ME 141B: The MEMS Class Introduction to MEMS and MEMS Design

Sumita Pennathur
UCSB

Optical MEMS Case Study: MEMS-Based Projection Displays

Sumita Pennathur
UCSB

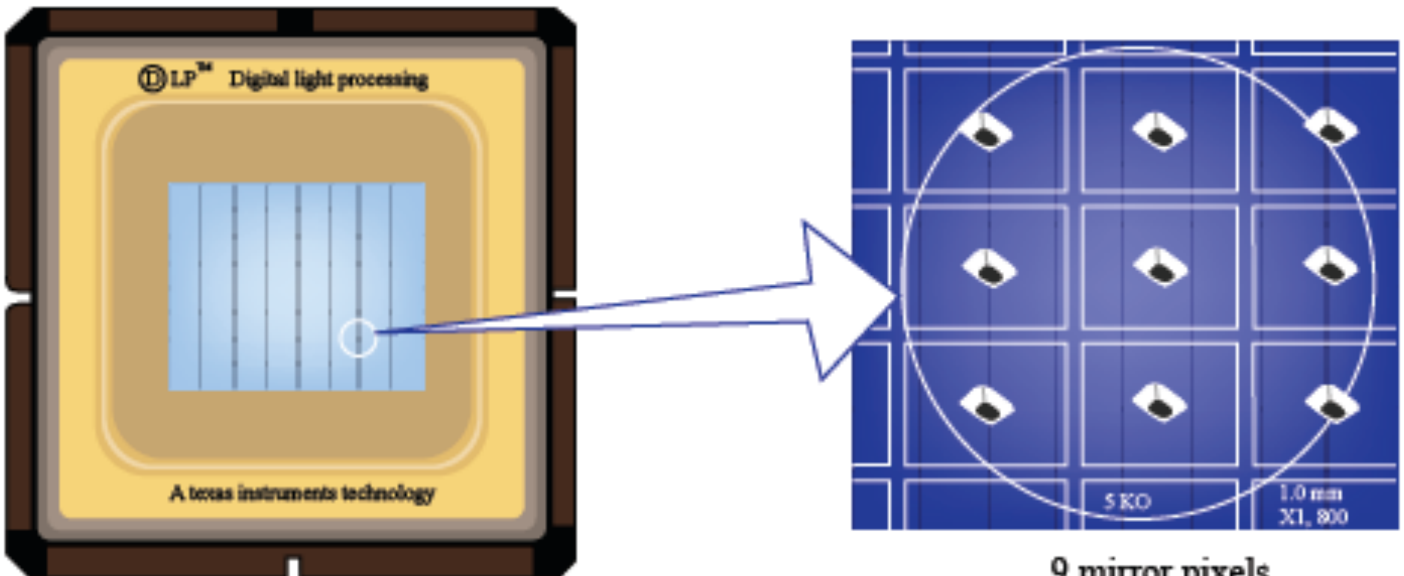
Optical MEMS

- MEMS = good for light
  - Structural dimension on same order as wavelength of IR or visible light
  - Can control reflection/diffraction with small movements
  - Microfabricating smooth surfaces = easy
  - Actuators for control of light → not a lot of work

Outline

- Reflection vs. diffraction
  - Texas Instruments DMD reflective display
  - Silicon Light Machines diffractive display
- DMD-based display: the basics
  - What it is
  - How it's made
  - How it works
- DMD-based display: the details
  - Reliability: why might this fail, and why doesn't it usually fail?
  - Packaging
  - Test Procedures

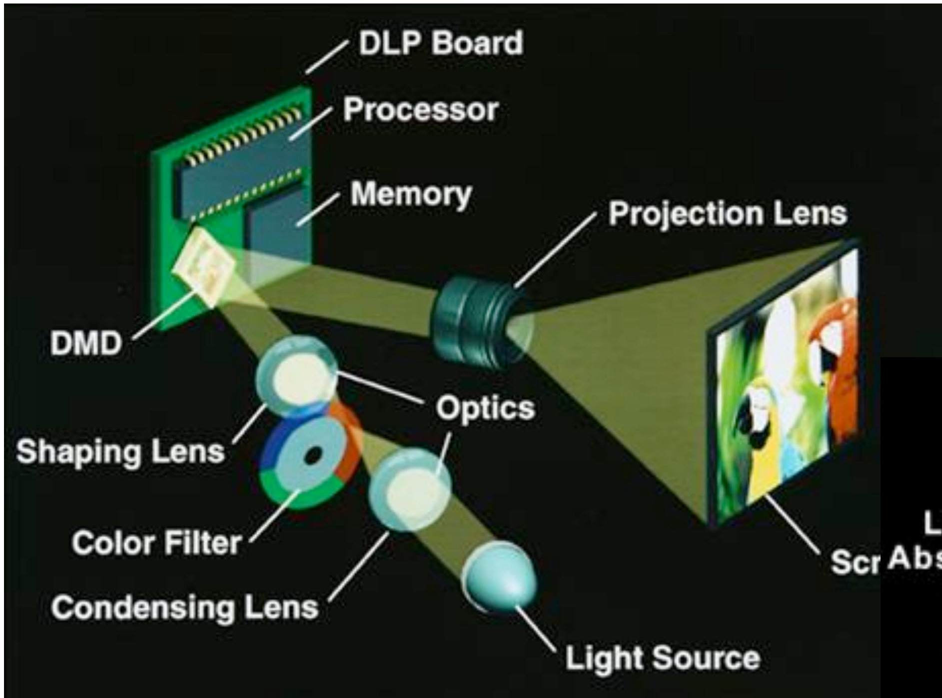
The Texas Instruments DMD

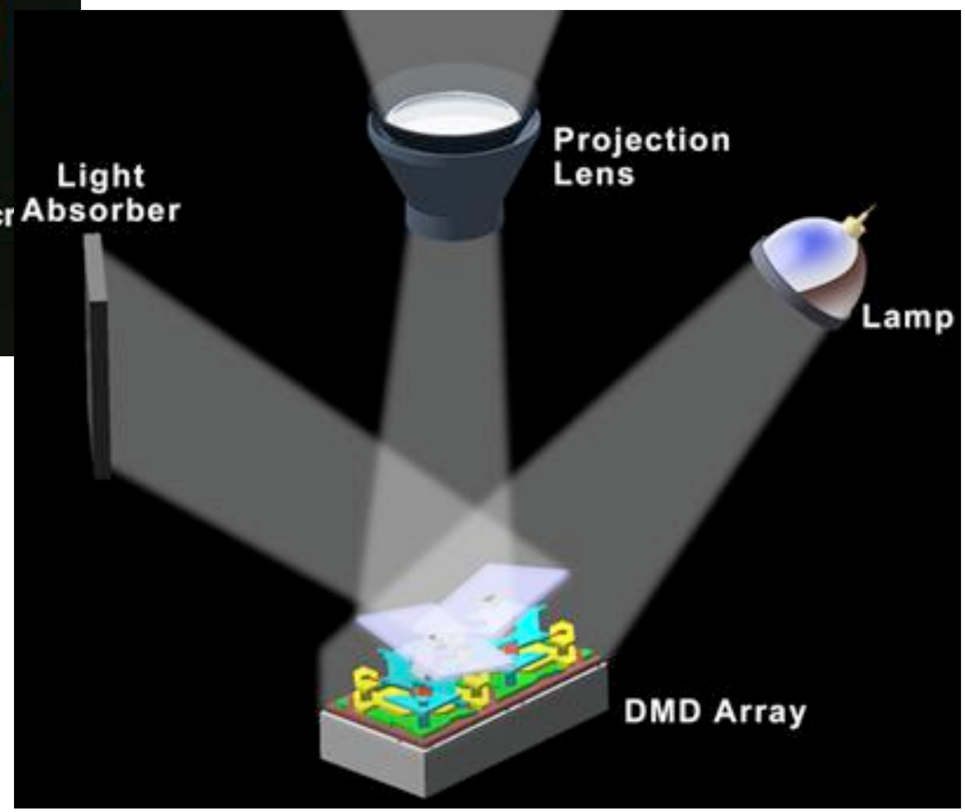


1,310,720 mirror pixels
(1280 x 1024)

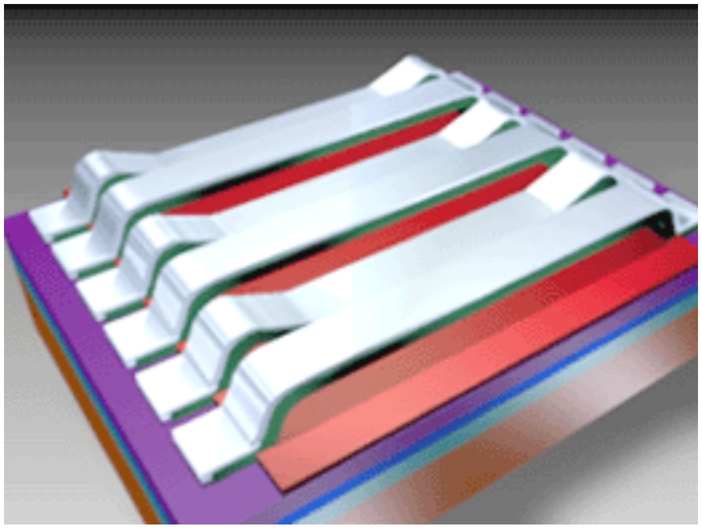
9 mirror pixels

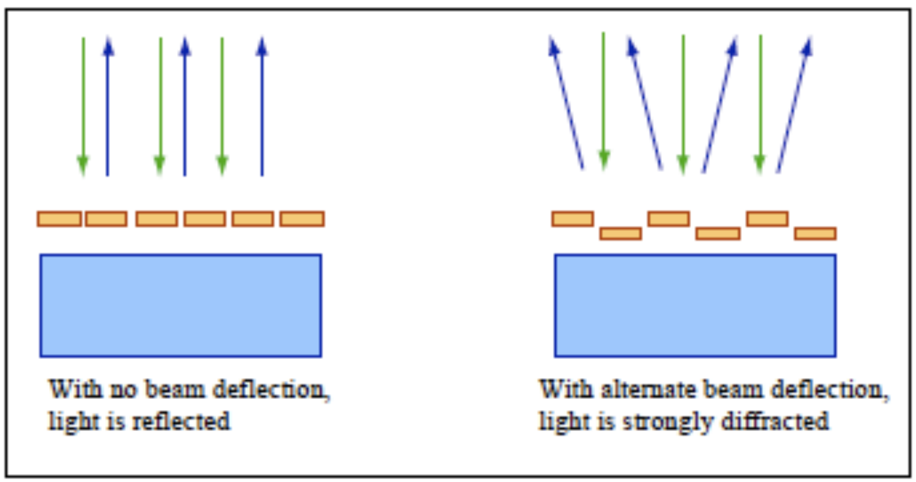
Projecting with the DMD





The Silicon Light Machines Approach

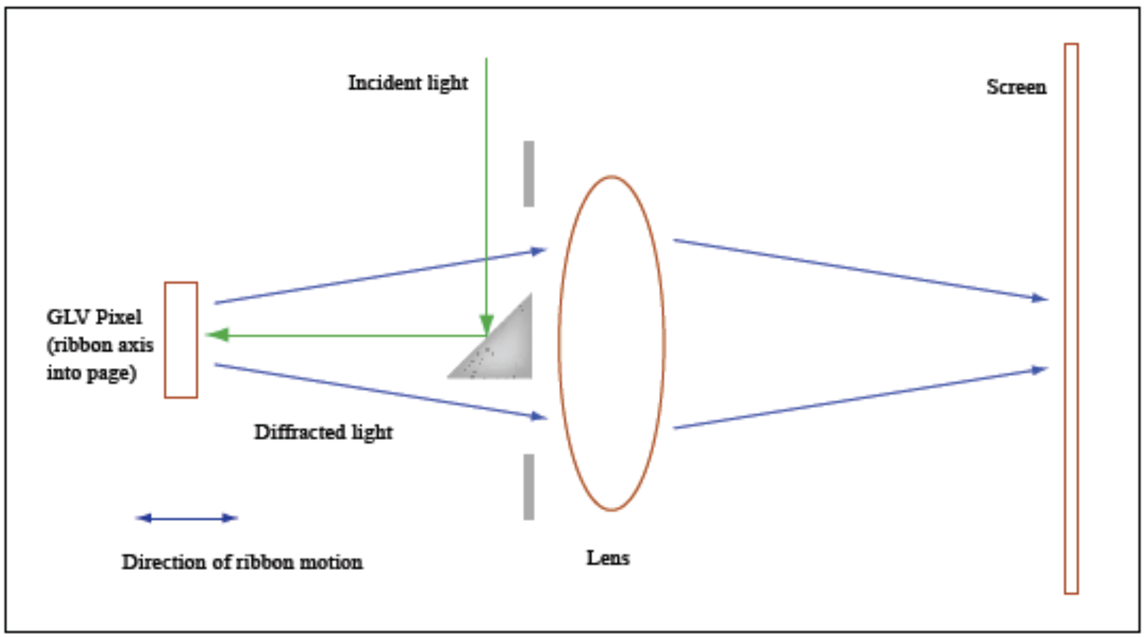




- Instead of using mirror, array of small electrostatically actuated diffraction gratings
- When unactuated → array reflects incident light back to source
- When actuated → array diffracts light @specific angle collected by optics
- Max diffraction -> of by quarter wavelength

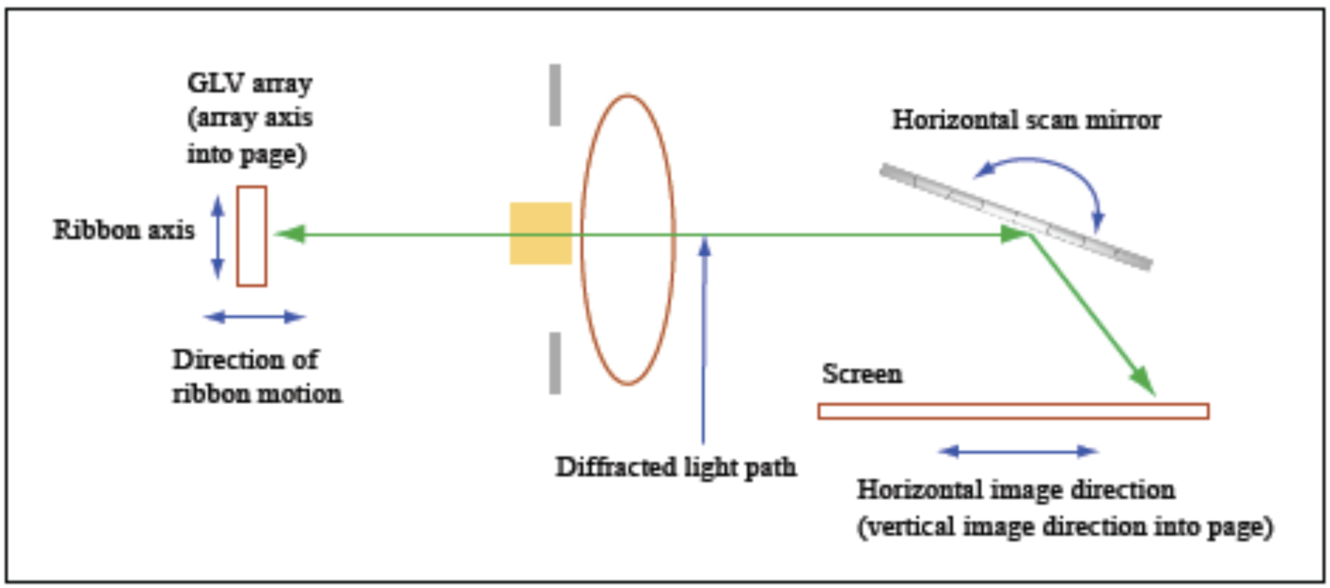
Pixel Operation

- Incoming light is directed onto pixel by centrally located mirror
- No actuation → screen is dark
- 2D array → linear array



Linear Array – Projection

- Linear array → can still get 2D projection
- Has horizontal scan mirror that moves
- Grayscale → adjusting the amount of time, but also can be manual → amplitude of grating display within a pixel



Both use suspended microstructures

- DMD
  - Supported by elastically linear torsional spring
  - As one electrode is actuated, electrostatic actuation tips mirror toward active electrode
  - Pull-in exceeded and mirror tips until it contacts landing pad
- GLV
  - Original device also used vertical pull-in until it contacted electrodes
  - Ok, but introduces problems with charging
  - Silicon Light Machines uses analog gray scale → amplitude of grating displacement within a pixel
  - No pull-in needed

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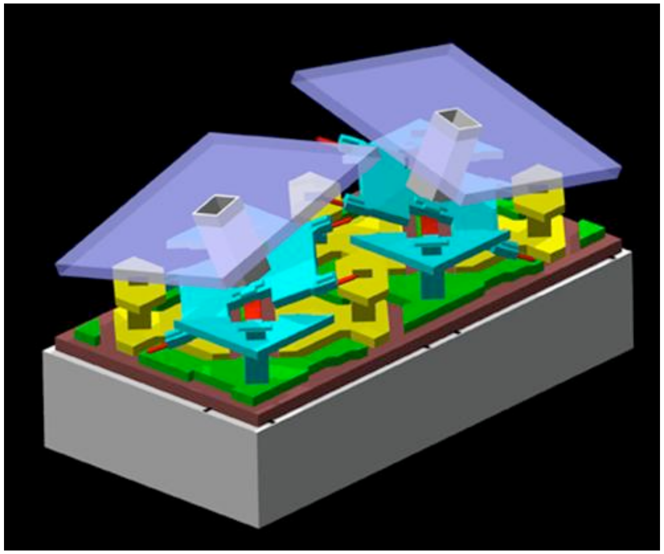
Timeline of the DMD at TI

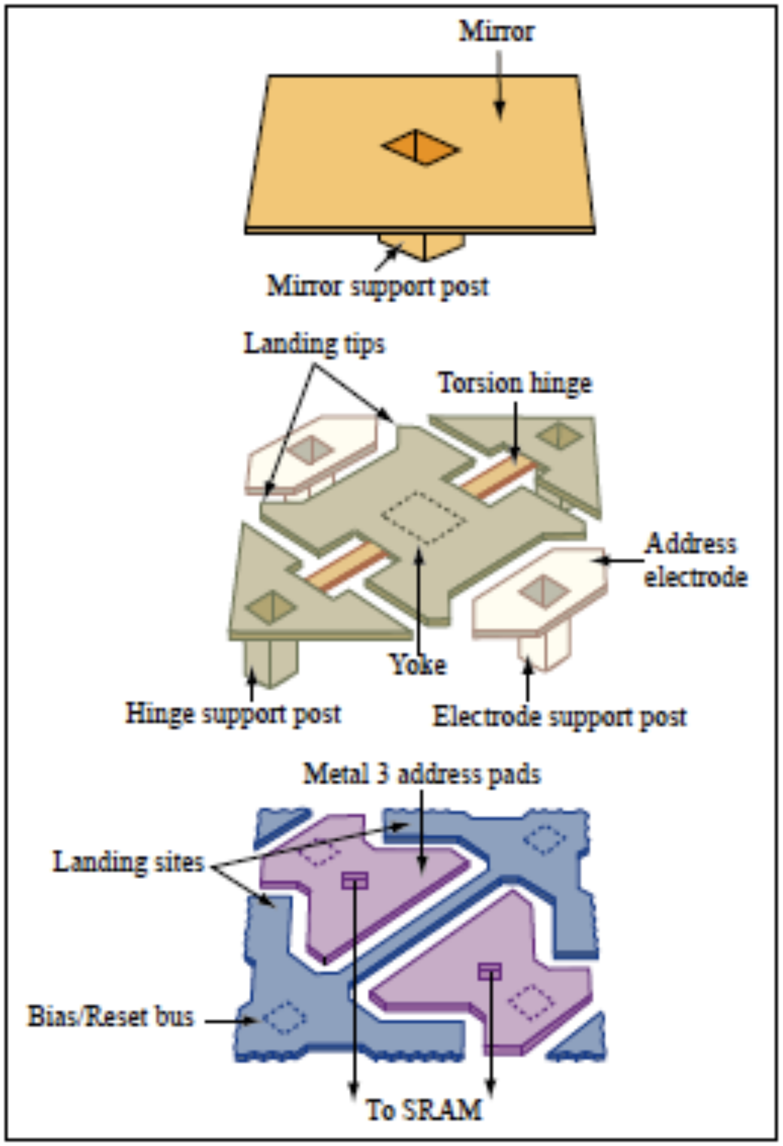
- 1977: Initial Explorations (DARPA contract)
- 1987: Demonstration of the DMD
- 1992: Is this commercially viable?
- 1994: Public demonstration of prototype
- 1996: First units shipped

