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

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

9 mirror pixels

Image by MIT OpenCourseWare.
Projecting with the DMD

The Silicon Light Machines Approach

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![Diagram](Image by MIT OpenCourseWare.)

- With no beam deflection, light is reflected
- With alternate beam deflection, light is strongly diffracted

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Pixel Operation

Image by MIT OpenCourseWare.
Projecting an Image

Device Wafer

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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 \( \mu \text{m} \) aluminum mirrors, 17 \( \mu \text{m} \) on center

> Address electronics under each pixel

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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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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

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, 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

- **Substrate with CMDS address circuitry**
  - After spacer-1 patterning
    - Metal-3
    - CMP oxide (via 2 not shown)
    - Spacervia-1

- **Oxide hinge mask**
  - Hinge metal
  - After oxide hinge mask patterning

- **Oxide yoke mask**
  - Yoke (beam) metal
  - After yoke oxide patterning

- **Mirror**
  - Mirror support post
  - After mirror oxide patterning

- **Completed device**
  - Yoke
  - Hinge support post

Image by MIT OpenCourseWare.
Electromechanics: DMD Structure

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Torsional Pull-in Model


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Capacitance Modeling

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

\[ C = \frac{\varepsilon_0WL}{g} \tan \theta_0 \]

\[ \frac{C(\theta_0)}{C(0)} \approx 1 + a_1 \theta_0 + a_3 \theta_0^3 \]

\[ W^*(\theta_0) = \frac{1}{2} C(\theta_0)V^2 \]

\[ \tau = -\frac{\partial W^*(\theta_0)}{\partial \theta_0} \]

\[ \theta_0 = -\frac{k_0}{3a_3C_0V^2} \pm \sqrt{\left(\frac{k_0}{3a_3C_0V^2}\right)^2 - \frac{a_1}{3a_3}} \]

\[ V_{PI} = \left(\frac{k_0^2}{3a_1a_3C_0^2}\right)^{1/4} \]

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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

> **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

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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/](http://www.dlp.com/)

> Some are from these articles: