Wright State University

EE480/680
Micro-Electro-Mechanical Systems (MEMS)
Summer 2006

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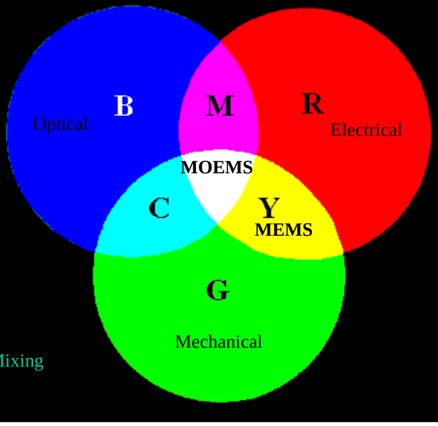
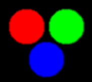
Optical MEMS

Optical MEMS: MOEMS

- Micro-Opto-Electro-Mechanical Systems (MOEMS)

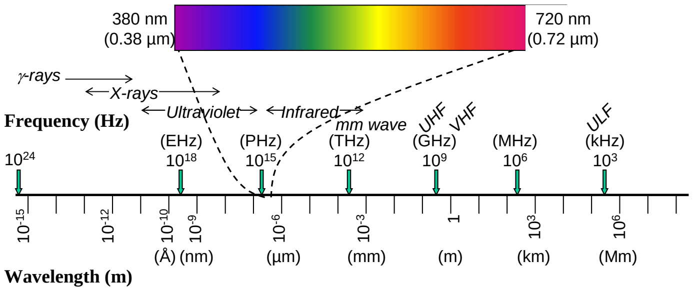




Additive Color Mixing

Optical MEMS

- Electromagnetic Spectrum
  - Energy of a quantum of electromagnetic radiation:
    - $E = hf = hc/\lambda$

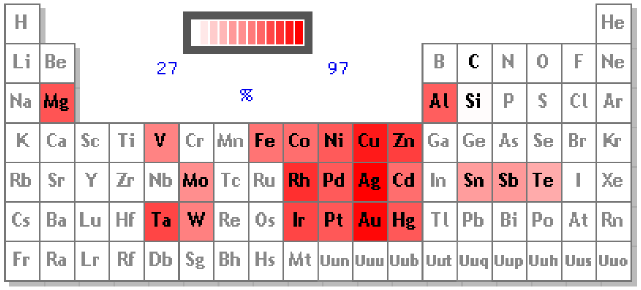


Overview

- Mirrors & Mirror Arrays
  - Beam Steering
    - Simple Reflection
    - Corner Cube Reflector
    - Grating
    - Blazed Grating
    - Phased Array
- Lenses
  - Refractive
  - Diffractive
- Systems

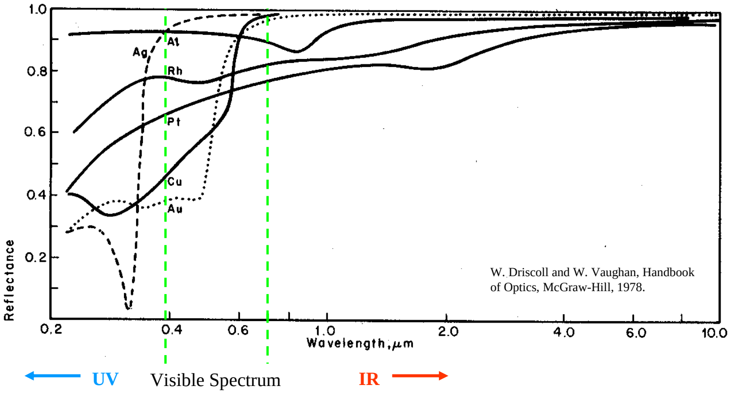
Mirrors

- Different materials reflect different wavelengths with varying efficiency -- almost anything can be a form of mirror.
  - Reflectivity: the percentage light reflected from a surface at a given wavelength
    - ex. elemental comparison at 1 µm wavelength



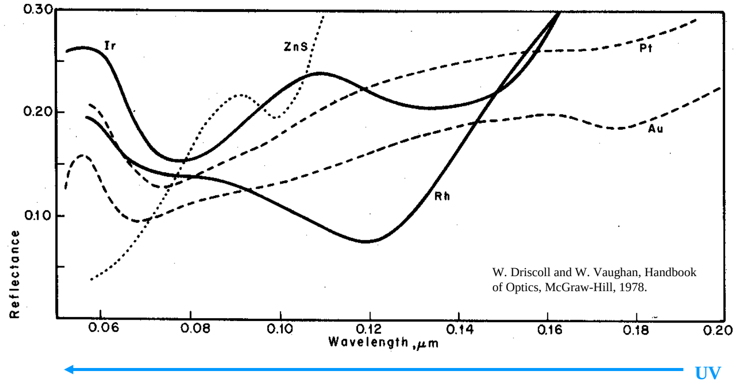
Web Elements

Mirrors: Reflectance



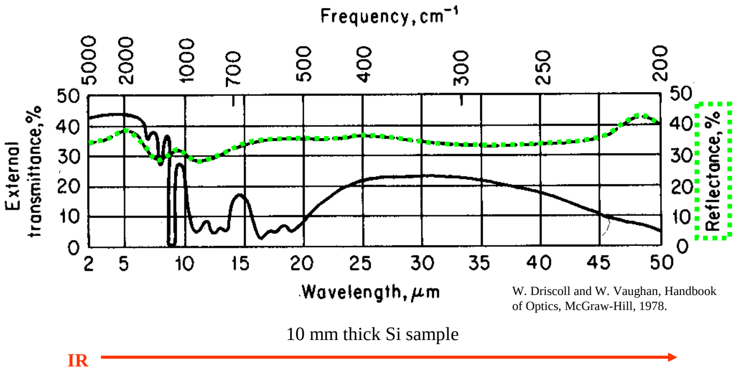
W. Driscoll and W. Vaughan, Handbook of Optics, McGraw-Hill, 1978.

Mirrors: UV Reflectance



W. Driscoll and W. Vaughan, Handbook of Optics, McGraw-Hill, 1978.

Mirrors: IR Reflectance Si



W. Driscoll and W. Vaughan, Handbook of Optics, McGraw-Hill, 1978.

10 mm thick Si sample

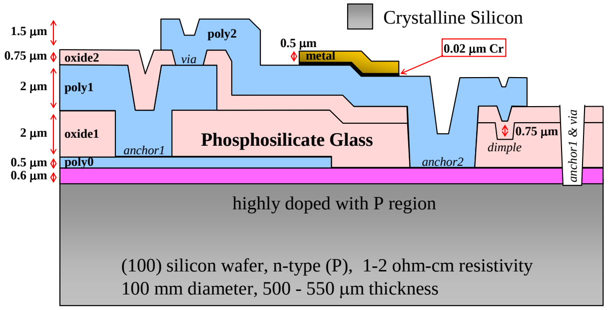
Mirrors: Distortion

- Most mirrors are fabricated from surface micromachining
- Some drawbacks causing distortion in reflected image include:
  - Deposited layers conform to the topology of lower layers, therefore, embossing the mirror surface.
  - Residual stress in deposited layers or combinations of layers can deform the mirror surface
- Solutions include:
  - Thinner reflective coatings
  - Stiffer mirror structures
  - Avoid topology under mirror by design
  - Use backsides of layers through assembly
  - Use fabrication processes with planarized layers
  - More appropriate combinations of multi-layer materials
  - Different fabrication processing conditions

Mirrors: Fabrication

- CRONOS -- The Multi-User MEMS Processes, or MUMPs®, 1992, www.memsrus.com
  - 15 copies of a 1 cm × 1 cm die, $3,200.00

- 🟨 Metal (gold)
- 🟦 Polycrystalline Silicon (doped with P)
- ▢ Oxide (PSG: SiO_2 doped with P)
- 🟪 Nitride (Si_3N_4)
- ▨ Crystalline Silicon

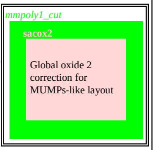


Mirrors: Fabrication

- SUMMiT IV & V, Sandia National Laboratory
  - 100 copies of a 6.34 mm × 2.82 mm die, $10,000
  - V provides a 5th planarized layer of poly