- More than ten million units shipped
- Initial focus limited to projectors to establish base market
- Jump to TVs, theater projection
- Now branching out into other market: lithography, medical imaging, scientific imagine

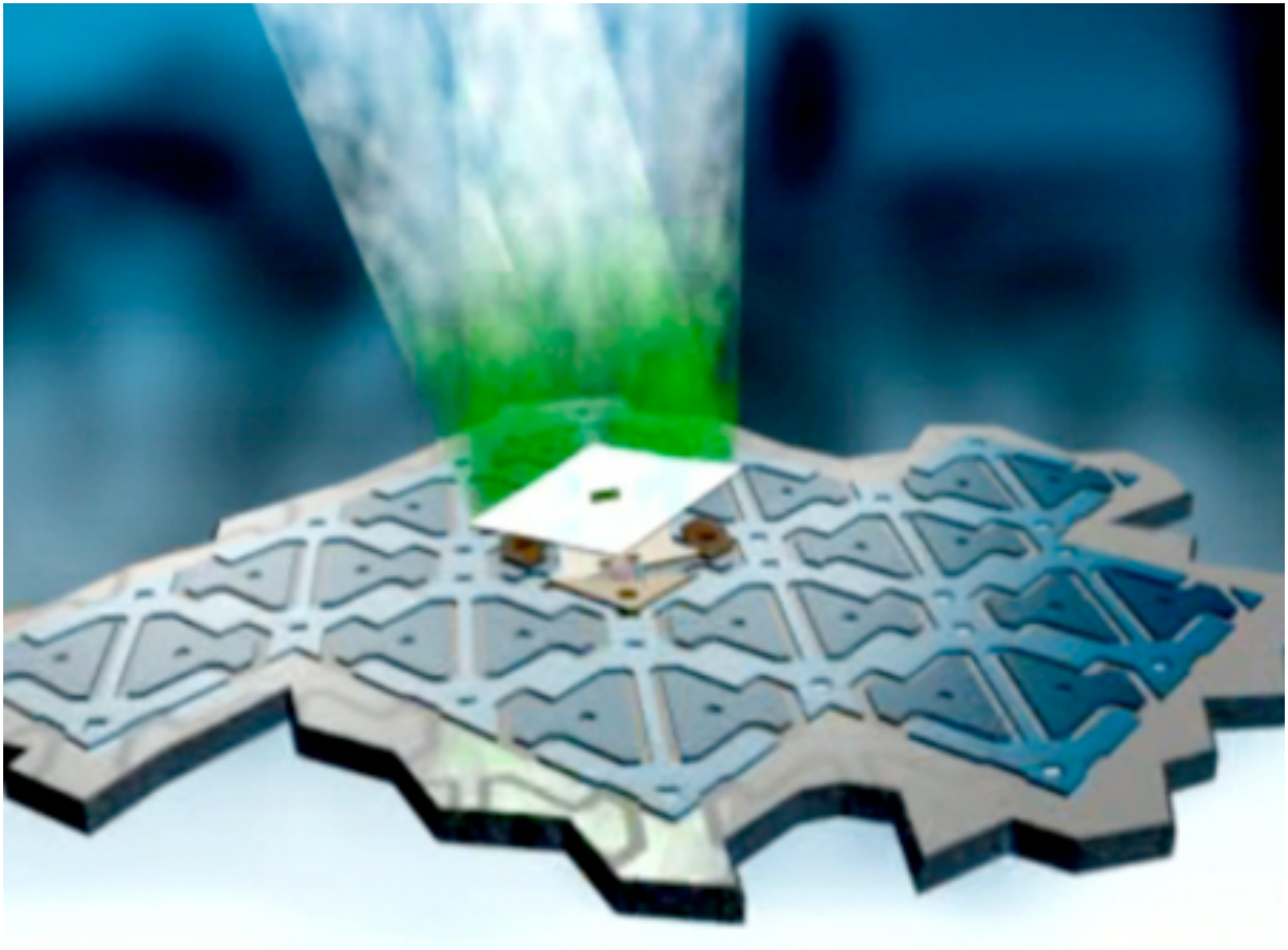
The pixels

- One mechanical mirror per optical pixel
- 16 um aluminum mirrors, 17um on center
- Address electronics under each pixel

