CASE STUDY:

MEMS-Based Projection Displays

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*** With thanks to Steve Senturia, from whose lecture notes some of these materials are adapted.**

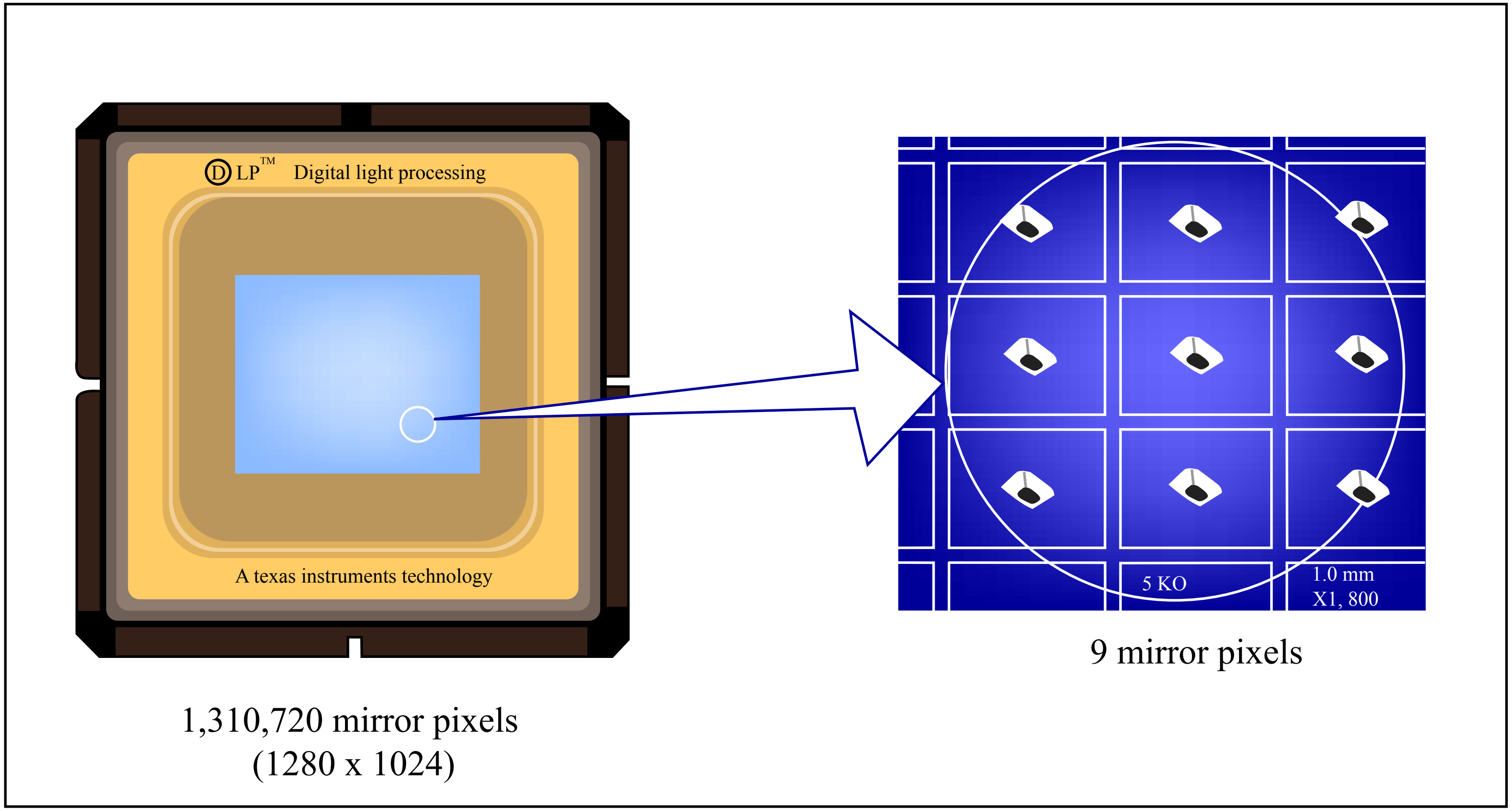
Outline

> **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



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Projecting with the DMD

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The Silicon Light Machines Approach

