Advanced MEMS and Microsystems

Dr. Danick Briand & Prof. Guillermo Villanueva

Course content and schedule

Dates	Topics	Lecturers
18.02	Introduction Transducers review: pre-recorded lectures	D. Briand / G. Villanueva
25.02	Sensors part I Exercices	D. Briand
04.03	Sensors part II Industrial seminar #1	D. Briand
11.03	Students presentations	D. Briand / G. Villanueva
18.03	Actuators and Optical MEMS Industrial seminar #2	D. Briand
25.03	Acoustic and Ultrasonic MEMS Industrial seminar #3	G. Villanueva
01.04	RF-MEMS	G. Villanueva
08.04	NEMS	G. Villanueva
15.04	Interactive session	D. Briand / G. Villanueva
29.04	Thermal and gas sensors Industrial seminar #4	D. Briand
06.05	Packaging	D. Briand
13.05	Packaging Industrial seminar #5	D. Briand
20.05	PowerMEMS Industrial seminar #6	D. Briand
27.05	Quiz + oral exam instructions Evaluation of the course	All

Announcements

<u>TODAY 18 March</u>

- **Lecture on Actuators and Optical MEMS**
- **Seminar 2 – Sercalo at 12h15**
  List of questions to answer available on moodle

<u>NEXT WEEK 25 March</u>

- **Hand-In Answers to Questions on Industrial Seminar 2 – Sercalo**
- **Answers form available on moodle**
- **Guillermo Villanueva will take over**
- **Seminar 3 – Sensirion at 12h15**

LECTURE 3

Actuators and Optical MEMS

Danick Briand

Maître d'Enseignement et de Recherche (MER)

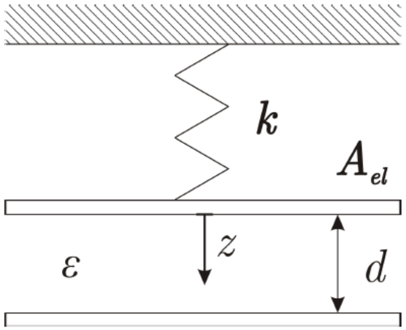
MEMS & Printed Microsystems group

EPFL-STI-LMTS

Content and Structure

1.) Optical MEMS Basics and Actuation Mechanisms

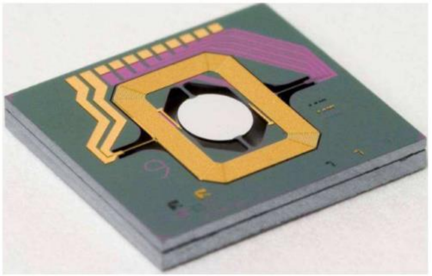
- *Introduction to Optical MEMS*
- *Review of Actuation Mechanisms*
- *Review of Electrostatic & Magnetic Actuators*



2.) Optical MEMS Systems

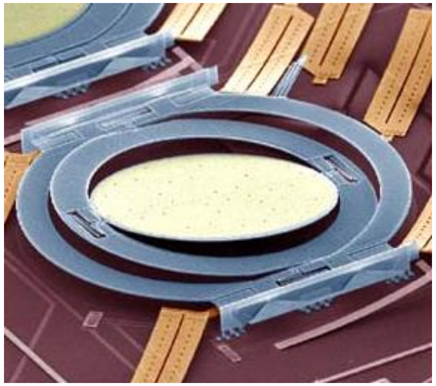
a) Consumer Electronics and Mobile

- *Micromirrors and Arrays*
- *Scanners, Projectors, Displays*

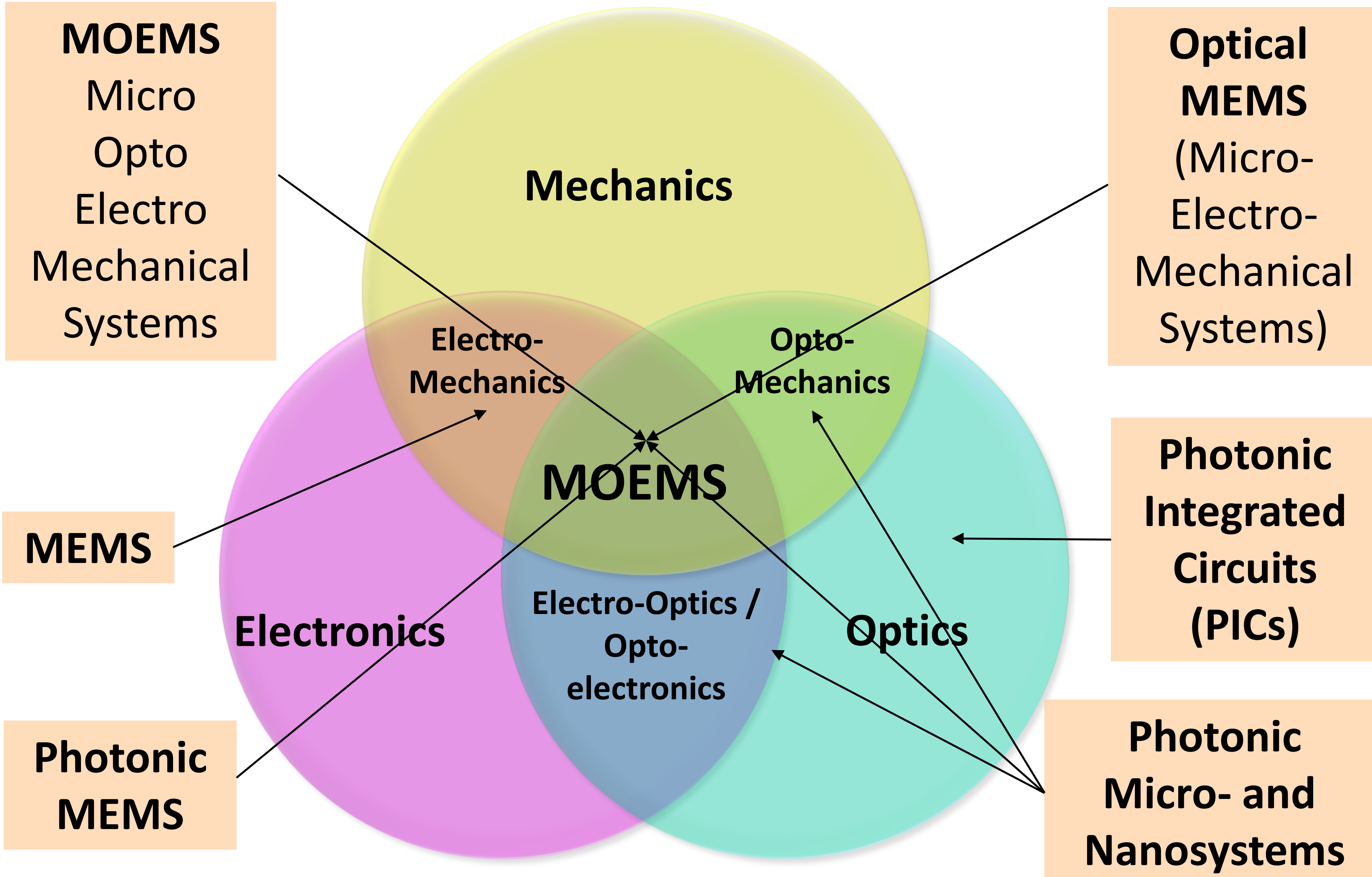


b) Telecommunications (not covered this year)

- *Optical Communication Systems*
- *Tunable Lasers*
- *Filters and Variable Optical Attenuators*
- *Optical Switches*



Terminology



after Motamedi, MOEMS

MOEMS

- Silicon / SOI Wafers
  - ø = 100 – 200 mm
  - t = 120 – 500 µm
  - *µ*-machining:
  - On surface
  - In bulk
  - Arbitrary shapes
  - µm & sub-µm patterns
- Movable structures
- Controlled actuation
- Electrical sensing
- Passive alignment
- Optically flat surfaces
- Thin film coatings
- Integrated Systems

Microoptics

- Glass (Wafers)
  (IR optics with Si)
- Optically flat surfaces
- Thin film coatings
- µ-machining
  - µ-lenses (refractive)
- nano-machining
  - diffractive optics
- Assembled Systems

Wavelength < Size of Optical Element

Nanophotonics

- Integrated Waveguides
- Dielectric Waveguides
- Silicon Photonics
- Planar Light Circuits
- Modal Control
- Polarization Control
- Carrier Displacement
- Plasmonics
- Modulators
- Detectors
- Couplers

Wavelength ≈ Size of Optical Element

Spectral Regions of Interest

[nm]
[μm]

$$\nu = \frac{c}{\lambda}$$

[Hz]

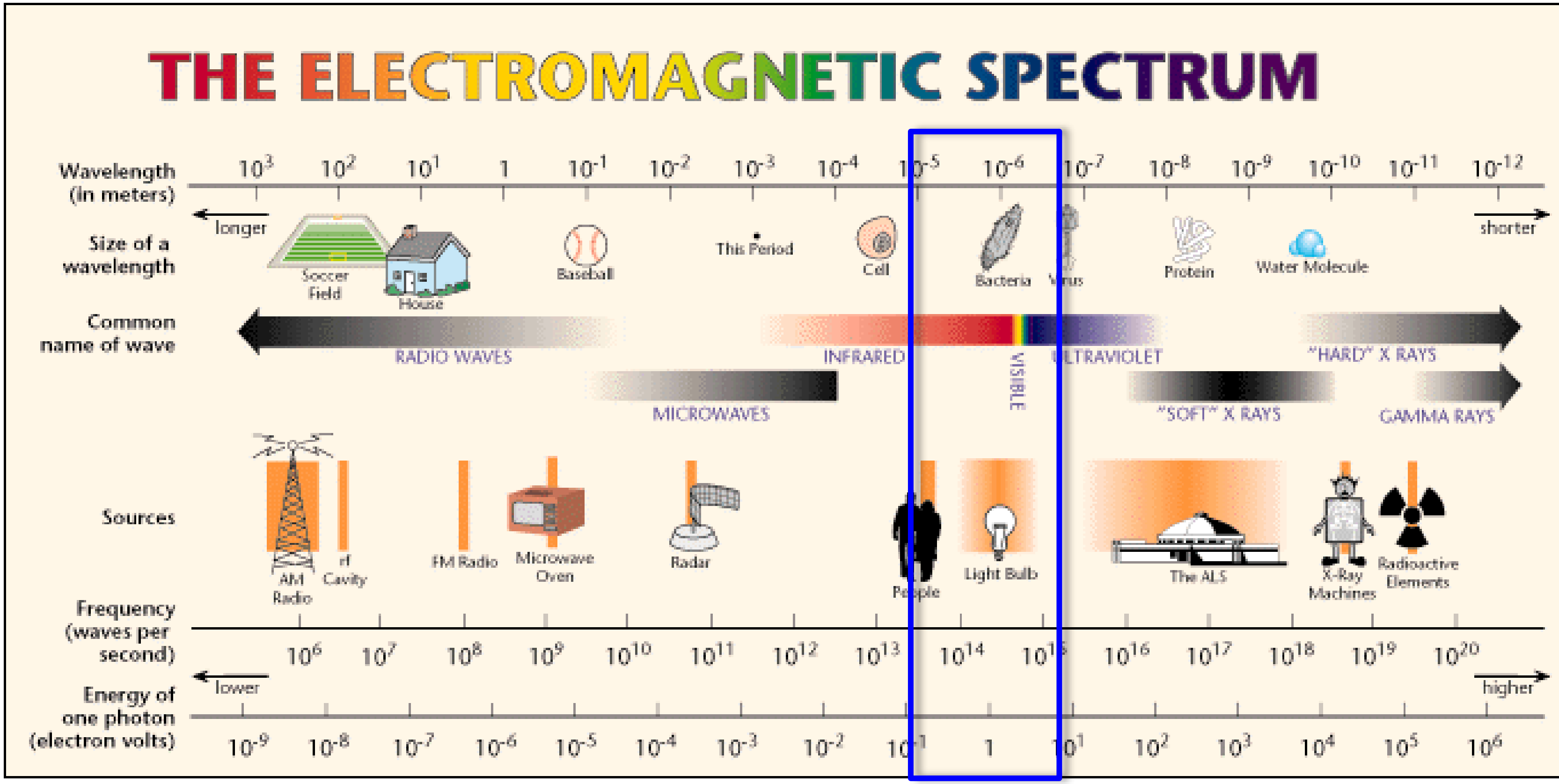
$$E = h\nu$$

[eV]

also:

$$\tilde{\nu} = \frac{1}{\lambda}$$

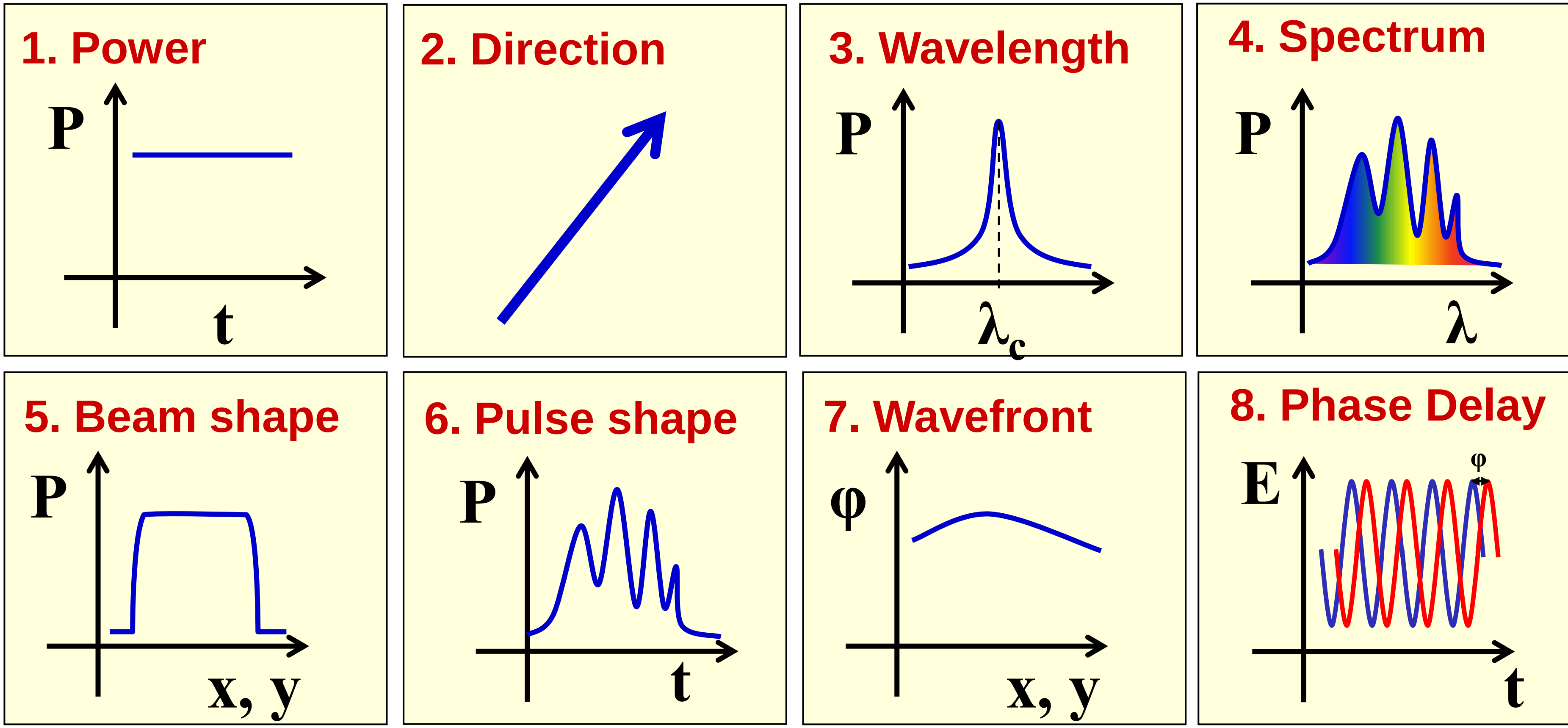
[cm^{-1}]



Domain	λ [μm]	ν [THz]	E [eV]	MOEMS Applications
Visible	0.4 – 0.7	400 – 750	1.65 – 3.10	Displays
Near-Infrared	0.7 – 3	100 – 400	0.41 – 1.65	Telecom (0.85, 1.3, 1.55)
Mid-Infrared	3 – 8	37 – 100	0.16 – 0.41	Spectroscopy
Long-Infrared	8 – 15	20 – 37	0.08 – 0.16	(Thermal Imaging)

The Case for Optical MEMS

Possibility to modify one or several of the following using mechanical motion:

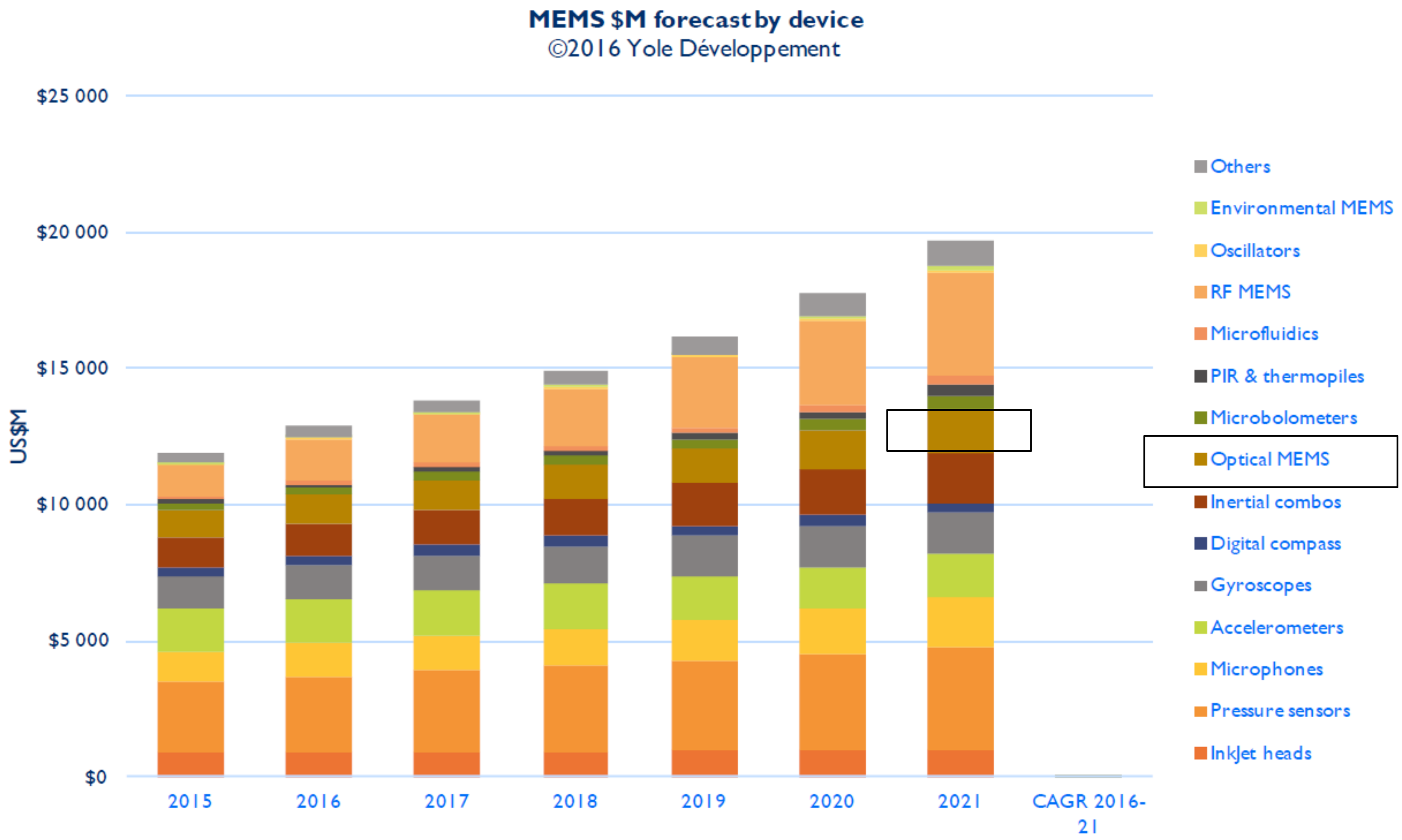


MEMS: Actuators, Integration, Thin Films, Structured Surfaces

MOEMS – Uses, Applications, Devices

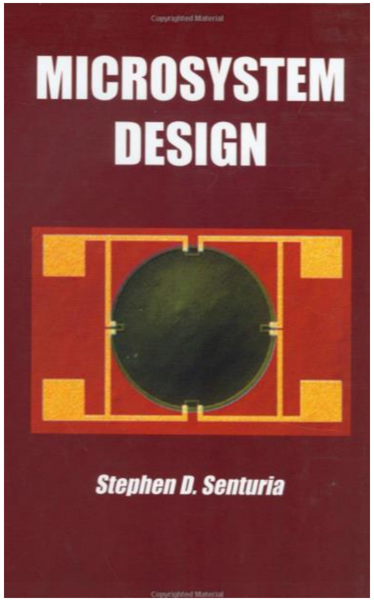
Sector	Application Examples	Devices and Systems
Consumer Electronics	Scanning Laser Displays Projection Displays Light Shows	MEMS Laser Scanners Digital Micromirrors MEMS Galvanometers
Mobile	Low Power Displays 3D Imaging / LIDAR Mobile Sensing Beam Steering	Digital Shutter MEMS Displays Interference Modulation Displays Tunable Lasers Scanning Micromirrors Microspectrometer Optical Phased Arrays, Scanners
Telecom	Switching Wavelength Division Multiplexing Variable Optical Attenuators	Optical MEMS Switch Optical Cross Connects Tunable Lasers Tunable Detectors Tunable Filters Analog Shutters
Biomedical	Miniature Microscopes Optical Coherence Tomography	Image Scanning Systems Tunable Lasers Laser Scanning Systems
Industrial	3D Printing Maskless Lithography Precision Machining, Laser Cutting	Laser Scanners Adaptive Optics Laser Scanning
Scientific	Astronomy: JWST Wavefront Correction, Adaptive Optics Spectroscopy	MEMS Shutter Arrays Adaptive/Deformable Mirrors Tunable Gratings, Tunable Filters

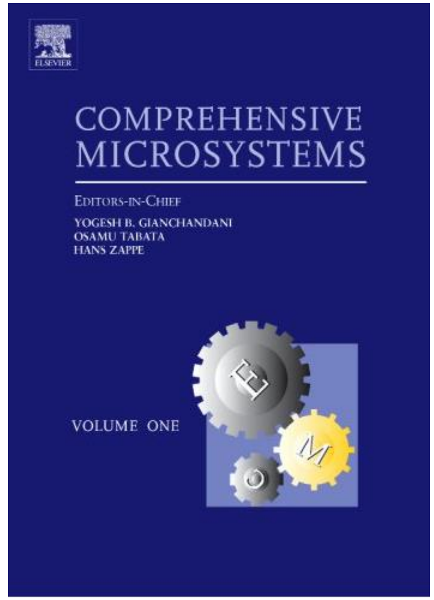
2015 – 2021 MEMS MARKET (US$M)

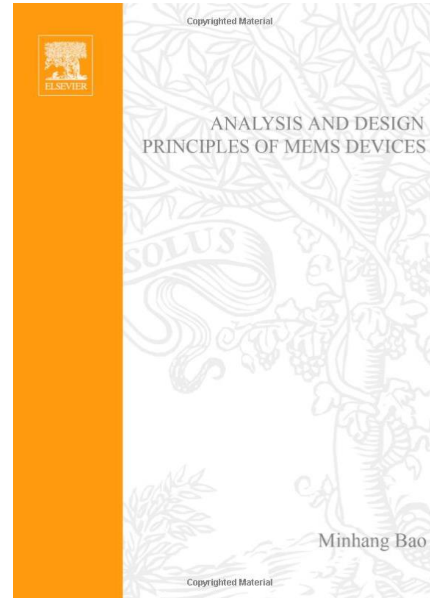


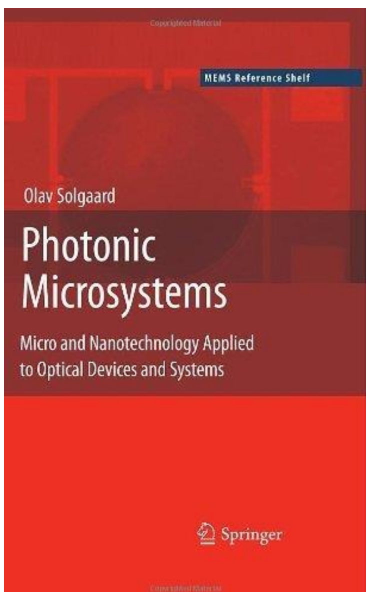
MOEMS: G$-market, dominated by Displays & Projectors

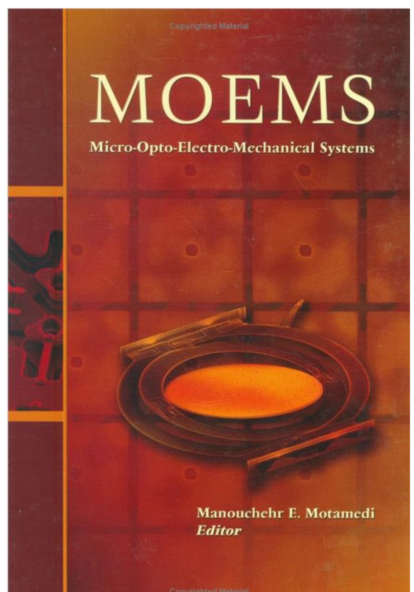
Reference Books

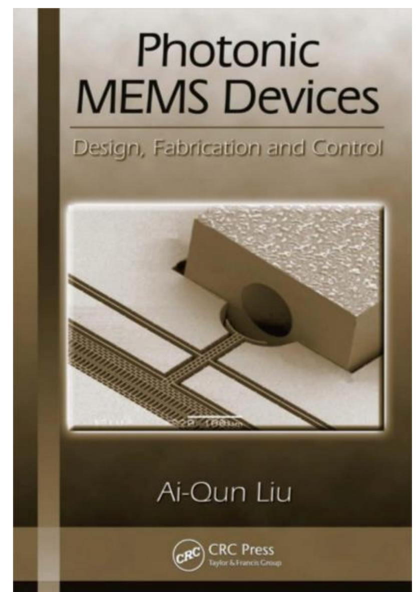






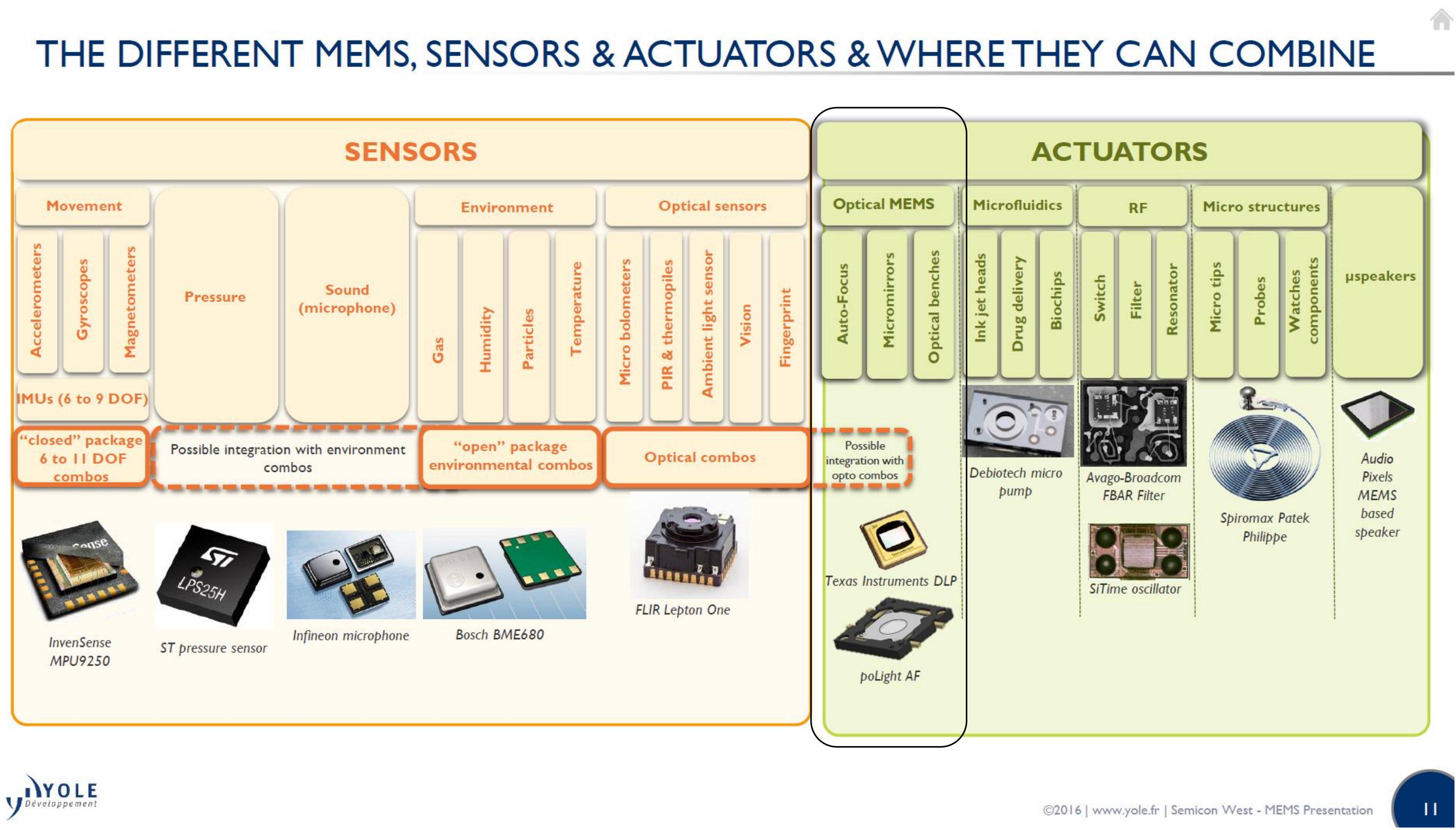






ACTUATORS FOR OPTICAL MEMS (REVIEW)

Actuators for Optical MEMS



Lecture Part Sensors **Lecture Part Actuators**

Actuation Principles – Qualitative Assessment

MOEMS majority

Actuation Principle	Force Density	Speed	Stroke	Power Consumption	Complexity and Cost	Size
Electrostatic: Parallel Plate	Low	High	Short	Low	Low	Medium
Electrostatic: Comb Drive	Medium	High	Medium	Low	Low	Small
Electromagnetic	High	High	Long	High	Medium	Large
Piezoelectric	High	High	Short	Low	Medium	Small
Thermal	High	Low	Long	High	Low	Small
Shape-Memory-Alloys (SMA)	High	Low	Long	Medium	High	Small
Scratch-Drive	Medium	Medium	Medium	Low	High	Medium
Pneumatic	High	Low	Long	High	Medium	Large
Pyrotechnical	High	High	High	High	High	Medium
Electro-Active Polymers	High	High	High	Low	High	Large

Other: Phase Change, Chemical, Biological...