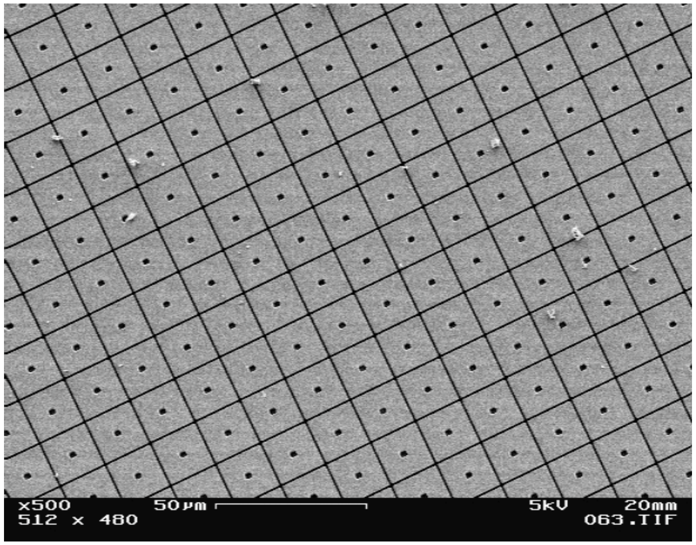


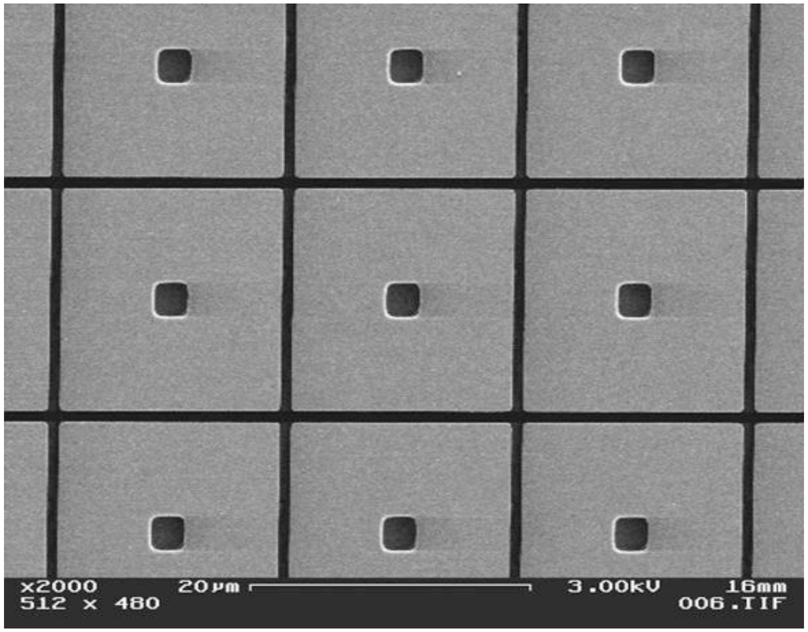


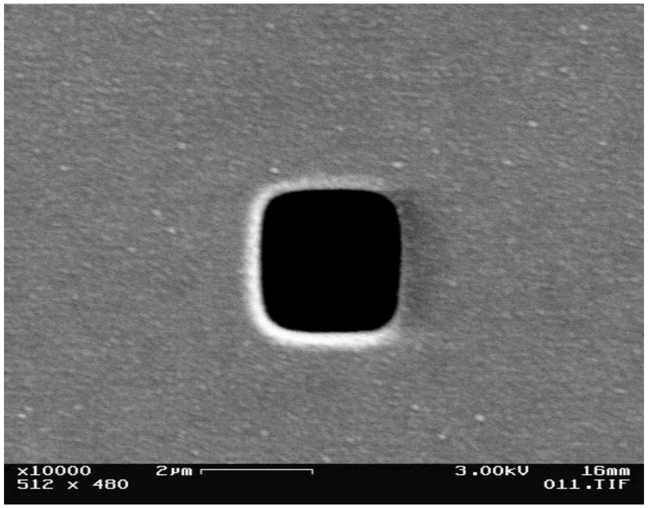
DMD Image



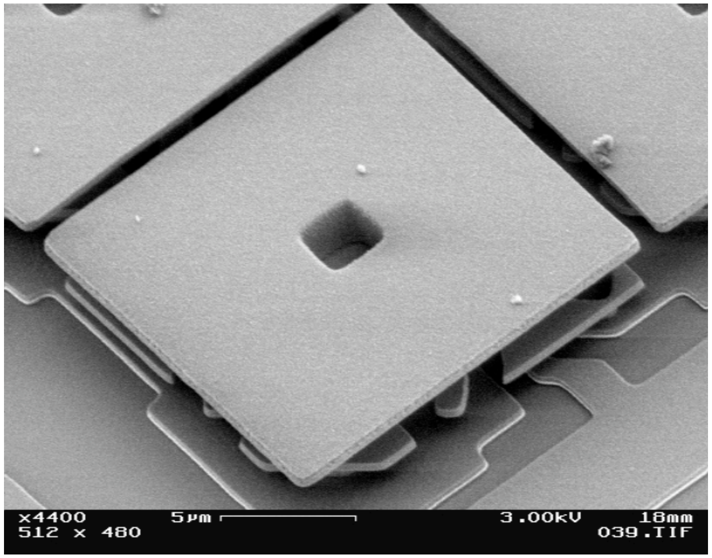
SEMs of DMD

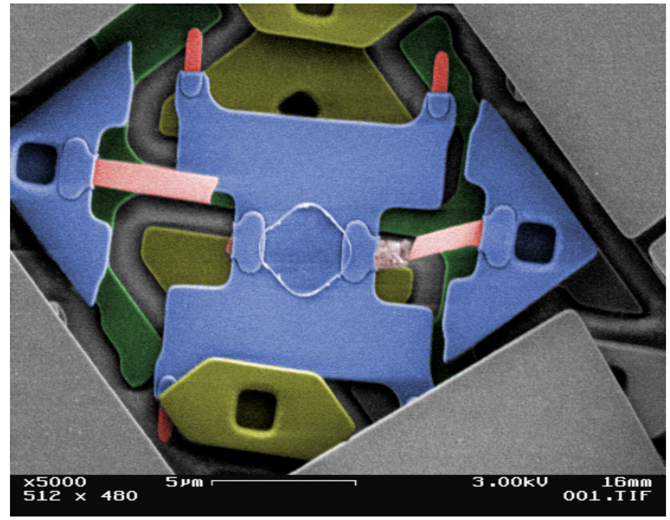

x500 50µm 5kV 20mm
512 x 480 063.TIF

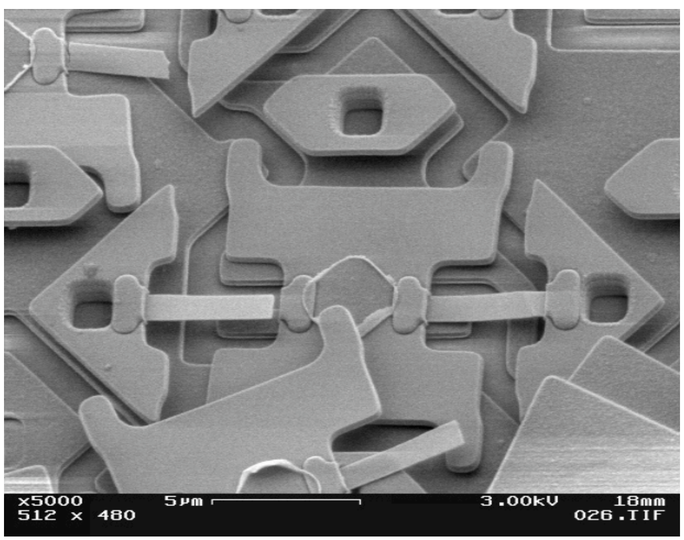

x2000 20µm 3.00kV 16mm
512 x 480 006.TIF

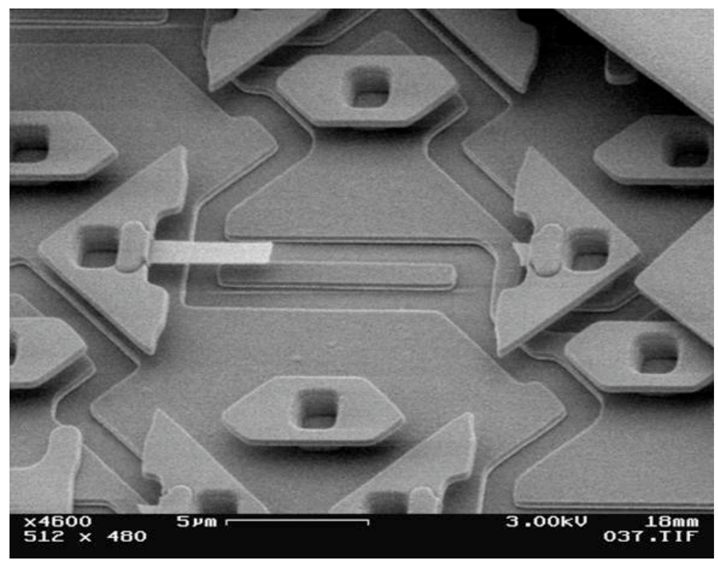

x10000 2µm 3.00kV 16mm
512 x 480 011.TIF

SEMs of DMD

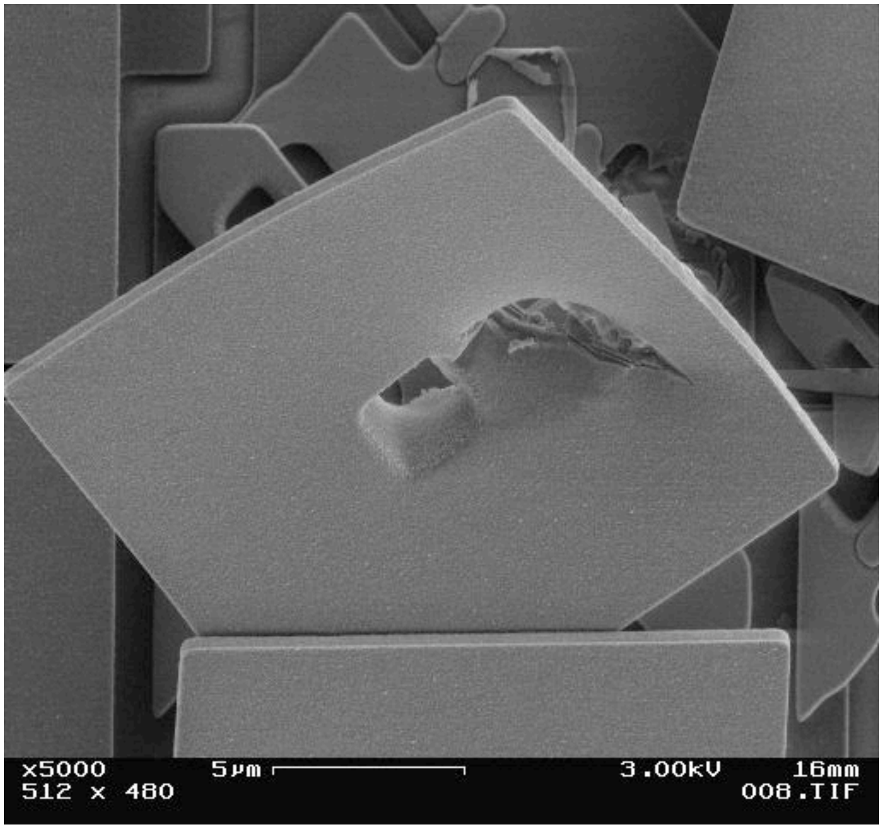

x4400 512 x 480
5µm
3.00kV 18mm 039.TIF