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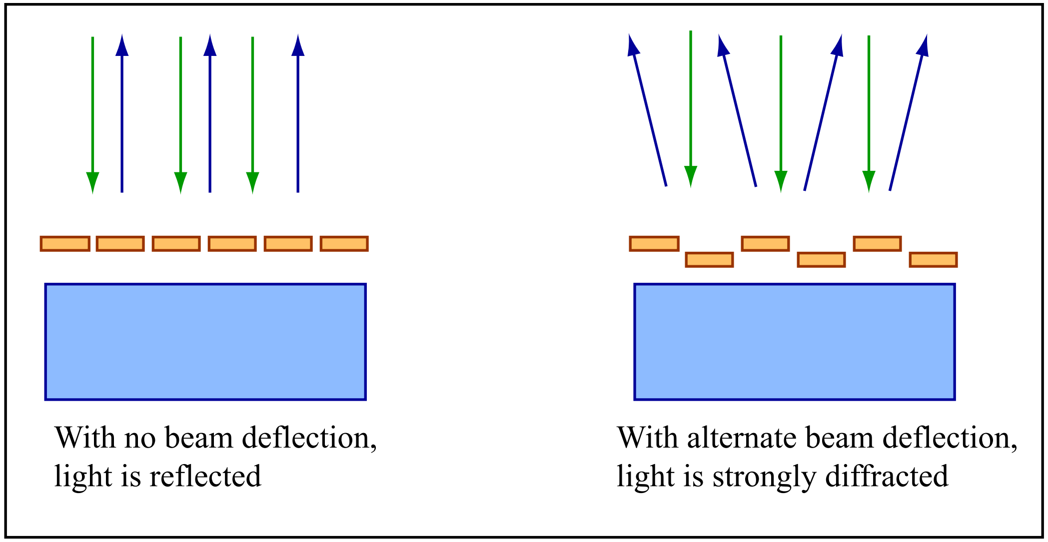
Figure 1.4 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 7. ISBN: 9780792372462.



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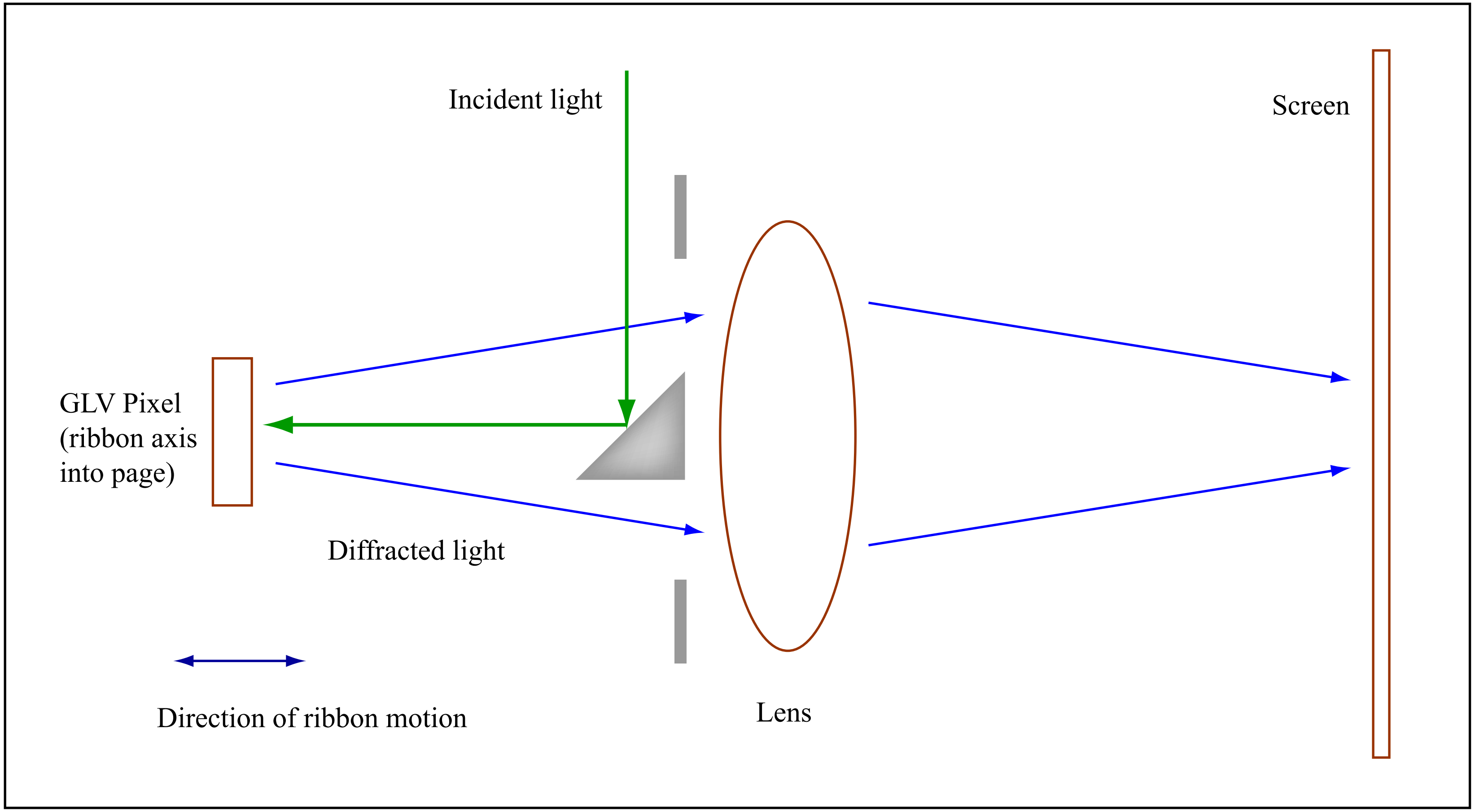
Pixel Operation