Large Variety of Actuation Methods
No ‘one size fits all’ solution
Choice depends heavily on application
Core of the design phase – Need for Engineering

MOEMS Actuators – Orders of Magnitude

From: Motamedi: MOEMS

Table 4.1: Comparison of electrostatic, thermal, piezoelectric, and SMA actuators.[4–13]

Actuator type	Disp. (μm)	Output force (μN)	Actuation voltage (V)	Speed (Hz)	W/v (J/m^3)	Comments
Electrostatic	0.1–30	0.1–(1 × 10^3)	≈50–120	3 × 10^3	7.0 × 10^2–1.8 × 10^5	Parallel plate, comb drive, force array
Thermal	10–100	10–(1 × 10^3)	<20	10^2–10^3	4.6 × 10^5	Bimorph, pseudo-bimorph, bent-beam actuator
Piezoelectric	≈10	10–(1 × 10^6)	20–10^3	10 × 10^3	1.2 × 10^5–1.8 × 10^2	PZT-based, ZnO-based
SMA	10–570	(10–200) × 10^3	1–3	20	2.5 × 10^7–6.0 × 10^6	Ni-Ti- based
Magnetic	Up to 10^3	Up to 10^5	<10 mA (current)	10^2–10^4	1.6 × 10^3–4.0 × 10^5	Magnetostatic, electromagnetic, magnetostrictive

- ***Typical Maximum Displacements:*** ***μm – mm***
- ***Position Control Range:*** ***nm – μm***
- ***Typical Forces:*** ***μN – mN***
- ***Typical Speed:*** ***μs – s***

Domain	λ [μm]	ν [THz]	E [eV]	MOEMS Applications
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Near-Infrared	0.7 – 3	100 – 400	0.41 – 1.65	Telecom *(0.85, 1.3, 1.55)*
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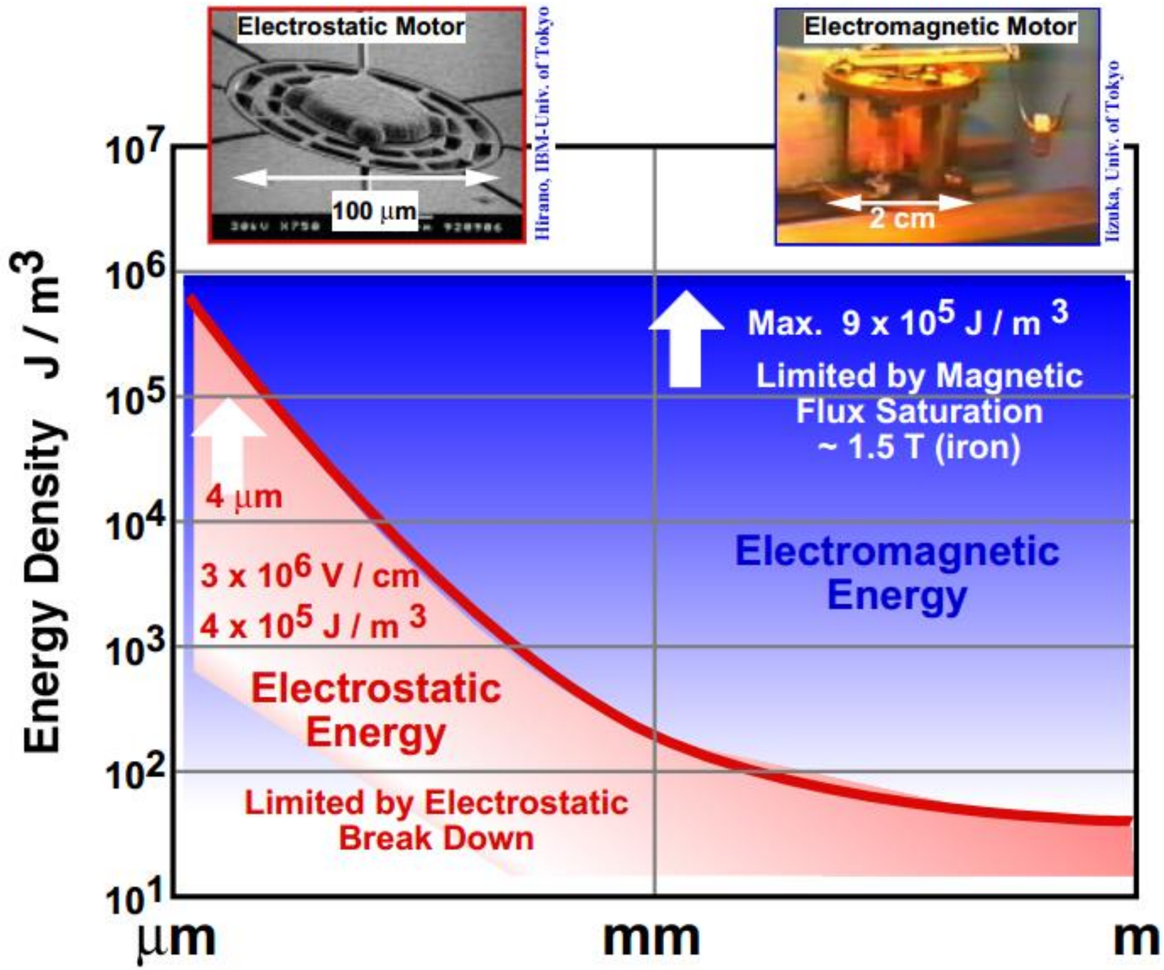
Actuators – Electrostatic vs. Magnetic Actuation

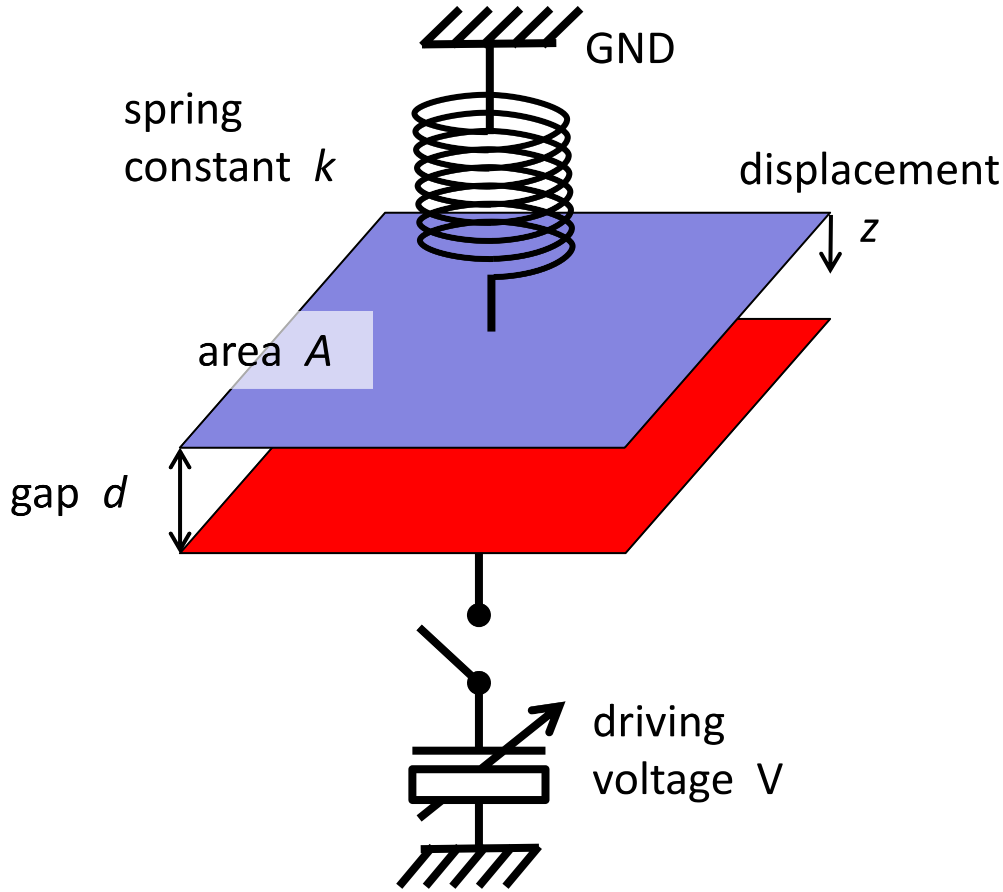


Electrostatic Parallel-Plate Actuator

Coulomb Forces due to Charges

Oppositely Charged: Attractive Force

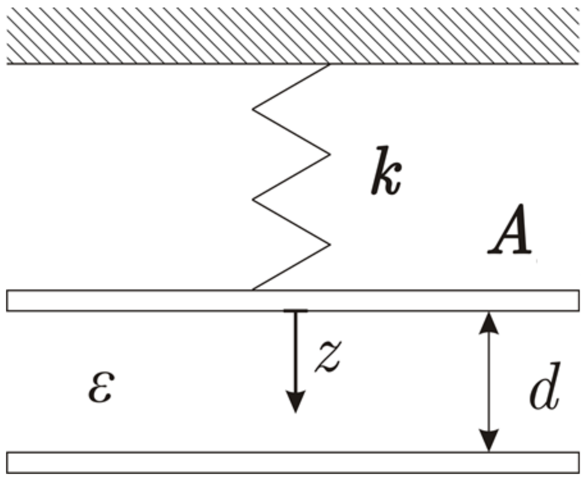
- Compact
- Simple
- Small Mass (Fast Response)
- Capacitive Readout for Position Sensing possible (Feedback)
- Limited Forces
- Pull-In Instability
- Nonlinear



Model:

- fringe/edge effects neglected
- spring “constant” independent of displacement

Electrostatic Parallel Plate Actuator



Parallel Plate Capacitor $C = \frac{\varepsilon A}{d - z}$

Stored Energy (Capacitor + Spring)

$$E = \frac{1}{2} C V^2 + \frac{1}{2} k z^2$$

$$E = \frac{1}{2} \frac{\varepsilon A}{d - z} V^2 + \frac{1}{2} k z^2$$

Resulting Forces

$$F_{tot} = \frac{1}{2} \frac{\varepsilon A}{(d - z)^2} V^2 - kz$$

Equilibrium Position: Net Zero Force, or:

Electrostatic Force = Restoring Spring Force

$$\frac{1}{2} \frac{\varepsilon A}{(d - z)^2} V^2 = kz$$

k Suspension spring constant
A Electrode surface
d Initial distance between the electrodes

z Displacement of the movable electrode
ε Dielectric constant of air
m Mirror mass
V Applied voltage between the electrodes

Electrostatic Parallel Plate Actuator

Equilibrium Position:

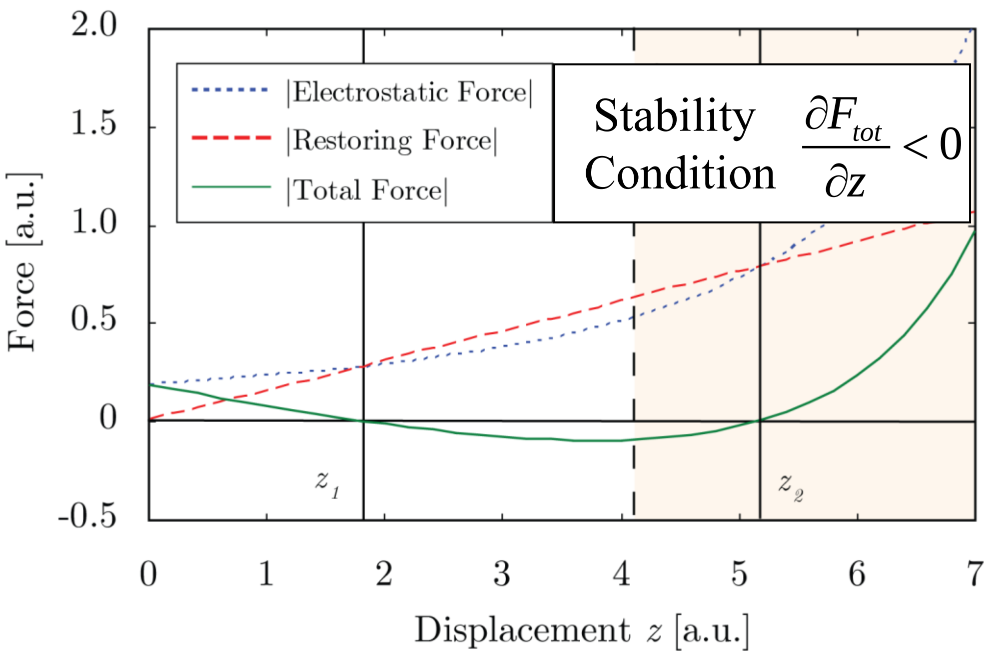
Electrostatic Force = Restoring Spring Force

$$\frac{1}{2}\frac{\varepsilon A}{(d-z)^2}V^2 = kz$$

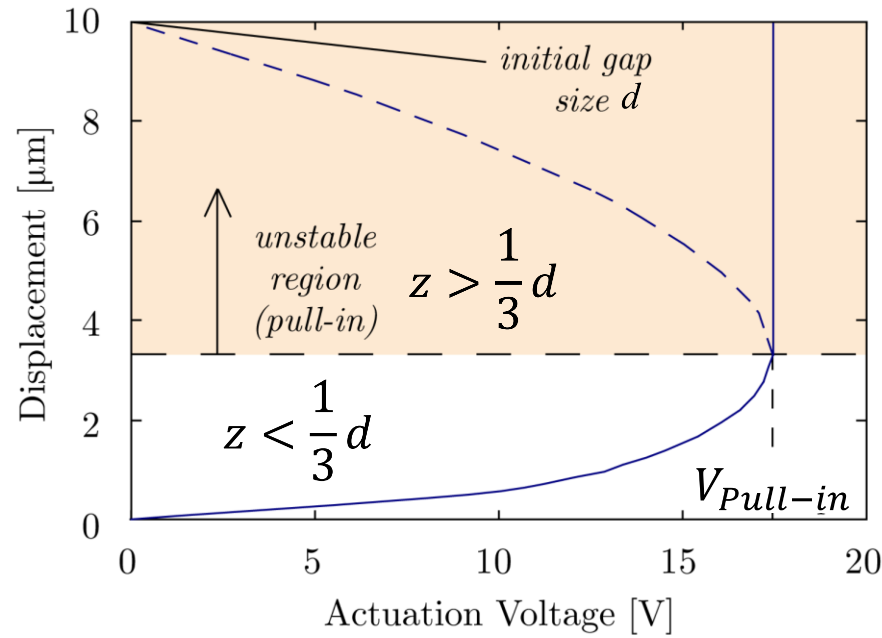
Maximum stable position z_c

$$\frac{\partial F_{tot}}{\partial z} = 0 \quad \text{and} \quad F_{tot} = 0$$

$$k = \frac{\varepsilon A}{(d-z_c)^3}V^2 \text{ and } kz_c = \frac{1}{2}\frac{\varepsilon A}{(d-z_c)^2}V^2$$



Numerical Example:



Illustrations/Example from Quack: http://e-collection.ethbib.ethz.ch/view/eth:801

Electrostatic Parallel Plate Actuator

Equilibrium Position:

Electrostatic Force = Restoring Spring Force

$$\frac{1}{2}\frac{\varepsilon A}{(d-z)^2}V^2 = kz$$

Maximum stable position z_c

$$\frac{\partial F_{tot}}{\partial z} = 0 \quad \text{and} \quad F_{tot} = 0$$

$$k = \frac{\varepsilon A}{(d-z_c)^3}V^2 \text{ and } kz_c = \frac{1}{2}\frac{\varepsilon A}{(d-z_c)^2}V^2$$

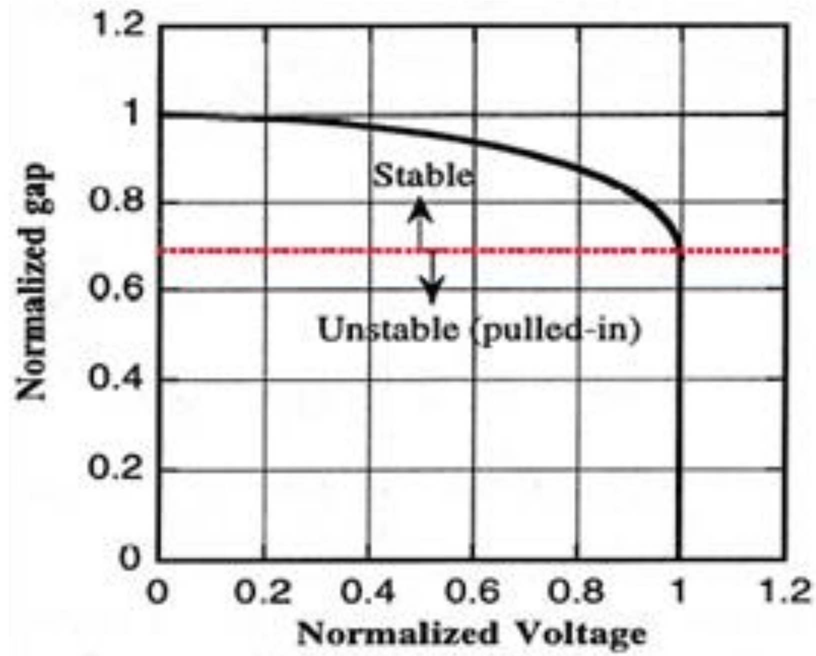
Pull-In Voltage at $z = z_c$

$$V_{Pull-in} = \sqrt{\frac{8kd^3}{27\varepsilon A}}$$

$$V_{Pull-in} \propto d^{3/2}$$

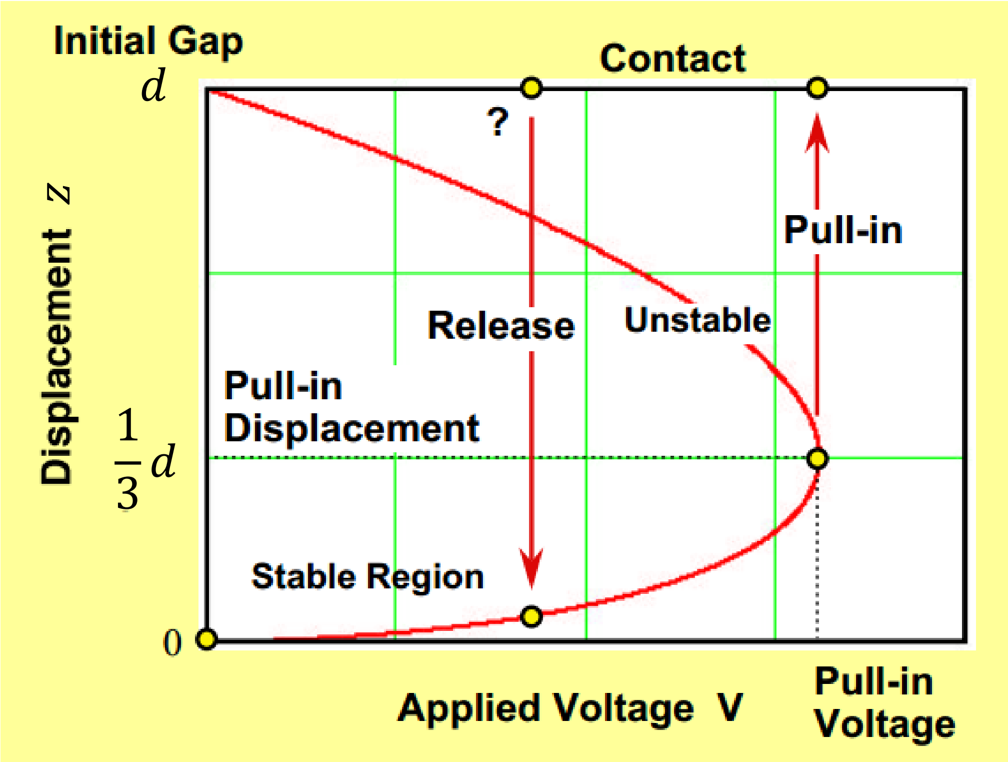
Maximum stable position

$$z < \frac{1}{3}d$$



Senturia: Microsystem Design

Electrostatic Parallel-Plate Actuator Summary



$$V_{Pull-in} = \sqrt{\frac{8kd^3}{27\varepsilon A}}$$

$$V_{Pull-in} \propto d^{3/2}$$

$$V_{Release} \sim t_{dielectric}\sqrt{\frac{kd}{\varepsilon_{dielectric}A}}$$

Pull-in: *Key Design Parameter for Parallel-Plate Electrostatic Actuators*

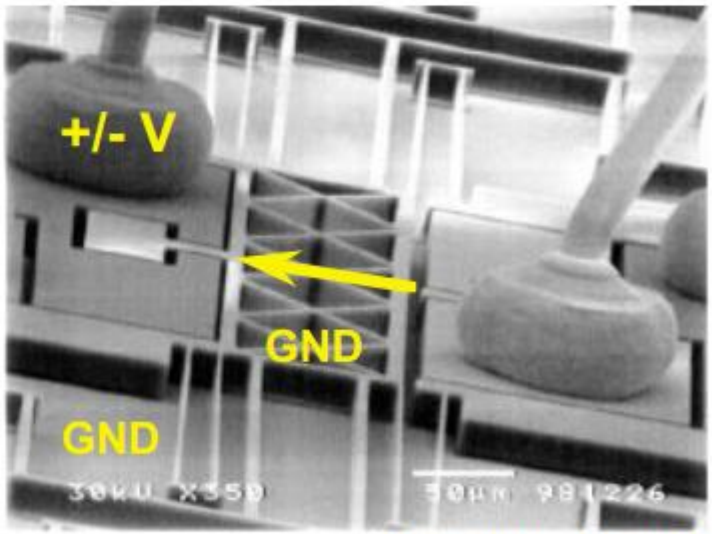
- *Only **1/3 of the gap** can be used for actuation*
- *Gap can be reduced using (high-k) **dielectric layer***
- *For **doubly clamped** beam, the pull-in limit can be up to ~½ d because of non linearity.*
- *Stoppers or a dielectric film are needed to prevent **short circuit** when snapping in*

Hysteresis:

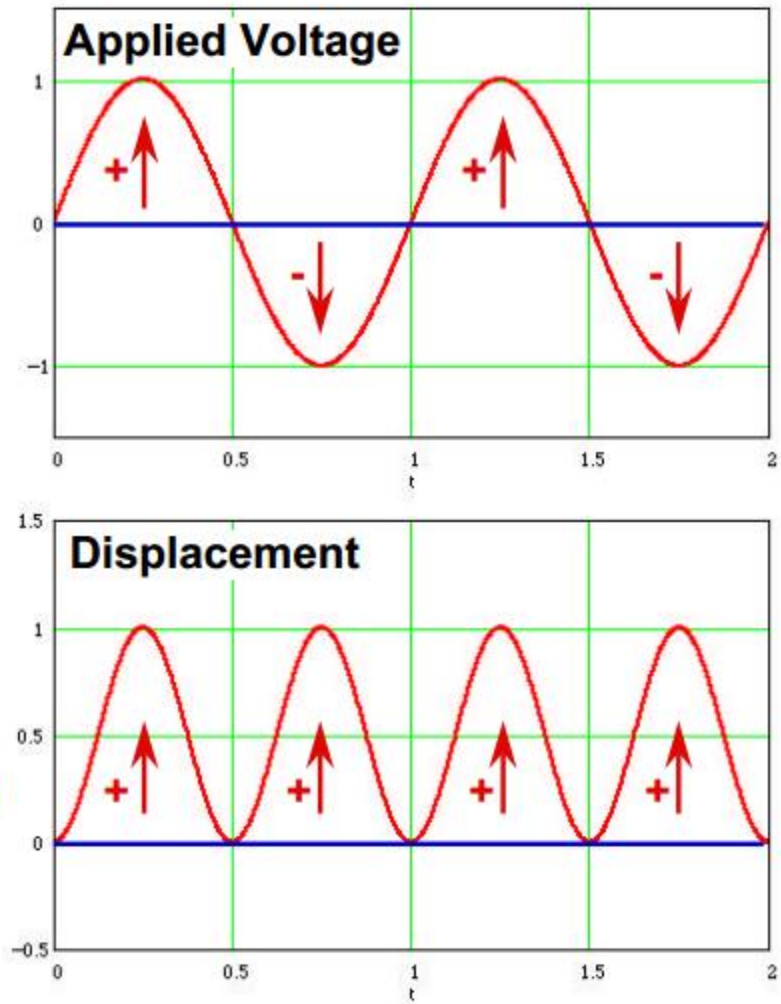
Release voltage lies well below pull-in voltage

