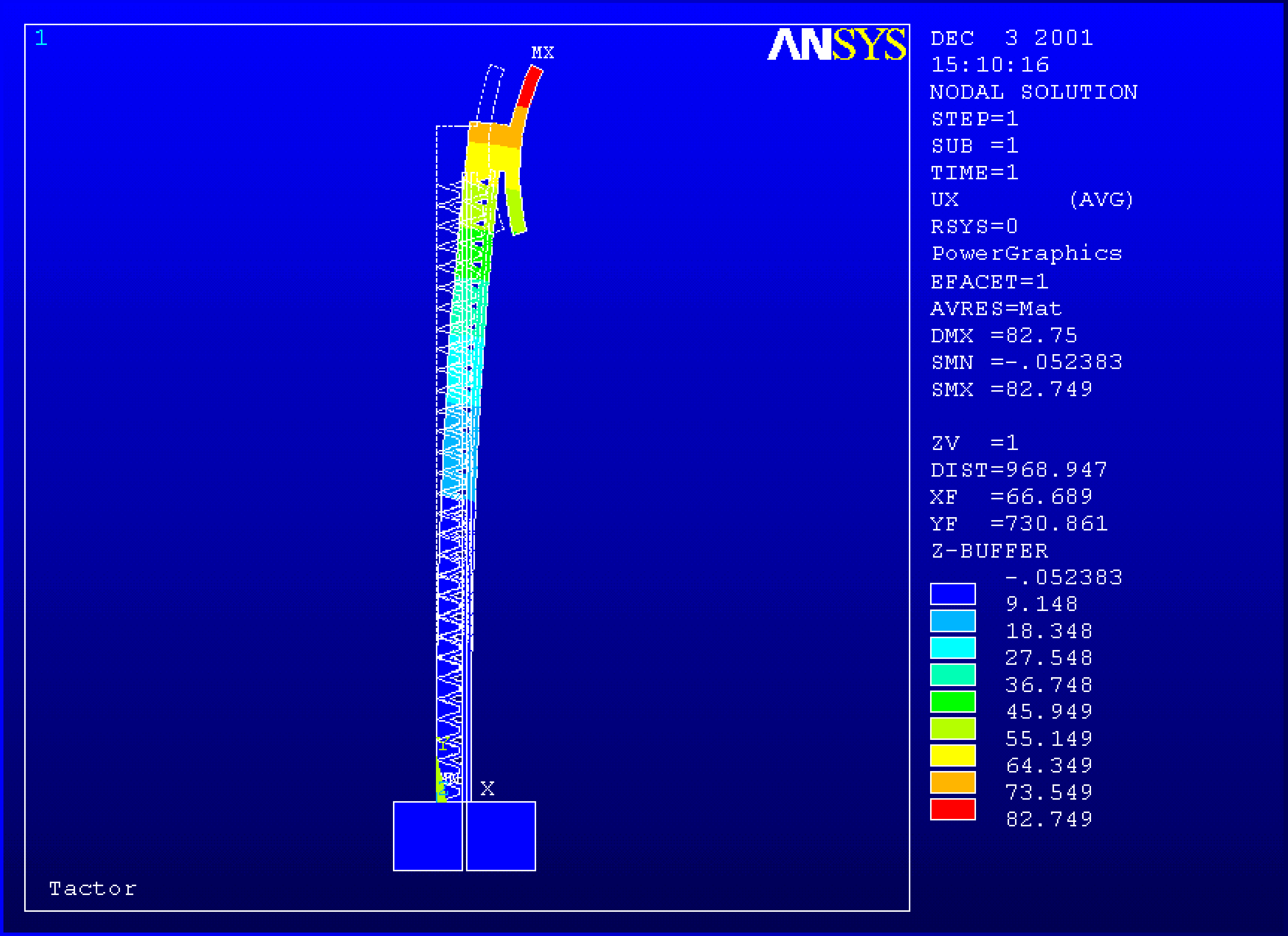
$$\bar{T}(t) = \frac{8T_{ON}}{\pi^2}\sum_{n=1}^{\infty}\frac{e^{-\alpha\beta_n^2 t}}{(2n-1)^2} = \frac{8T_{ON}}{\pi^2}\left(\frac{e^{-\frac{\alpha\pi^2 t}{4L^2}}}{1} + \frac{e^{\frac{-9\alpha\pi^2 t}{4L^2}}}{9} + \dots\right)$$

$$\tau_{\text{cooling}} = \frac{4L^2}{\alpha\pi^2} \approx \underline{9.5ms}$$

Tactile MEMS: FEA analysis

Composite Actuator

Displacement



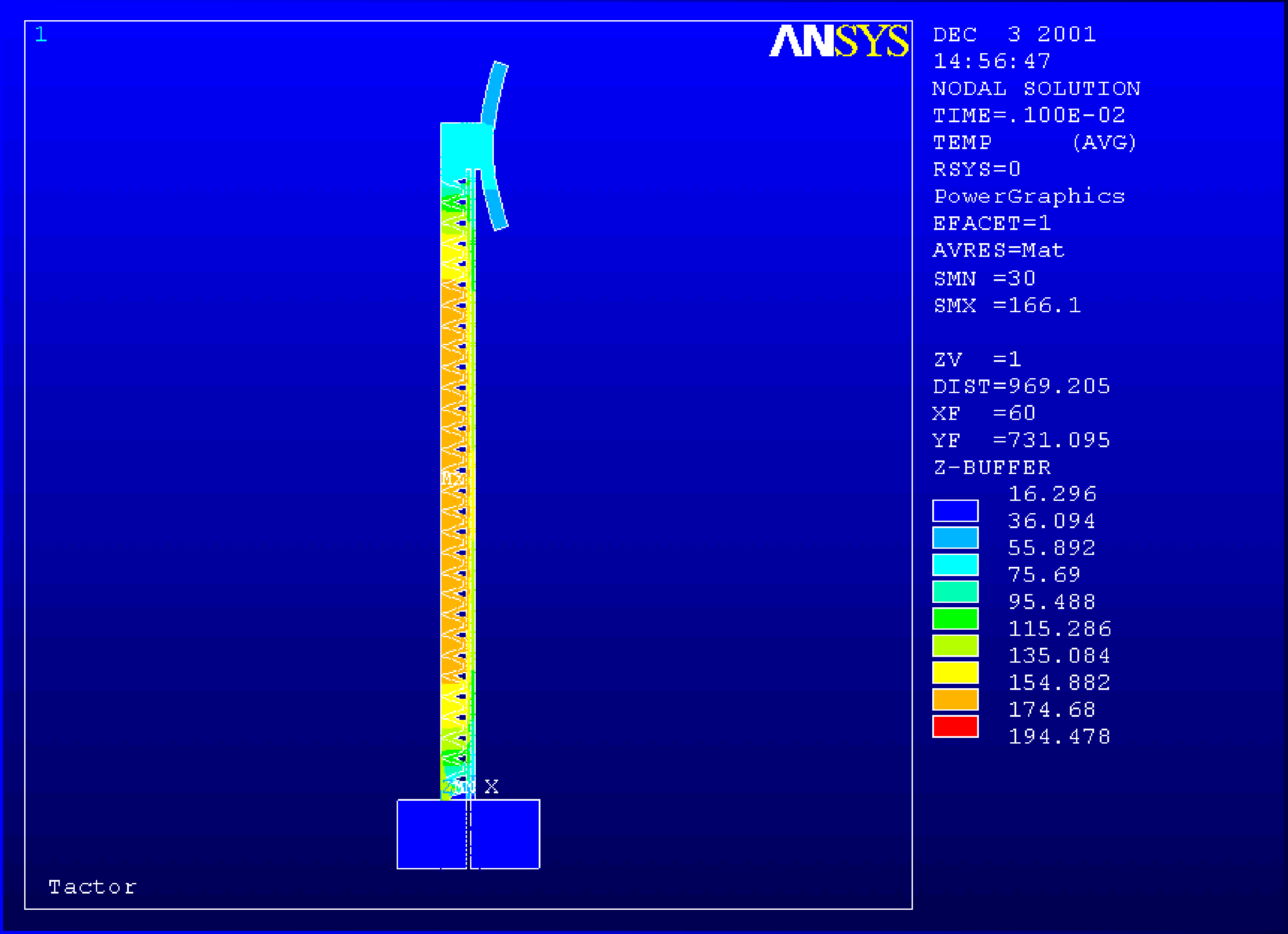
```
DEC  3 2001
15:10:16
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UX          (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =82.75
SMN =-.052383
SMX =82.749

ZV  =1
DIST=968.947
XF  =66.689
YF  =730.861
Z-BUFFER
     -.052383
     9.148
     18.348
     27.548
     36.748
     45.949
     55.149
     64.349
     73.549
     82.749
```

Tactile MEMS: FEA analysis

Composite Actuator

Transient Thermal Analysis



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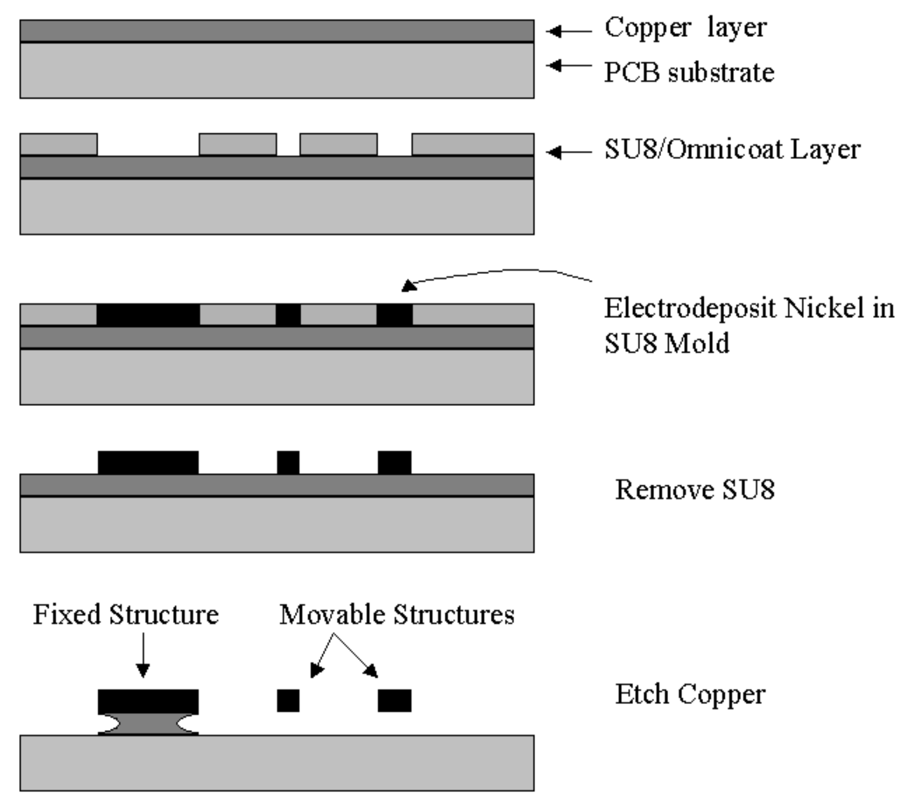
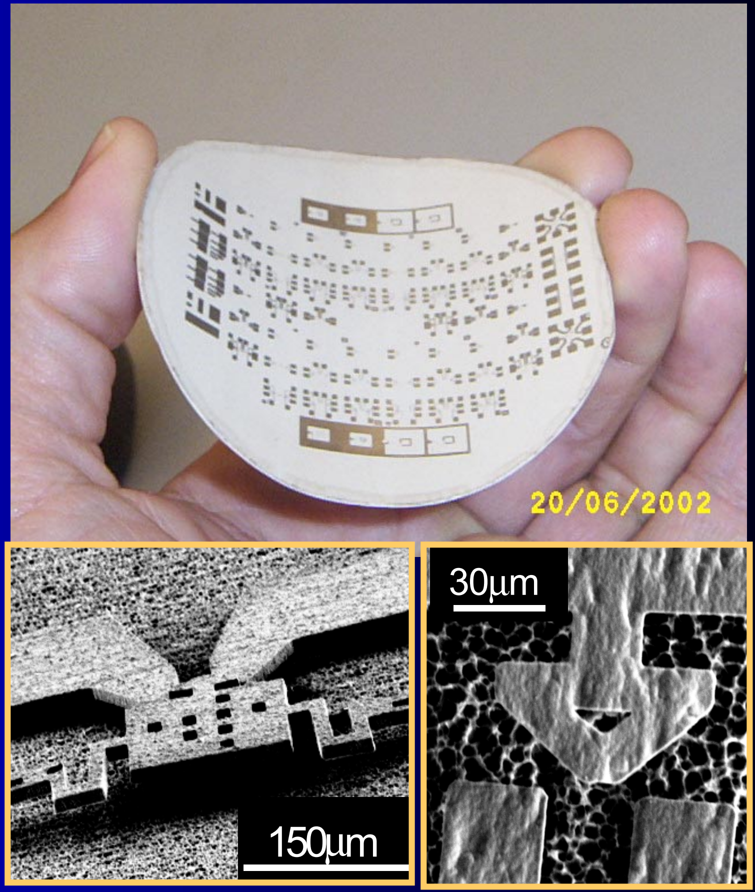
DEC  3 2001
14:56:47
NODAL SOLUTION
TIME=.100E-02
TEMP       (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN  =30
SMX  =166.1

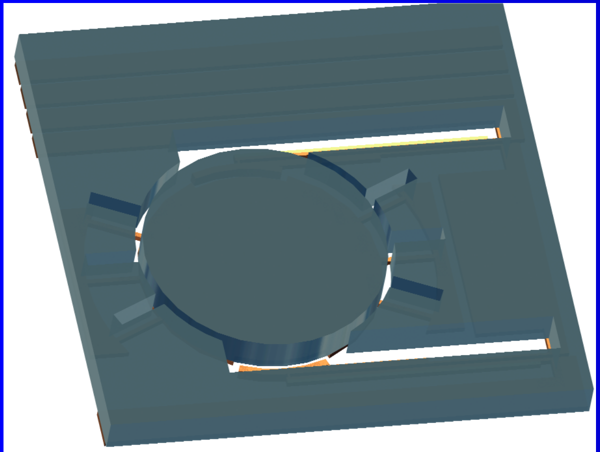
ZV   =1
DIST=969.205
XF   =60
YF   =731.095
Z-BUFFER
     16.296
     36.094
     55.892
     75.69
     95.488
     115.286
     135.084
     154.882
     174.68
     194.478
```

Fabrication on PCB substrates

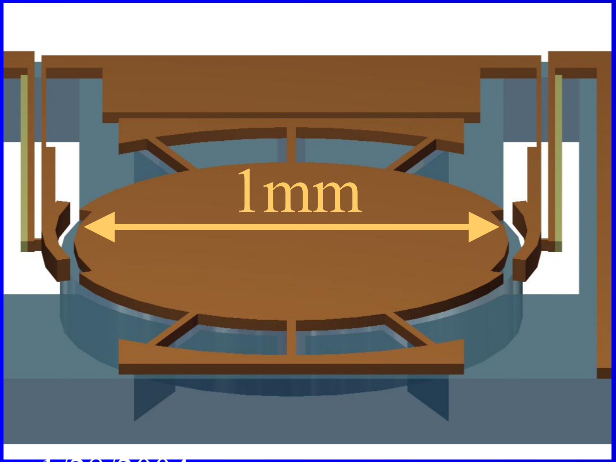


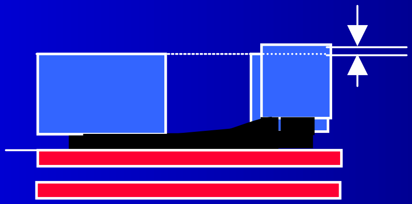


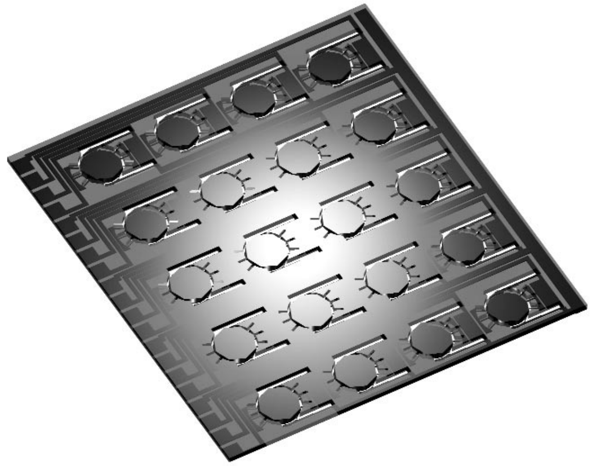
Thermal Actuators as a Mechanical Switch



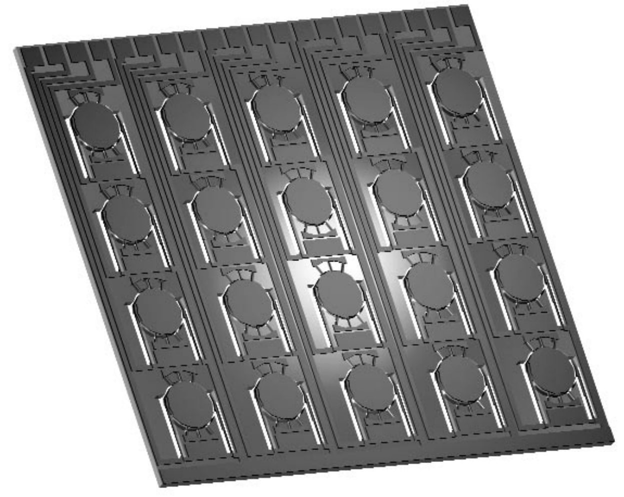
Close view of the switching mechanism





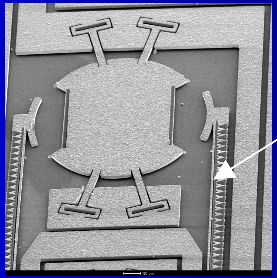


Array of Switches (Top and Bottom Views)

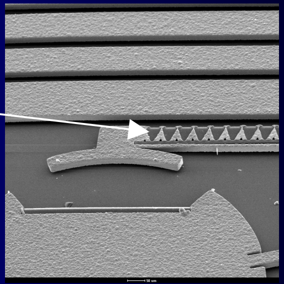


Development History

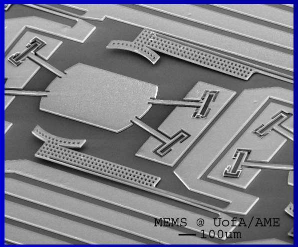
- Initial concept, November 2001 used composite (inlayed) actuators



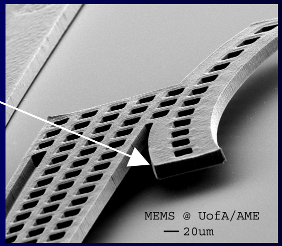
Inlayed SU8



- Second generation used metallic actuators plated in SU8 (Fall 2002)

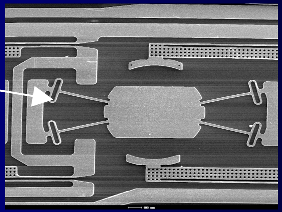


SU8 is used for electro-forming



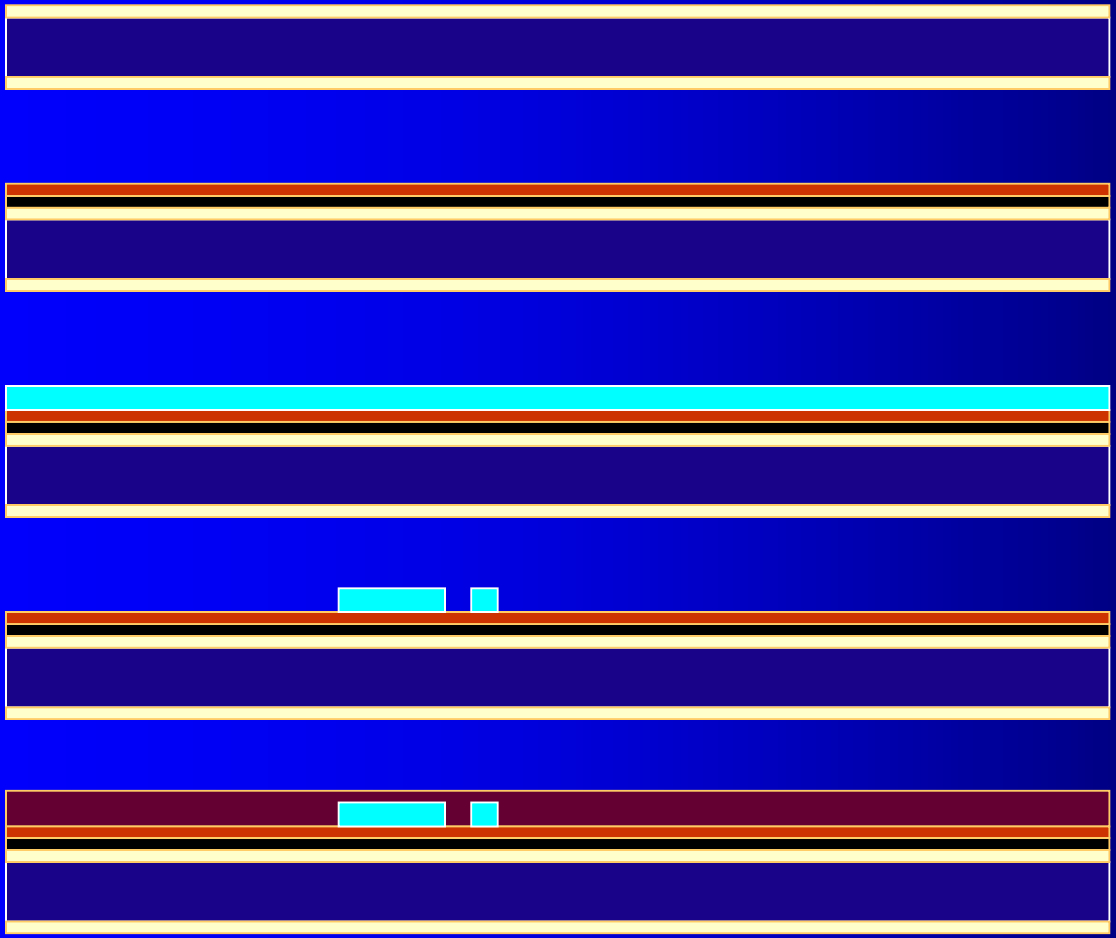
- Third generation devices (Spring 2003) utilized AZ4903 photoresist instead of SU8.

Sharp corners removed to reduce stress concentration



Processing Sequence: SU8/Ni composite

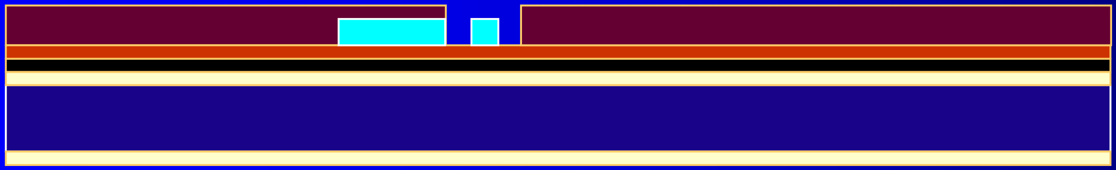
SU8/Ni



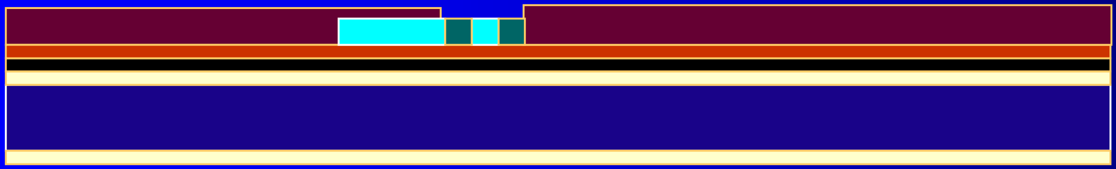
1. Wafer Oxidation
2. Deposit Ti/Cu seed layer
3. Spin SU8
4. Pattern the SU8 with UV
5. Spin thick Photoresist

Processing Sequence: SU8/Ni composite (cont.)

SU8/Ni

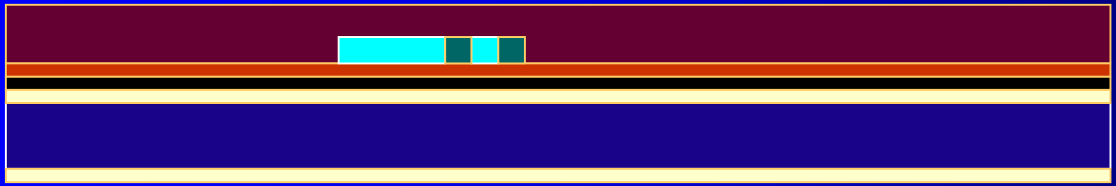


6. Pattern the photoresist

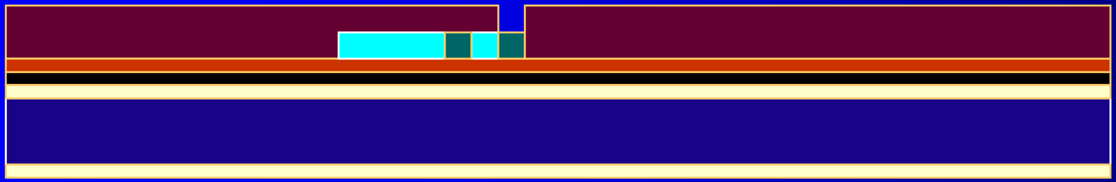


7. Plate Nickel

8. Strip the photoresist



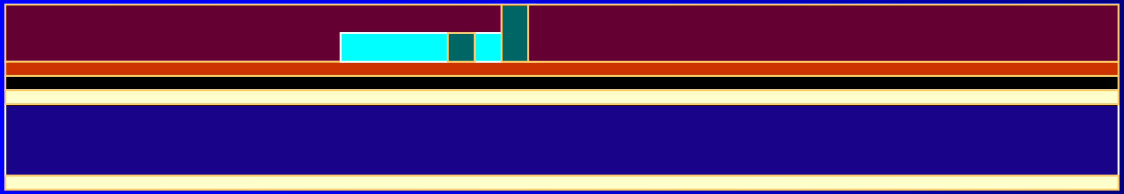
9. Spin photoresist



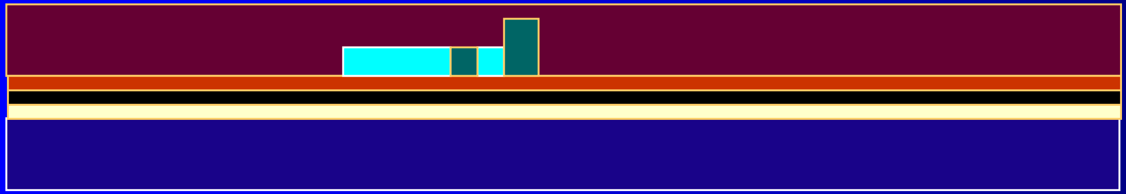
10. Pattern the photoresist

Processing Sequence SU8/Ni composite (Cont.)

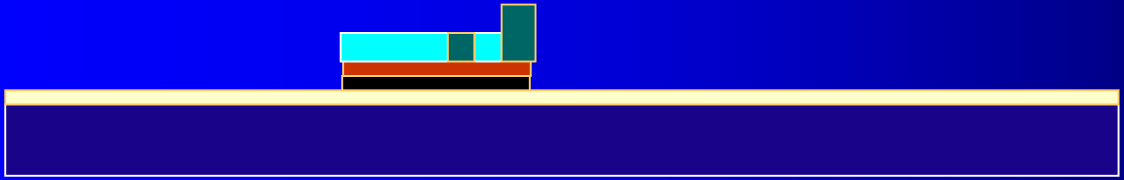
SU8/Ni



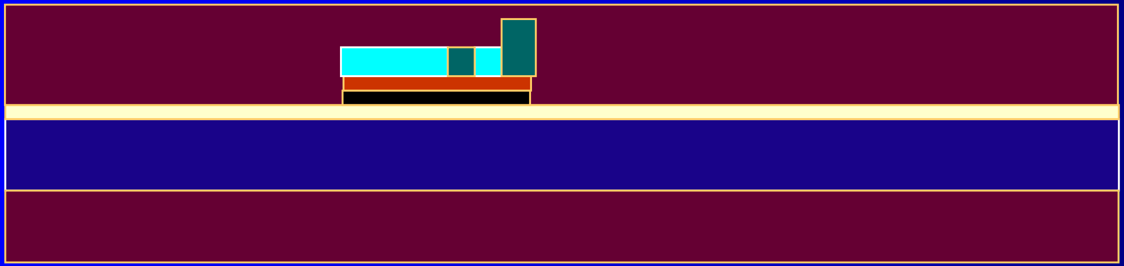
11. Plate second layer of Ni



12. Spin PR and etch the backside oxide with BOE



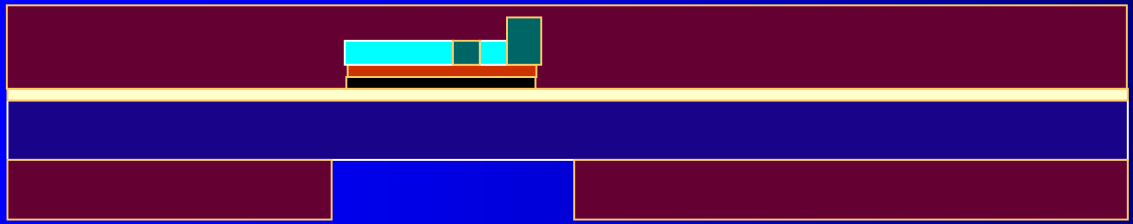
13. Strip the PR and etch the seed layers



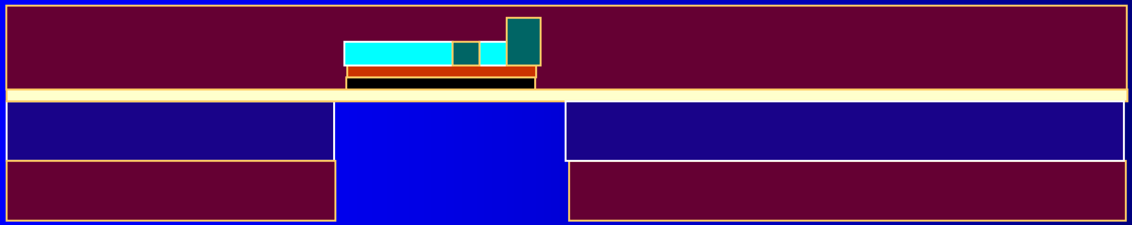
14. Spin resist on both sides of the wafer

Processing Sequence: SU8/Ni composite (cont.)

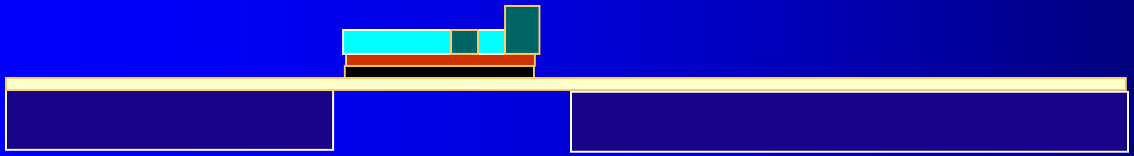
SU8/Ni



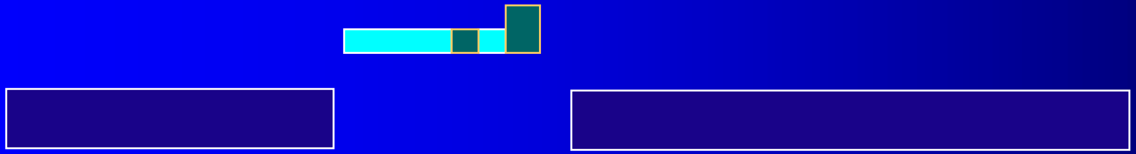
15. Pattern the backside photoresist



16. Etch the Silicon with DRIE



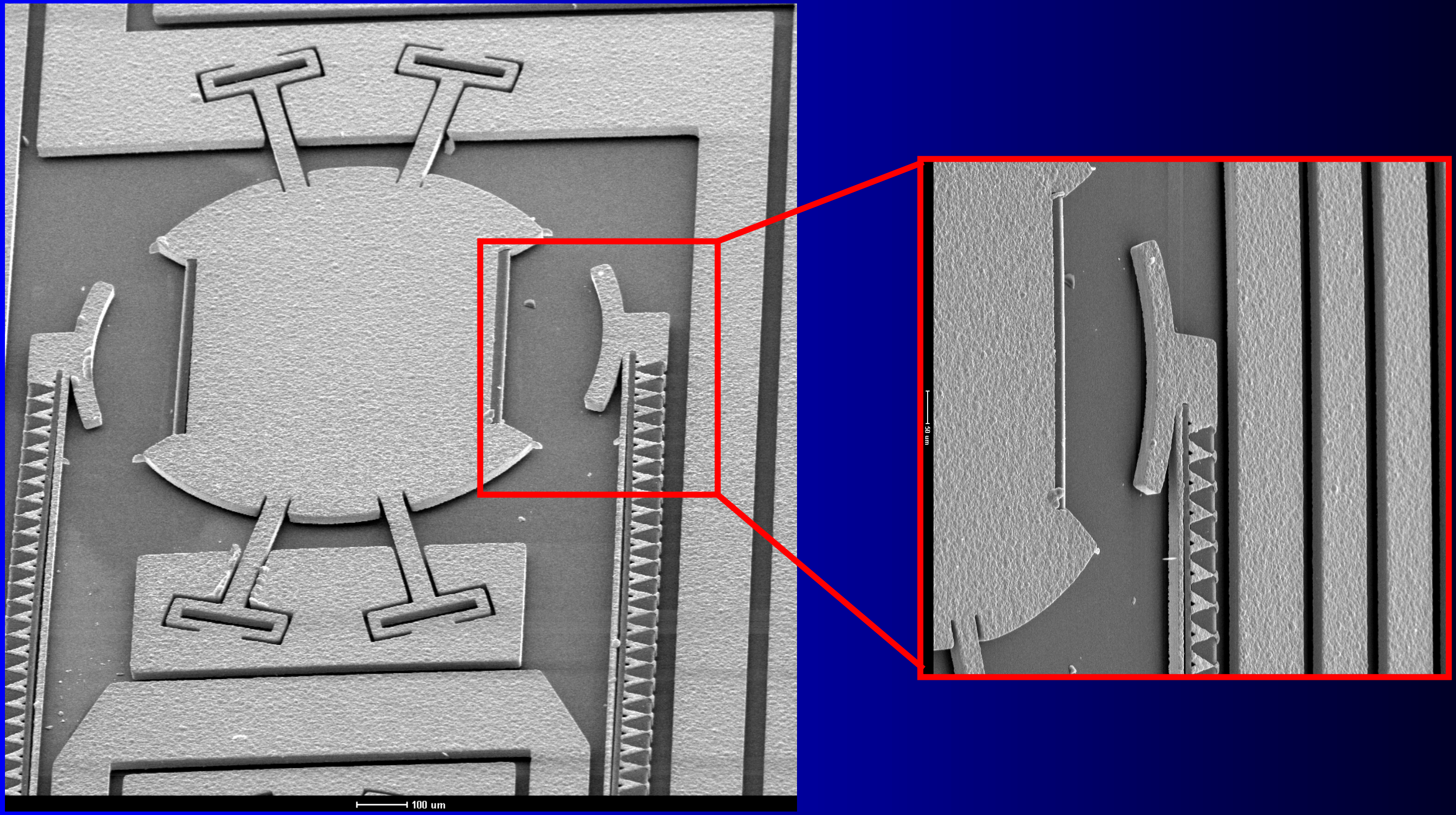
17. Remove the PR



18. Etch the exposed oxide and the seed layers

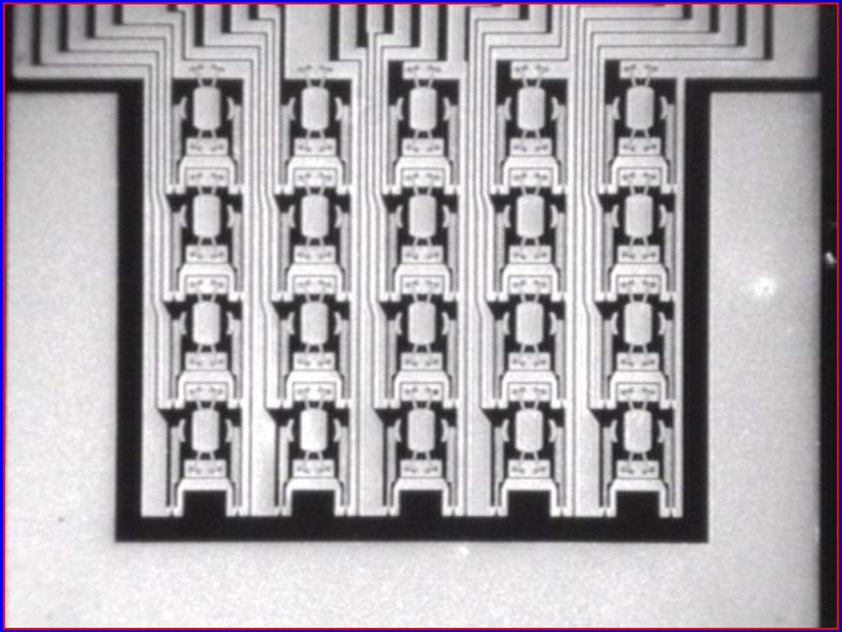
Single Thermal Actuator Pair (First Generation Device)

SU8/Ni composite actuator. SU8 has higher TCE allowing lowering of the operating temperature and power.