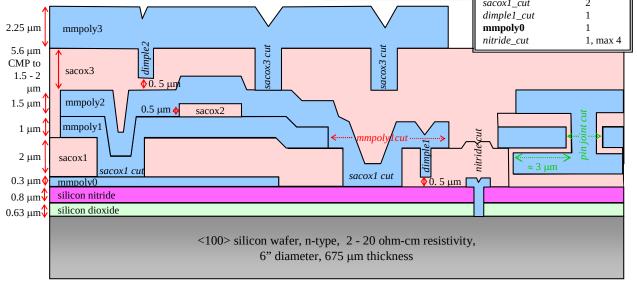
- 🟦 Polycrystalline Silicon
- ▢ Oxide (SiO_2 deposited from TEOS tetra-ethyl-ortho-silicate)
- 🟪 Nitride (Si_3N_4)
- ▨ Crystalline Silicon

Max etch hole spacing 38 μm
Max dimple spacing 75 μm



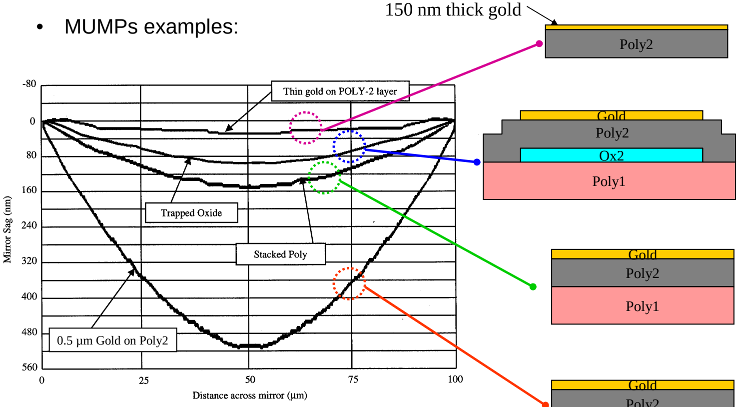
Available CAD Layers & Minimum Width (μm):

mmpoly3_cut	1
mmpoly3	1
sacox3_cut	2
dimple3_cut	1.5
mmpoly2_cut	1
mmpoly2	1
sacox2_cut	2
sacox2	1
mmpoly1_cut	1
mmpoly1	1
pin_joint_cut	3
sacox1_cut	2
dimple1_cut	1
mmpoly0	1
nitride_cut	1, max 4



Mirrors: Residual Stress

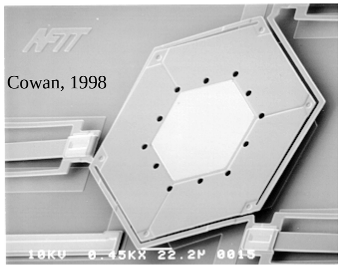
- MUMPs examples:



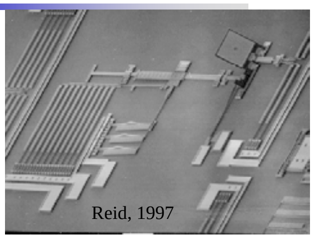
D. Burns, *Microelectromechanical Optical Beam Steering Systems*, AFIT Dissertation, 1998.