Electrostatic Parallel-Plate Actuator

Electrostatic Force



H. Toshiyoshi, 1999

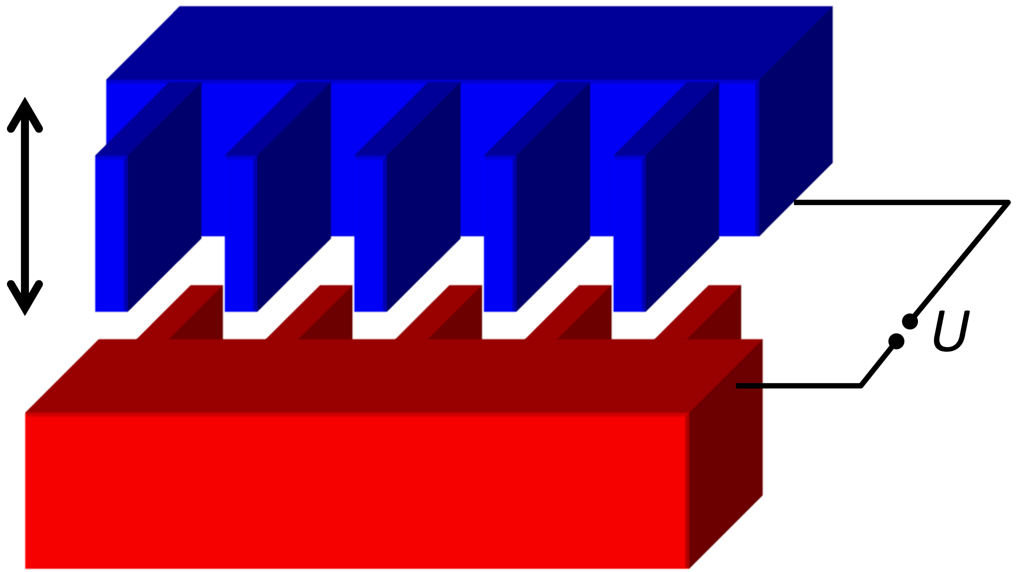


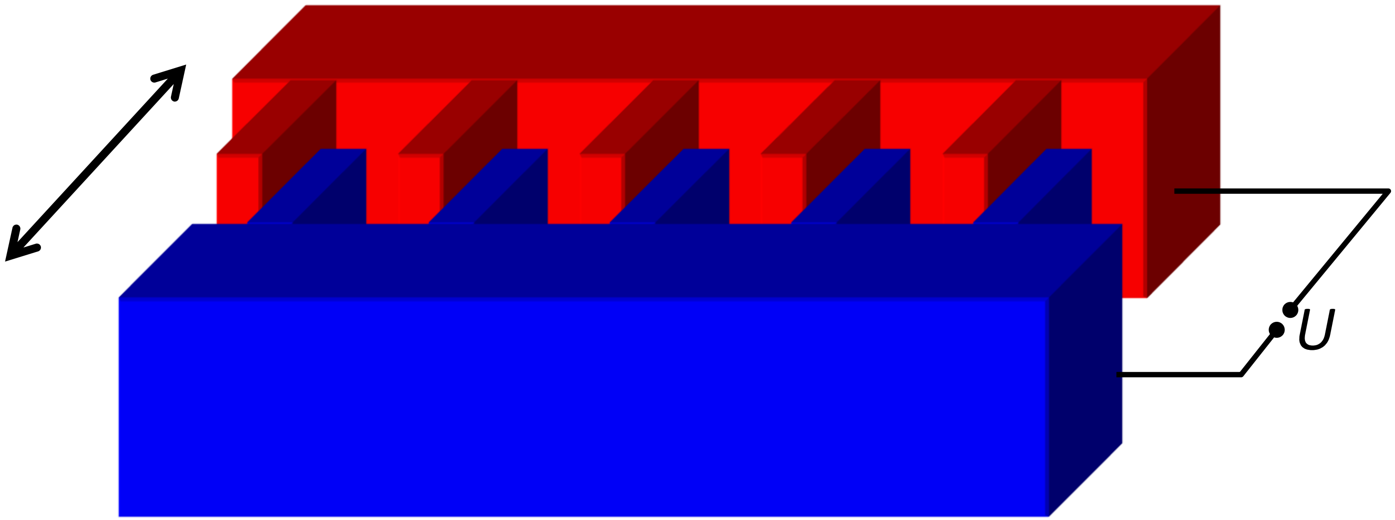
- Displacement is independent of polarity
  (if free from permanent charges on electrodes)
- Frequency is doubled

(Dynamics: See Resonators & NEMS Part)

Electrostatic Comb Drive Actuators

- Low power
- Lateral actuation
  - In-plane motion
- Vertical actuation
  - Out-of-plane
- Movement depends on degree of freedom
- Vary accurate movement
- <u>Large range without pull in</u> ☺





Electrostatic Force in Comb Drive Actuator

$$C_{\perp} = \varepsilon_0\, \varepsilon_r \frac{h(l+x)}{g} \quad and \quad C_{||} = \varepsilon_0\, \varepsilon_r \frac{h\,w}{d-x}$$

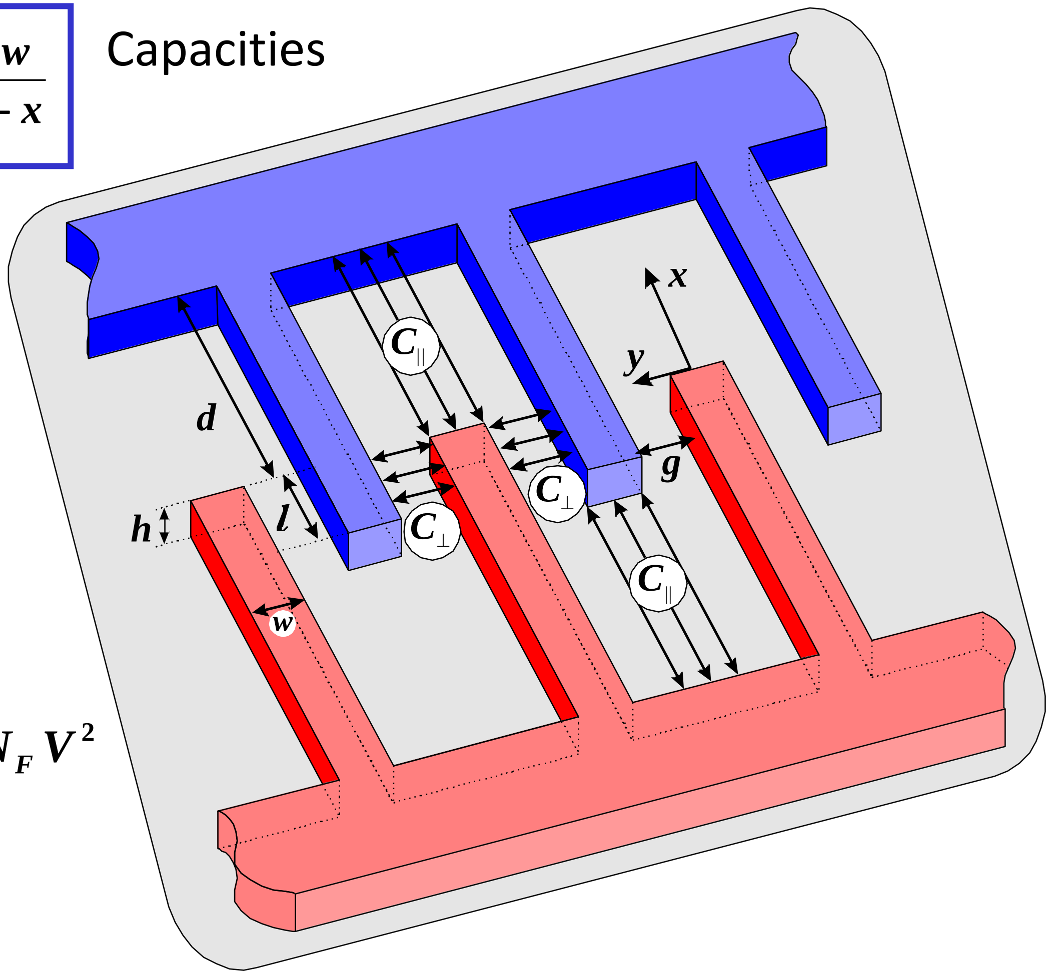
Capacities

$$C_{tot} = \left(2\,C_{\perp} + 2\,C_{||}\right) \times N_F$$

$$C_{tot} = 2\,\varepsilon_0\,\varepsilon_r \left[\frac{h(l+x)}{g} + \frac{h\,w}{d-x} \right] \times N_F$$

$$F_E = -\frac{1}{2}\frac{\partial C}{\partial x} V^2 = -\,\varepsilon_0\,\varepsilon_r \left[\frac{h}{g} + \overbrace{\frac{h\,w}{(d-x)^2}}^{<<\,\frac{h}{g}} \right] N_F\, V^2$$

$$\Rightarrow \quad F_E \approx -\varepsilon_0\,\varepsilon_r \frac{h\,N_F}{g} V^2$$



Electrostatic force

Electrostatic Force in Comb Drive Actuator

Comb actuator

Axial force $$F_x = \frac{1}{2}\frac{dC}{dx}V^2 = N \cdot \frac{\varepsilon_0 h}{g}V^2$$

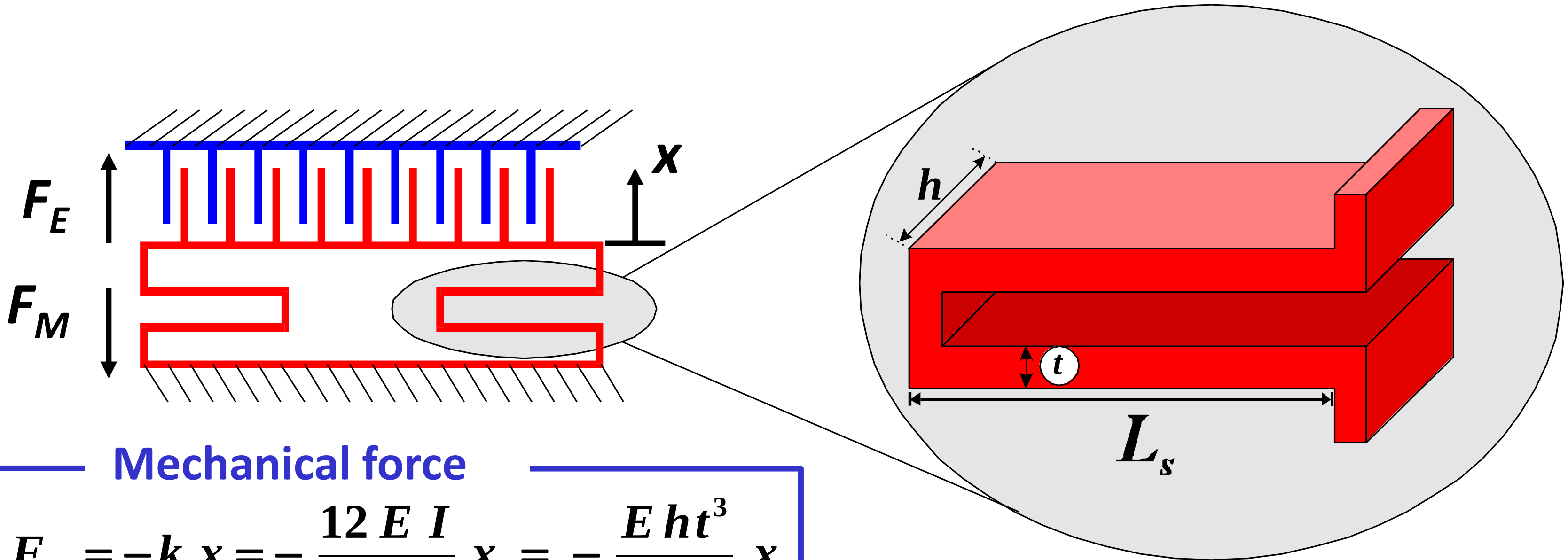
Lateral force $$F_y = \frac{1}{2}N\varepsilon_0 V^2 hl\left(\frac{1}{(g-y)^2} - \frac{1}{(g+y)^2}\right)$$

Transverse stability (lateral pull-in)

Stability condition $$k_y > \left.\frac{dF_y}{dy}\right|_{y=0} \quad \text{or} \quad \frac{k_y}{k_x} > 2\frac{x_{\max}(l + x_{\max})}{g^2}$$

- Axial force is independent of overlapping length
- Comb drive allow large displacement, but resonance frequency is limited by the spring mechanism
- Smaller forces than parallel plate actuators (large gap)
- The force does not depend on displacement x
- Vertical (lifting) forces can occur if the base plane is not properly grounded for thin actuators
- The force can be increased by using thick (high aspect-ratio) structures: increase h
- twisting movement instability

Electrostatic Actuation: Spring Design Example



Mechanical force

$$F_M = -k\,x = -\frac{12\,E\,I}{L_S^3}\,x = -\frac{E\,h t^3}{L_S^3}\,x$$

for 1 bending beam

With $F_E = F_M$

We obtain $V = \sqrt{\dfrac{E\,g\,t^3\,x}{\varepsilon_0\,\varepsilon_r\,N_F\,L_S^3}}$ and $x = \dfrac{\varepsilon_0\,\varepsilon_r\,N_F\,L_S^3}{g\,E\,t^3}\,V^2$

$$\Rightarrow \quad x \propto V^2$$

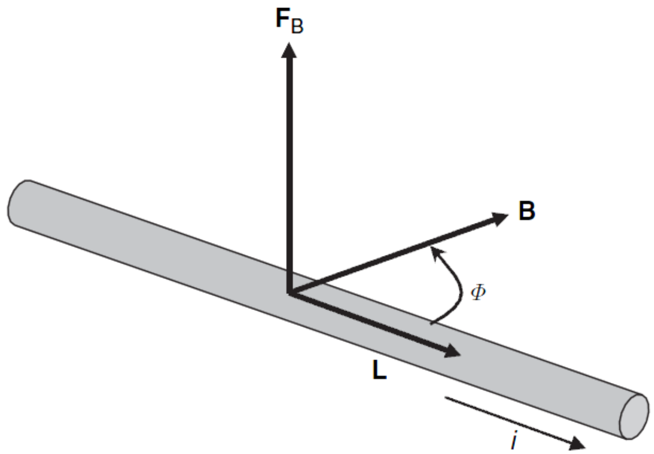


Figure 2 A wire segment of length *L* makes an angle *Φ* with a magnetic field.

$$\boldsymbol{F} = q\boldsymbol{v} \times \mathrm{B}$$

Lorentz force law for magnetism

$$\boldsymbol{F_b} = i\,\mathrm{L} \times \mathrm{B}$$

source of the field B:

- *permanent magnet*
- *current carrying wire*
- *solenoid*

Advantages:
- low voltage (few V)
- push and pull
- large forces
- linear

Drawbacks:
- power consumption (current)
- magnetic thin/thick films difficult
- scaling unfavorable

Review of Magnetic Actuators

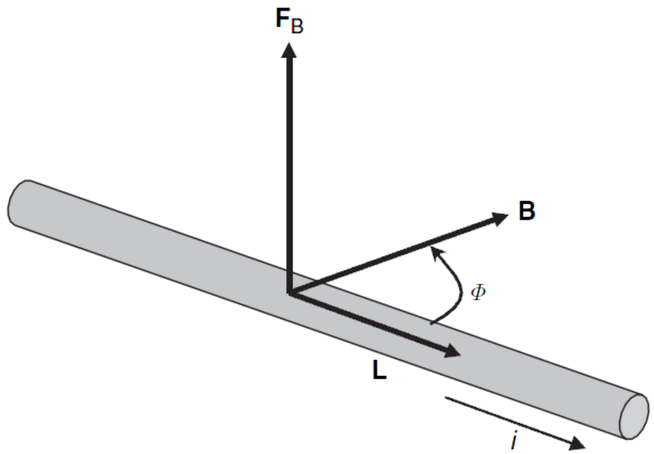


Figure 2 A wire segment of length *L* makes an angle *Φ* with a magnetic field.

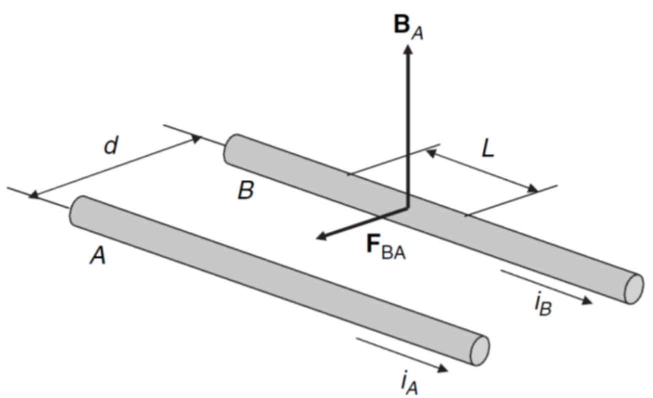


Figure 3 Two parallel wires carrying currents in the same direction attract each other. The magnetic field at wire B set up by the current in wire A is shown. For antiparallel currents, the two wires repel each other.

$$\boldsymbol{F} = q\boldsymbol{v} \times \mathrm{B}$$

Lorentz force law for magnetism

$$\boldsymbol{F_b} = i\,\mathrm{L} \times \mathrm{B}$$

Coulomb's law for magnetism / Biot–Savart law

$$d\boldsymbol{B} = \frac{\mu_0}{4\pi}\frac{id\boldsymbol{s}}{r^3} \times \mathbf{r}$$

*d**s**: differential element of length*

$$\boldsymbol{B}(r) = \frac{\mu_0}{2\pi}\frac{i}{r}$$

(long, straight wire)

example of 2 parallel wires

$$\boldsymbol{B_A} = \frac{\mu_0}{2\pi}\frac{i_A}{d}$$

field produced by current i_A in wire A at site of wire B

$$F_{BA} = i_B L B_A = \frac{\mu_0 L i_B i_A}{2\pi d}$$

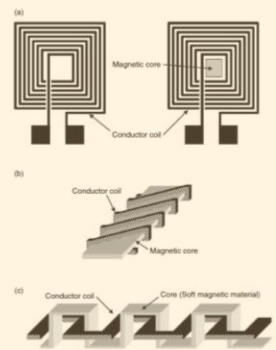
B is submitted to force F_{BA} due to current in A

Source: Comprehensive Microsystems

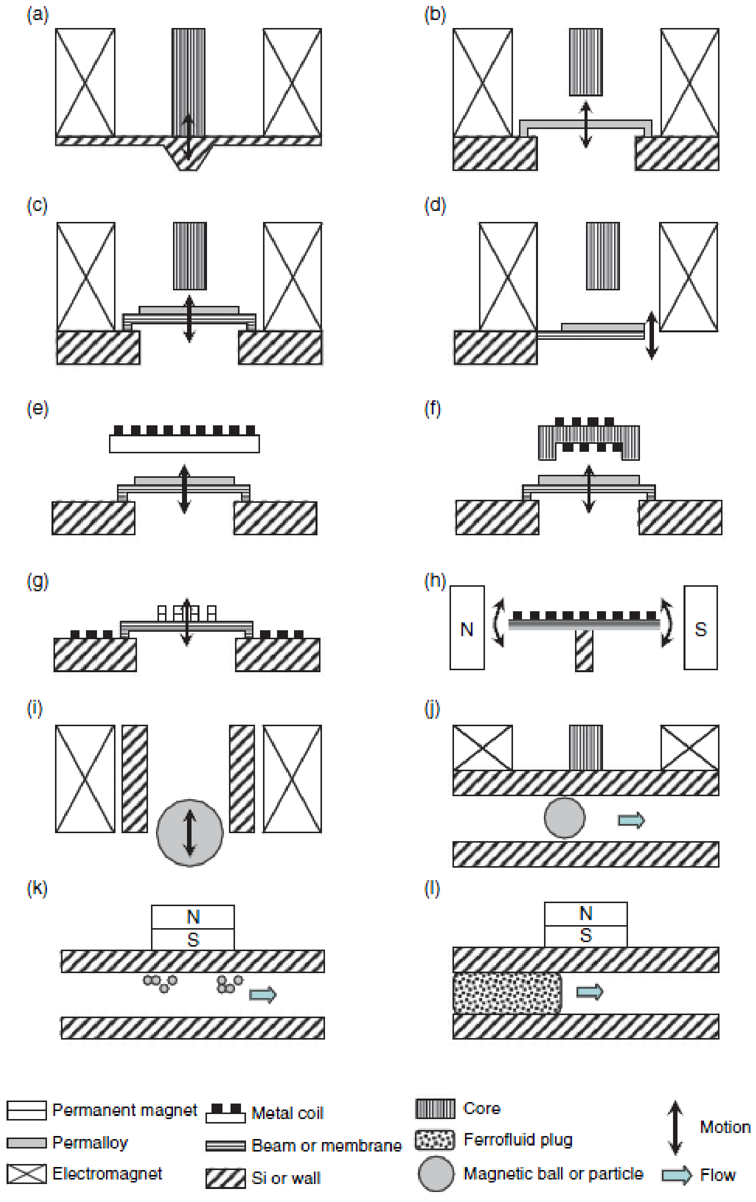
MEMS Magnetic Actuation Configurations

Source of field	On-chip microstructure	Movable part: Membrane	Beam	Ball	Particles	Ferrofluid
External solenoid	Permanent magnet					
	Soft ferromagnet	b, c	d			
	Integrated coil					
	Others	a		i, j		
Integrated coil	Permanent magnet		g			
	Soft ferromagnet	e, f				
	Integrated coil					
Permanent magnet	Permanent magnet					
	Soft ferromagnet					
	Integrated coil		h			
	Others				k	l

- **Thin Film Technology**
  - **Coils**
    - **Standard Thin Films**
    - **Planar: limited field**
    - **Meander/3D: complex**
  - **Magnetic Thin Films**
    - **Non-Standard Thin Films**
    - **Electroplated or Particles**
    - **Limited Coercivity**
- **External Permanent Magnet**
    - **Highest Forces**
    - **Assembly**



igure 12 Schematic diagrams of three types of integrated electromagnetic coils: (a) spiral type without a core and with ore. (b) solenoid type, and (c) meander type.



On-Chip Coils

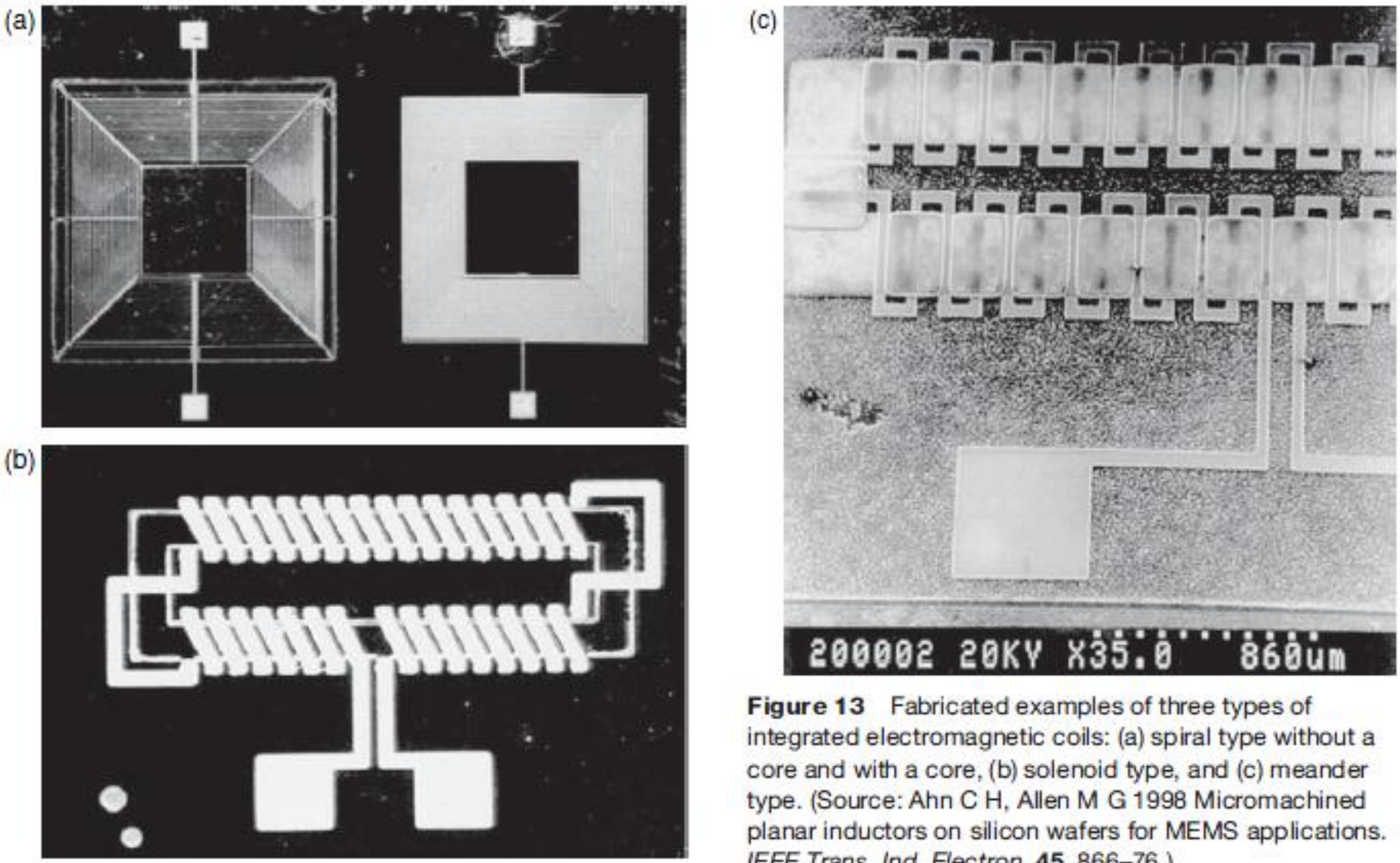


Figure 13 Fabricated examples of three types of integrated electromagnetic coils: (a) spiral type without a core and with a core, (b) solenoid type, and (c) meander type. (Source: Ahn C H, Allen M G 1998 Micromachined planar inductors on silicon wafers for MEMS applications. *IEEE Trans. Ind. Electron.* **45**, 866–76.)