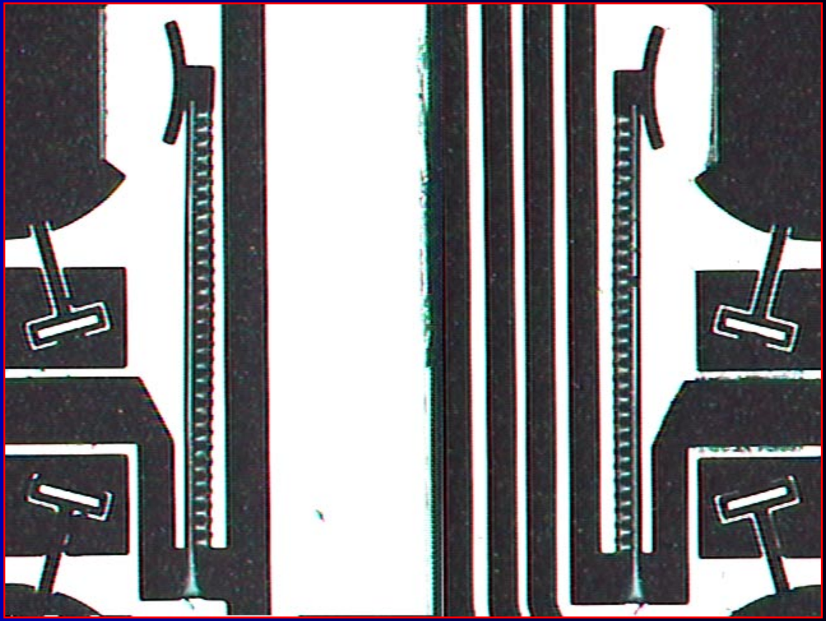


4 x 5 Tactile Array (First Generation)

Actuation Experiments

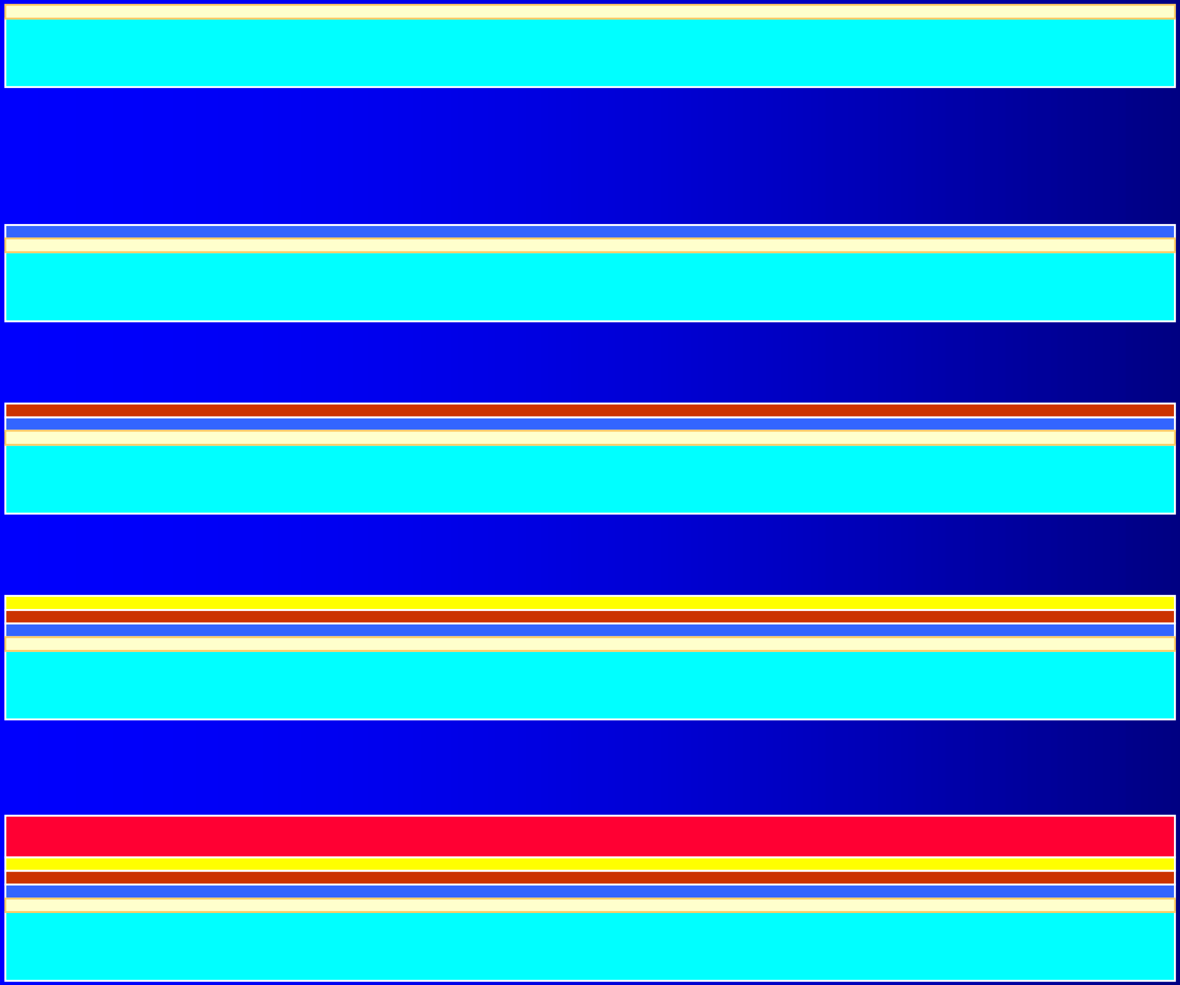


Fabricated Tactile Arrays



Single Pixel (movie)

Fabrication with SU8

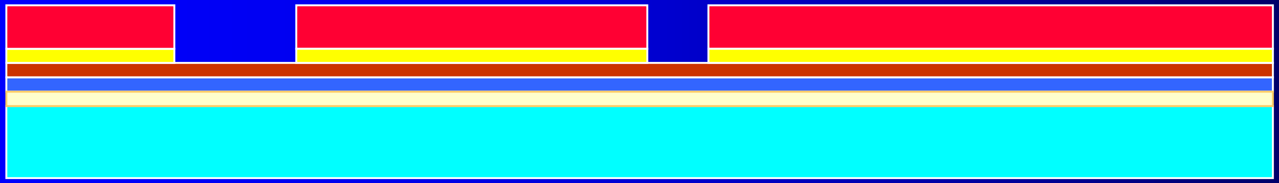


1. Wafer Oxidation
2. Deposit E-beam Ti
3. Deposit E-beam Cu
4. Spin OmniCoat
5. Spin SU8

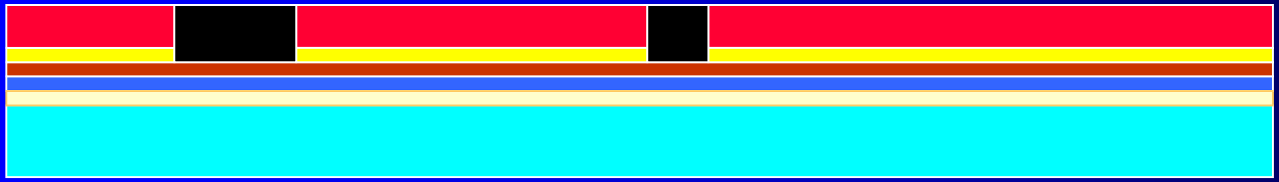
1/28/2004

Fabrication with SU8 (cont.)

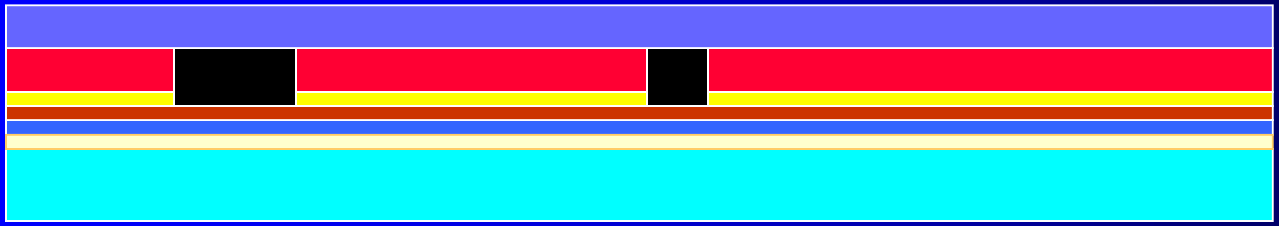
6. Pattern SU8



7. Etch OmniCoat
with oxygen plasma



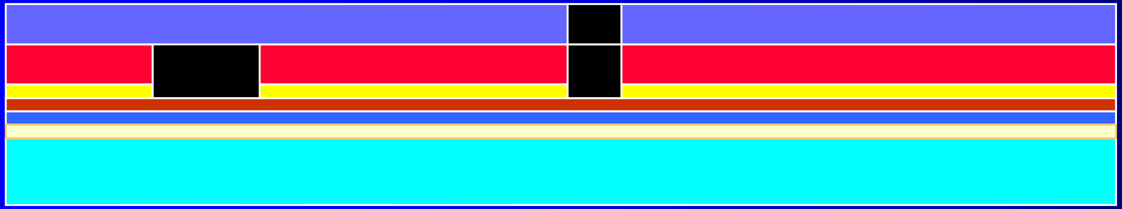
8. Plate Ni



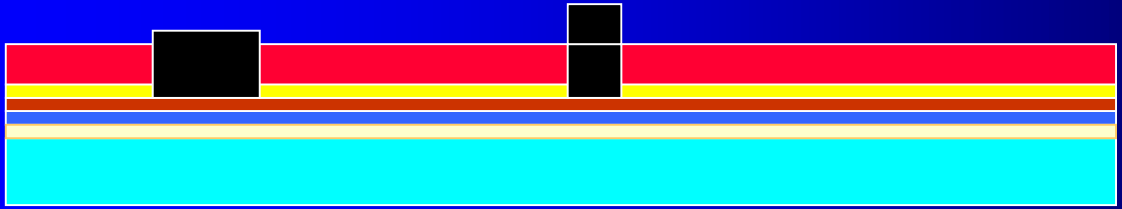
9. Spin AZ4903

Fabrication with SU8 (cont.)

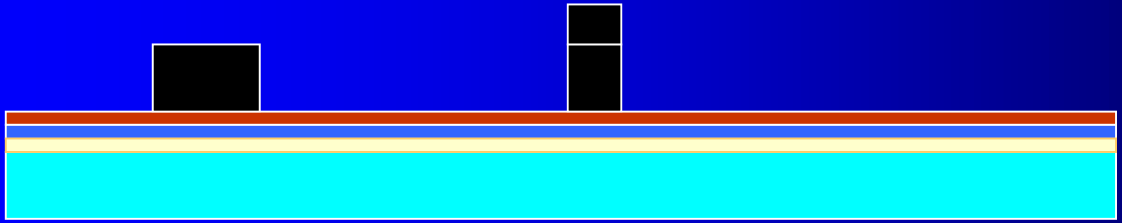
10. Pattern the PR



11. Electroplate Ni

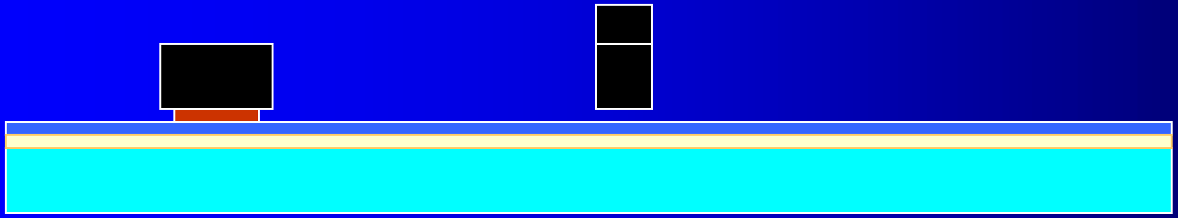


12. Strip the PR with acetone

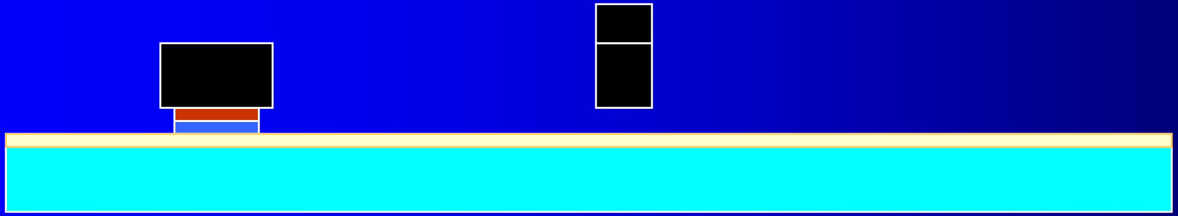


13. Remove SU8/ OmniCoat with PG

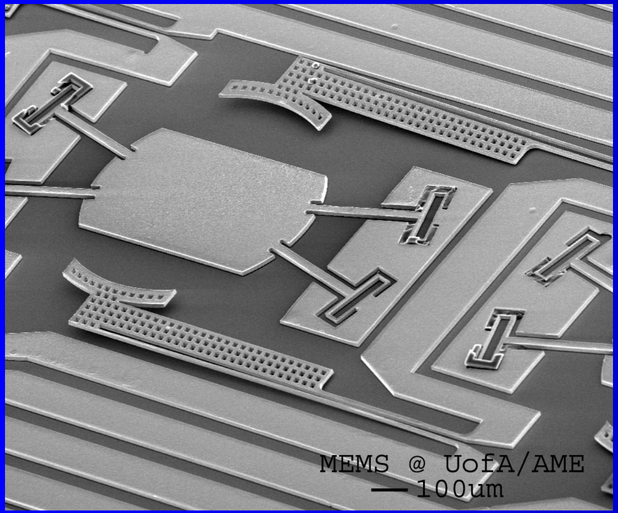
Fabrication with SU8 (cont.)