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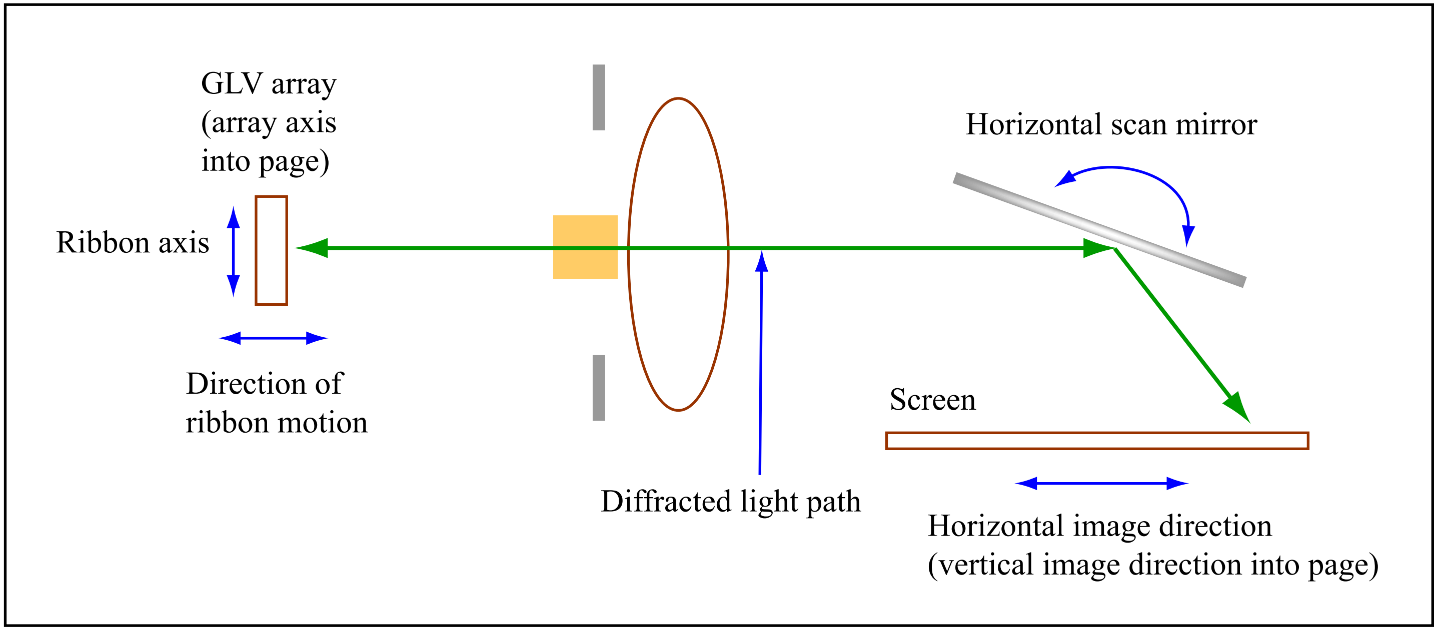
Adapted from Figure 20.4 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 534. ISBN: 9780792372462.