Actuators – Electrostatic vs. Magnetic Actuation

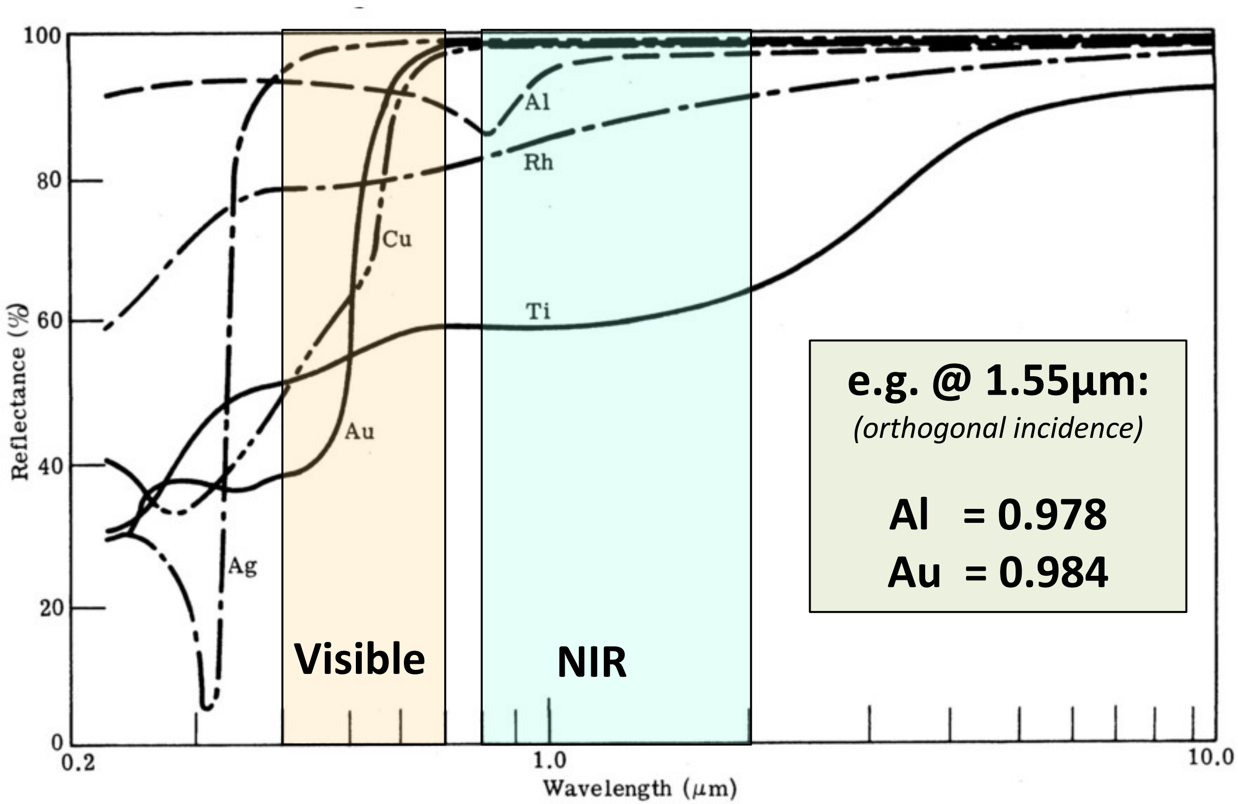
Actuation Method	Electrostatic	Magnetic
Field energy density	4×10^5 Jm^{-3} (max)	4×10^5 Jm^{-3} (1 T)
Scaling of Force	(L^2)	(L^4) (constant current)
Scaling of energy density	(L^0) (for small gaps)	(L^2)
Gap contamination	Very sensitive to humidity and dust	Fairly insensitive
IC compatibility	Good	Not very good
Range	Short	Long
Power efficiency	Very good	High power consumption
Miniaturization	Excellent	Difficult
Complexity	Low	High
Control	Voltage switching faster, efficient	Current switching less efficient, more complex

MICROMIRRORS

- **Use of Micromirrors**
  - **Redirect Light**
    - **Scanning, Projection, Switching**
  - **Reflect Light**
    - **Feedback in Lasers**
    - **Path Difference in Spectrometers**

- **Microsystems Design and Engineering**
  - **Optical Aspects**
    - **Size, Power Handling, Reflectivity**
  - **Actuator Aspects**
    - **Power Consumption, Stroke, Speed**
  - **Mechanical Aspects**
    - **Size, Mass, Stiffness, Speed**
  - **Feedback**
    - **Linearity, Speed, Accuracy**

Reflective Coatings: Metal Coatings



e.g. @ 1.55μm:
(orthogonal incidence)

Al = 0.978
Au = 0.984

- **Thin Film Coatings**
- **High Reflectivity**
- **Metallic Coatings**
  - **Evaporated**
  - **Sputtered**
  - **Electroplated**

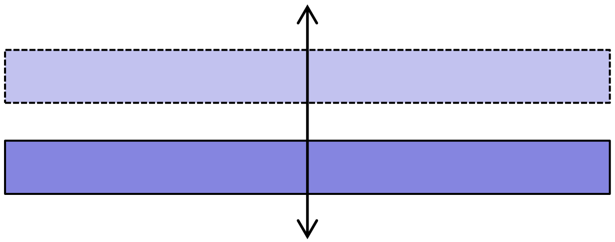
- **Wavelength Dependece**
  - **Au for IR**
  - **Al for visible**
  - **Al as low cost alternative for IR**
- **Al compatible with most fabs (CMOS)**
- **Microstructure, Curvature**

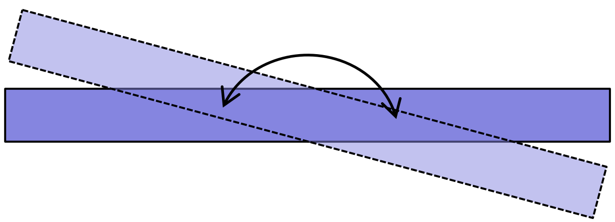
Values: Solgaard, Photonic Microsystems

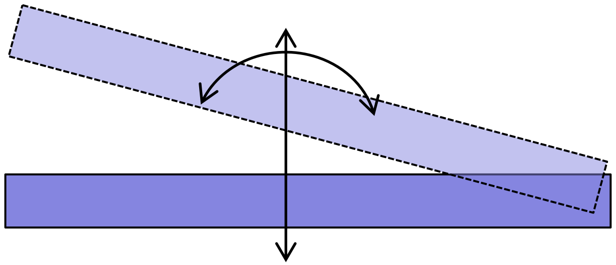
Image: “Reflectance of metallic coatings.” W.L. Wolfe and and G.J. Zissis Eds., The Infrared Handbook (1993).

Typical Micromirror Configurations

Movement depends on degree of freedom (suspension) and actuation
Arrays vs. Individual Devices
(equivalently applicable for diffraction gratings)







- Piston µmirror
- Translation Movement
- In-Plane, Out-of-Plane
- Analog vs. Digital

- up to 100s of um
- Spectrometers
- Displays
- Lasers
- Interferometers
- Optical Phased Arrays

- Tilting µmirror
- Angular Movement
- In-Plane, Out-of-Plane
- Analog vs. Digital

- +/- 10° typ. (mechanical)
- Displays (digital)
- Beam Steering (analog)
- Switches
- Filters

- Tip/Tilt/Piston µmirror
- Tilt + Translation
- Out-of-Plane
- Analog

- combined movement
- Spectroscopy
- Adaptive Optics

- ***Examples of Advanced Optical MEMS (Systems) for Mobile and Consumer Electronics***

- ***Scanning and Projection Systems based on Micromirrors***
- ***Interference Modulator Displays***
- ***MEMS Shutter Displays***

MEMS DISPLAY SYSTEMS

How to win an Oscar with MOEMS

IEEE SPECTRUM

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The Oscar Goes to… Engineer Larry Hornbeck and His Digital Micromirrors

By Tekla Perry
Posted 20 Feb 2015 | 15:00 GMT

Michael Yada/A.M.P.A.S.

Larry Hornbeck shows off his Oscar-winning technology at the Academy of Motion Picture Arts and Sciences' Scientific and Technical Achievement Awards

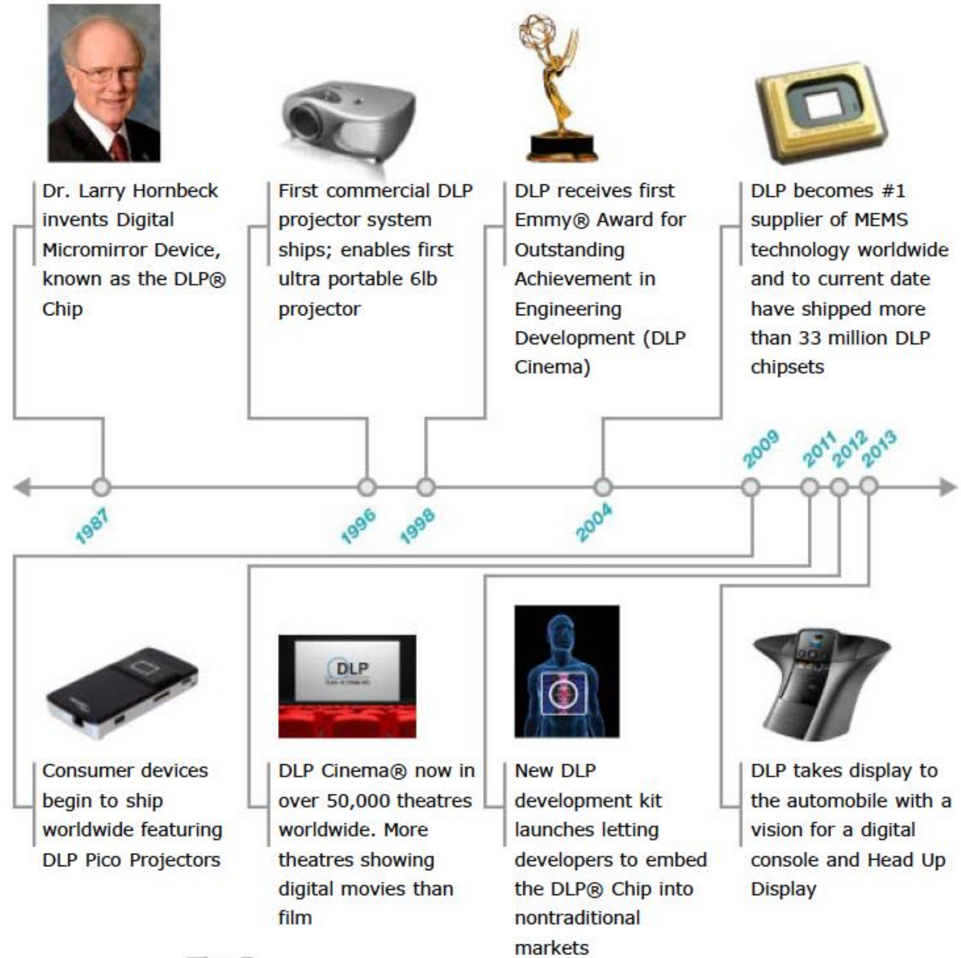
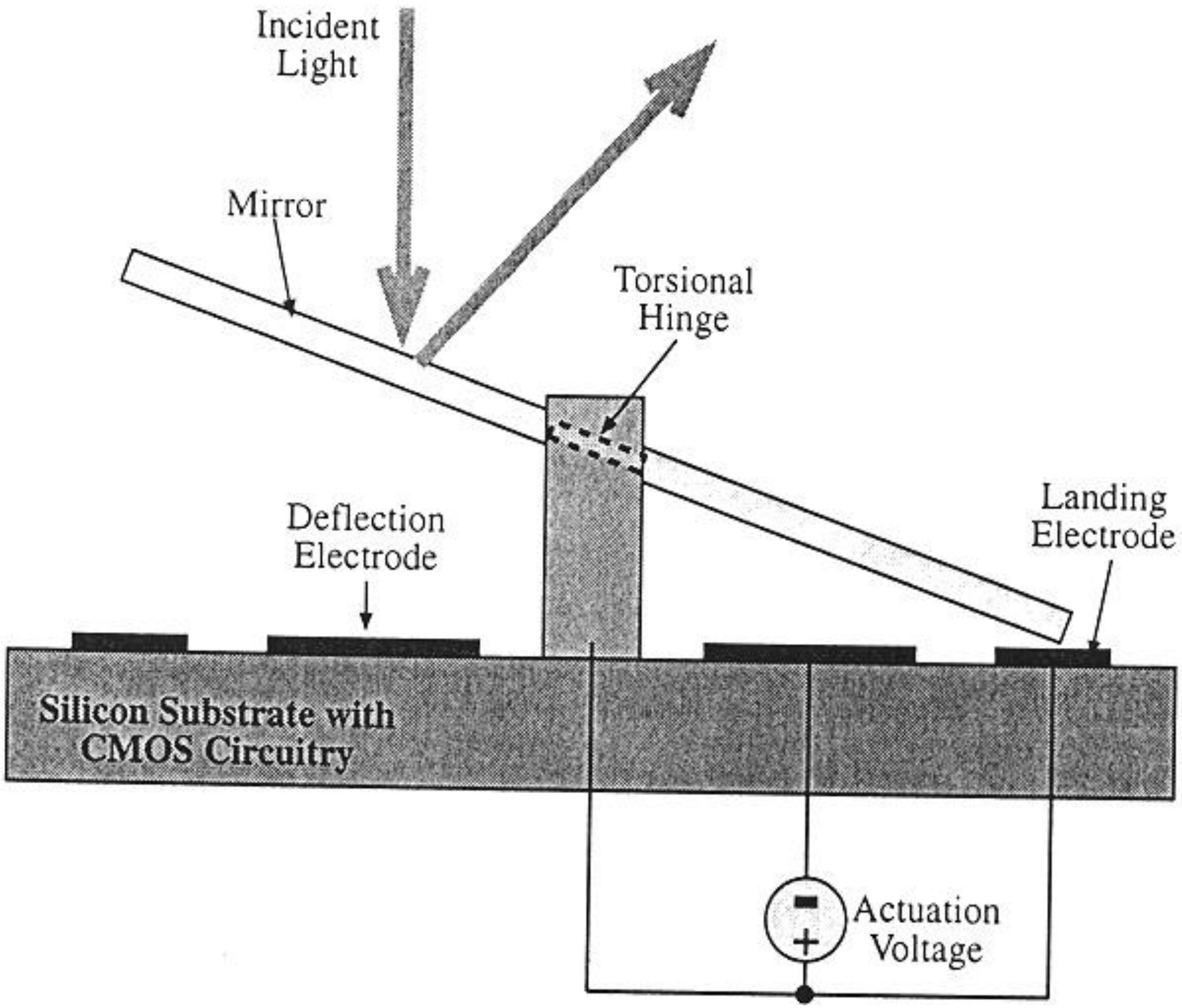


Fig. 20. DLP Cinema® projectors.

TABLE 8
DLP CINEMA® PROJECTORS

http://www.dlp.com/technology/dlp-history/

Digital Tilting Mirror



L. Hornbeck, Electronic Imaging, 1997

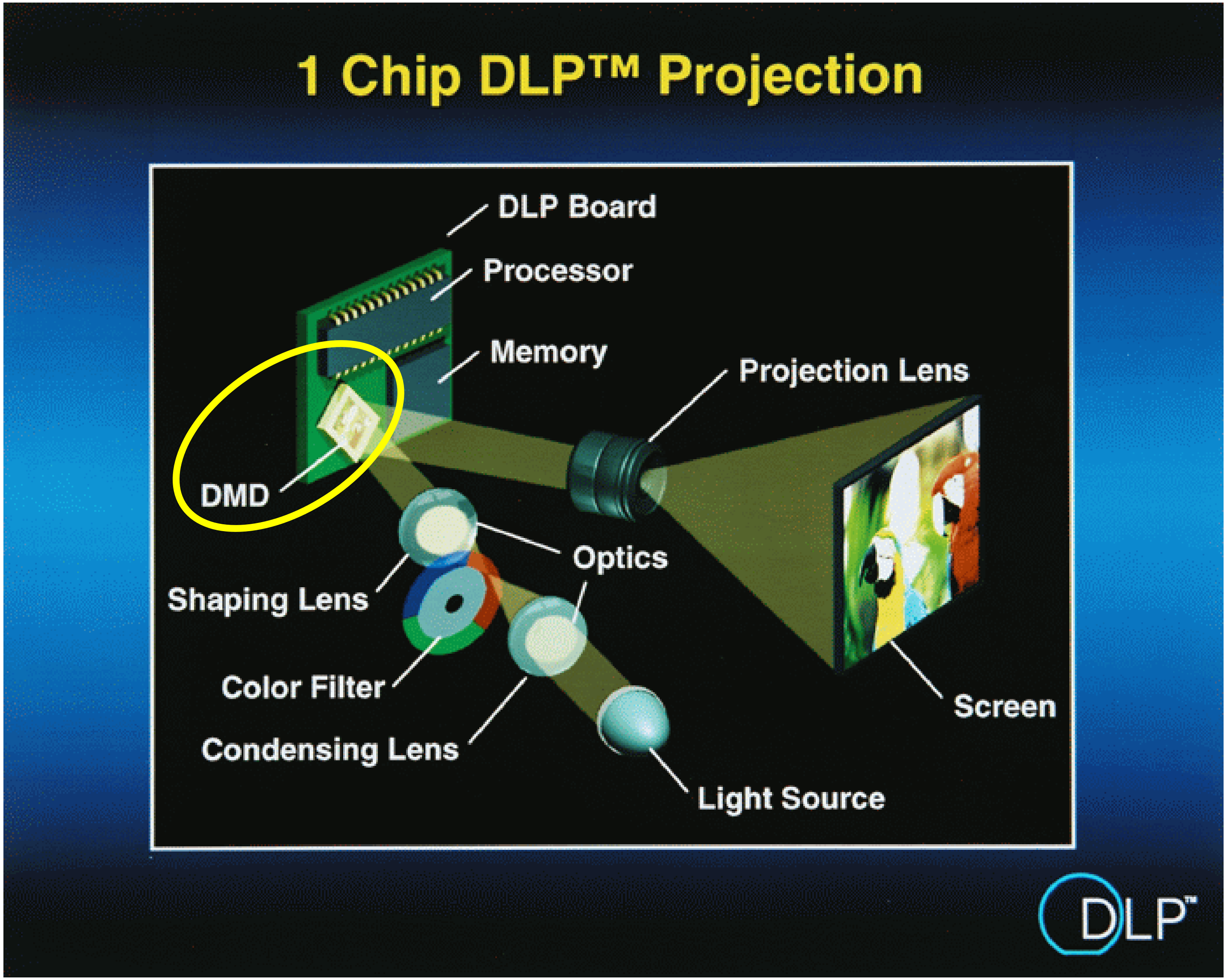


Image source: http://www.dlp.com/dlp_technology/

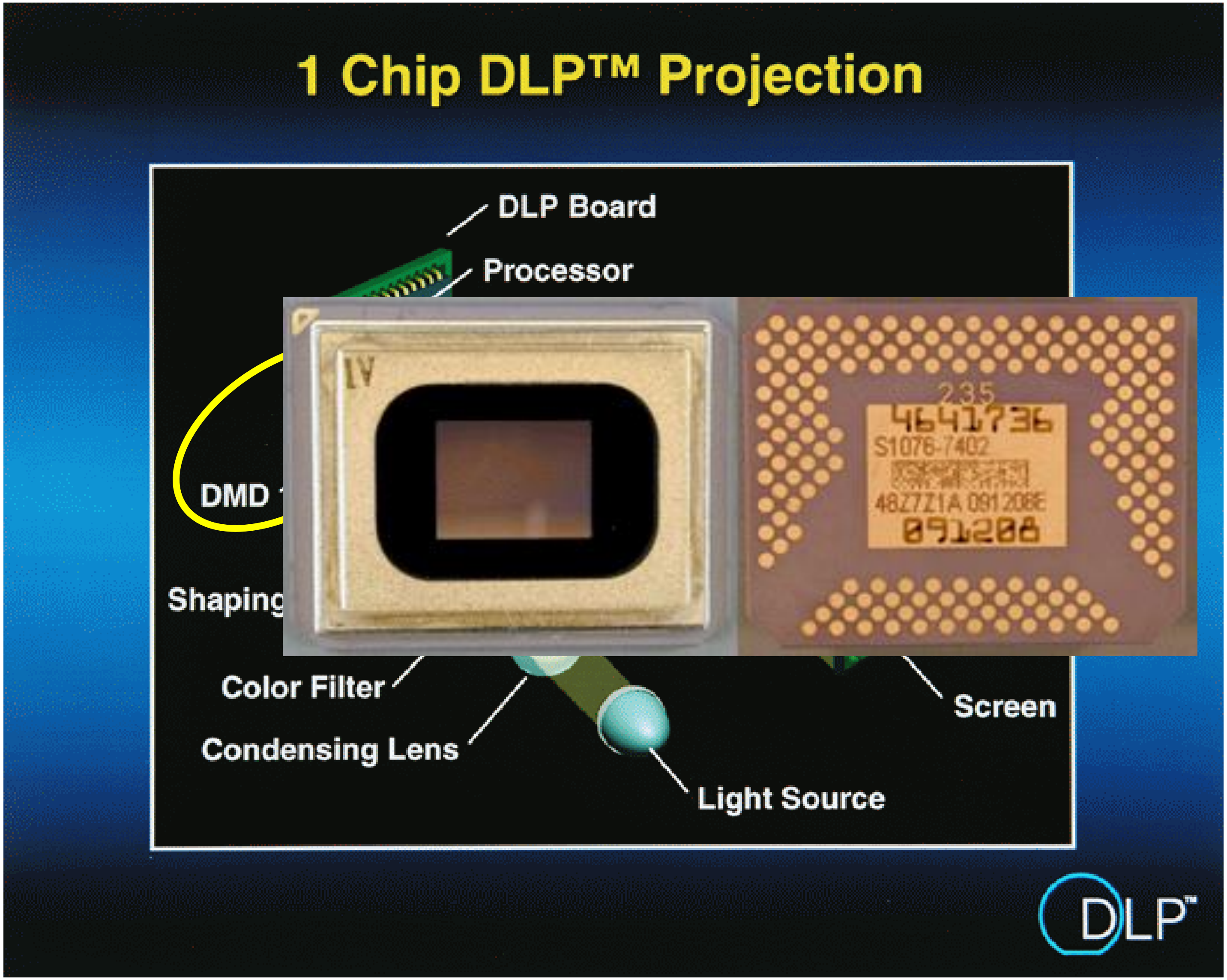
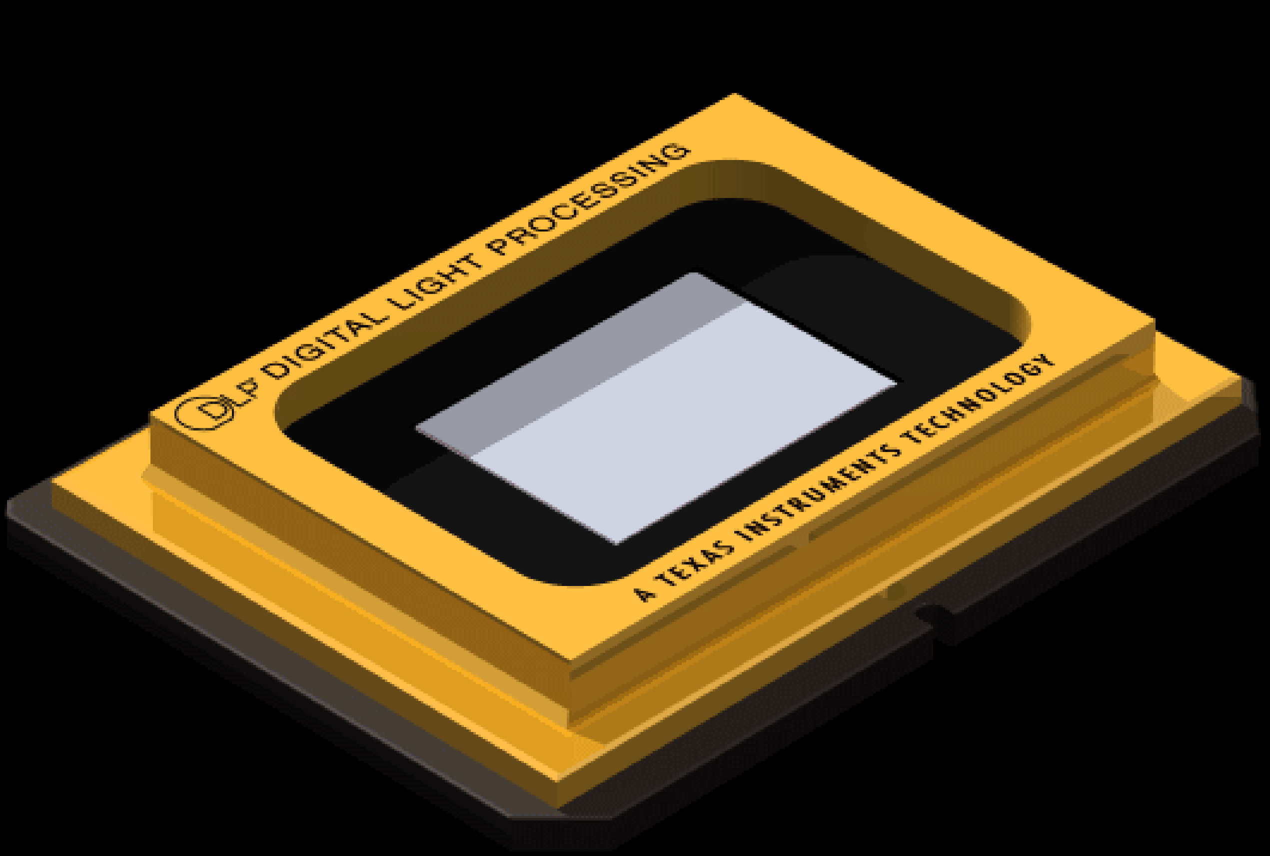