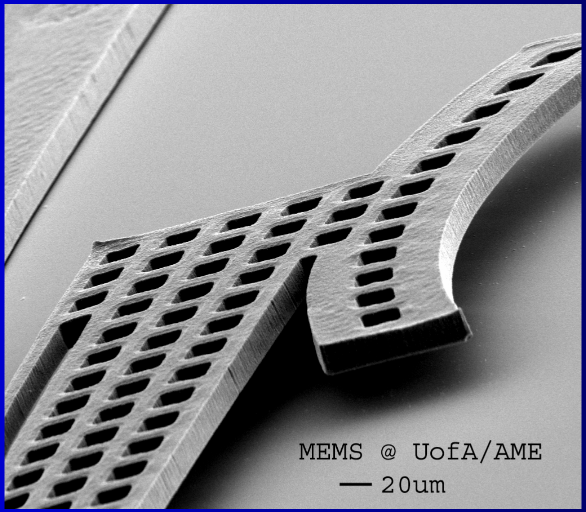


14. Etch the copper



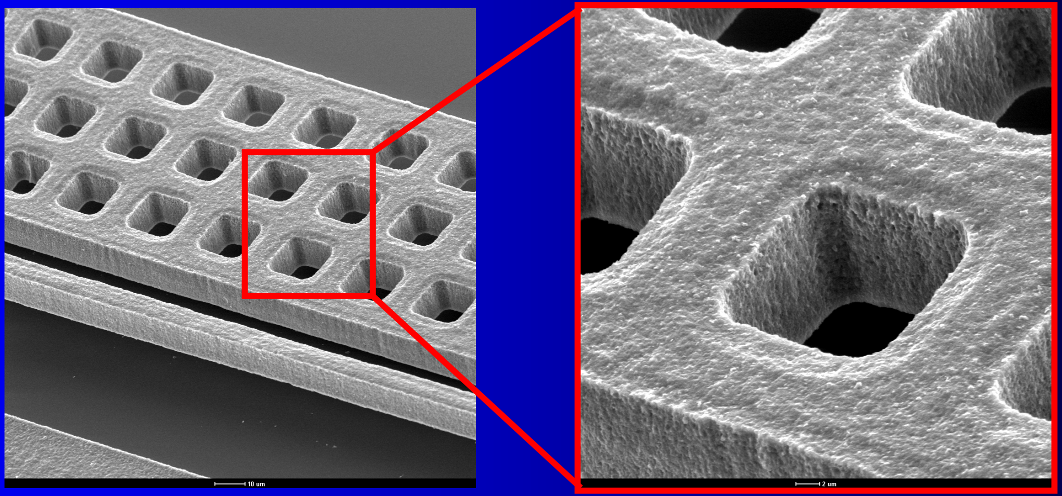
15. Remove theTi layer with HF dip





Advantages of SU8 process

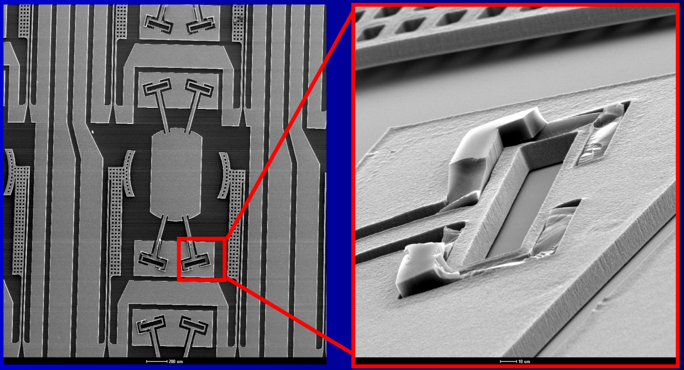
- The SU8 can achieve very high aspect ratios and up to 100 microns thickness

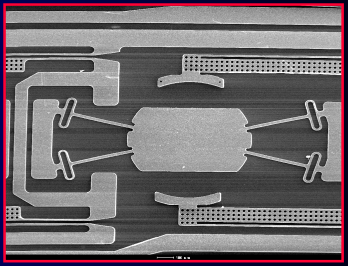


- SU8-Copper adhesion problem was solved by using OmniCoat (used also as a release layer)

Problems with SU8

- The main difficulty with SU8 plating is the mold removal. Since SU8 is epoxy, it is highly cross-linked and therefore difficult to etch.
- The SU8 is chemically attacked by PG remover and is cleaned completely from the large areas after approximately 1 hour
- The remaining SU8 is ***mechanically*** lodged between the fine lines but is detached from the seed layer
- Ultrasound and water jet is required
- The nickel etchant has to be carefully chosen
- The yield is an issue





Better Design

Possible Solution with SU8

Nickel etchant advantages:

- Removes the residual SU8 on the sidewalls of the plated features
- Helps remove the SU8 prisms for the release holes
- Loosens the large pieces of SU8

Problems

- Nickel etchants may attack the copper seed layer which is a problem for the second plating
- Some etchants modify the uncured SU8 and make it difficult to remove (stiff)

Issues with Second Ni Layer

Problems with plating on SU8

- Difficult SU8 release after plating with thick resist mold. The SU8 becomes stiff and cannot be peeled off with PG
- Thin resist is less harsh on the SU8 but does not hold well in the electroplating bath during reverse plating (etching). The etching is needed for good adhesion between the two nickel layers

Solution to this problem:

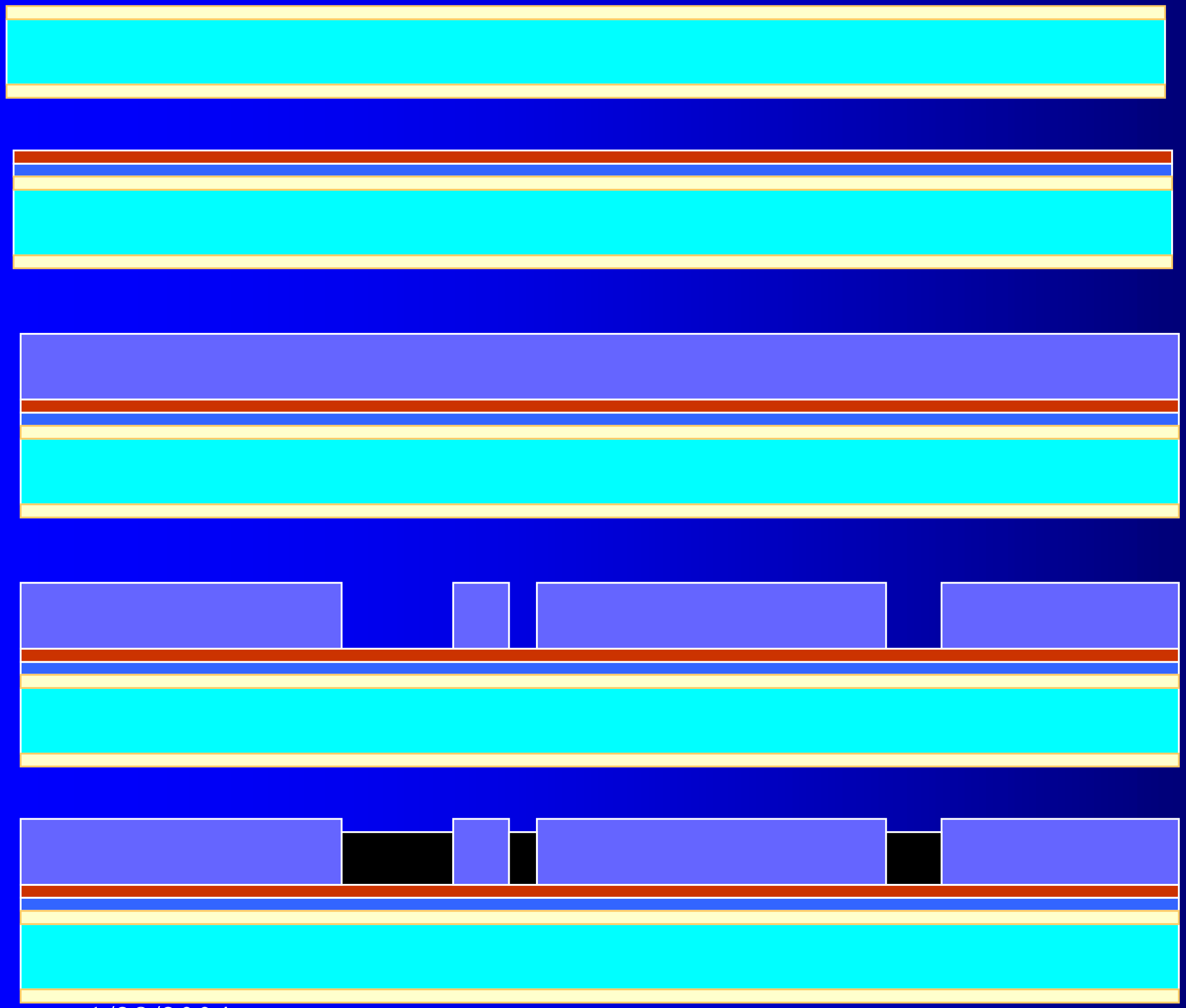
- Remove the SU8 prior to plating

AZ4903 Process

- Photoresist limitations
  - Thinner films
  - Lower aspect ratio
  - More sensitive to processing tolerances (exposure,development)
  - Shape distortions due to the softness of the resist
  - Difficult to re-flow and therefore problematic spinning over severe topography (our case)
- Advantages
  - Well established technology
  - Removal is extremely easy – acetone
  - Multiple coats possible to increase the thickness
  - High yield

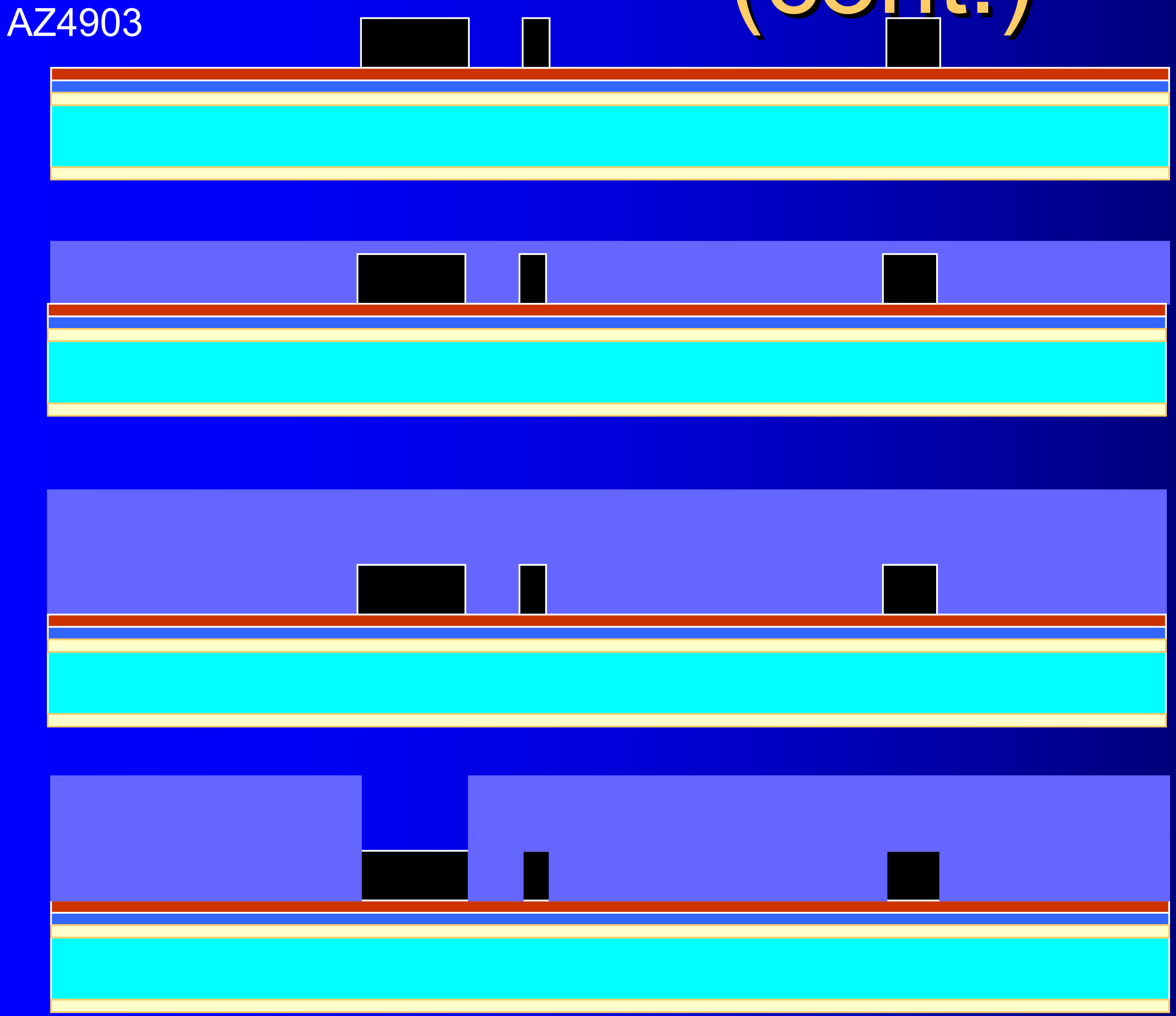
AZ4903 Process Sequence

AZ4903



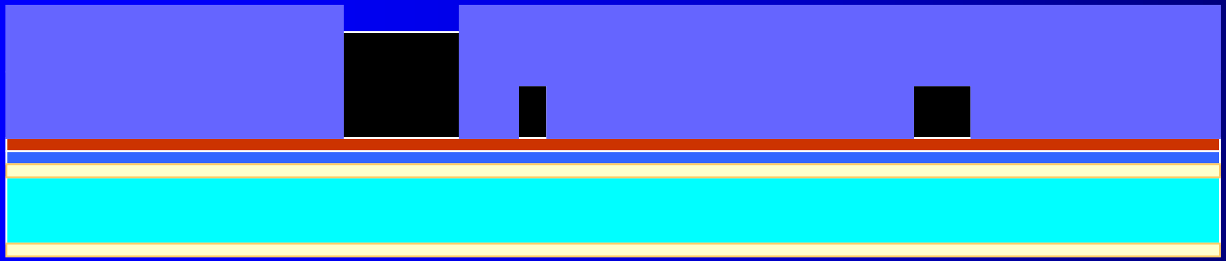
1. Wafer Oxidation
2. Deposit E-beam Ti/Cu
3. Spin PR-AZ4903
4. Pattern the PR
5. Plate Ni

AZ4903 Process Sequence (cont.)

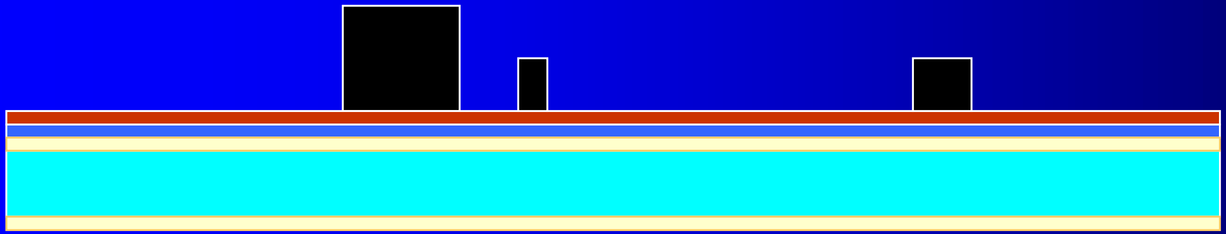


6. Strip the PR
7. Spin one layer of PR
8. Spin second layer of PR – AZ4903
9. Pattern the resist

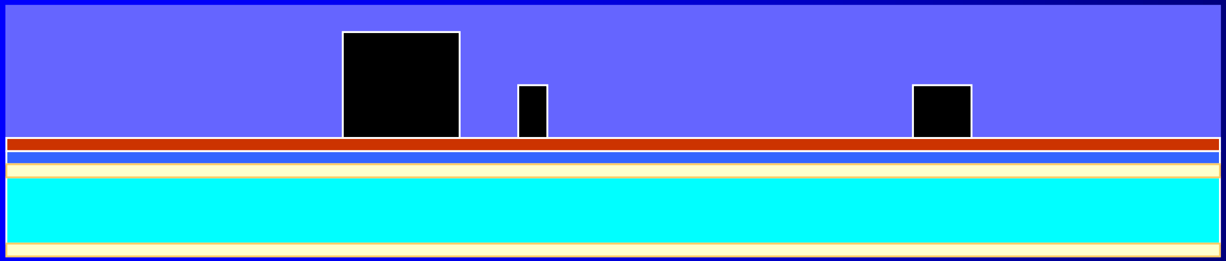
AZ4903 Process Sequence (cont.)



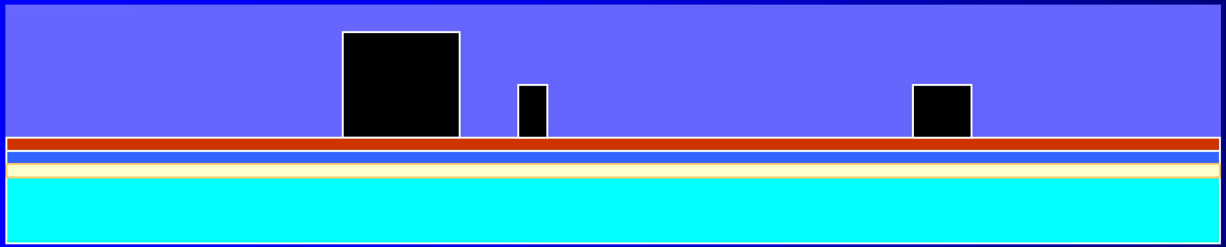
10. Plate second level of Nickel



11. Remove the PR

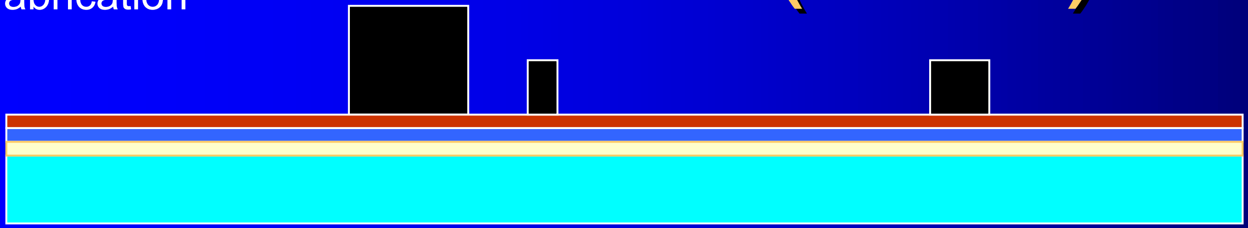


12. Spin PR

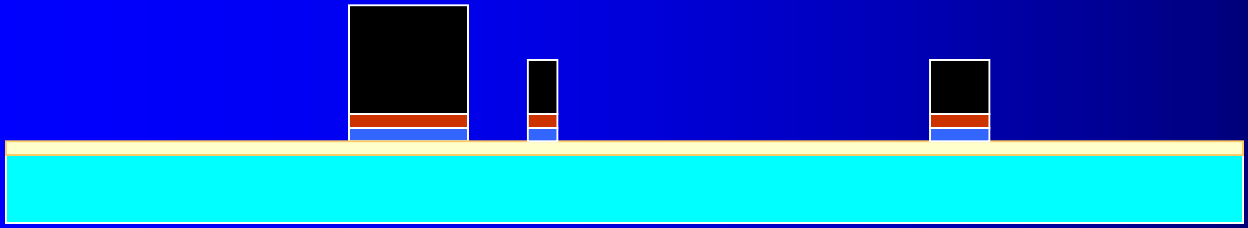


13. Etch the backside oxide with BOE

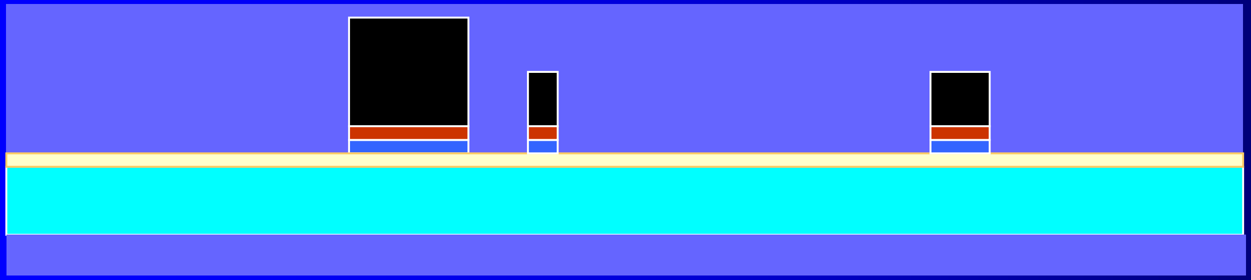
AZ4903 Process Sequence (cont.)



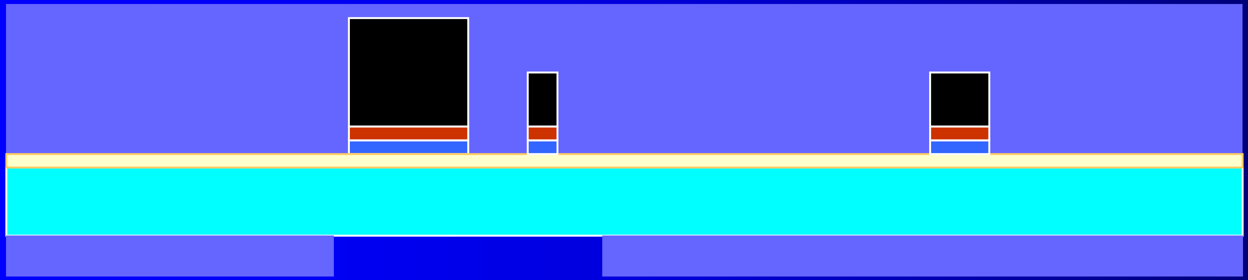
14. Remove the PR



15. Remove seed layer with copper etch and BOE

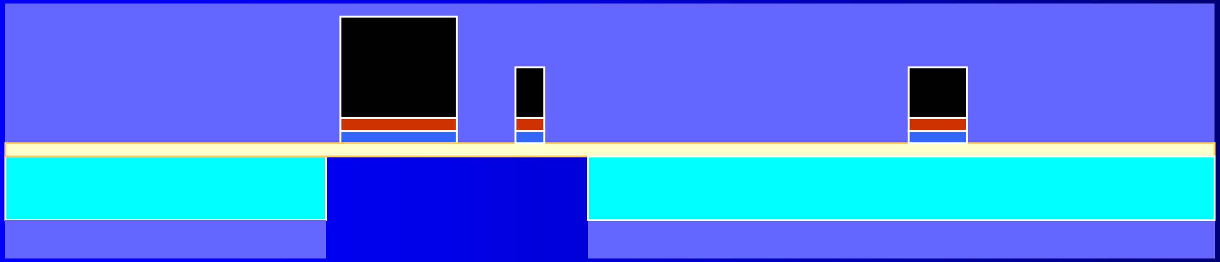


16. Spin PR on both sides of the wafer

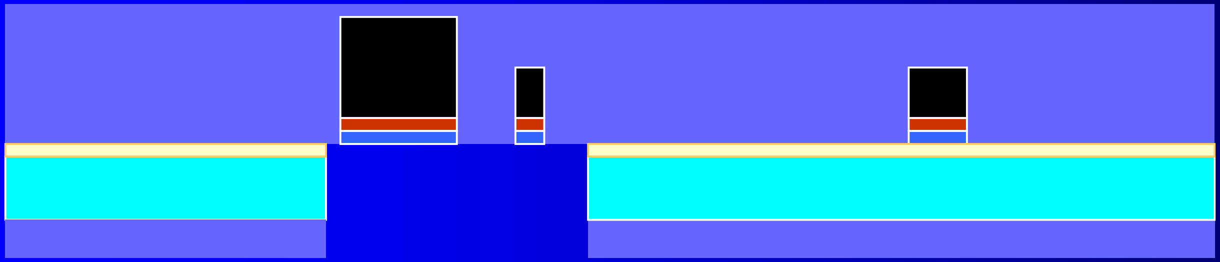


17. Pattern the backside PR

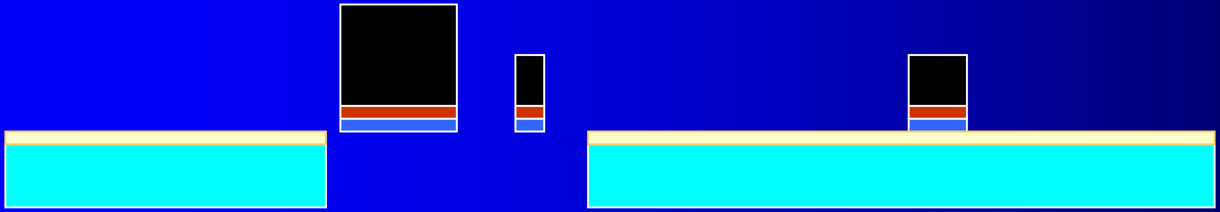
AZ4903 Process Sequence (cont.)