Projecting an Image



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Adapted from Figure 20.6 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 535. ISBN: 9780792372462.

Device Wafer

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Figure 20.5 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 535. ISBN: 9780792372462.

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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 markets: lithography, medical imaging, scientific imaging**

The pixels

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

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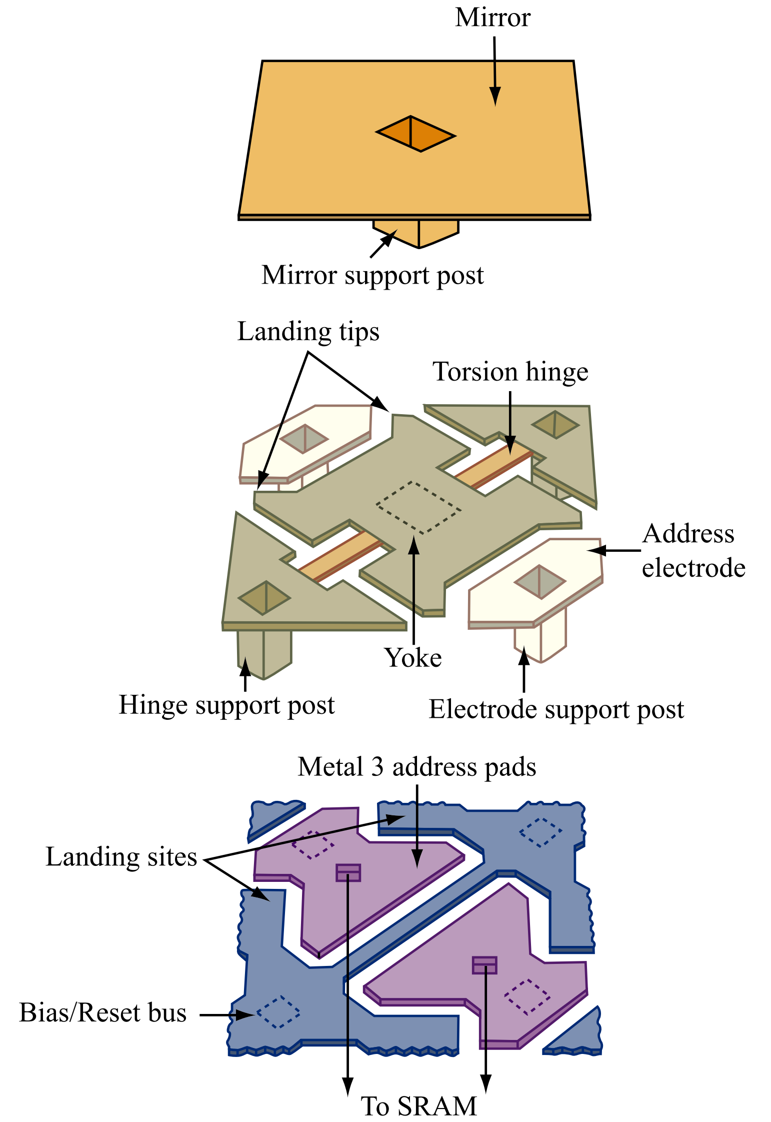
Figure 51 on p. 39 in Hornbeck, Larry J. "From Cathode Rays to Digital Micromirrors: A History of Electronic Projection Display Technology." *Texas Instruments Technical Journal* 15, no. 3 (July-September 1998): 7-46.



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Pixel operation

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

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Figures 48 and 50 in Hornbeck, Larry J. "From Cathode Rays to Digital Micromirrors: A History of Electronic Projection Display Technology." *Texas Instruments Technical Journal* 15, no. 3 (July-September 1998): 7-46.