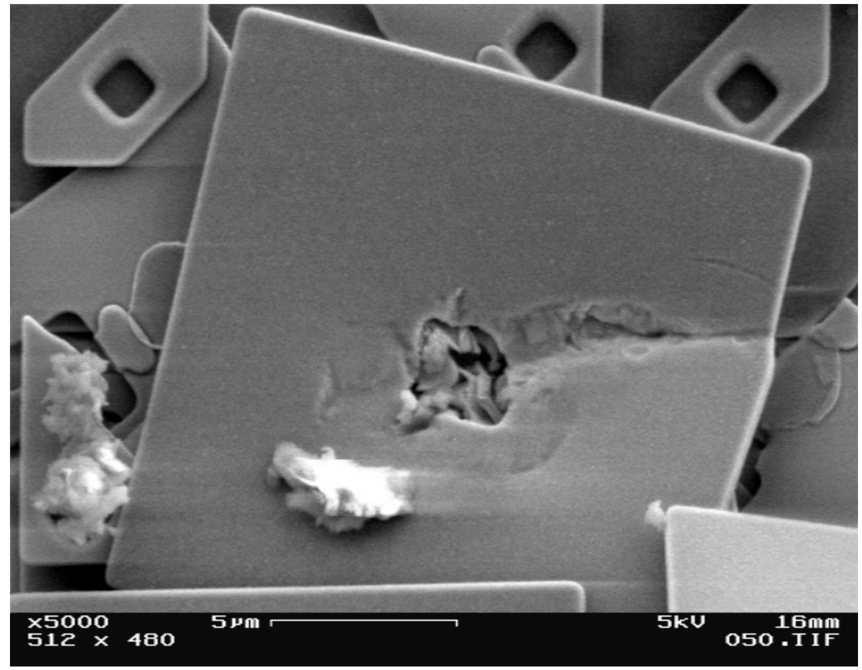

x5000 512 x 480
5µm
3.00kV 16mm 001.TIF


x5000 512 x 480
5µm
3.00kV 18mm 026.TIF


x4600 512 x 480
5µm
3.00kV 18mm 037.TIF

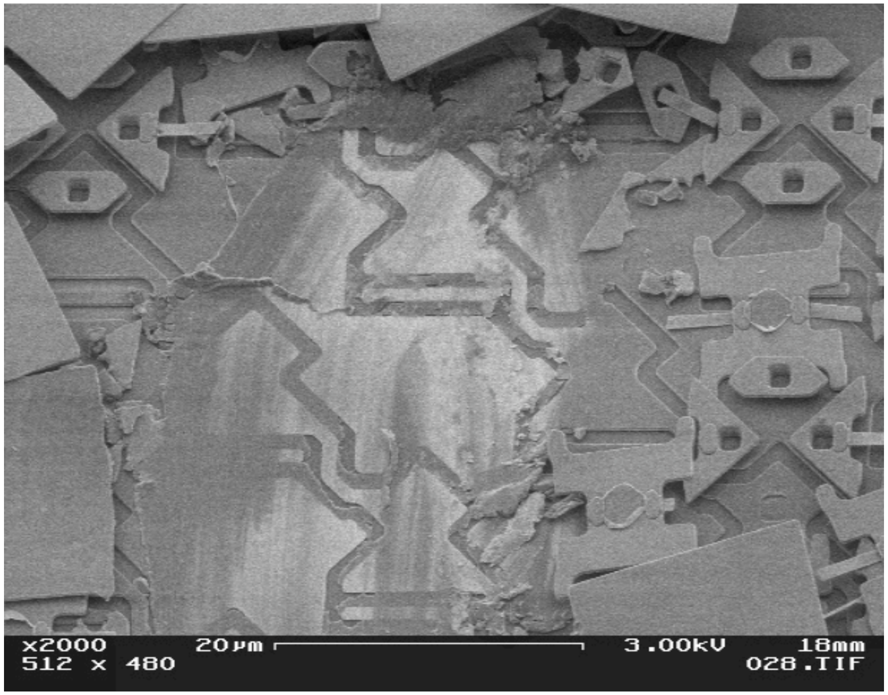
Damaged mirrors

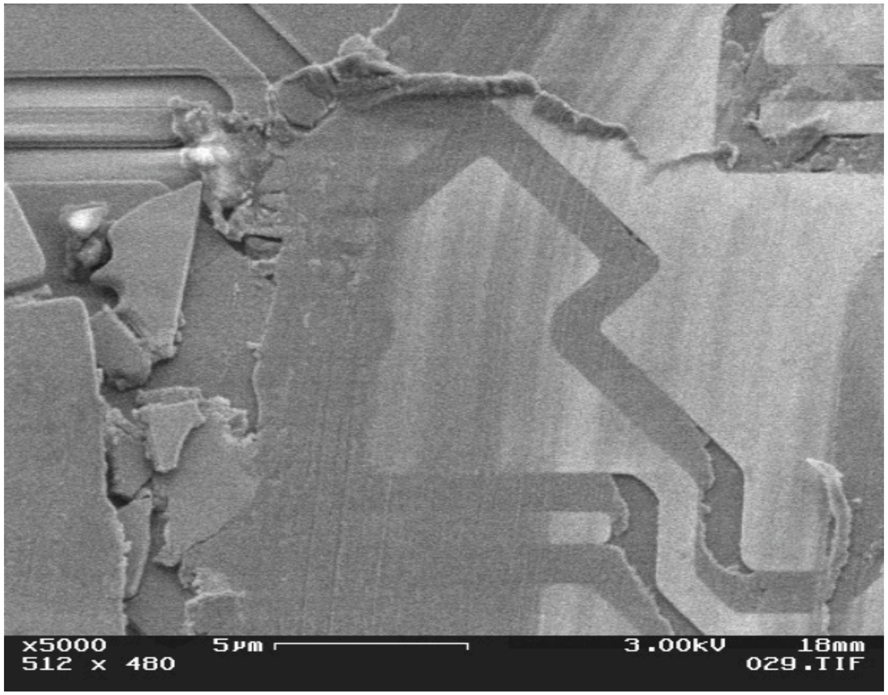




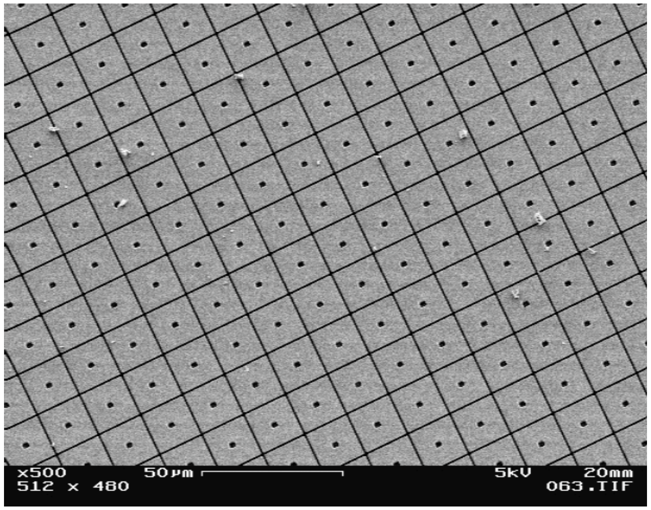
Paper Clip Abrasion

- Abrasion by a paper clip



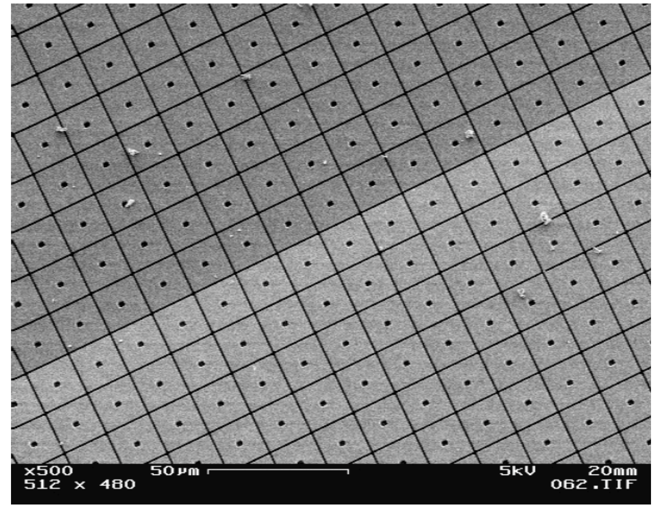


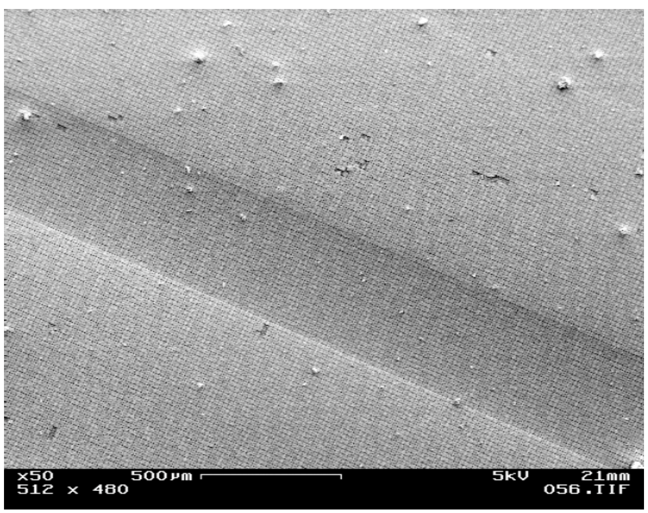
Mirrors with 5V bias



←Off

5V bias →

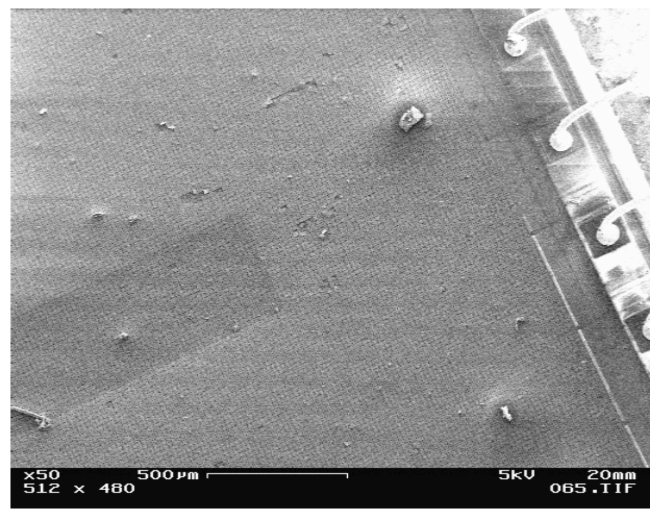