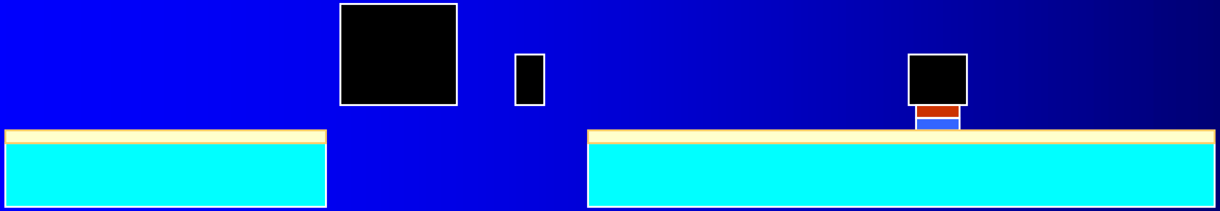
18. Silicon DRIE



19. Oxide etch

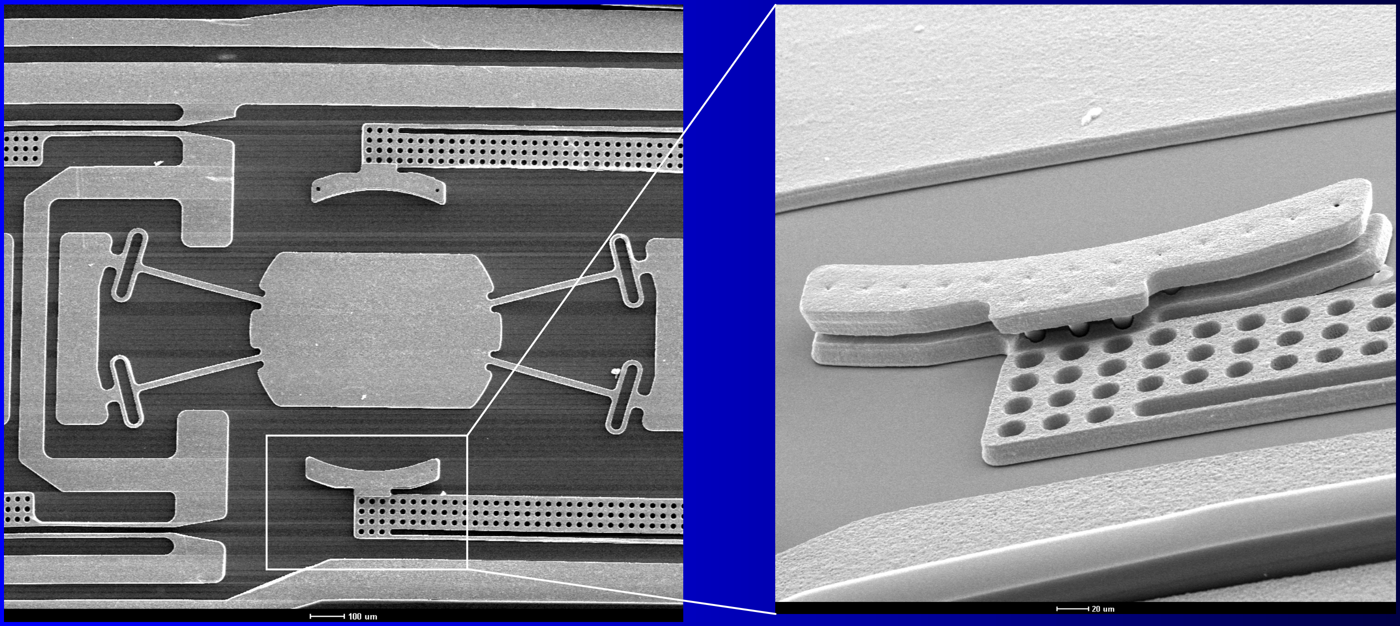


20. Remove PR

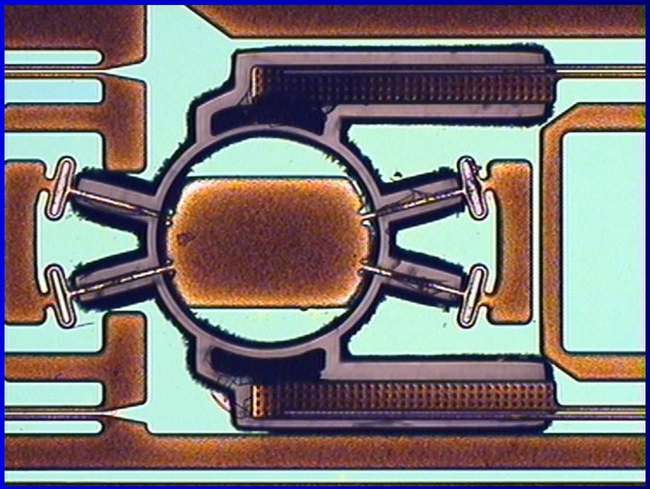


21. Remove seed layers and undercut

Third Generation Device (AZ4903 process)

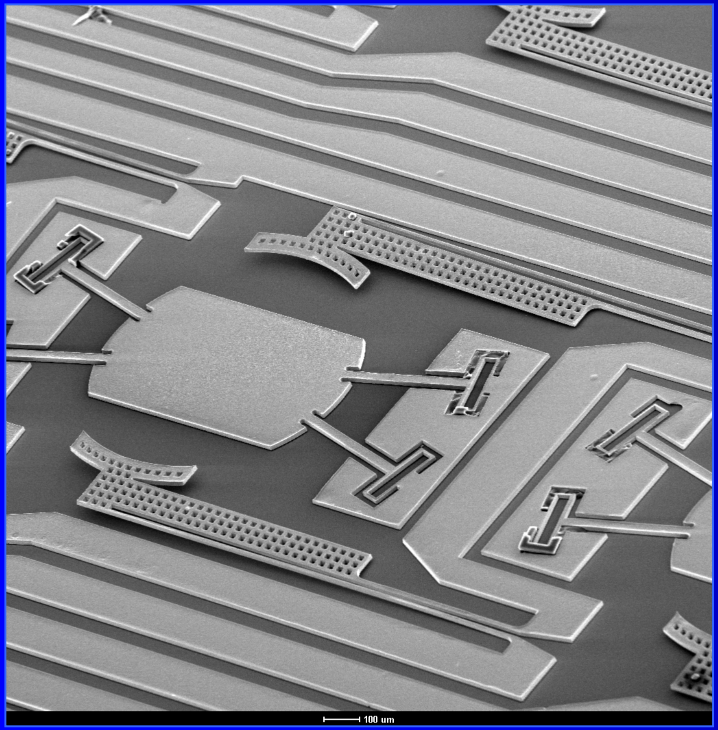


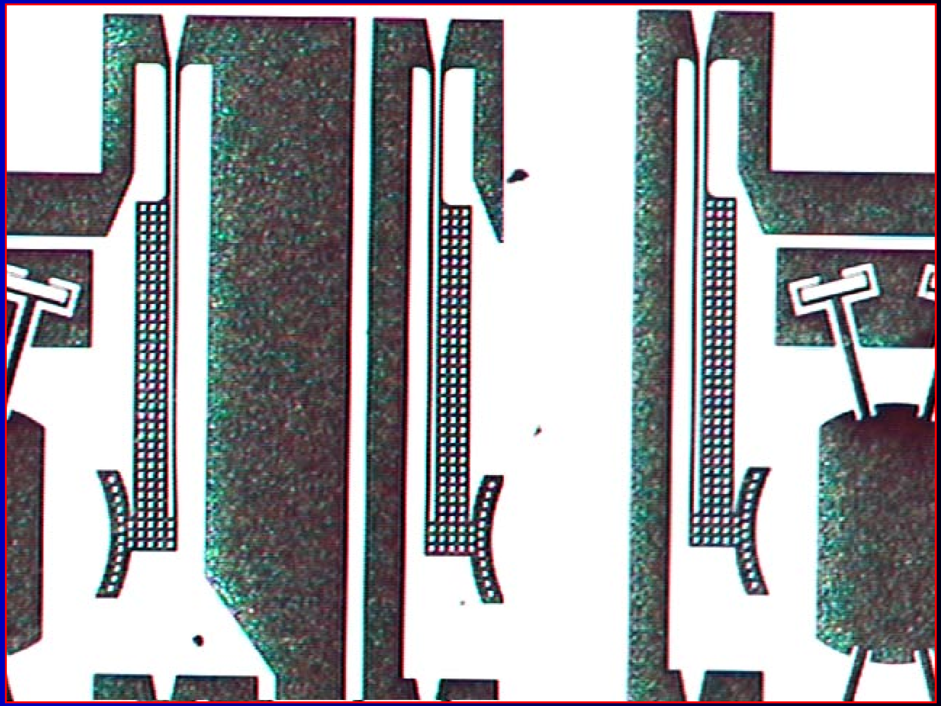
Before Si etching



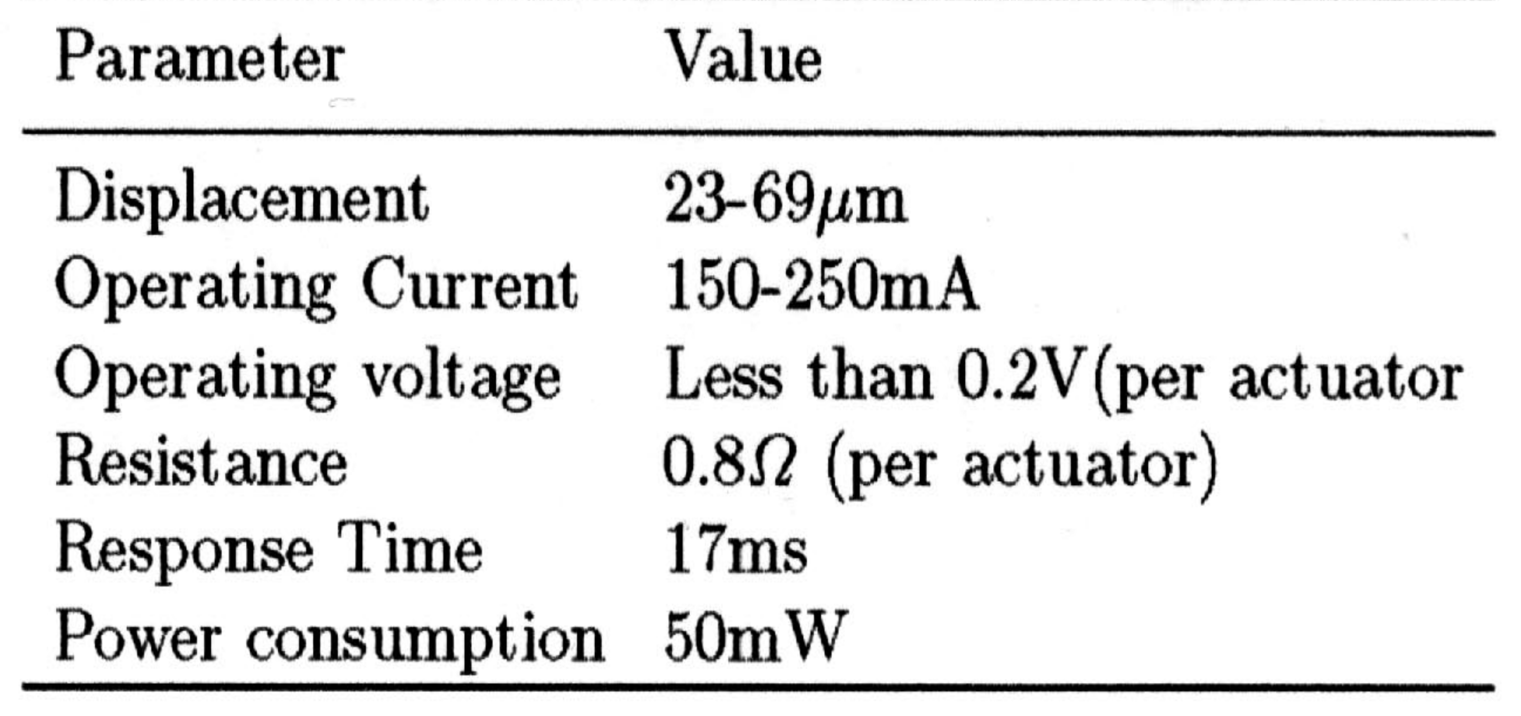
After Si etching

Actuation Experiments (second generation)



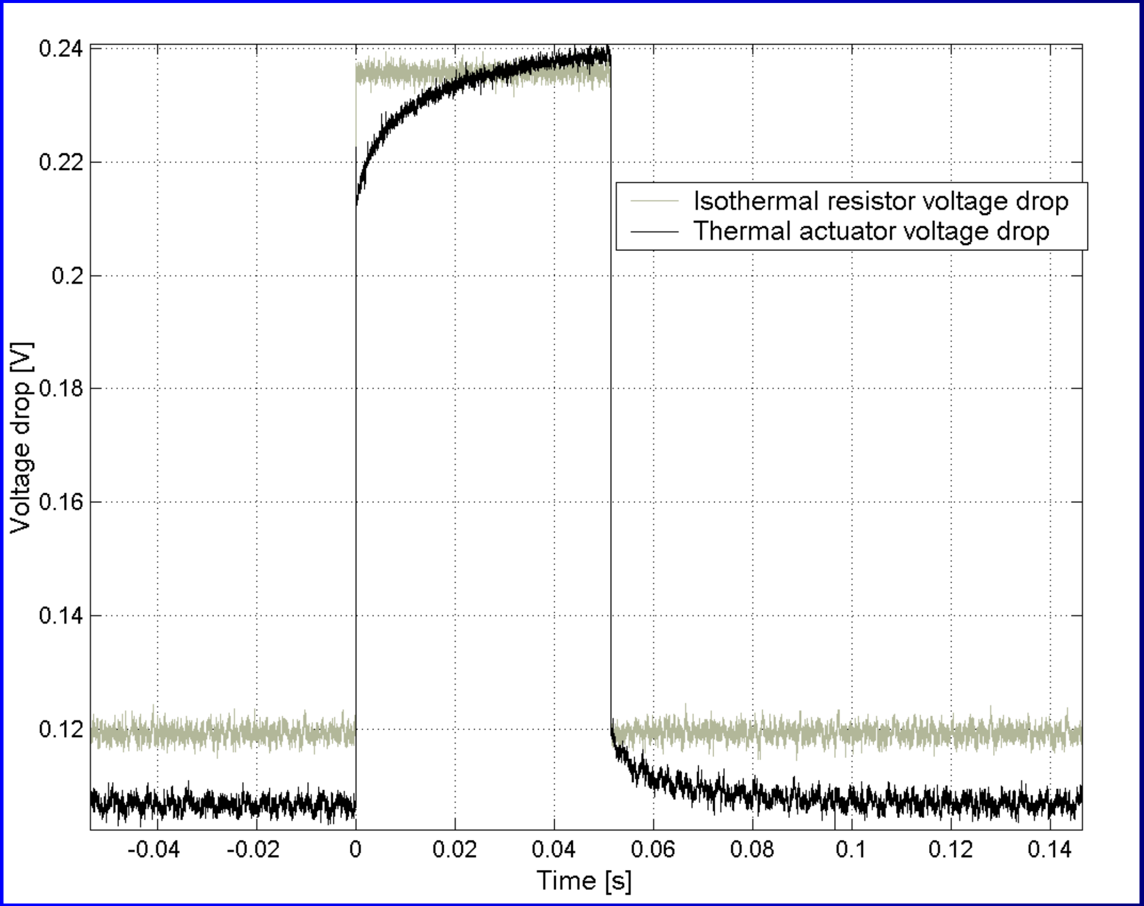


Actuation Data (SU8 based device)



Parameter	Value
Displacement	23-69μm
Operating Current	150-250mA
Operating voltage	Less than 0.2V(per actuator
Resistance	0.8Ω (per actuator)
Response Time	17ms
Power consumption	50mW

Transient Analysis Validation (SU8-base device)



$$T - T_0 = \Delta T e^{-t/\tau_{\text{th}}},$$

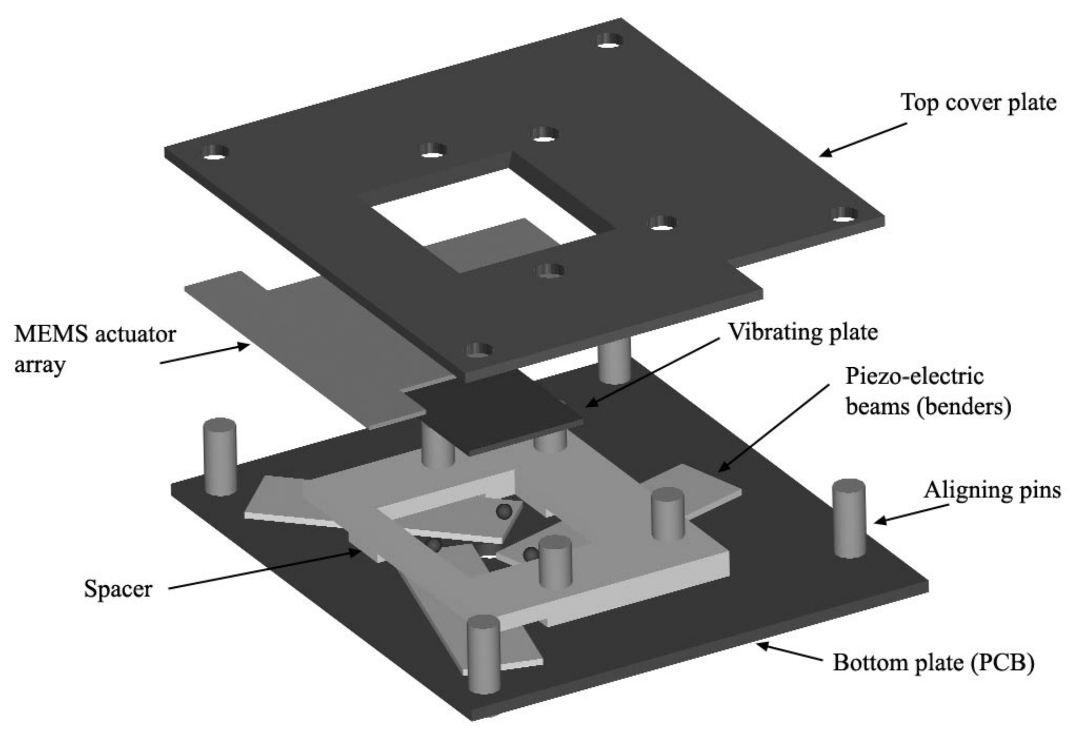
$$\Delta T = T_{\max} - T_0.$$

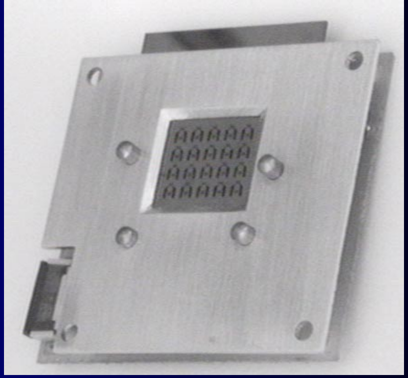
$$\Delta V = IR_{\text{tot}} = I\left(R_s + R_a\left(1 + \alpha \Delta T\right)\right)$$

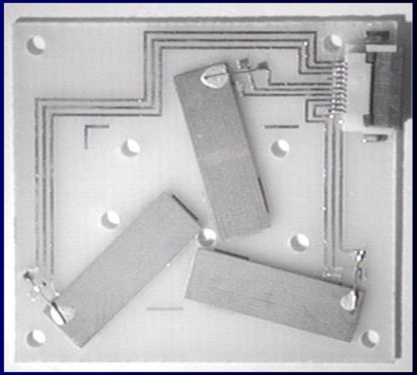
$$\Delta V = I\left(R_s + R_a\right) + I\alpha R_a \Delta T e^{-t/\tau_{\text{th}}}.$$

Thermal transient time measurement with a two-level current source

Assembly of Complete Stack: Piezoelectric + Thermal

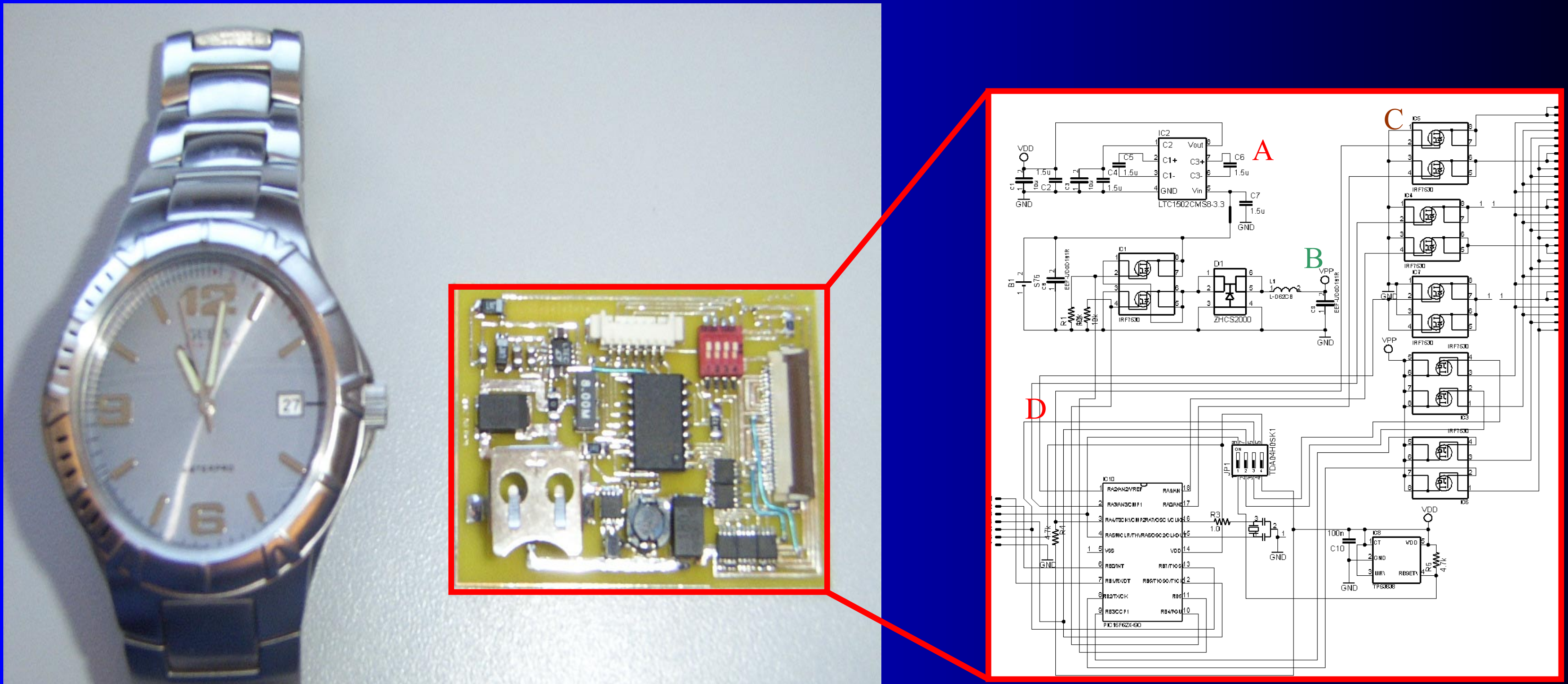