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 algorithm, projection optics**

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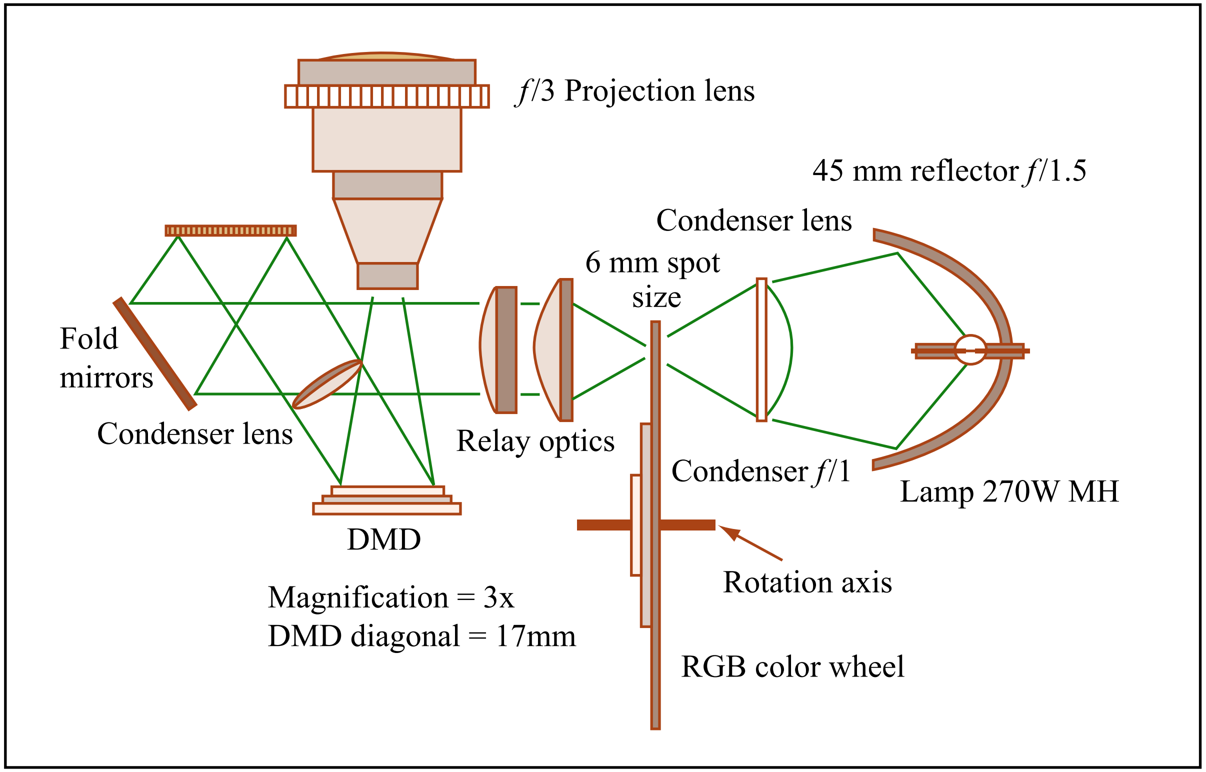
See http://www.dlp.com/tech/what.aspx for more information.