Mirrors: Beam Steering

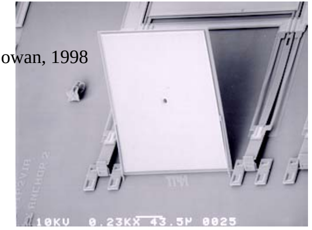
- Simple Reflection



Cowan, 1998



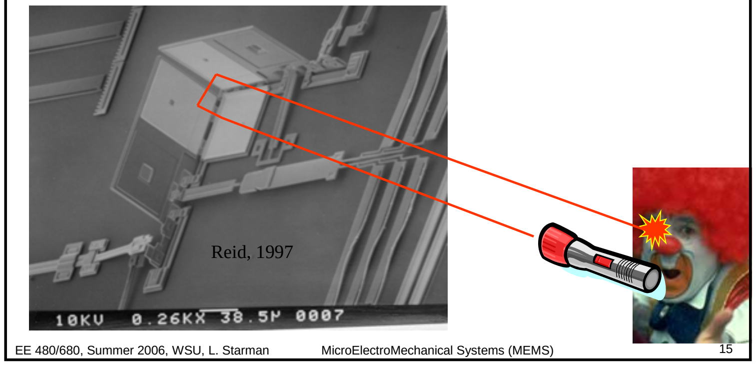
Reid, 1997



Cowan, 1998

Mirrors: Beam Steering

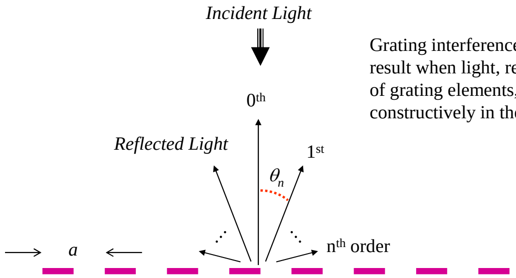
- Corner Cube Reflector
  - Modulation device -- signal always returns to source if mirrors are orthogonal to each other.



Reid, 1997

Mirrors: Beam Steering

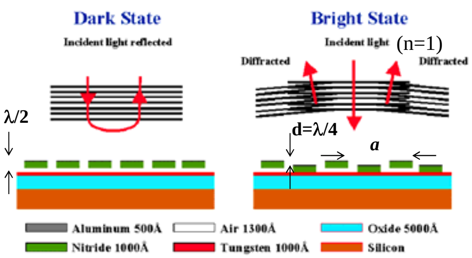
- Diffraction Gratings
  - Scatter reflected in discrete directions:
    - $$\sin(\theta_n) = \frac{n\lambda}{a}$$
    - where *n* is the discrete order, θ_n is the order direction, λ is the wave length, and *a* is the period of the grating elements.



Grating interference orders result when light, reflected off of grating elements, combines constructively in the far field.

Mirrors: Beam Steering

- Grating Light Valve (GLV) by Silicon Light Machines
  - Destructive interference attenuates 0th order.



A pixel

$$\sin(\theta_n) = \frac{n\lambda}{a}$$

The maximum diffracted intensity of the first order is when d = λ/4.

For same θ, but different colors, choose a different *a* such that λ/*a* is same.
-or-
Build one pixel for "red" and deflect the same pixel less for green and blue.

Mirrors: Beam Steering

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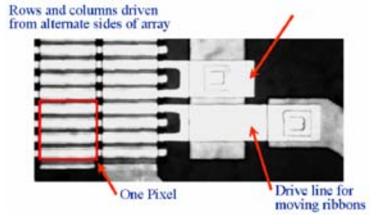
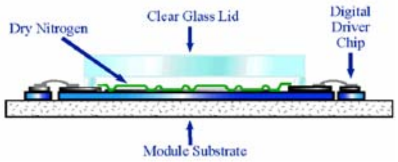
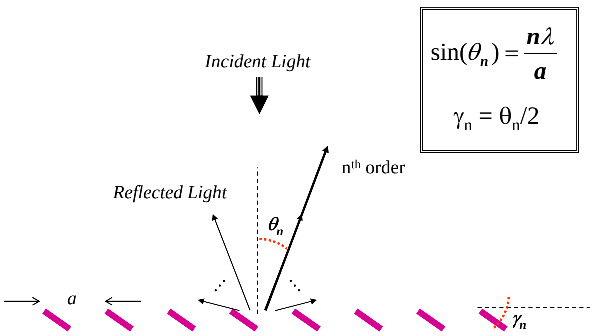




Mirrors: Beam Steering

- Blazed Grating
  - Gratings can be angled to direct the 0th order intensity into the direction of a higher order, therefore, enhancing the higher order direction.