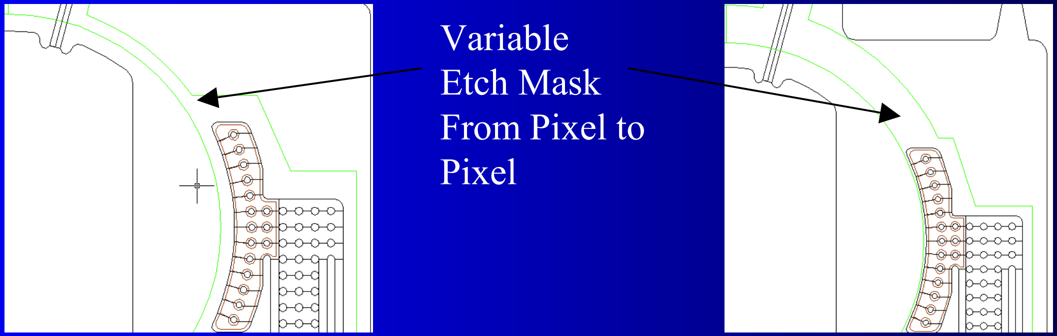
Vibrating Plate Assembly

Driver Circuit with Microprocessor



Current State

- The AZ4903-based device uses well-established process and is easy to reproduce
- The DRIE etching of the individual pixels produced larger then optimal gaps, requiring larger stroke from the thermal actuators.
- To resolve this process issue, a fourth generation device with variable gaps in the DRIE etching mask is being fabricated



Variable Etch Mask From Pixel to Pixel

Summary and Conclusions

- Three generations of the development of tactile communication array have been completed.
- The AZ4903 photoresist-based device is the most reproducible.
- DRIE etch is the single most expensive fabrication step ($400/wafer), which also introduces process variations due to the diverging etch profile.
- Preliminary experiments with the piezo benders confirmed that 20-30 μm displacements are perceivable. The required driving voltage of the piezo benders was 90V.
- The total power consumption was 80mW, which allows battery operation.
- A fourth generation device is being processed to determine the optimal etch gap for the DRIE step.

Acknowledgments

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- University of Arizona Small Grants Program
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