Image source: http://www.dlp.com/dlp_technology/

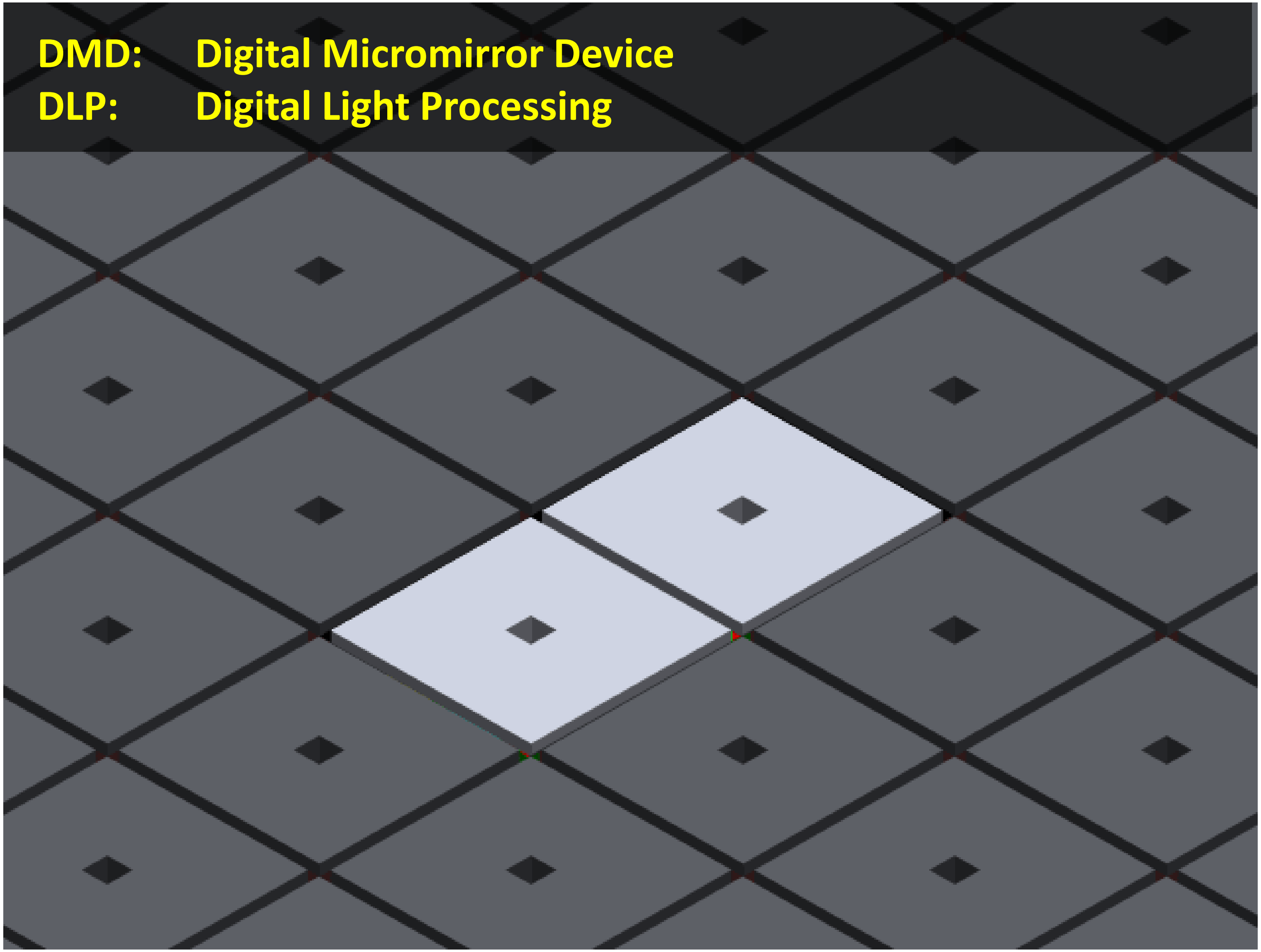
Display: Texas Instruments - DLP & DMD

DMD: Digital Micromirror Device
DLP: Digital Light Processing



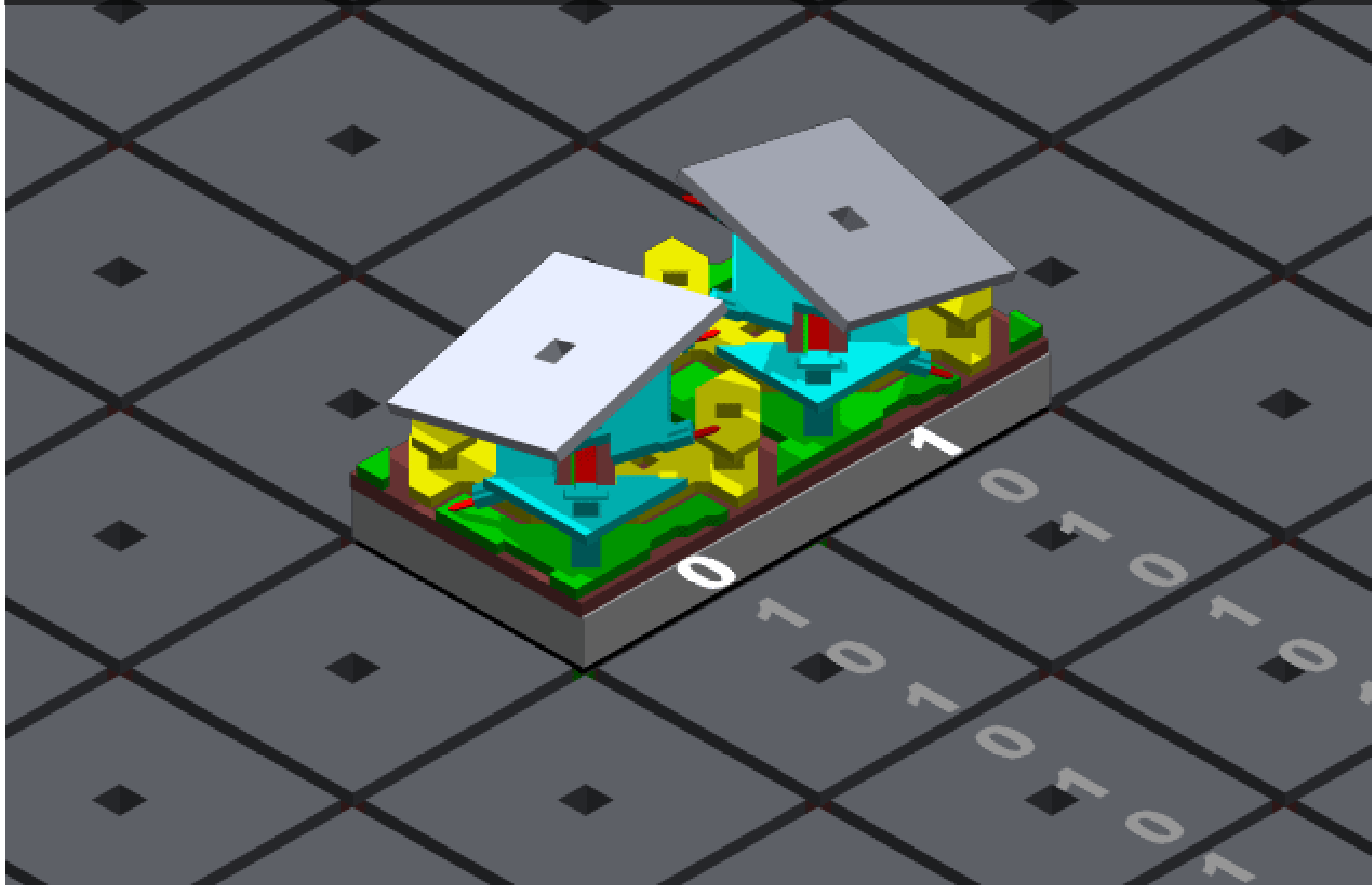
Media source: Presentation from Larry Hornbeck (TI): "DLP - How It Works" (2007)

Display: Texas Instruments - DLP & DMD



Media source: Presentation from Larry Hornbeck (TI): "DLP - How It Works" (2007)

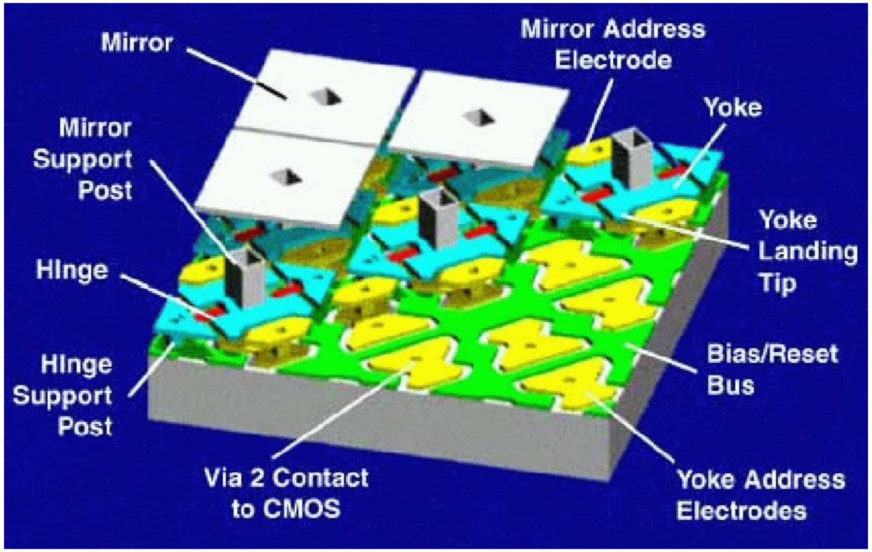
DMD: Digital Micromirror Device
DLP: Digital Light Processing

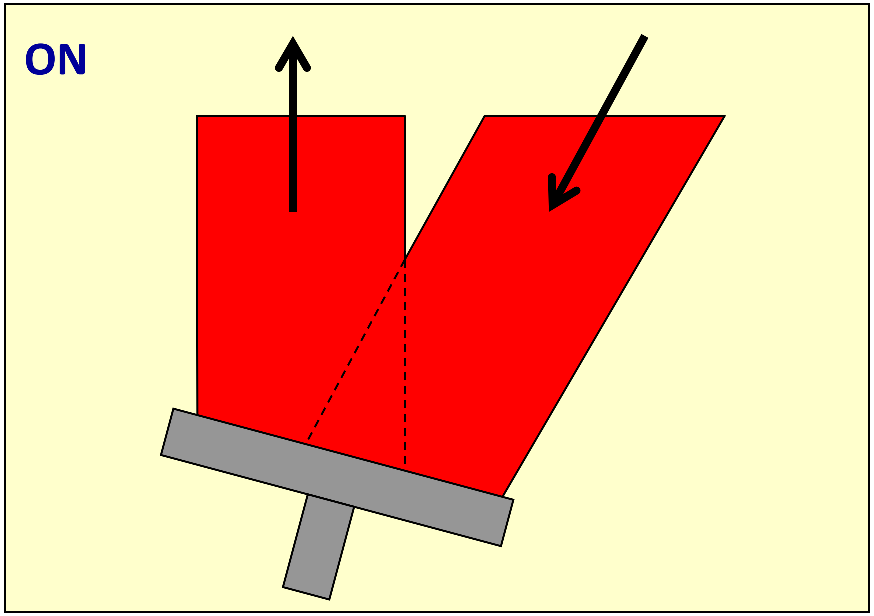


Media source: Presentation from Larry Hornbeck (TI): “DLP - How It Works” (2007)

Mirror Arrays

- DMD – Digital Micromirror Device
- DLP – Digital Light Processing
- One Mirror per pixel
- e.g. HD2 1280 x 720
- Mirror tilts ±12° → ON / OFF
- Rotating color wheel
- Invented in 1987





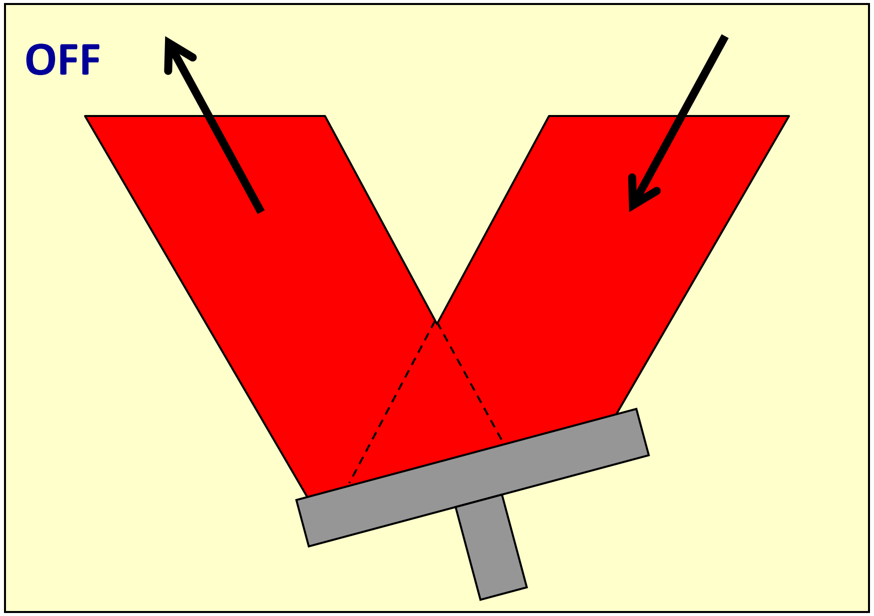
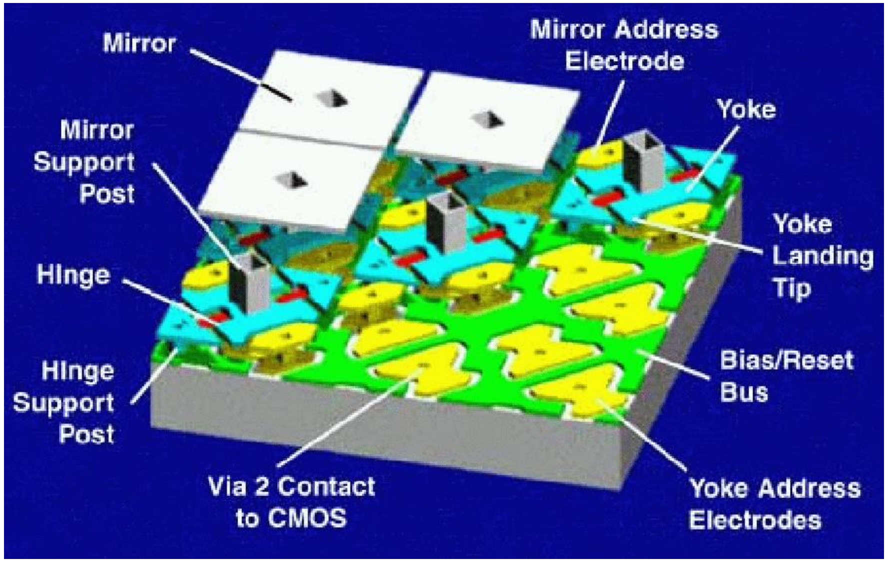


Image source: http://www.dlp.com/dlp_technology/

Mirror Arrays

- DMD – Digital Micromirror Device
- DLP – Digital Light Processing
- One Mirror per pixel (~13 µm)
- e.g. HD2 1280 x 720
- Mirror tilts ±12° → ON / OFF
- Rotating color wheel
- Color mixing by fast switching



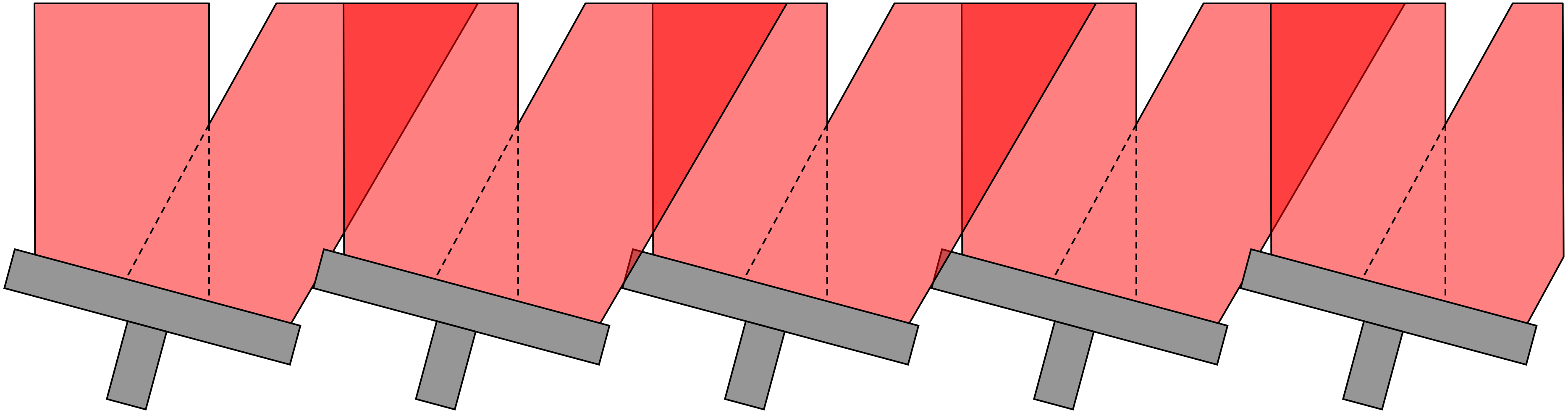
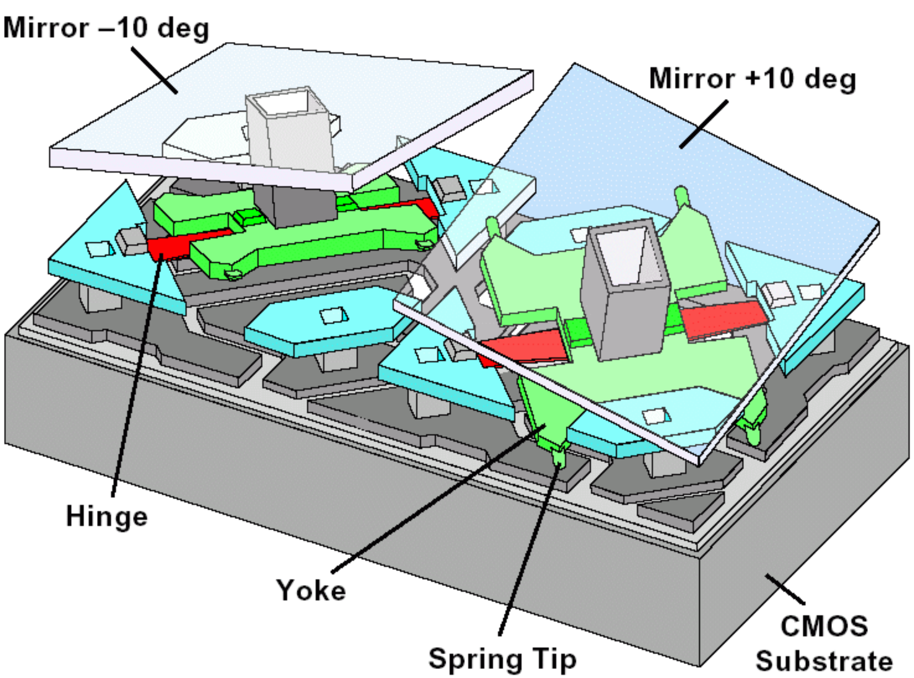


Image source: http://www.dlp.com/dlp_technology/

DMD Micromirrors

- Tilting ±10°
- Pixel size ≈ 15 µm
- Under each mirror:
  - Driving electronics
  - Memory electronics



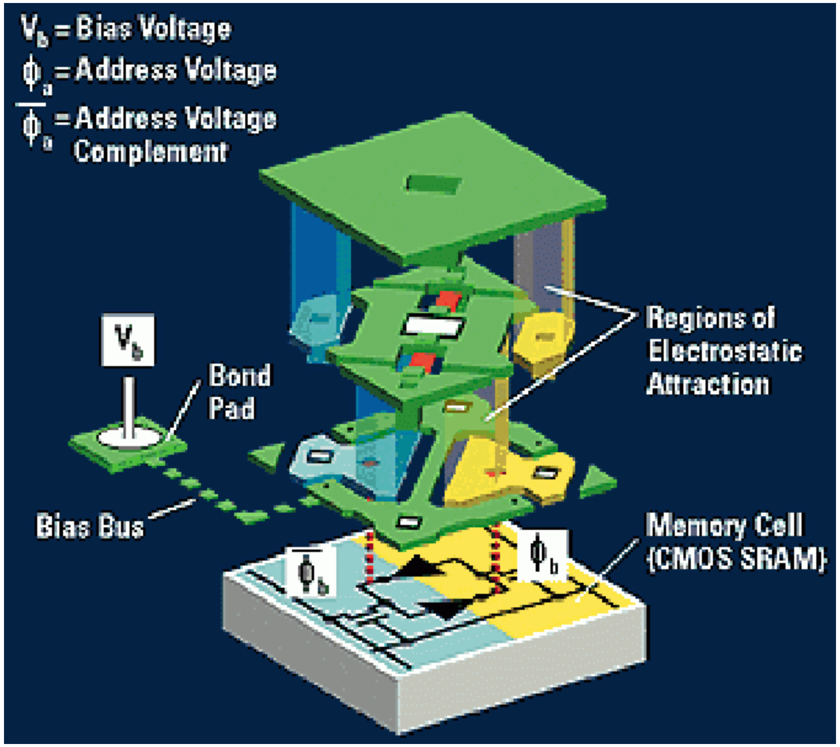
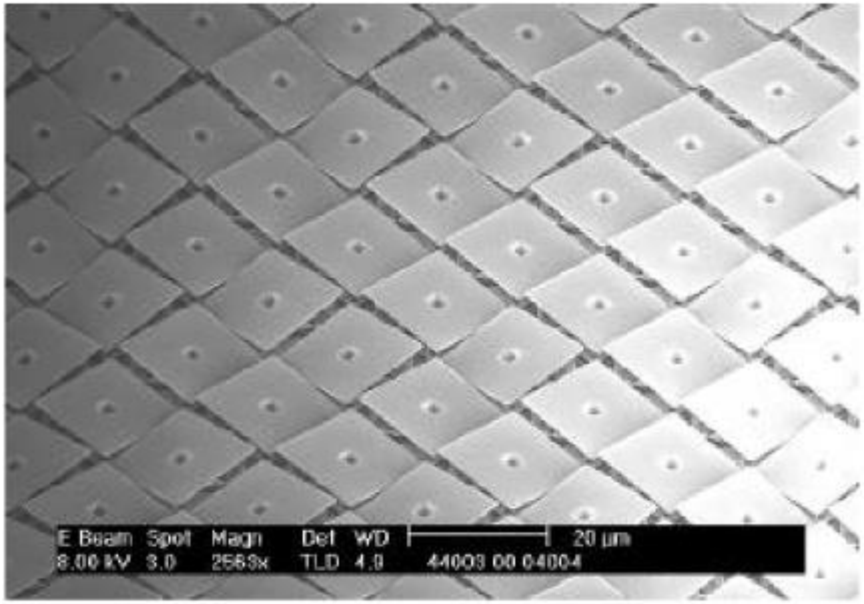
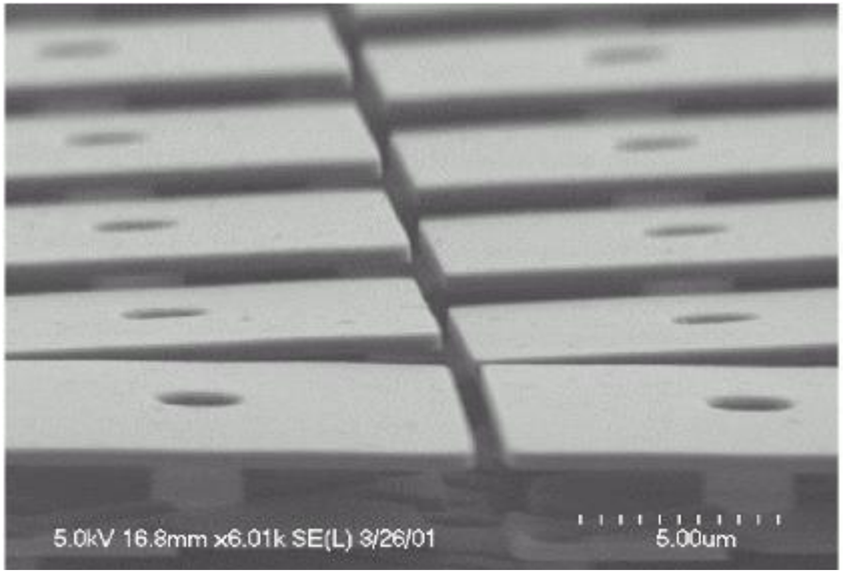


Image source: http://www.dlp.com/dlp_technology/

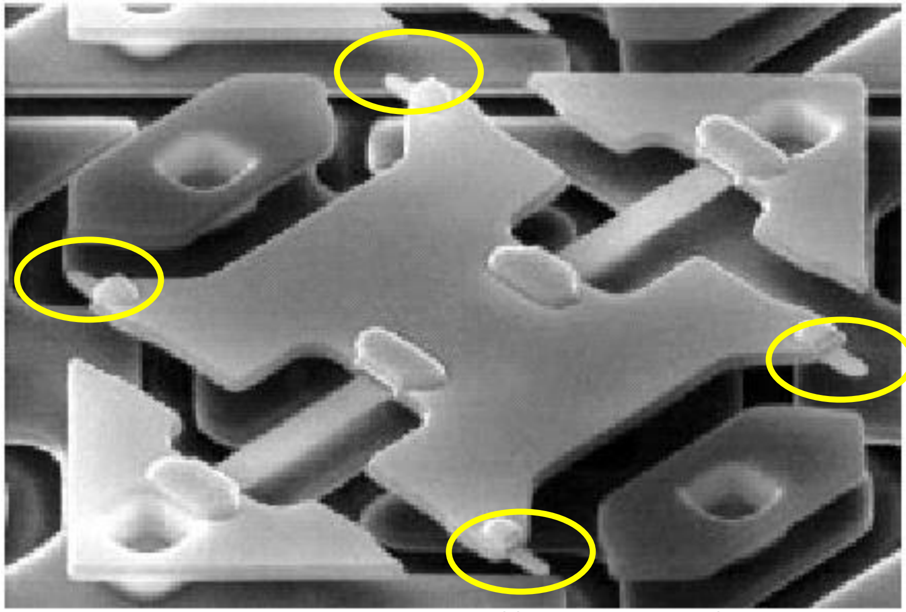
Display: Texas Instruments - DLP & DMD





DMD Micromirrors

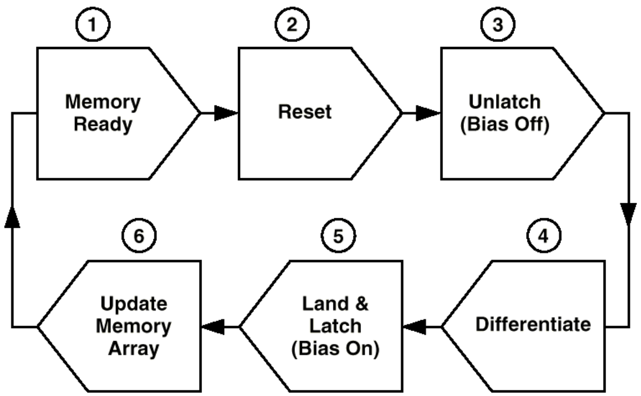
- **Mirror size ≈ 13 µm**
- **Spring tips avoid sticking**
- **CMOS technology**
- **MEMS on top**
- **Aluminum as Structural Material**
- **Photoresist as sacrifical layer (dry release)**
- **Antistiction Coating**

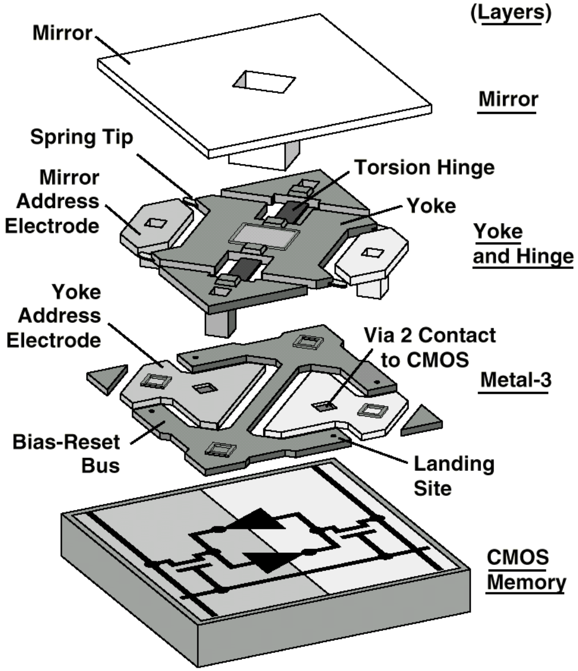


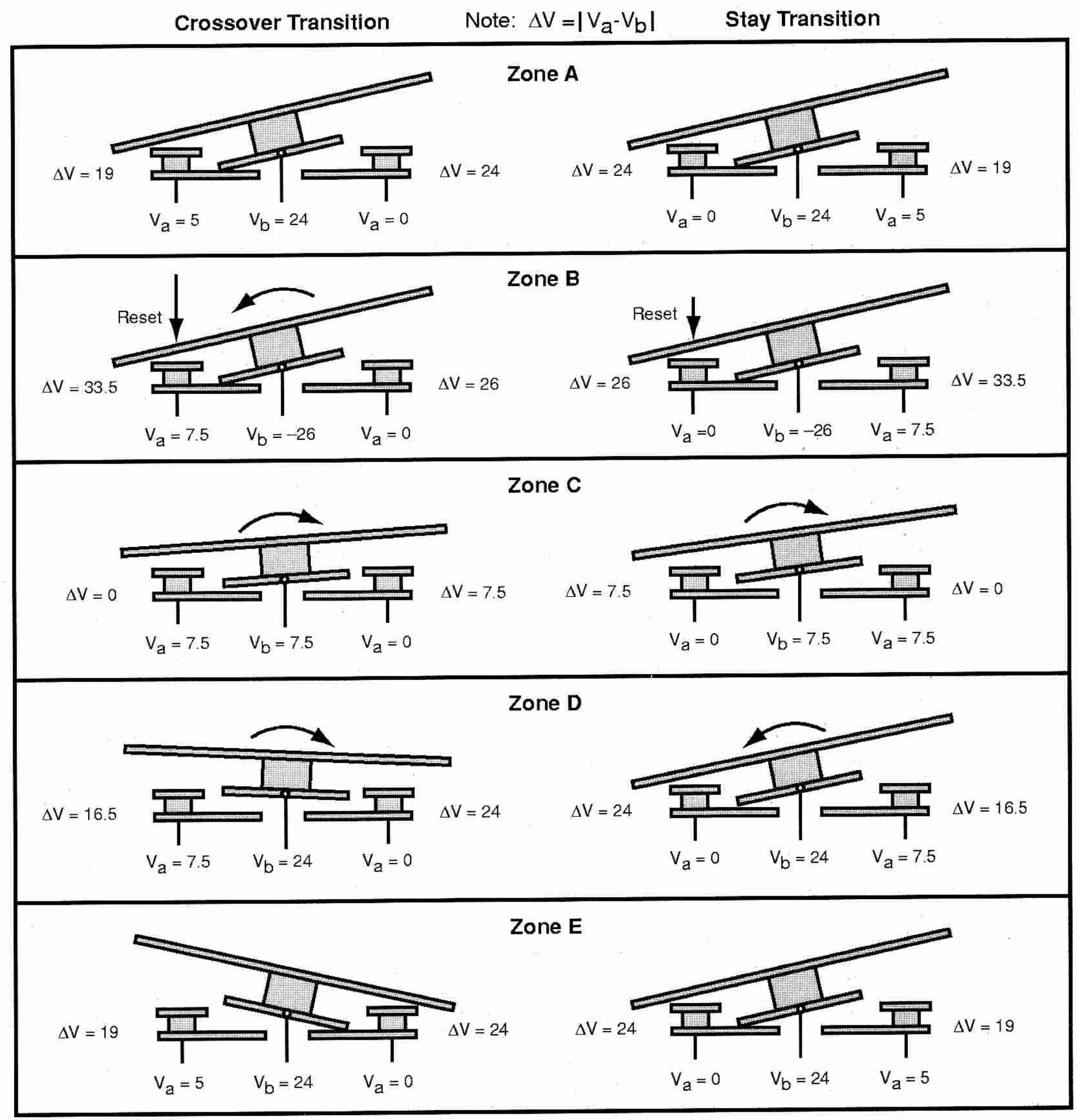
Voltage pulse + "super springs" were the breakthrough for the DMD!