The product

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



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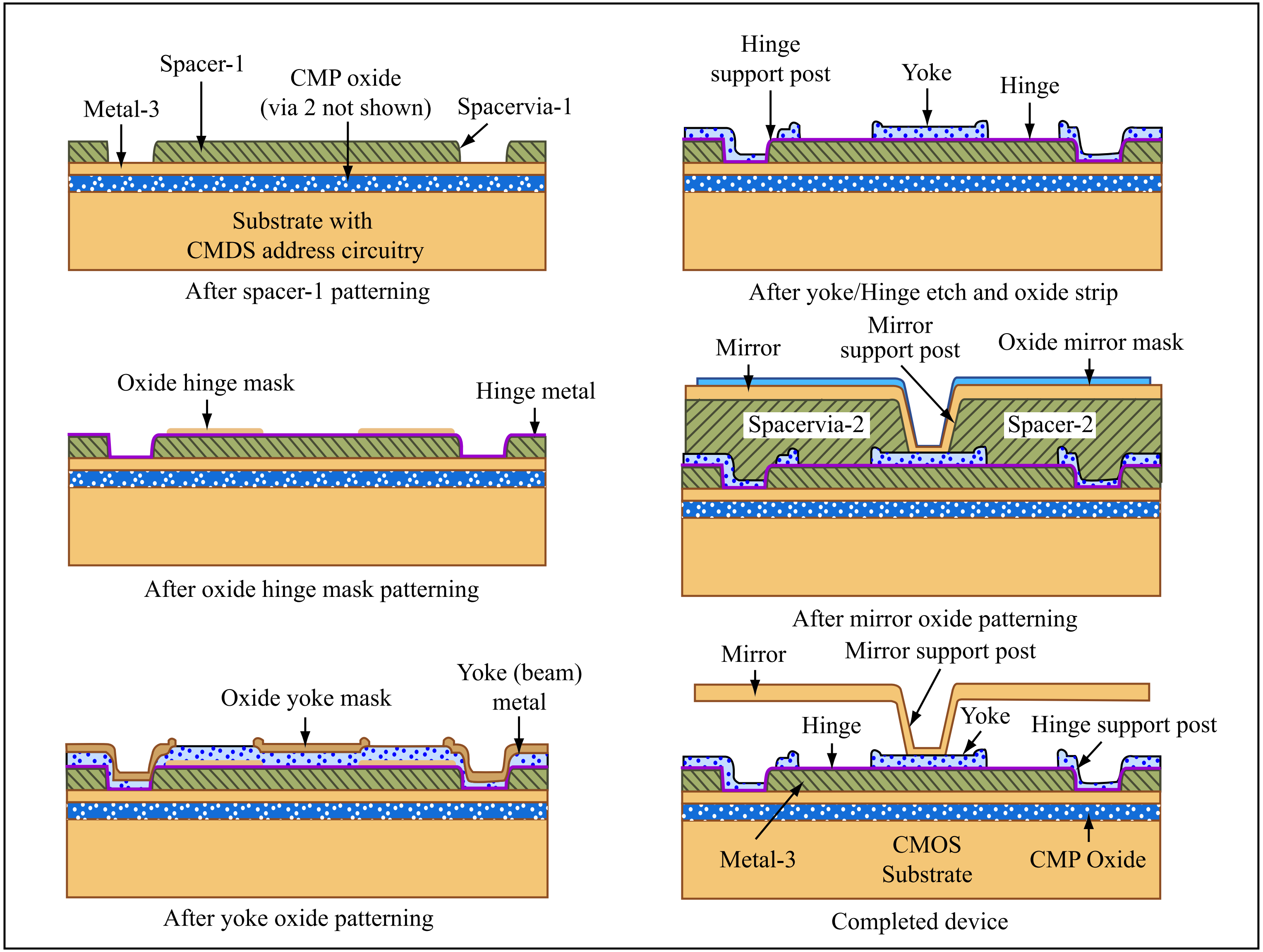
Fabrication considerations

- MEMS parts must be fabricated over SRAM memory cells
- MEMS processing must not damage circuits, including 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



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Electromechanics: DMD Structure

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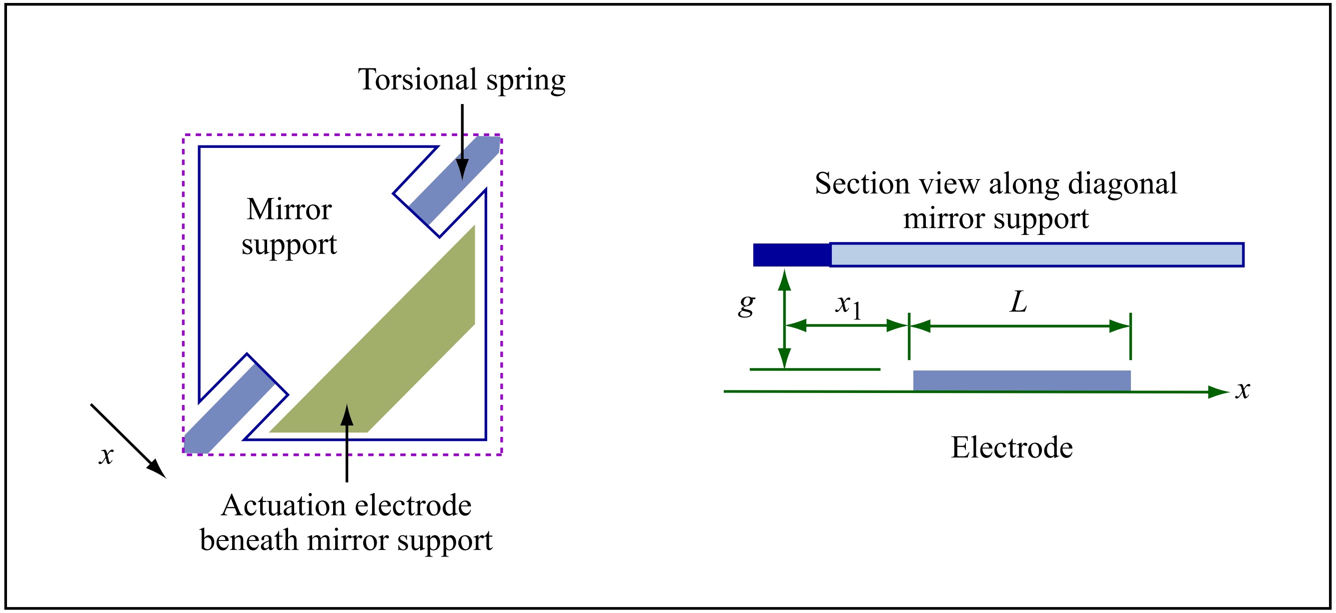
Figure 51 on p. 39 in Hornbeck, Larry J. "From Cathode Rays to Digital Micromirrors: A History of Electronic Projection Display Technology." *Texas Instruments Technical Journal* 15, no. 3 (July-September 1998): 7-46.