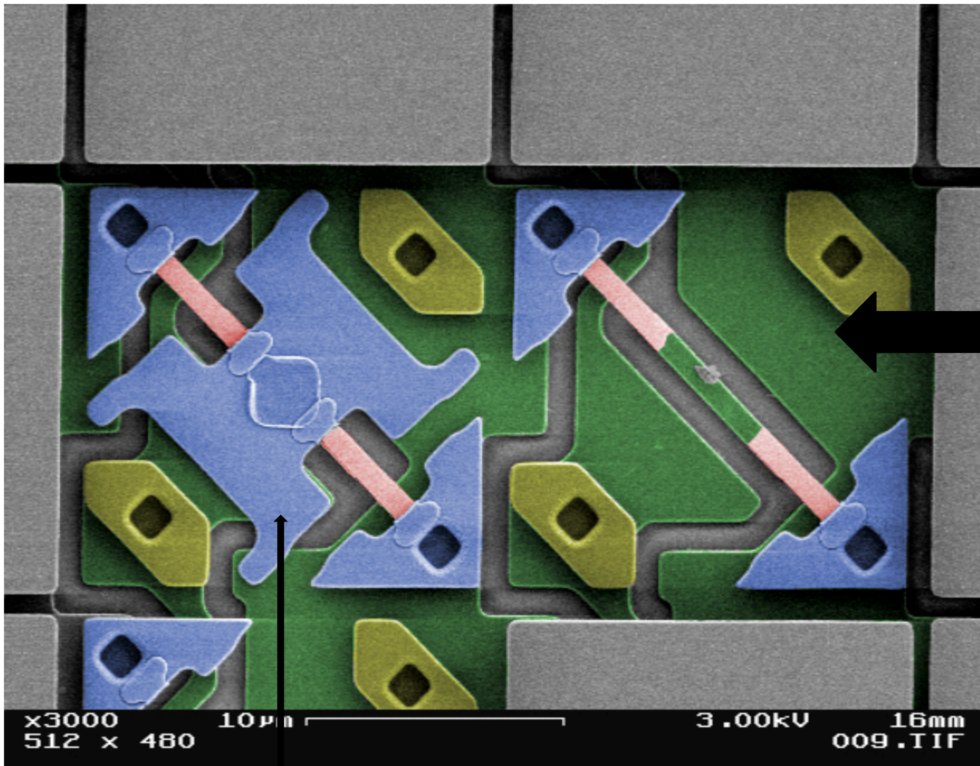
←5V bias

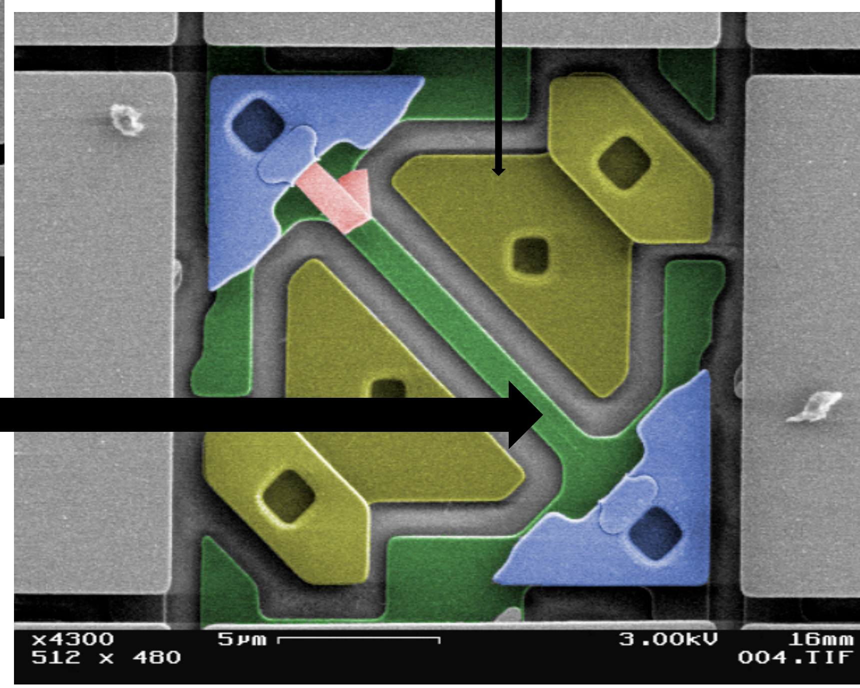
Near electrode

→



Colored SEMs of DMD devices



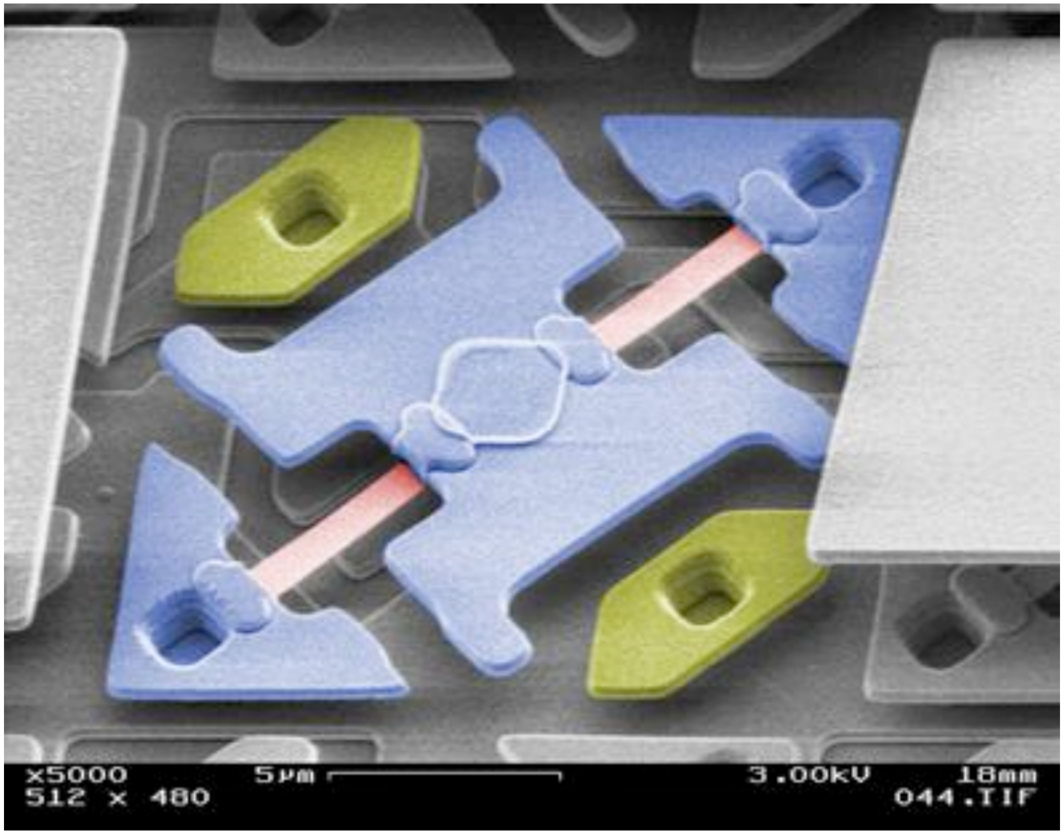


Address system

Pixel substructure

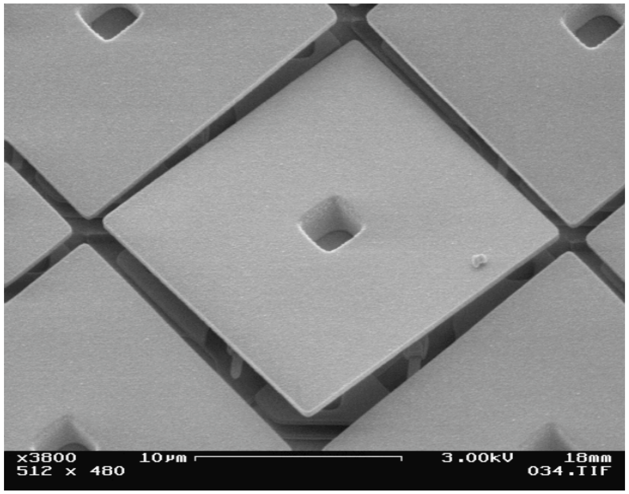
Bias reset

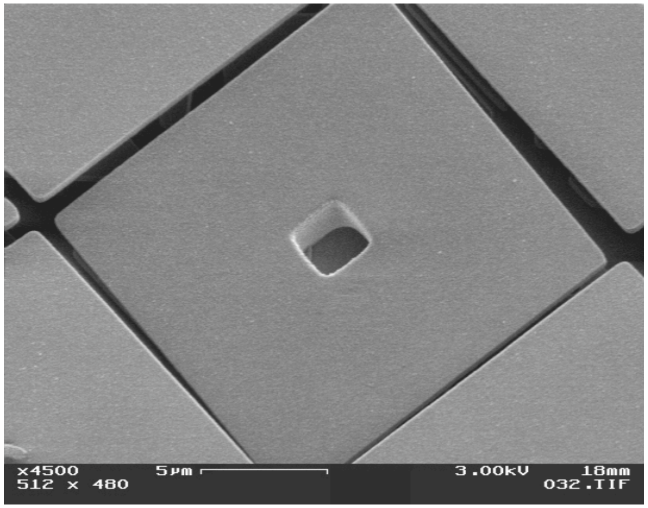
Colored SEM



Pixel Operation

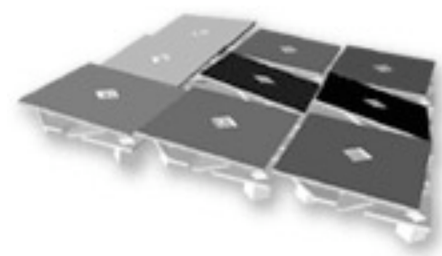
- Pixels rotate 10 degrees in either direction
- Mirrors pull in
- Motion is limited by mechanical stops
- On: +10 degrees
- Off: -10 degrees

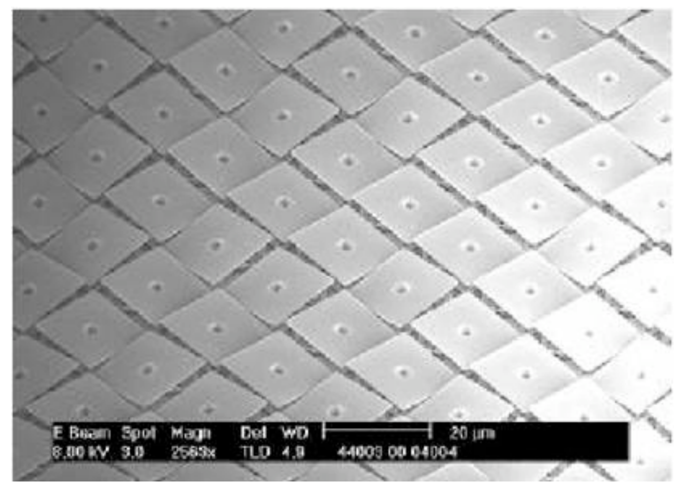




System Operation

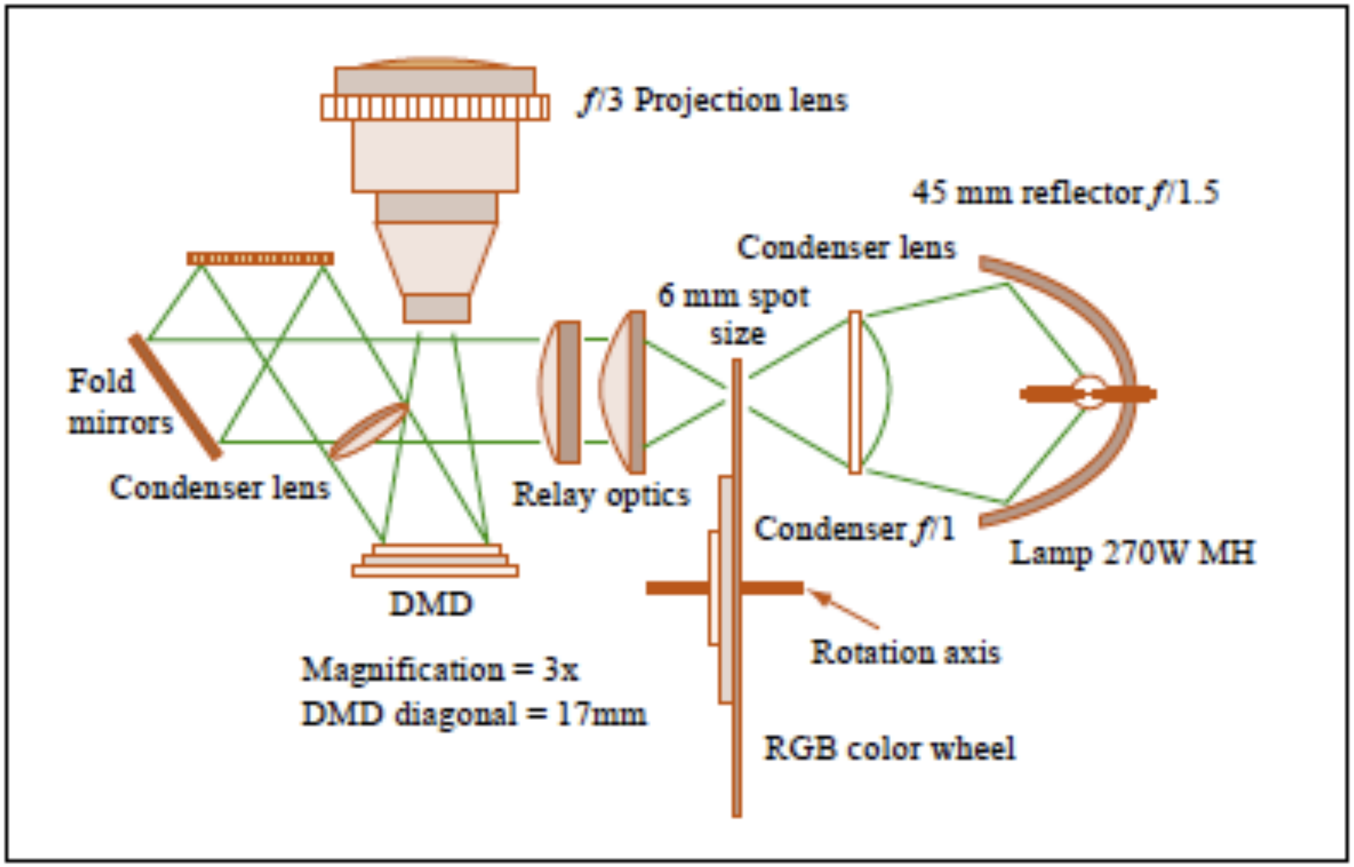
- Grayscale obtained by alternating each mirror between on and off positions in time
  - ➢ Multiple switch events per frame update
- Color obtained by rotating color wheel
  - ➢ Mirror switching events are synchronized with wheel
- Color alternative: use three chips
- Other system elements: light source, drive electronics, switching electronics, switching algorithm, projection optics





The Product

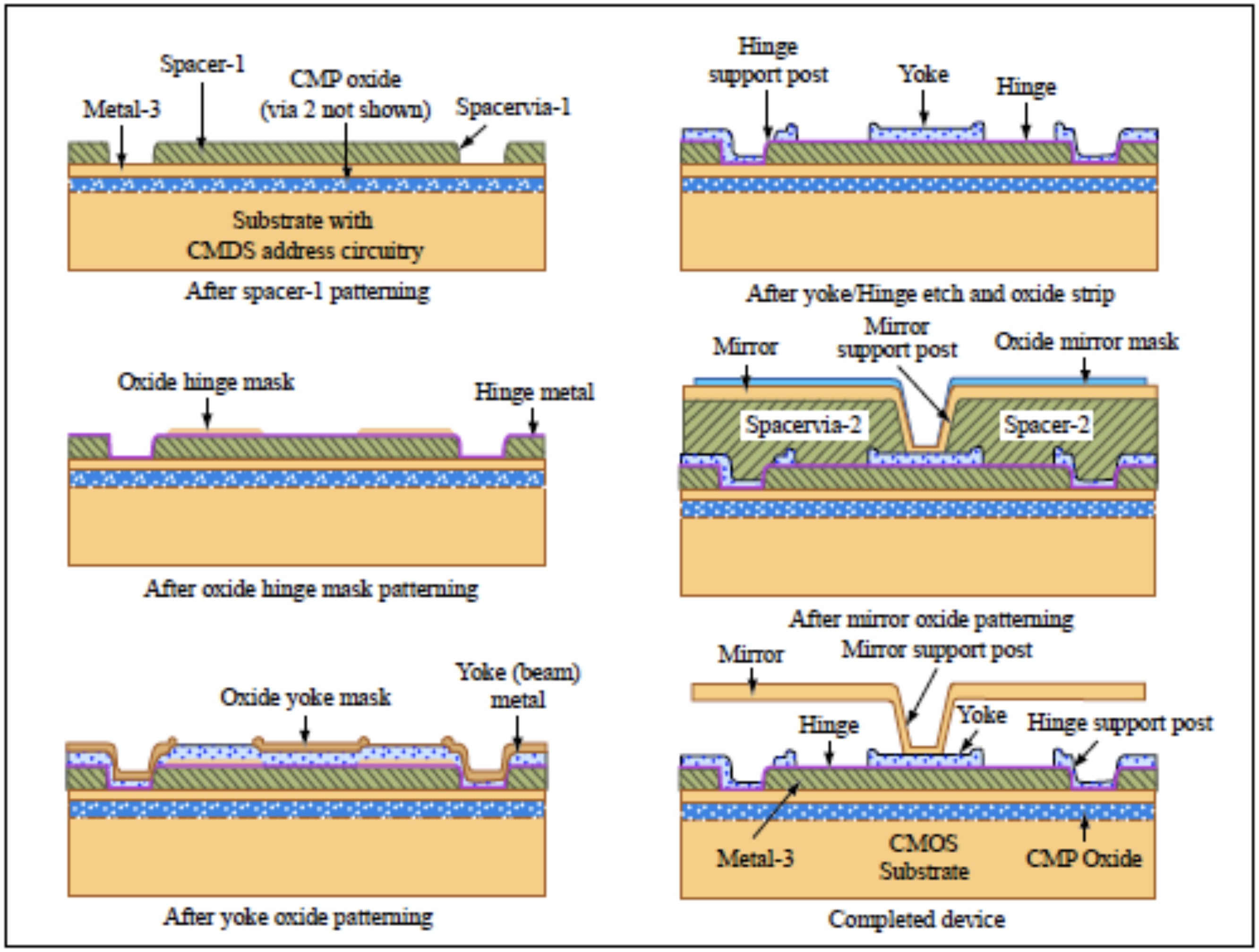
- MEMS are fun, but products sell
- The core of the product is the “digital display engine”, or DDE



Fabrication considerations

- MEMS parts must be fabricated over SRAM memory cells
- MEMS processing must not damage circuits, inclding aluminum interconnects
- Polysilicon? High Temperature Oxides?
- Alternate approach: aluminum as a structural material, with photoresist as a sacrificial layer
- Dry release by plasma strip is a benefit

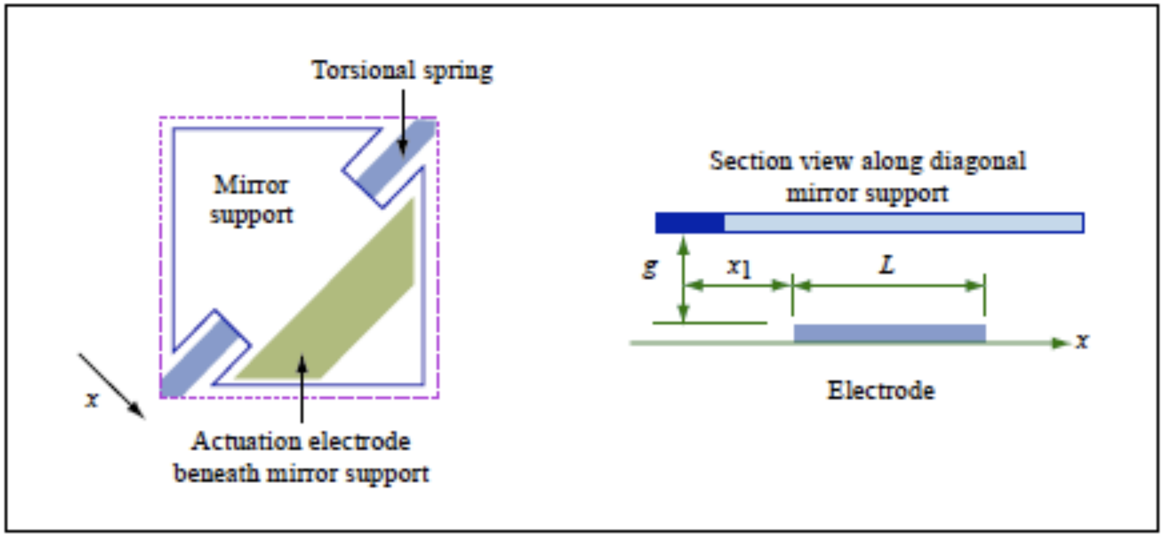
Fabrication Process

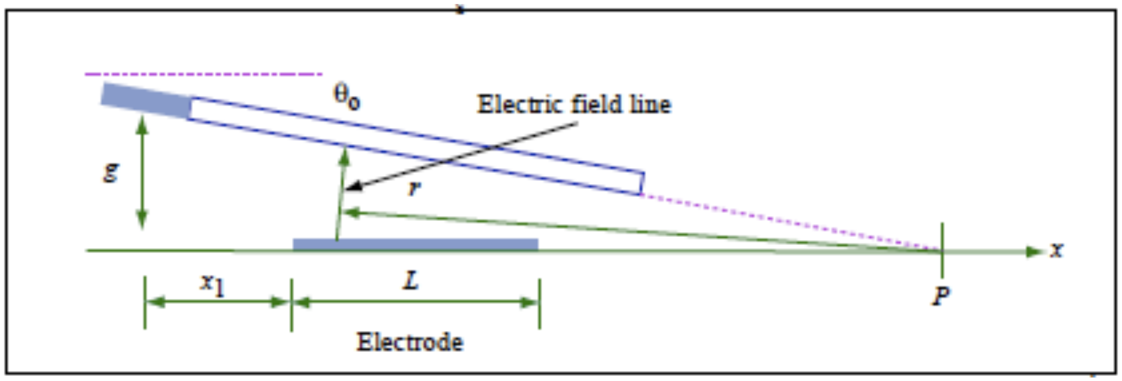


Pull-in Analysis

- 2 methods of analysis
  - Energy-based method of calculating capacitance as a function of angle
    - Demonstrates that resulting torque is nonlinear and increasing as a function of angle
    - There will be an angle where equilibrium between torque and linear restoring force will become unstable
  - Hornbeck
    - Calculate torque directly from parallel plate approximation of a tilted capacitor