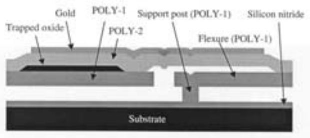


$$\sin(\theta_n) = \frac{n\lambda}{a}$$

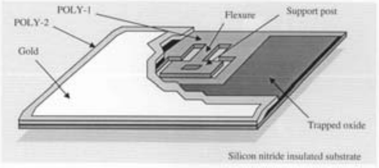
$$\gamma_n = \theta_n/2$$

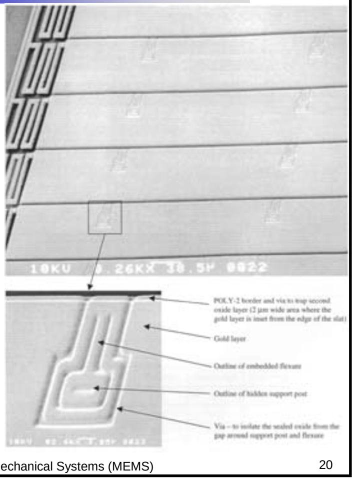
Mirrors: Beam Steering

- Blazed Grating



Cross-sectional view of a VBG slat.



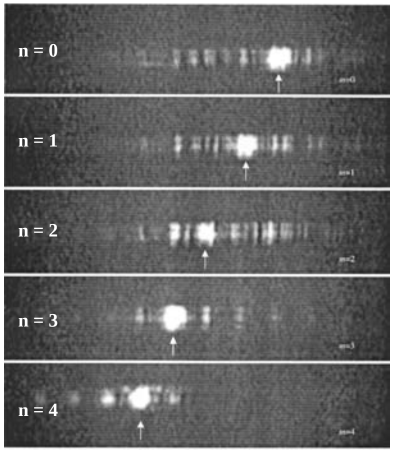


D. Burns, *Microelectromechanical Optical Beam Steering Systems*, AFIT Dissertation, 1998.

Mirrors: Beam Steering

- Blazed Grating

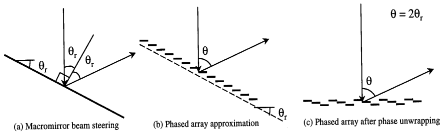
Diffraction order	Blaze angle	Steering angle	Drive voltage
0	0°	0°	0
1	0.23°	0.45°	13.4
2	0.46°	0.91°	22.9
3	0.68°	1.36°	26.6
4	0.91°	1.81°	29.4

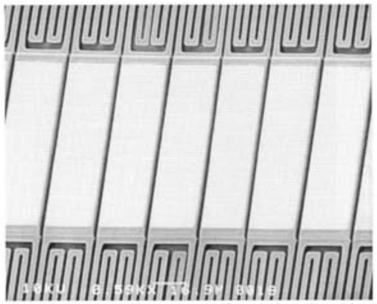


D. Burns, *Microelectromechanical Optical Beam Steering Systems*, AFIT Dissertation, 1998.

Mirrors: Beam Steering

- Phased Array
  - A digital approximation of beam steering with a single tilted mirror.





	4th Generation	5th Generation
MUMPs Fabrication Run	15	19
Number of Elements	128	10
Vertical Range of Motion* (µm)	2.0	2.0
Array Period (µm)	30.0	30.0
Linear Fill Factor (%)	63.33	93.33
Number of Flexures	4**	4
Flexure Length (µm)	85.0**	243.0
Flexure Width (µm)	1.75	2.0
Surface Area Above Bottom Electrode (µm^2)	3,294.0	2,912.0
Width of Element's Gold Layer (µm)	19.0	28.0
Curvature Across Width (peak to valley) (nm)	9.9	13.7
Curvature Across Length (peak to valley) (nm)	65.5	104.4
Bottom Electrode Construction	Substrate	Substrate
Calculated Pull Down Voltage (V)	23.1	6.3
Measured Pull Down Voltage (V)	24.5	5.5

*Vertical range of motion has not been corrected for curvature.

**Equivalent flexure after accounting for the yoke flexure design.

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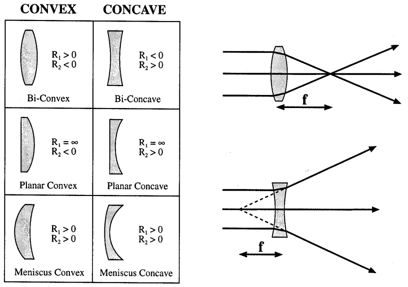
- Systems

Lenses: Refractive



$$\frac{1}{f} \approx (n_1 - n_m)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

where,

n_1 = refractive index of the lens material

n_m = refractive index of the medium (for air, n_m = 1)