Torsional Pull-in Model



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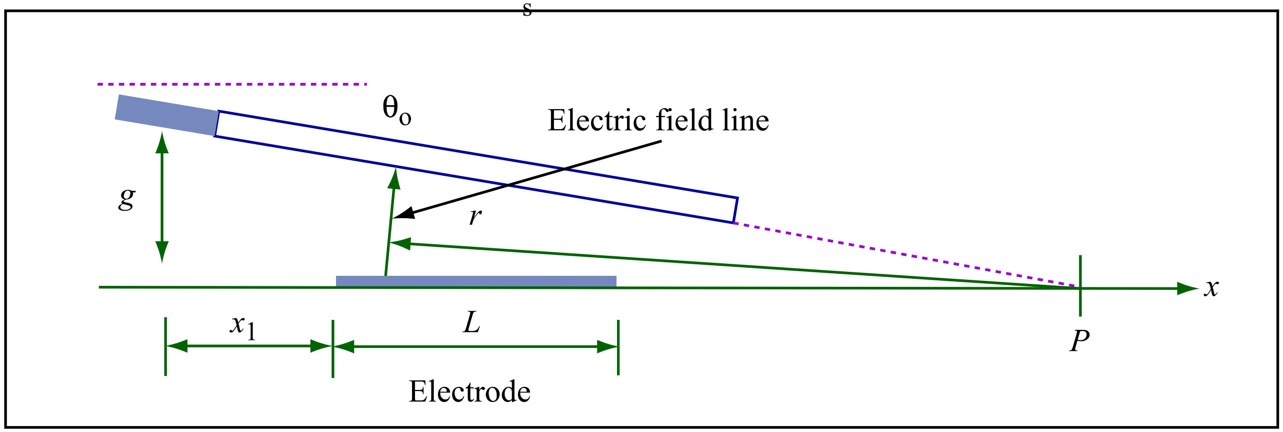

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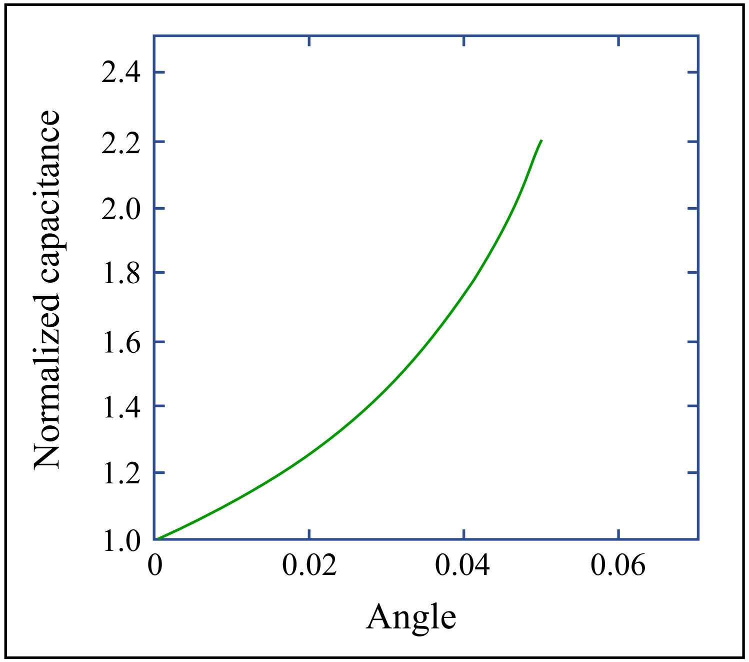
Capacitance Modeling