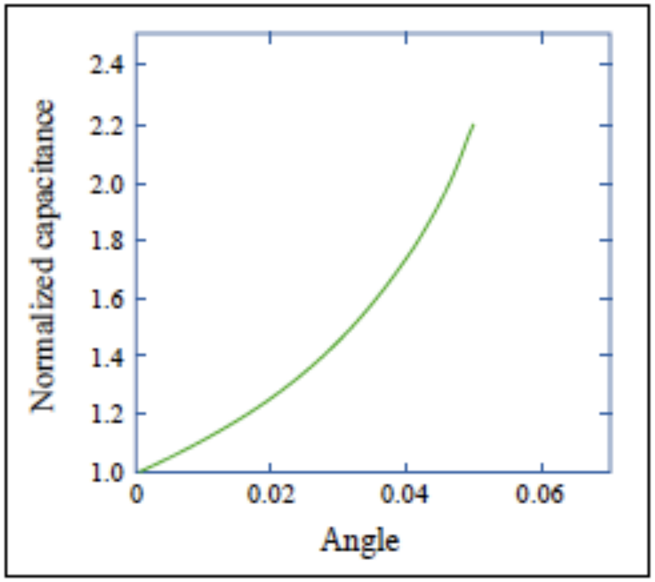
Torsional Pull-in Model





Capacitance Modeling

- Calculate capacitance vs. tilt angle
- Fit to cubic polynomial
- Perform conventional pull-in analysis



$$C = \frac{\varepsilon_0 WL}{g}\frac{\tan\theta_0}{\theta_0}$$

$$\frac{C(\theta_0)}{C(0)} \cong 1 + a_1\theta_0 + a_3\theta_0^3$$

$$\mathcal{W}^*(\theta_0) = \frac{1}{2}C(\theta_0)V^2$$

$$\tau = -\frac{\partial \mathcal{W}^*(\theta_0)}{\partial \theta_0}$$

$$\Downarrow$$

$$\theta_0 = -\frac{k_\theta}{3a_3C_0V^2} \pm \sqrt{\left(\frac{k_\theta}{3a_3C_0V^2}\right)^2 - \frac{a_1}{3a_3}}$$

$$\Downarrow$$

$$V_{PI} = \left(\frac{k_\theta^2}{3a_1a_3C_0^2}\right)^{1/4}$$

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Brainstorm: why might this fail?

- Breakage due to handling/shock
- Stiction (from surface contamination, moisture, or van der Waals forces)
- Light exposure
- Thermal cycling
- Particle effects (electrical short, stuck mirrors, etc.)
- Metal fatigue in hinges
- Hinge memory (permanent deformation)

- Other mechanisms can impact yield right out of the fab: CMOS defects, particles

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- Green: no problem, Yellow: use preventative measures, Red: use preventative measures and cross your fingers

Things not to worry about

- Breakage due to handling/shock
  - Resonant frequencies from about 100 kHz to MHz range
  - Macroscopic shocks and vibrations cannot couple to those modes
  - Might worry about the package, though
- Metal fatigue in hinges
  - Initially expected to be a problem
  - Test didn't show fatigue
  - Subsequent modeling shows that small size has a protective effect
  - Bulk materials: dislocations accumulate at grain boundaries, causing cracks
  - Thin film material: structures are on grain thick, so stressed are immediately relived on the surface

Big Picture: some solutions

- Stiction from surface contamination
  - Monitor voltage required to life mirrors out of pull in
  - Too much voltage indicates a possible increase in surface contamination and a need to check the process
  - Include spring tips at the contact point; stored energy provides a mechanical assist
- Stiction from moisture
  - Package design (hermeticity, getters)
  - Stiction from van der Waals forces
    - Anti-stiction passivation layers
  - Light Exposure
    - No fundamental degradation observed after light exposure
    - However, UV exposure slightly increases the rate of stuck pixels
    - Solution: include a UV filter to limit exposure below 400 nm

Particles

- Particles limit yield AND reliability, since loose particles are a failure waiting to happen
- Not many failures, but most are traceable to particles
  - Detailed analysis of each and ever returned unit: what went wrong, where did this particle come from, and how can I prevent it?
- Particle sources
  - Die attach adhesive can interact with antistiction coating
  - Debris from die separation
  - Generic handling
- Some elements of the ongoing anti-particle battle
  - Be careful!
  - Particle monitoring
  - Change die attach adhesive
  - Adjust die separation process

Hinge memory and thermal cycling

- The problem: if you leave a mirror actuated in one direction for too long, the metal can creep
- Mirror develops a permanent tilt in that direction and ultimately cannot be switched
- High temperatures are an aggravating factor
- Some solutions
  - Choose a hinge material that is less prone to creep
  - Tailor the actuating voltage pulses to be able to transition mirrors from a wider range of starting positions (this also offers higher transition speed)
  - Resent pulse jiggles mirror out of position, even if it’s just going to switch back to that position after the reset
  - Design projector system to control temperature

Packaging process I

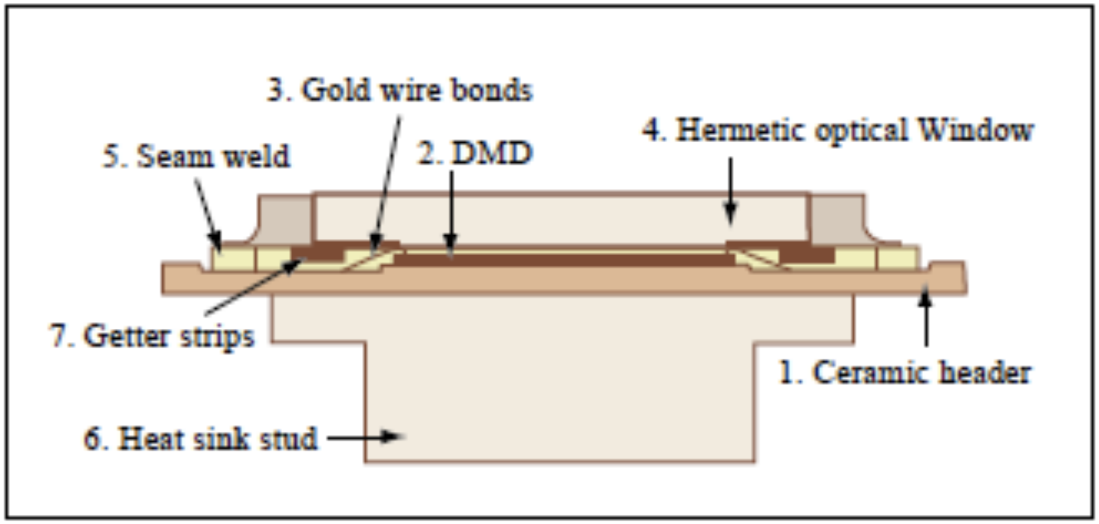
- Preliminary die separation steps
  - Before release, spin coat a protective layer
  - Die saw partway through the wafer to form cleave lines
  - Clean, removing debris and protective layer
- Test for functionality at the wafer scale
  - Plasma ash to remove the sacrificial photoresist spacer layers
  - Deposit an anti-adhesion passivation layer to prevent stiction of landing tips during testing
  - Test for electrical and optical functionality on a test station
- Break to separate into dies

Packaging process II

- Final preparation for die attach
  - Plasma clean
  - Repassivate to prevent stiction in operation
- Attach die to a ceramic package with an unspecified adhesive
- Wirebond to make electrical connections
- Cap package with a welded-on metal lid contained an optical window to form a hermetic seal
- Include an unspecified getter to control moisture, along the lines of a zeolite
- Moisture control not only limits stiction, but impacts hinge memory as well

The Package

- Ceramic package
- Heat sink for temperature control
- Dust control critical to prevent future failures
- Package validation: accelerated lifetime tests (humidity and up to 100C) on a selection of devices



Testing

- If one mirror on a chip doesn't work, the projector is broken
- For good reliability, the failure rate of projectors, EVER, should be well below 1%
- Question: how do you ensure that you're not sending out a batch of projectors that are just waiting to fail
- Testing with more than just binary information
- Custom tool: the MirrorMaster
  - Drive DMD with electronics, inspect with a CCD camera on a microscope
  - Careful protocols

Bias Adhesion Mapping

- Gradually increase voltage to actuate mirrors, capturing an image of mirrors at each step
- Distribution of switching and release voltages is an early warning system for structural variations, surface contamination, process problems

Conclusions

- Intuition can be deceiving. Who would have thought that you could get reliability at such an immense scale?
- If you want people to get excited about your MEMS technology, show them the product
- If the MEMS part alone doesn't meet the spec, ask yourself if the overall system can be designed to meet the spec.
  - Hinge memory was partly cured by materials and partly by design of the control system