Image source: http://www.dlp.com/dlp_technology/

Addressing: Mirror Array Update

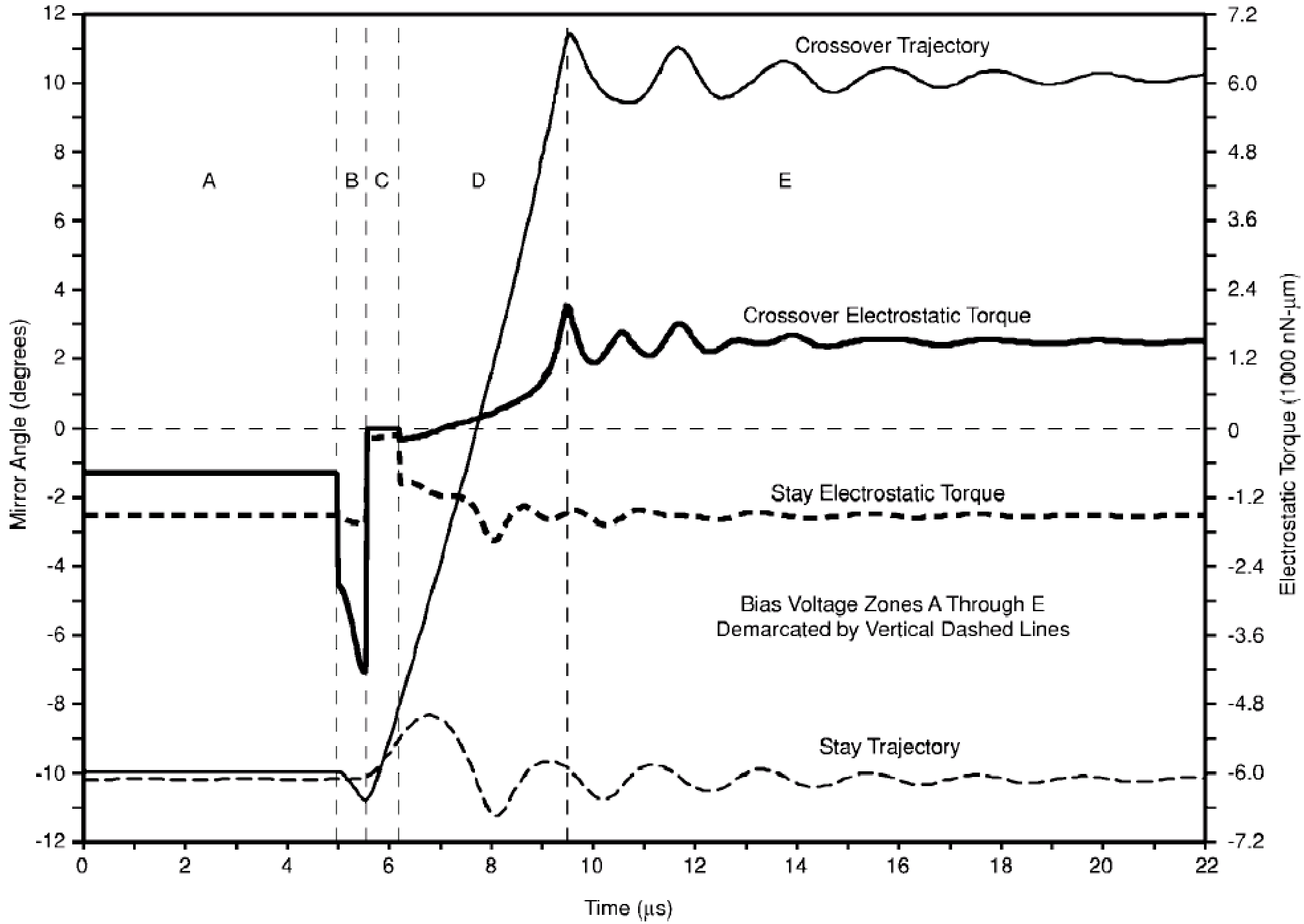






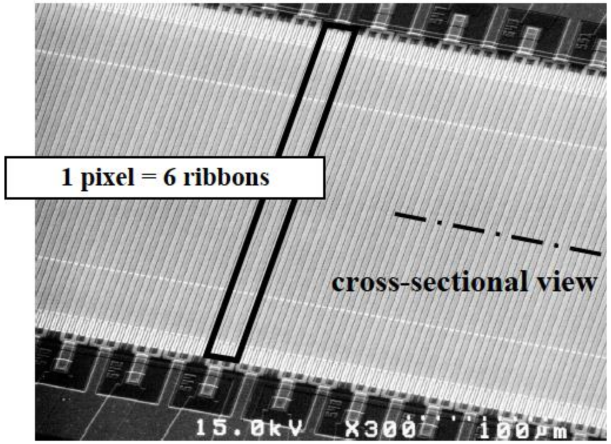
L. Hornbeck, Electronic Imaging, 1997

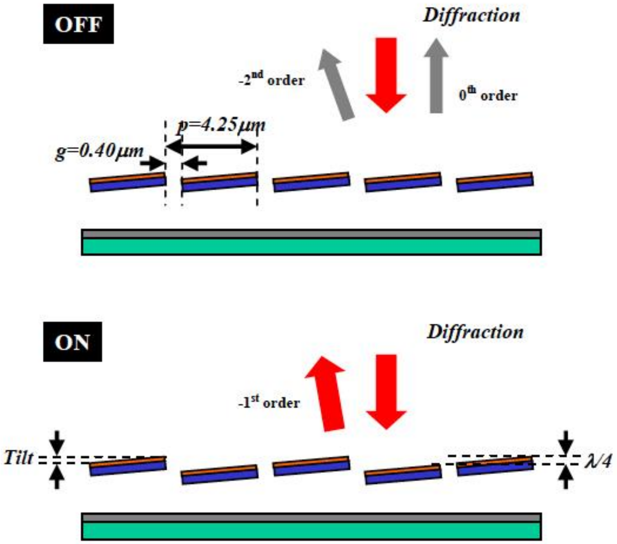
Addressing: Mirror Array Update



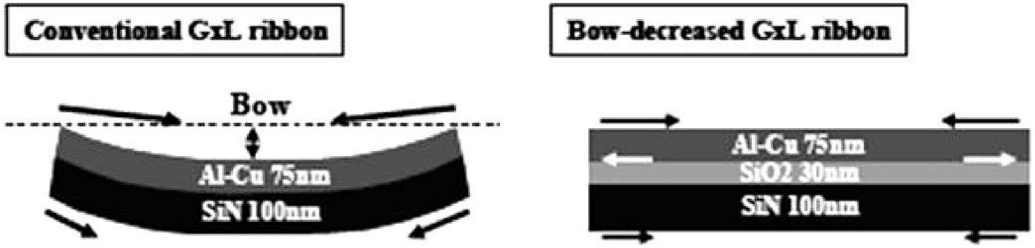
L. Hornbeck, Electronic Imaging, 1997

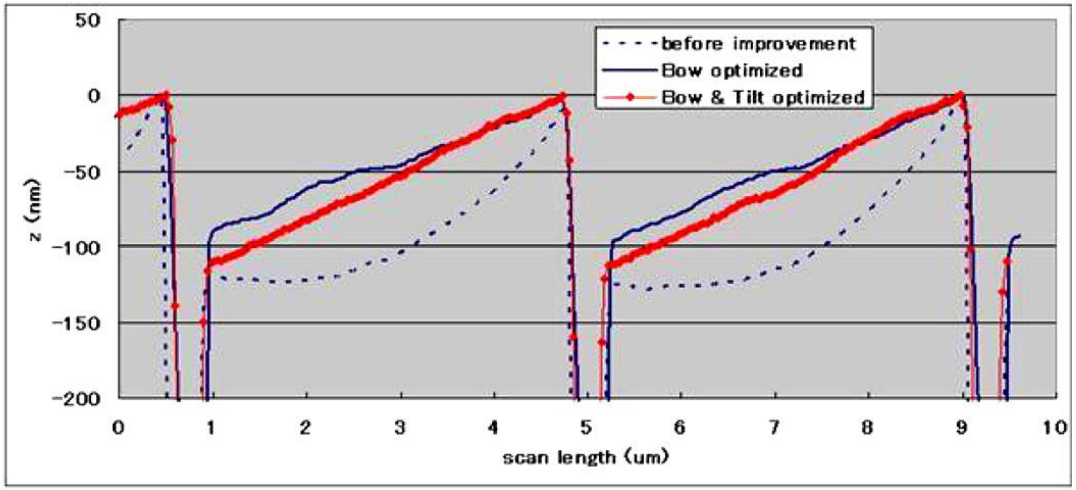
Pixel Design





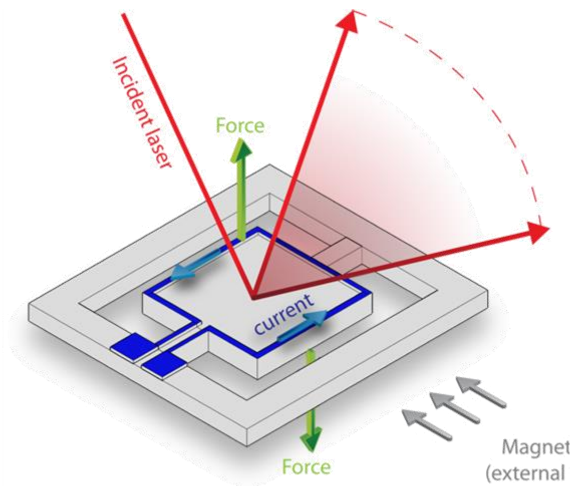
Stress Engineering for Curvature Control





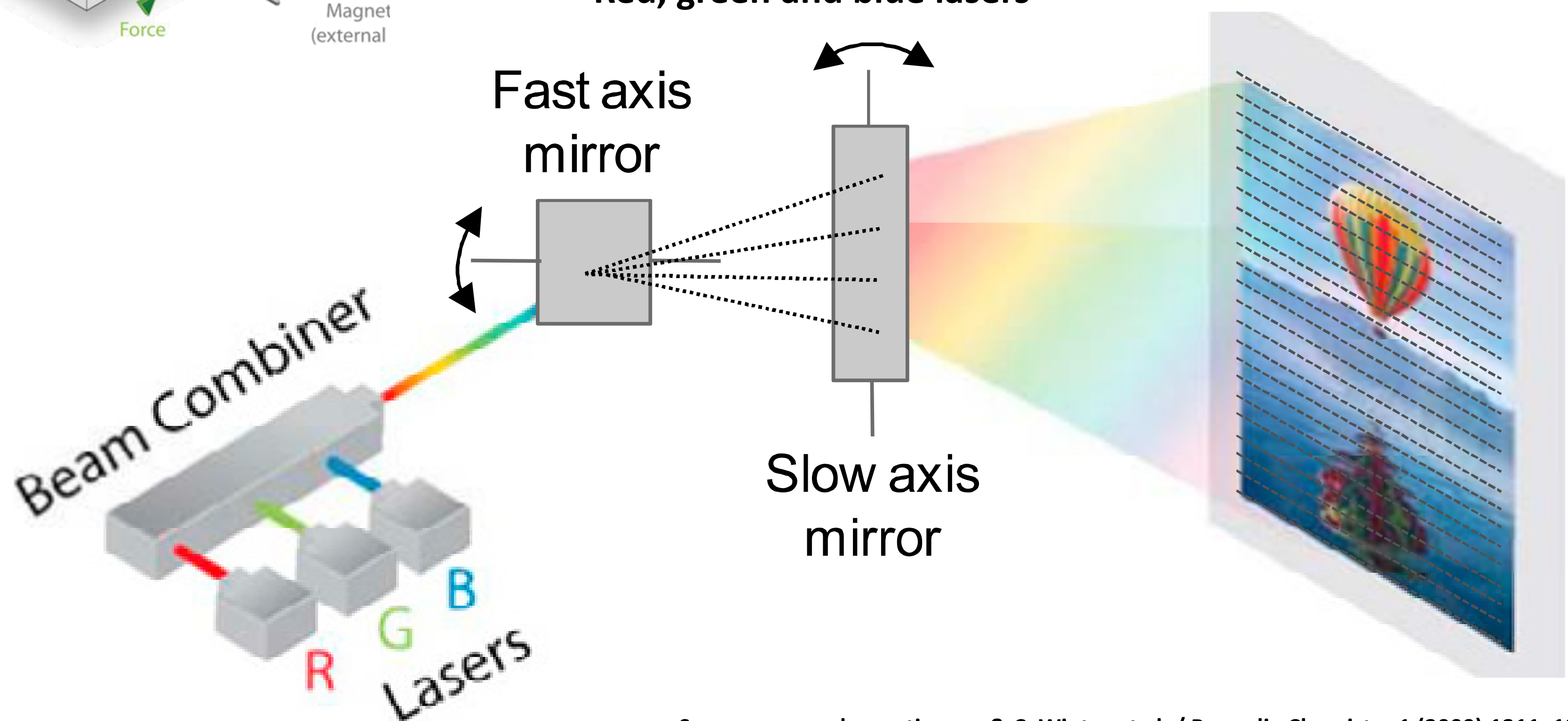
H. Tamada, "Blazed GxLPTM light modulators for laser projectors," Journal of the Society for Information Display, vol. 15, no. 10, pp. 817–823, 2007.

Scanning Systems → "Light Engine"



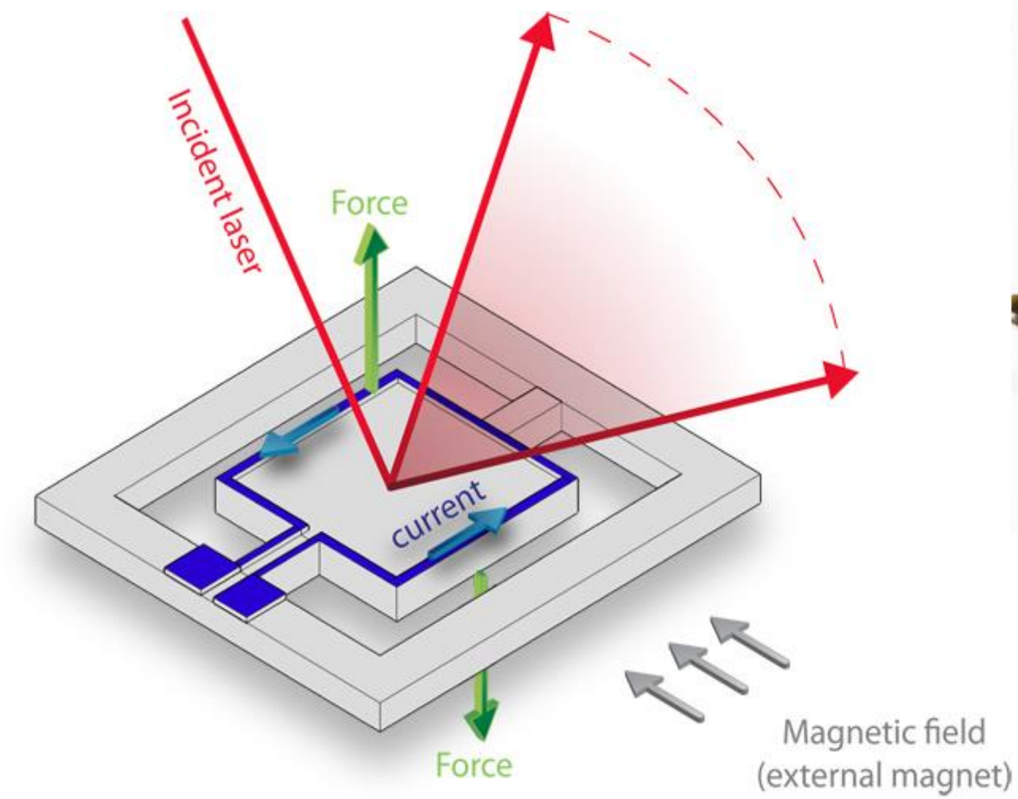
Scanning system

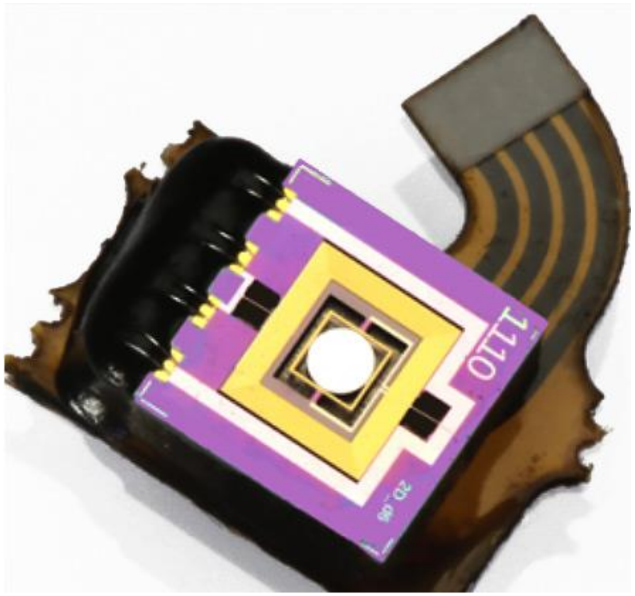
- **Two single mirrors**
- **Each mirror scans in 1D**
- **Fast mirror (17.2 kHz) → pixels in each line**
- **Slow mirror (50Hz) → scanning whole lines = image refresh rate**
- **Red, green and blue lasers**



Sources: www.lemoptix.com & C. Winter et al. / Procedia Chemistry 1 (2009) 1311–1314

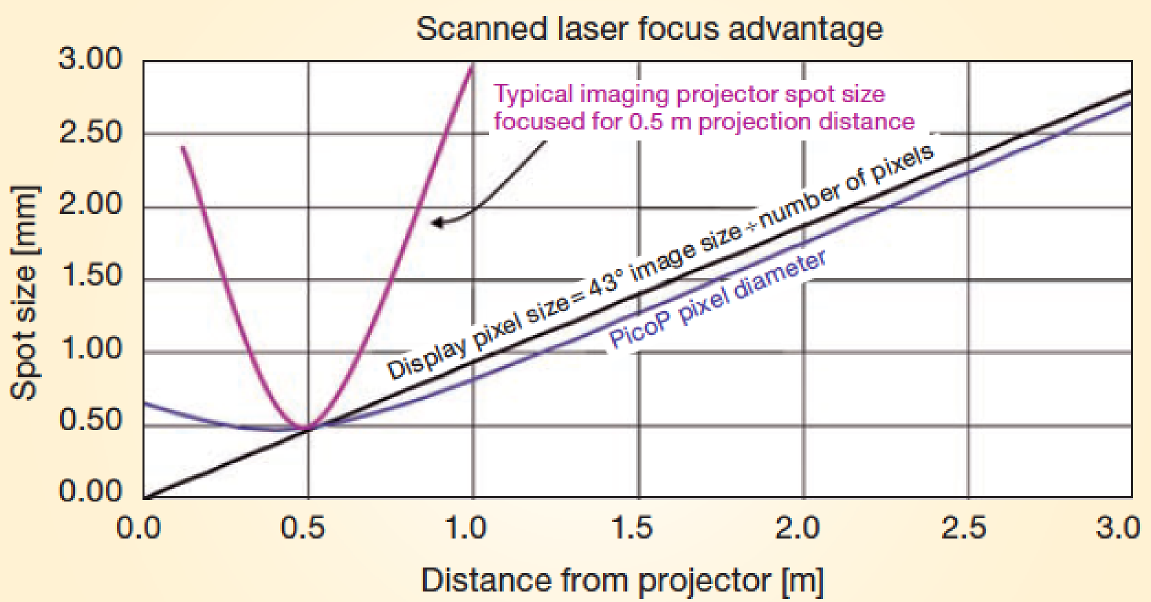
Magnetic Scanning Mirror – Lemoptix





F_{res}: 3 to 50 kHz, angles up to 30° at resonance for a few Volts

[Scanned vs. imaging projectors]



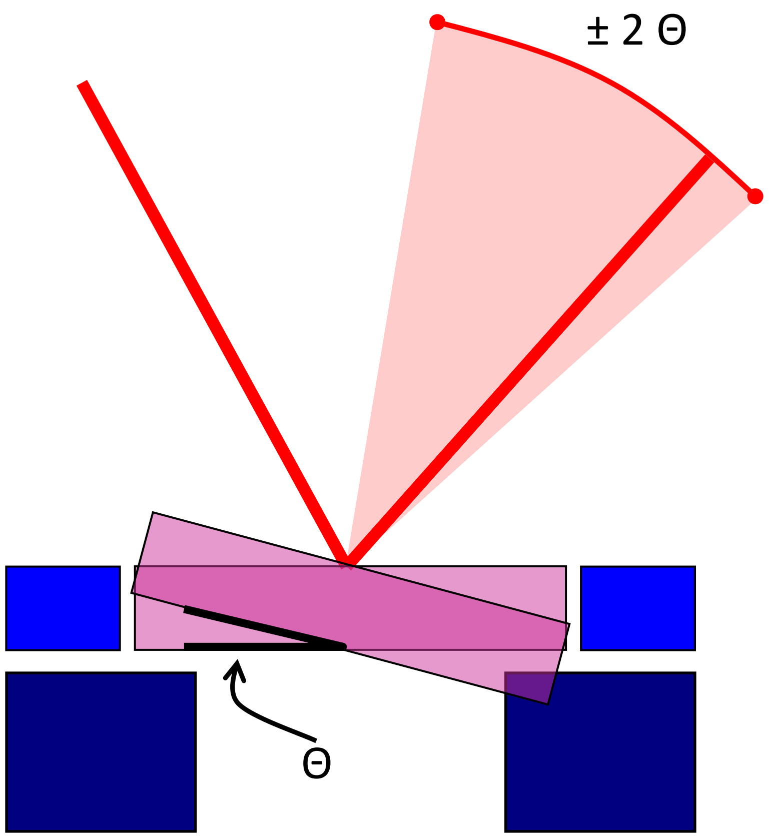
"Infinite focus" property of the scanned laser projector compared with an imaging-type projector.

- **Picoprojectors**
- **structured light projection (3D imaging, cf. Lenovo, Kinect)**
- **LIDAR Scanning (e.g. 3D imaging for autonomous cars)**
- **Overhead Display Applications / VR Goggles /**

MEMS Magnetic Scanner – Microvision

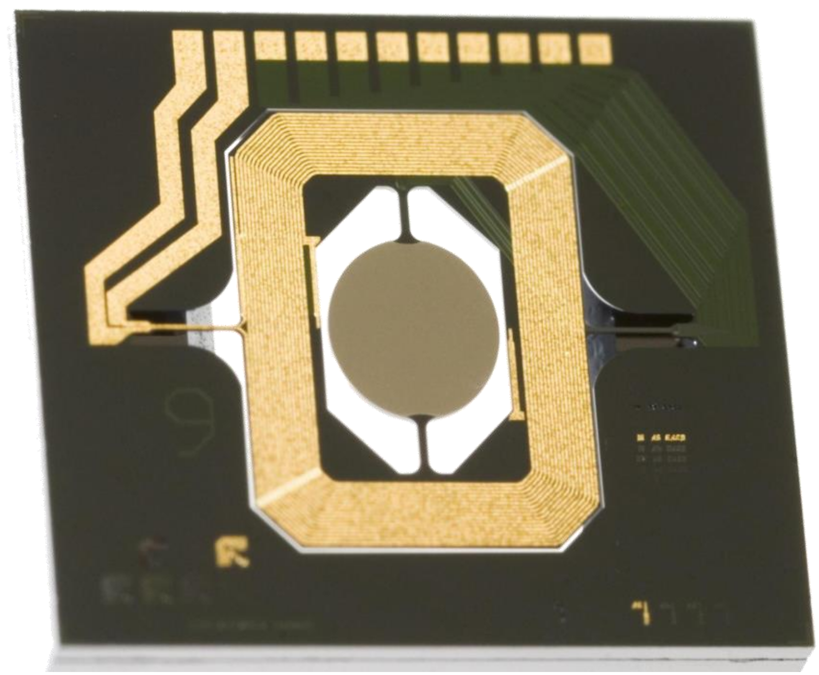
Scanning mirror

- Single mirror
- Scanning in 2D
- Full Optical tilt angle = 4x mechanical tilt



MEMS technology

- DRIE and KOH etching on 300µm Si wafer
- Integrated PZR sensors on flexures
  - Angle detection
- Electroplated coil
- Al coated mirror

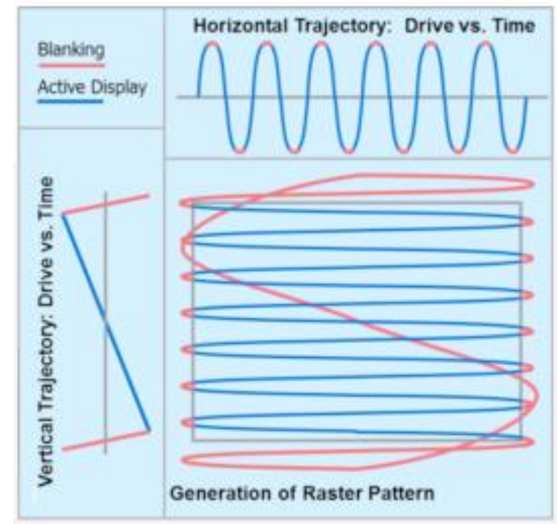


Source: Courtesy of Prof. Hakan Ürey, Koç University, Turkey

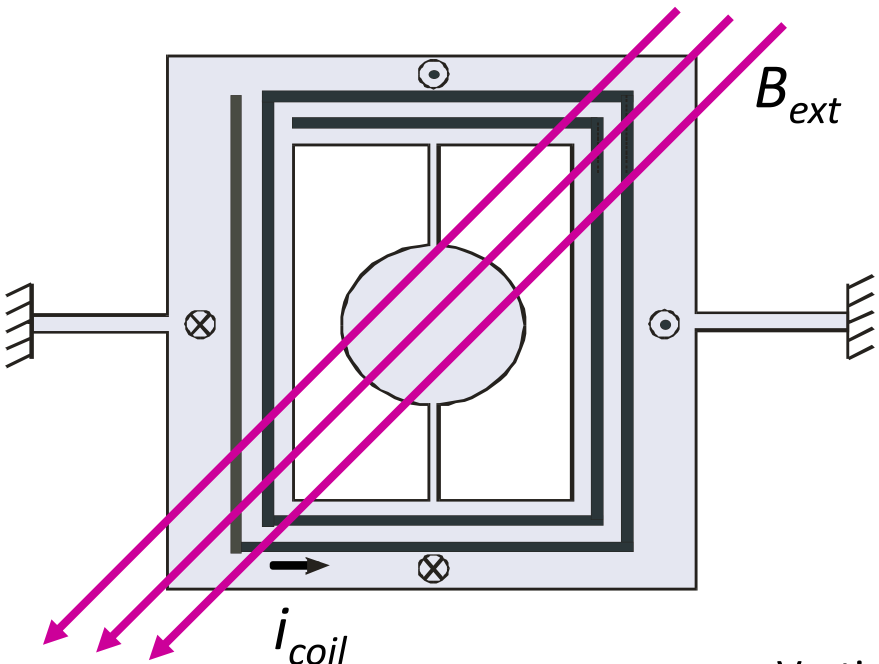
Microvision – 2D MEMS Scanner

Driving scheme

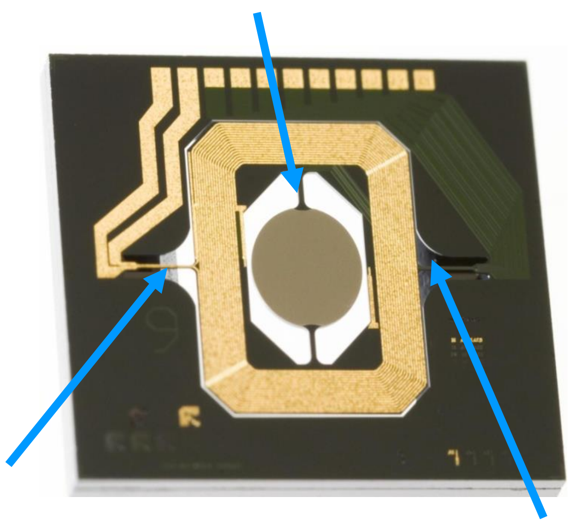
- External magnetic field at 45° angle
- Lorentz force for dynamic actuation
- B-field is modulated
  - 60 Hz saw-tooth → slow axis
  - 20 kHz sine → fast axis (resonance)