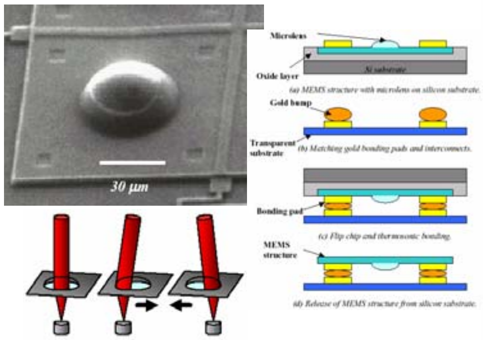
R_1 = entrance radius of lens

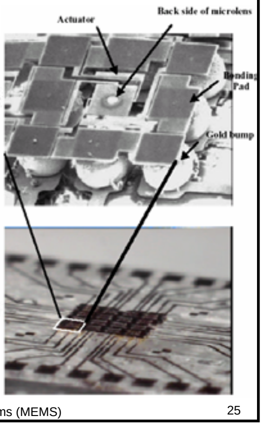
R_2 = exit radius of lens

Material	Refractive Index (n = c/v)
Air (0°C, 1 atm)	1.0002926
Liquid Nitrogen	1.21
Ice	1.31
Methanol	1.326
Water (20°C)	1.333
Acetone	1.357
Ethanol	1.359
Fused Silica (SiO_2)	1.438
Hoya QZ Quartz Glass	1.46
Thermal Silicon Dioxide (TF)	1.46
PECVD Silicon Dioxide (TF)	≈ 1.47 (may vary)
Corning 7740 Pyrex™ Glass	1.473
Benzene	1.498
Plexiglass™ (PMMA)	1.5014
Borosilicate Glass	1.517
Phosphate Crown Glass	1.518
Hoya SL (70% SiO_2, 8% Na_2O, 9% K_2O, 13% Refractory Metal Oxides)	1.52
Sodium Chloride	1.53
Hoya LE (Aluminosilicate)	1.53
Light Flint Glass	1.581
Flint Glass	1.620
PECVD Silicon Nitride (TF)	1.8 to 2.5
LPCVD Silicon Nitride (TF)	2.01
Gallium Nitride (ordinary-ray)	2.35
Diamond	2.38
Gallium Arsenide	3.32
Silicon	3.415
Germanium	4.001

Lenses: Refractive

- Reflowed BCB lens for VCSEL de-centered lens beam steering

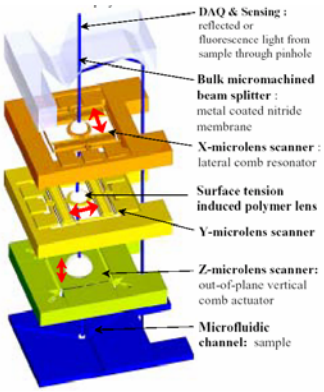


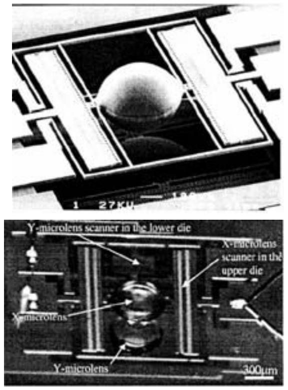


A. Tuantranont et al., "MEMS-Controllable Microlens Array for Beam Steering and Precision Alignment in Optical Interconnect System," *Proceedings of the 2000 Solid-State Sensor and Actuator Workshop*, pp. 101-104, June 4-8, 2000.

Lenses: Refractive

- UV curable polymer lenses for 2-D scanning

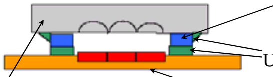




S. Kwon et al., "Stacked Two Dimensional Micro-Lens Scanner for Micro Confocal Imaging Array," 2002.

Lenses: Refractive

- Lenslet arrays with piston micromirrors for aberration correction using phase alteration.

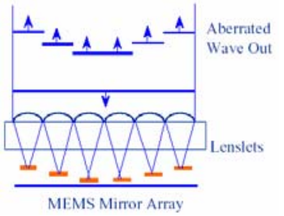


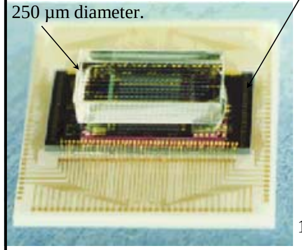
540 µm Thick Glass Spacer

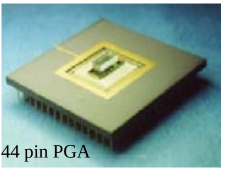
UV curable epoxy

Lenslet Array, Nippon Sheet Glass Company, 250 µm diameter.

Micromirrors







144 pin PGA

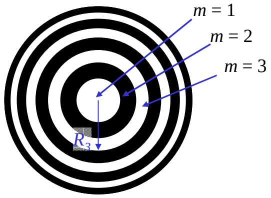
A. Tuantranont et al., "Packaging of Lenslet Array on Micromirrors," *Proceedings of the SPIE* `99, vol. 3631, pp. 156-164, 1999.

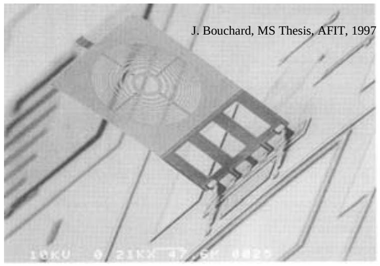
Lenses: Diffractive

- Fresnel Lens
  - Diffraction and constructive interference shape the near-field light beam exiting the lens.

$$f = \frac{R_m^2}{m\lambda}$$

    - where f is the focal length, R_m is the radius of the outer zone, m is the largest integer number of zones in the lens, and λ is the wavelength of the source.





J. Bouchard, MS Thesis, AFIT, 1997

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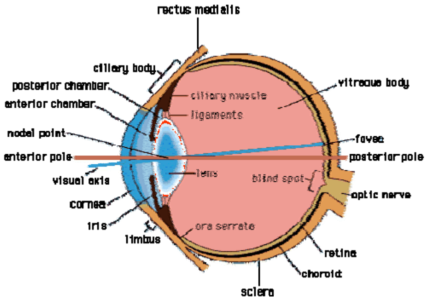
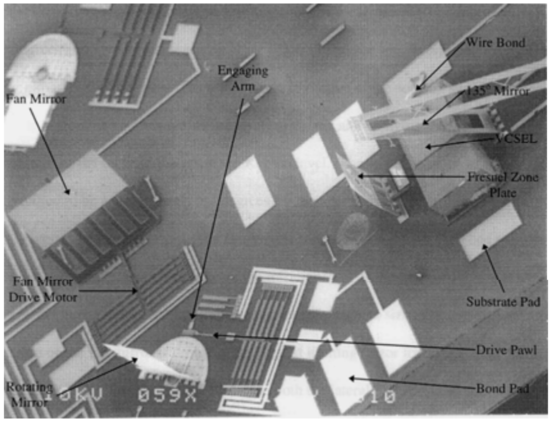


Optical Systems

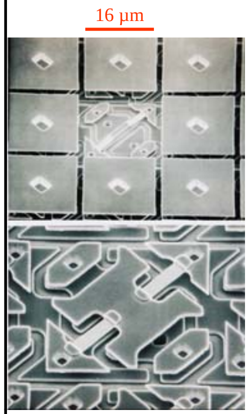
- Surface micromachined VCSEL scanning system

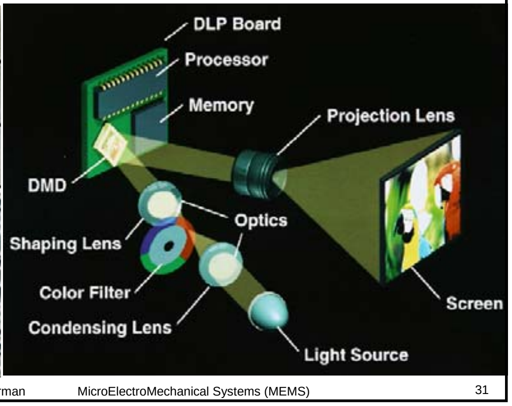


J. Bouchard, MS Thesis, AFIT, 1997

Optical Systems

- Texas Instruments Digital Micromirror Device™





Optical Systems

- 3-Chip, Texas Instruments Digital Micromirror Device™