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



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Adapted from Figure 20.11 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 540. ISBN: 9780792372462.

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

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

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

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

$$\Downarrow$$

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

$$\Downarrow$$

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

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- **Reliability: why might this fail, and why doesn't it happen most of the time?**
- **Packaging**
- **Test procedures**

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

The ratings

- **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)**

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

Things not to worry about

> **Breakage due to handling/shock**
- **Resonant frequencies range from about 100 kHz to the 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 one grain thick, so stresses are immediately relieved on the surface**

Big picture: some solutions

- **Stiction from surface contamination**
  - **Monitor voltage required to lift 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**

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Figure 51 on p. 39 in Hornbeck, Larry J. "From Cathode Rays to Digital Micromirrors: A History of Electronic Projection Display Technology." *Texas Instruments Technical Journal* 15, no. 3 (July-September 1998): 7-46.

- **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 every 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)
- Reset 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

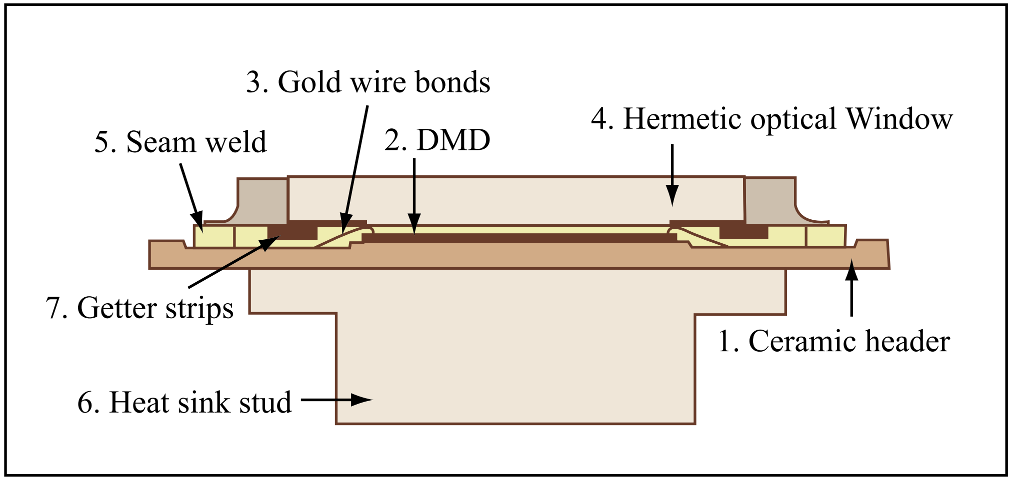
- Preliminary die separation steps
  - Before release, spin coat a protective layer
  - Die saw partway through the wafer to form cleave lines
  - Clean, removing debris and protective layer
- Test for functionality at the wafer scale
  - Plasma ash to remove the sacrificial photoresist spacer layers
  - 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 containing 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



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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

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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

For more information, and credits

- Some of these images are from the Texas Instruments web site
  - http://www.dlp.com/
- Some are from these articles:
  - P.F. Van Kessel et al, “A MEMS-Based Projection Display”, Proc. of the IEEE, vol. 86, p. 1687-1703 (1998).
  - M.R. Douglass, “Lifetime Estimates and Unique Failure Mechanisms of the Digital Micromirror Device (DMD)”, IEEE 36th Annual International Reliability Physics Symposium, Reno, Nevada, 1998.
  - S. Jacobs et al, “Hermeticity and Stiction in MEMS Packaging”, IEEE 40th Annual International Reliability Physics Symposium, Dallas, TX, 2002.