MICROVISION



Horizontal Scan Flexures (20 kHz)



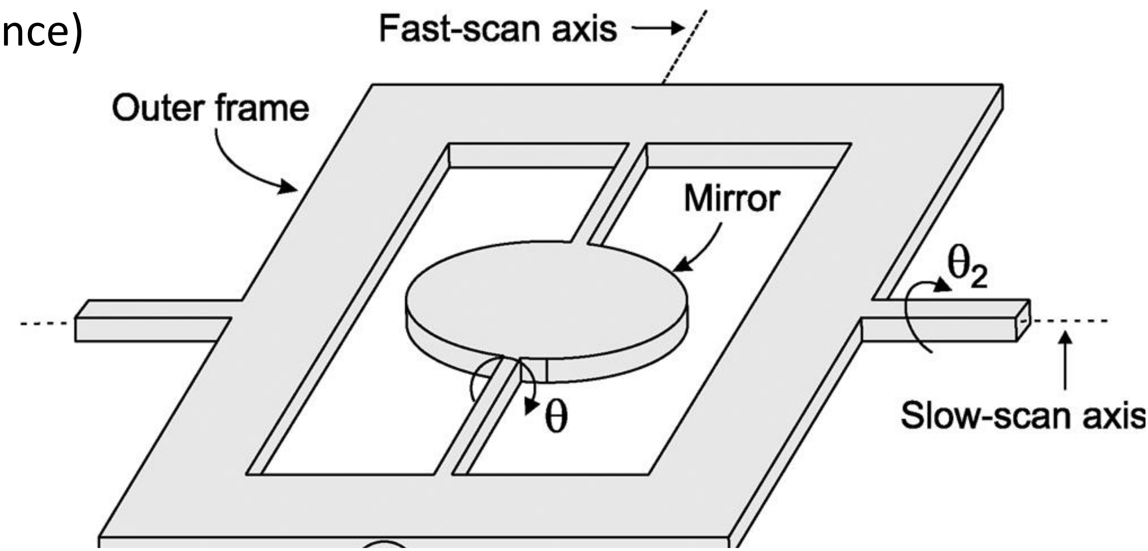
Vertical Scan Flexures (60 Hz)

Drive coil

Microvision – 2D MEMS Scanner

Driving scheme

- External magnetic field at 45° angle
- Lorentz force for dynamic actuation
- B-field is modulated
  - 60 Hz saw-tooth → slow axis
  - 20 kHz sine → fast axis (resonance)



Lorentz Force (general)

$$\vec{F} = I\,(\vec{\ell} \times \vec{B})$$

Electromagnetic Torque

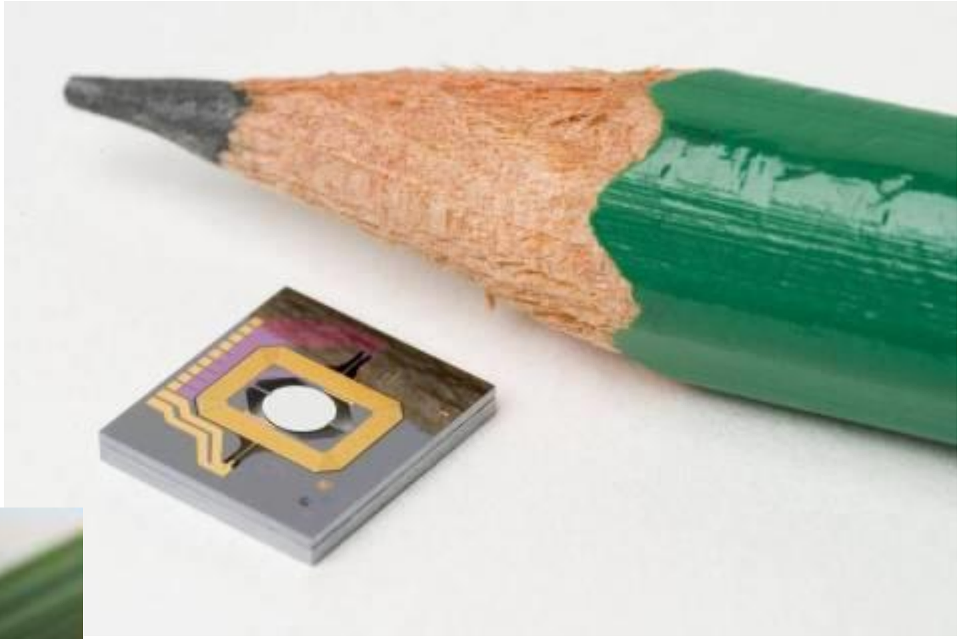
$$T_e \approx i_{\mathrm{coil}} B_{\mathrm{ext}} \cos 45^\circ \sum_{m=0}^{N-1} (l_s + 2m \cdot \delta l)(l_f + 2m \cdot \delta l)$$

Source: JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 15, NO. 4, AUGUST 2006, 786

2D MEMS Scanner – Barcode Reader / Projector / LIDAR

Packaged device

- No vacuum
- Magnet under MEMS die

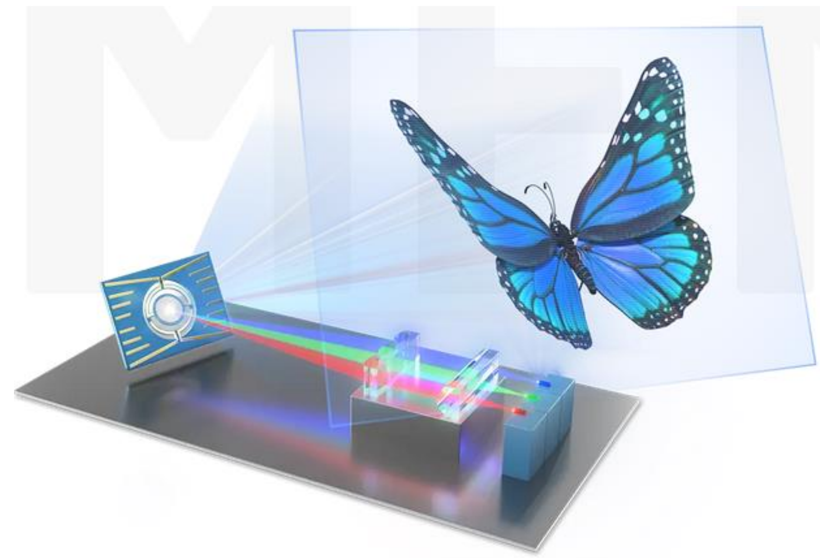


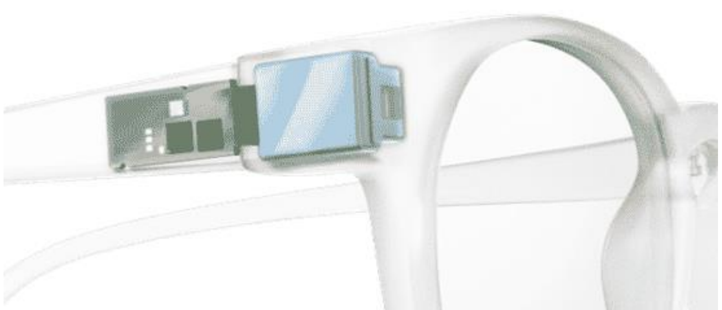
Source: Courtesy of Prof. Hakan Ürey, Koç University, Turkey

Display for AR from TriLite

Claimed as world smallest projection display:

- Piezoelectric driving scheme
- 2D MEMS micro-mirror
- MEMS sub-contracted to TDK
- Proprietary multiparameter algorithms for laser and mirror control to minimize complexity and size of the optical system





Key Parameters	LBS Trixel® 3	mLED / OLED	LCOS / DLP
Low Weight	■■■■■	■■□□□	■□□□□
Small Form Factor	■■■■■	■■□□□	■□□□□
Low Power Consumption	■■■■□	■■□□□	■□□□□
High Brightness & Contrast	■■■■■	■■■■□	■□□□□
Large Field of View (FOV)	■■■■□	■■□□□	■□□□□
Focus Free	■■■■□	■□□□□	■□□□□

Startup company from Austria: https://www.trilite-tech.com/technology/

Qualcomm IMOD "mirasol" – Display Concept

Reflective display

- Open state → light is reflected
  - air gap creates a reflecting Fabry-Perot (interference) filter
- closed state → light is absorbed,
  - filter is "de-tuned"
  - reduced reflection
- Fast response (10s microseconds)
- *Power Consumption: No Internal Light Source Required, Electrostatic Actuation*

Mirasol Display History
Mark W. Miles: Founder & CTO, Iridigm, Inventor of **Interferometric Modulator (IMod)** technology

- EE MIT, 1985
- 1994: Mark Miles and Erik Larson found Iridigm Display Corporation in Boston
- Acquired by Qualcomm in 2004

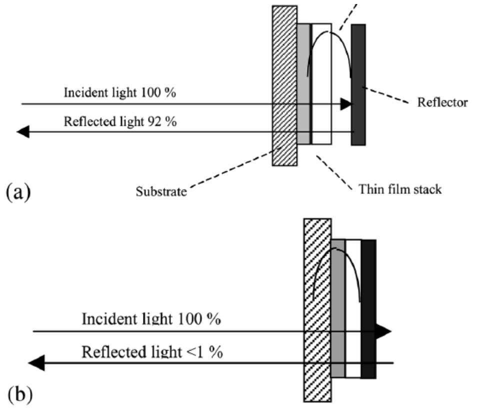
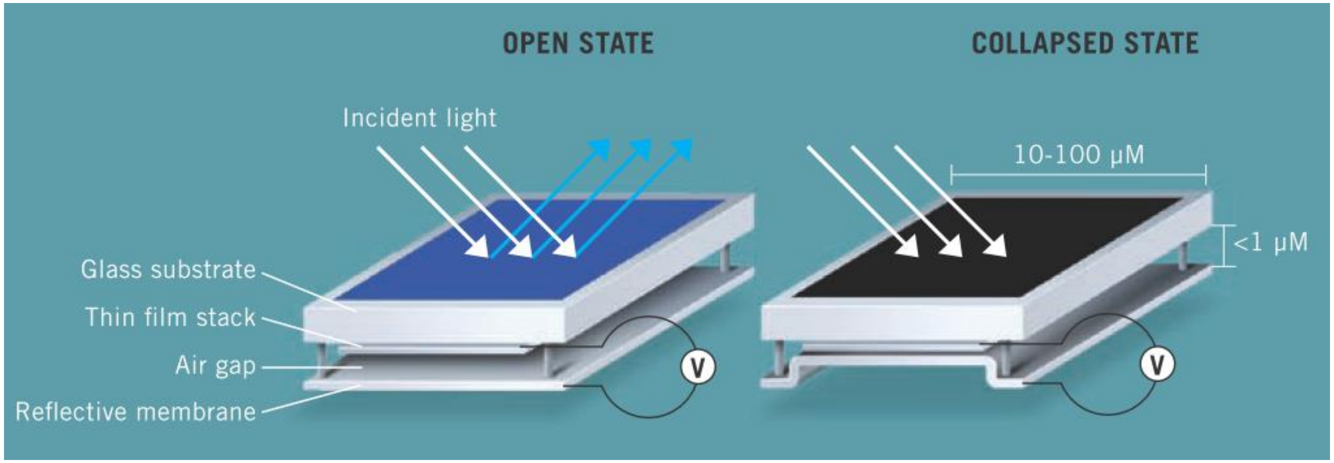


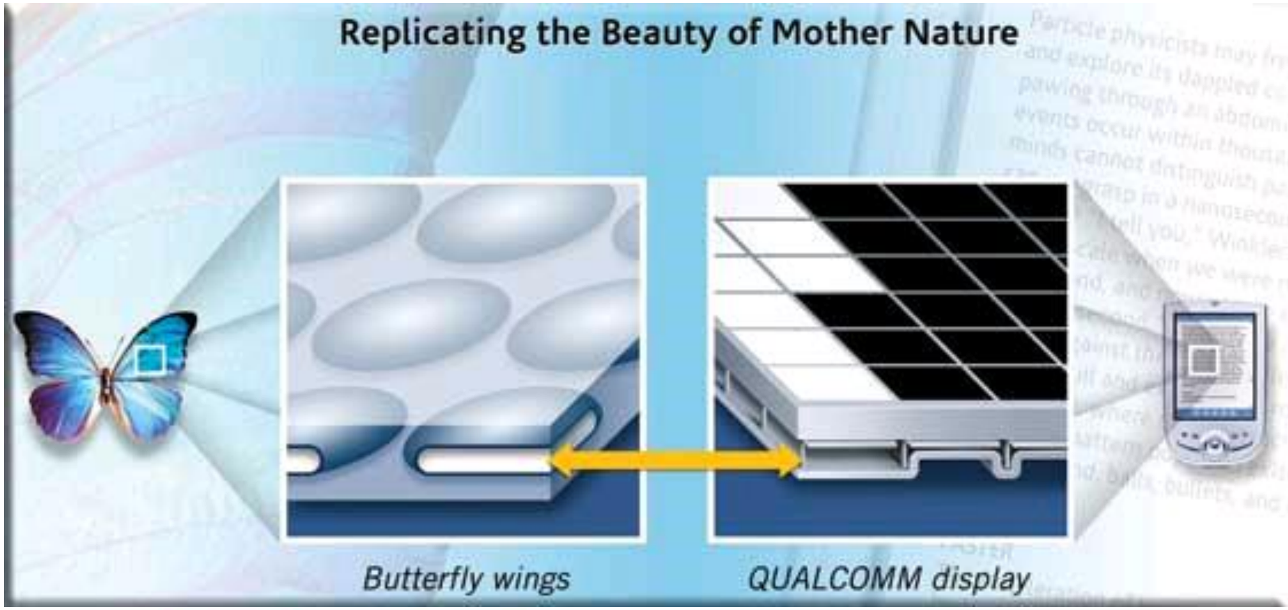
FIGURE 2 — (a) iMoD in resonant mode. (b) iMoD in induced absorption mode.

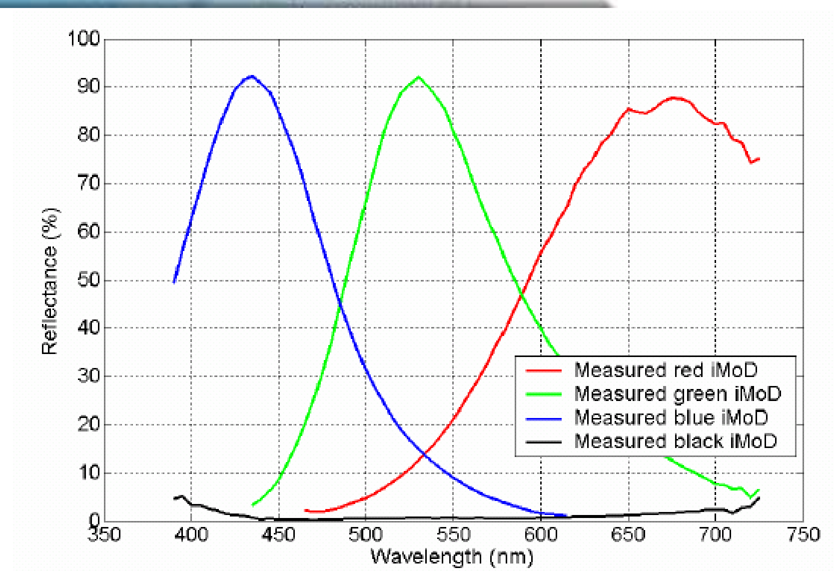


M. Miles, E. Larson, C. Chui, M. Kothari, B. Gally, and J. Batey,, Journal of the Society for Information Display, vol. 11, no. 1, pp. 209–215, 2003.

Source: http://www.qualcomm.com/qmt/press/index.html
For more information, see also Optica, 2, 7, pp589, 2015

Interference Modulator Display Mirasol

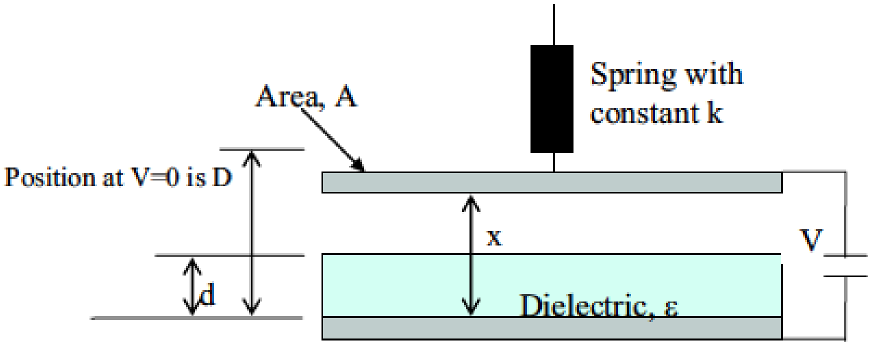


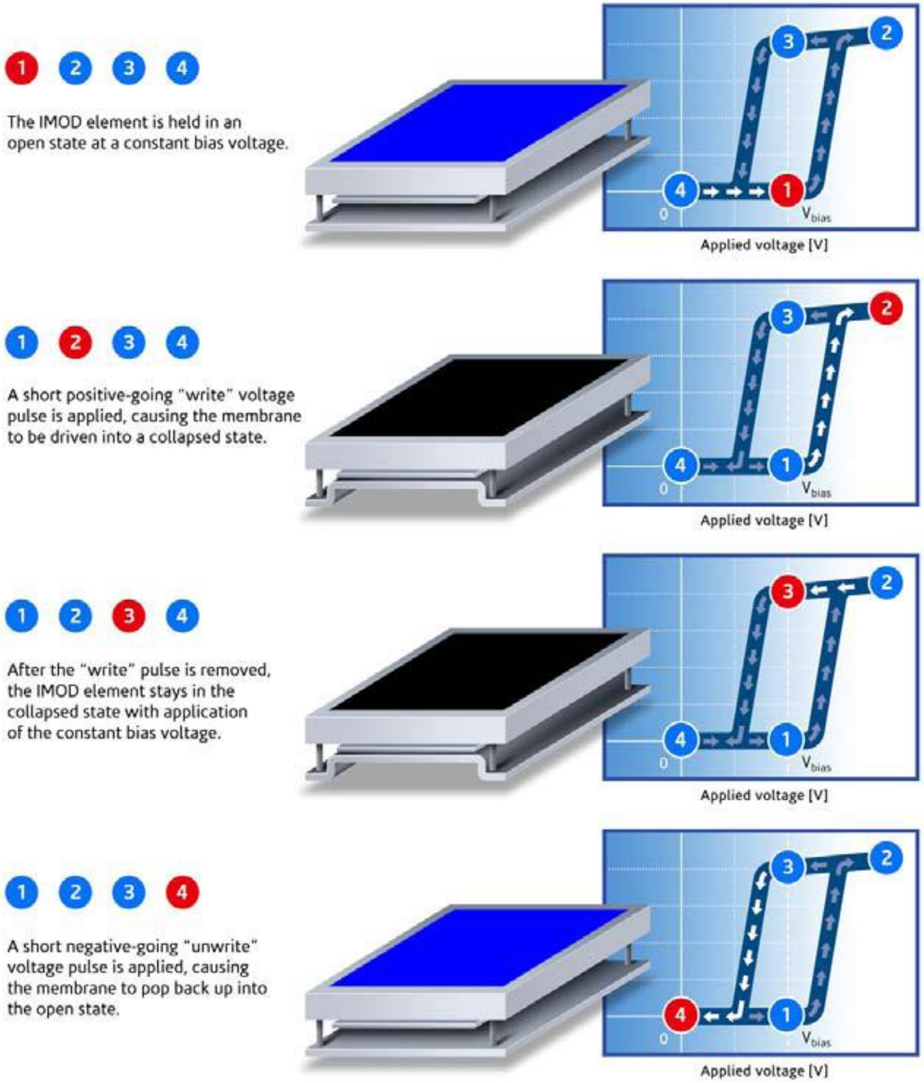


Chui, et al, Proc. SPIE, Vol. 6466, 646609 (2007)

http://www.qualcomm.com/qmt/

Qualcomm IMOD "mirasol" – Hysteresis



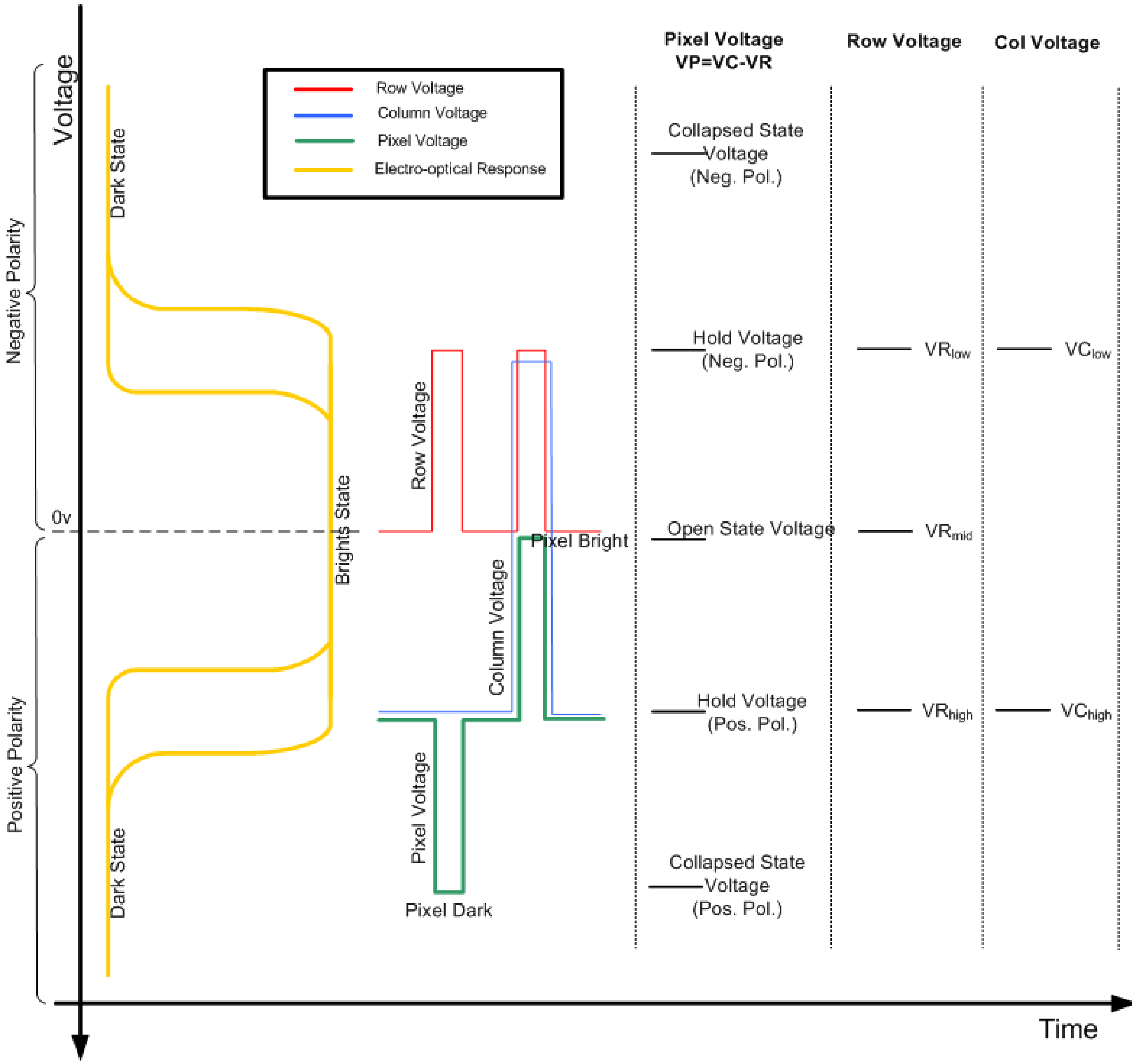


Reflective display/pixels

- Vertically displaced membrane
- Electrostatic actuation
- Thin-film stack defines color
  - interference filter
- Challenges:
  - Angular dependence
  - Stiction
  - Homogeneity over large areas

Source: http://www.qualcomm.com/qmt/press/index.html

Electrostatic Actuator Nonlinearity



http://www.qualcomm.com/qmt/

Pull-in

Row/Column Drivers

Bias Rows at 0

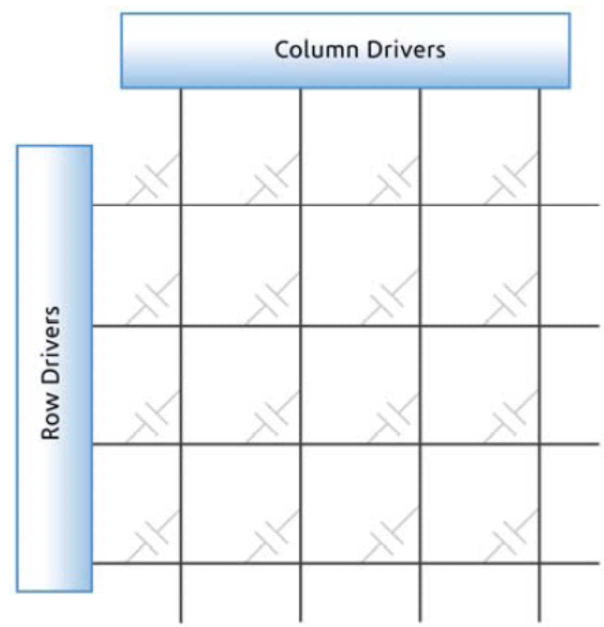
Bias Columns at Hold Voltage

Switch Dark:

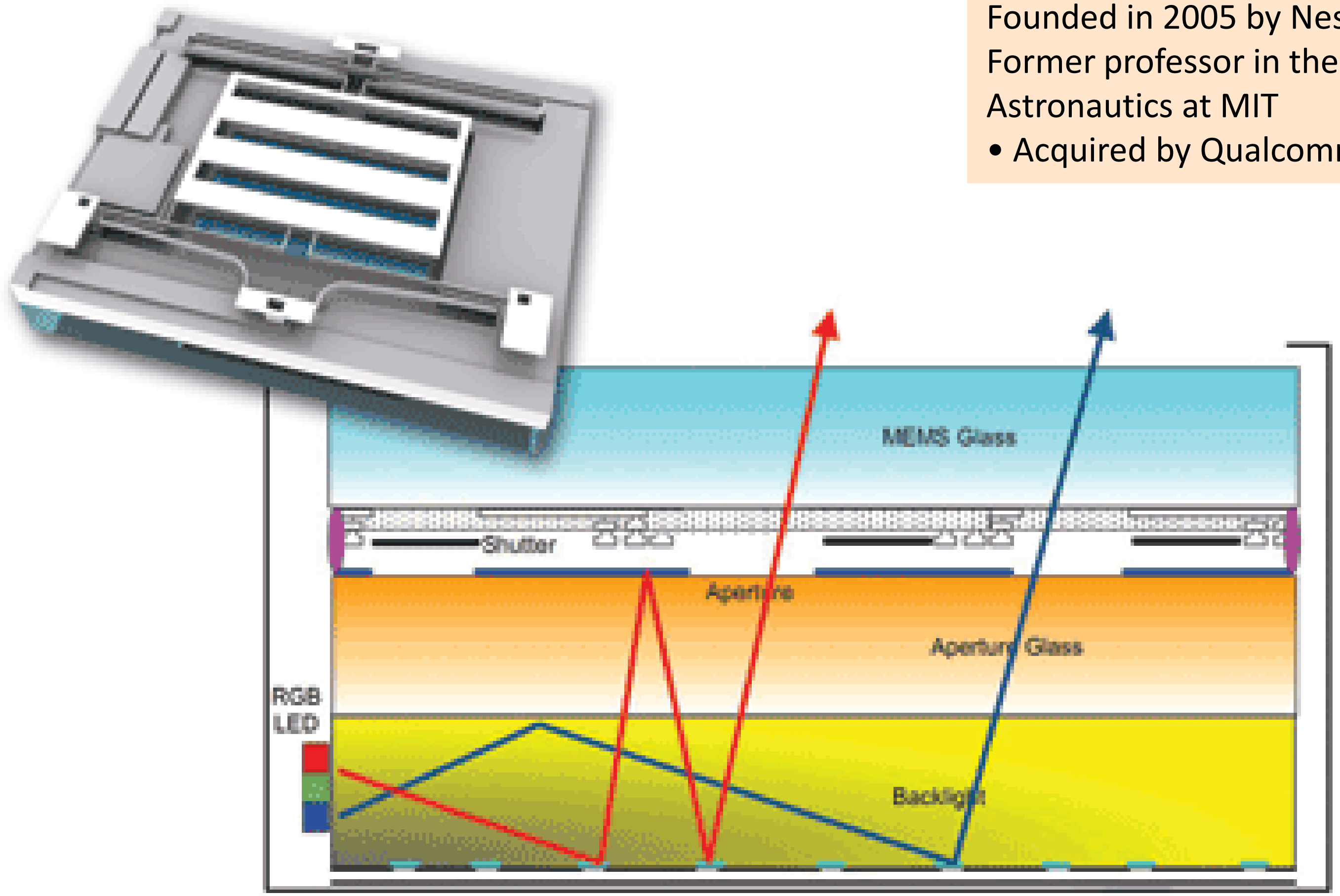
- Apply Row Voltage only
- (switches only intersection)

Switch Bright:

- Apply Row and Column Voltages



Pixtronix Microshutter Display



Pixtronix Display History

Founded in 2005 by Nesbitt Hagood
Former professor in the Department of Aeronautics & Astronautics at MIT

- Acquired by Qualcomm in 2011

http://www.electronicproducts.com/Optoelectronics/Displays/MEMS_displays_aim_small_while_LCDs_get_big_amp_bright.aspx

Electrostatic Curved Electrode Actuator

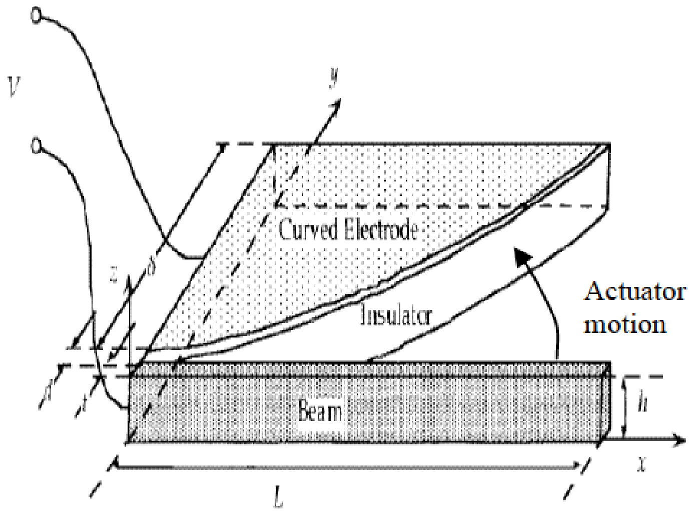


Figure 2a: Curved Electrode Actuator Concept. Legtenberg et. al.[3]

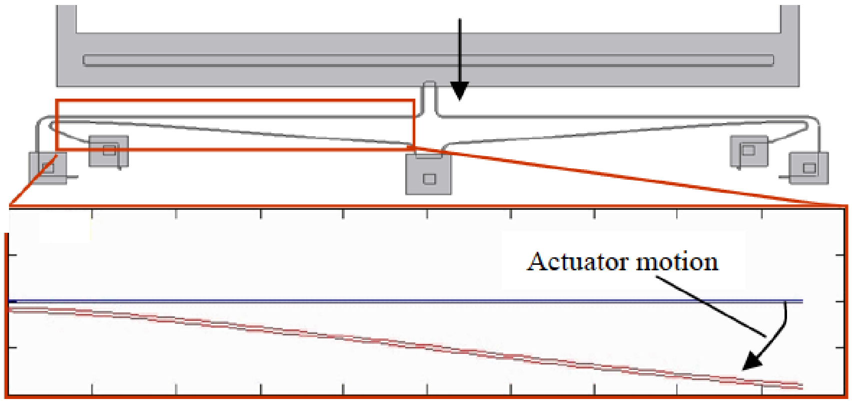


Figure 2b: Actuator on Digital Micro Shutter

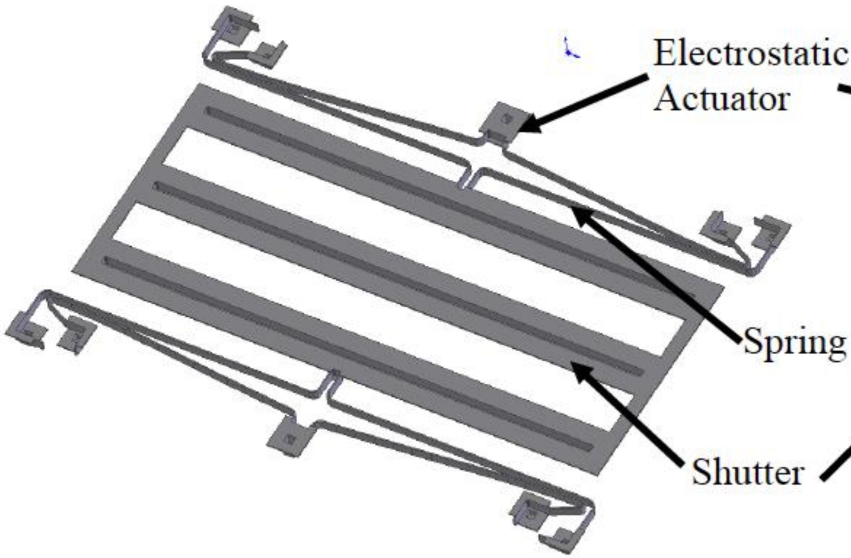


Figure 1a: Diagram of a Digital Micro Shutter.

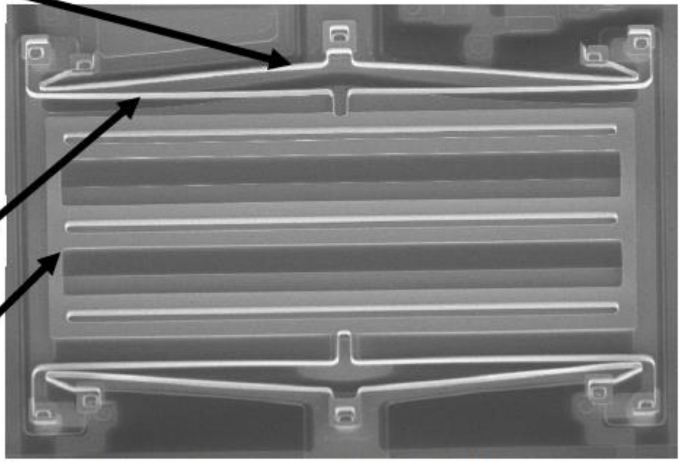


Figure 1b: SEM micrograph of fabricated shutter

Zipper Actuators: Pull-in Variation of Electrostatic Actuator

Vertical parallel plate

- High force generation
- Long-distance and stable displacement
- Low voltage drive

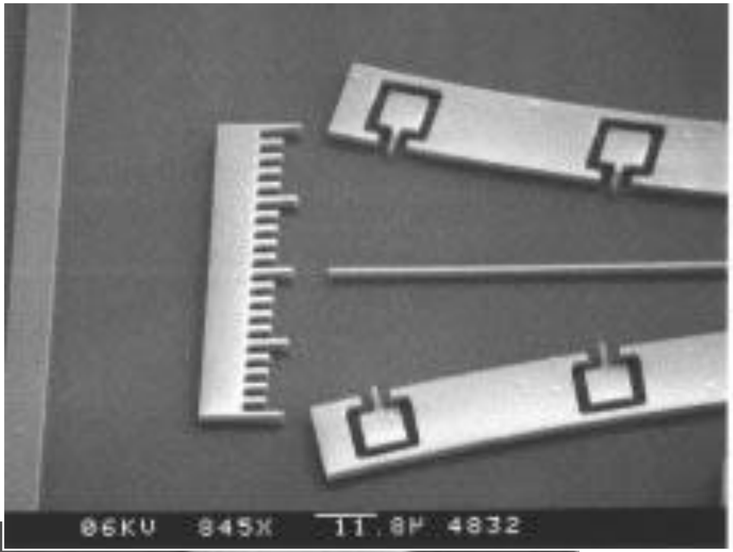
Design:

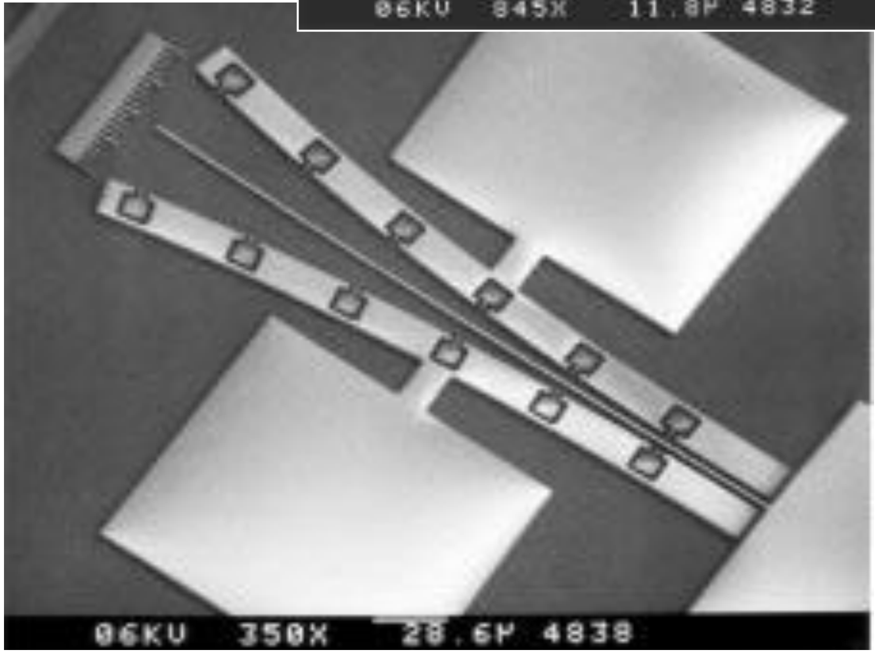
- Small gap at the clamped end
- One electrode coated with dielectric layer

Stopper reduce contact surface

Issues:

- Sticking and jump-over
- Short circuits

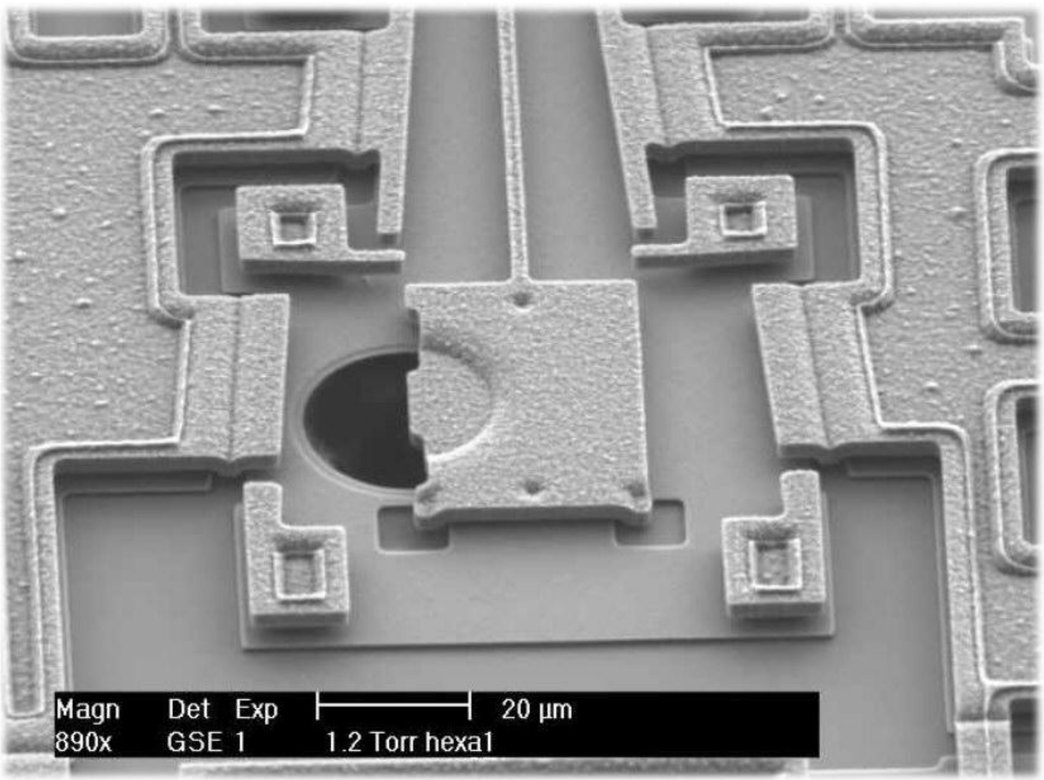




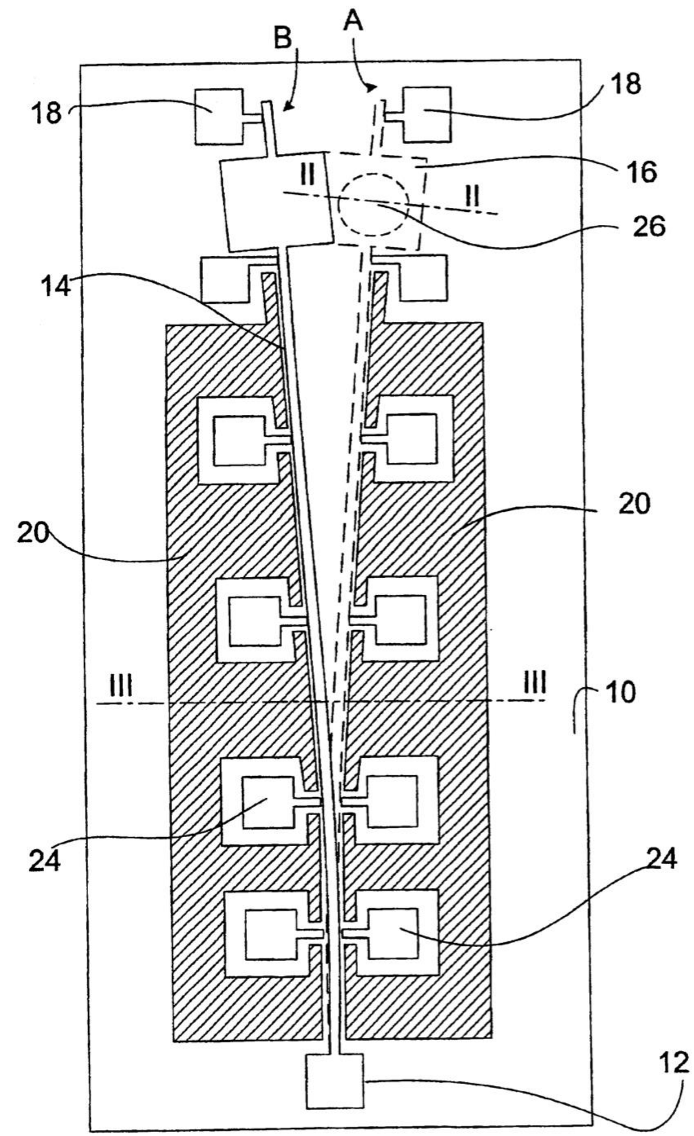
source: **JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 6, NO. 3, SEPTEMBER 1997, 257**

Snap-in / Zipper Actuators → Colibrys Shutter

- Vertical parallel plate
- Optical shutter
- Stopper reduce contact surface
- Both “on” and “off” actuation
- Issue: Sticking and jump-over



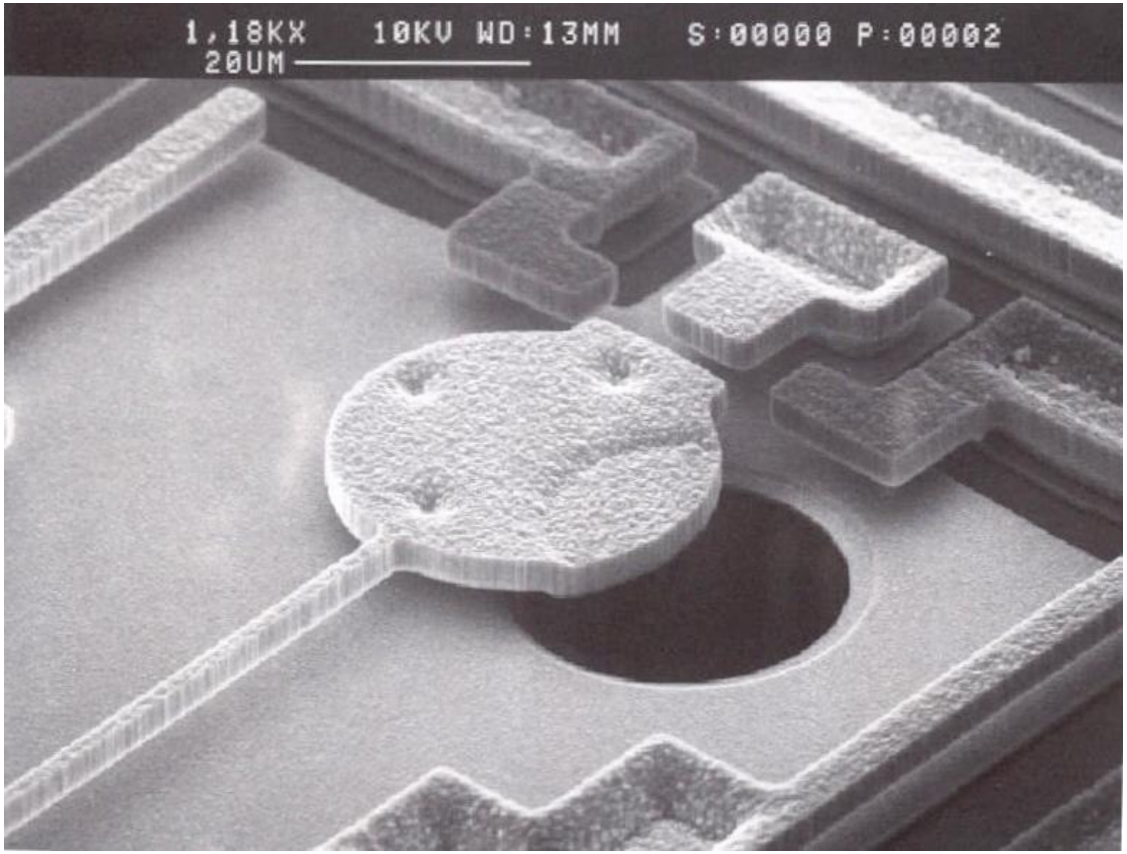
source: **Microsyst Technol (2005) 11: 1171–1175**



Zipper Issues → "End-face" Actuator

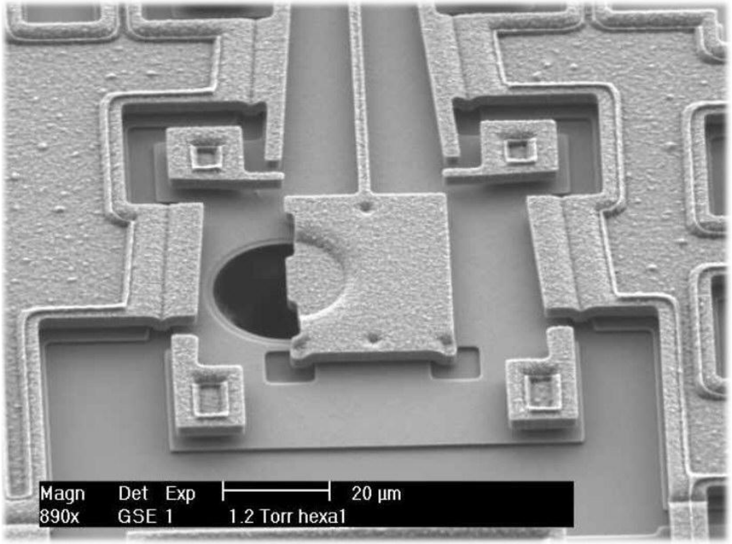
Vertical parallel plate Optical shutter

- **New design:**
  - No more contact
  - End face of shutter is electrode



- **Old design:**
  - Mechanical stoppers

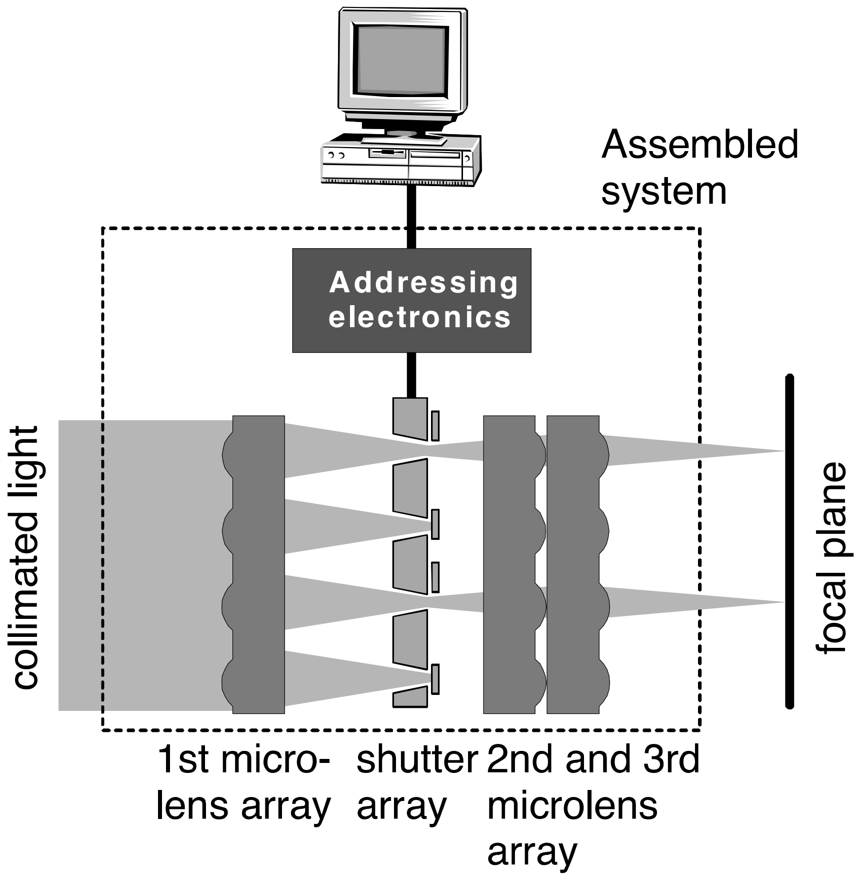
Issues: Sticking and jump-over

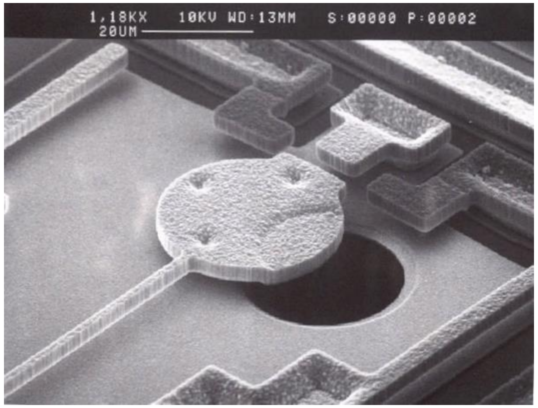


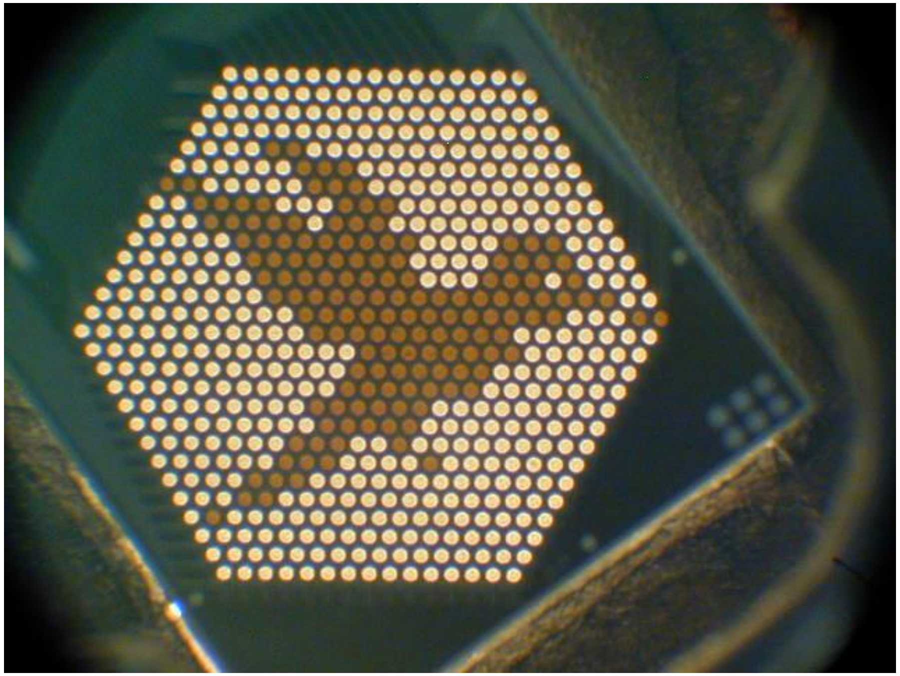
source: Microsyst Technol (2005) 11: 1171–1175

Colibrys Optical-Shutter Array

- Vertical parallel plate benefitting from fringing fields
- Possible issue: Short circuit & sparks at ends

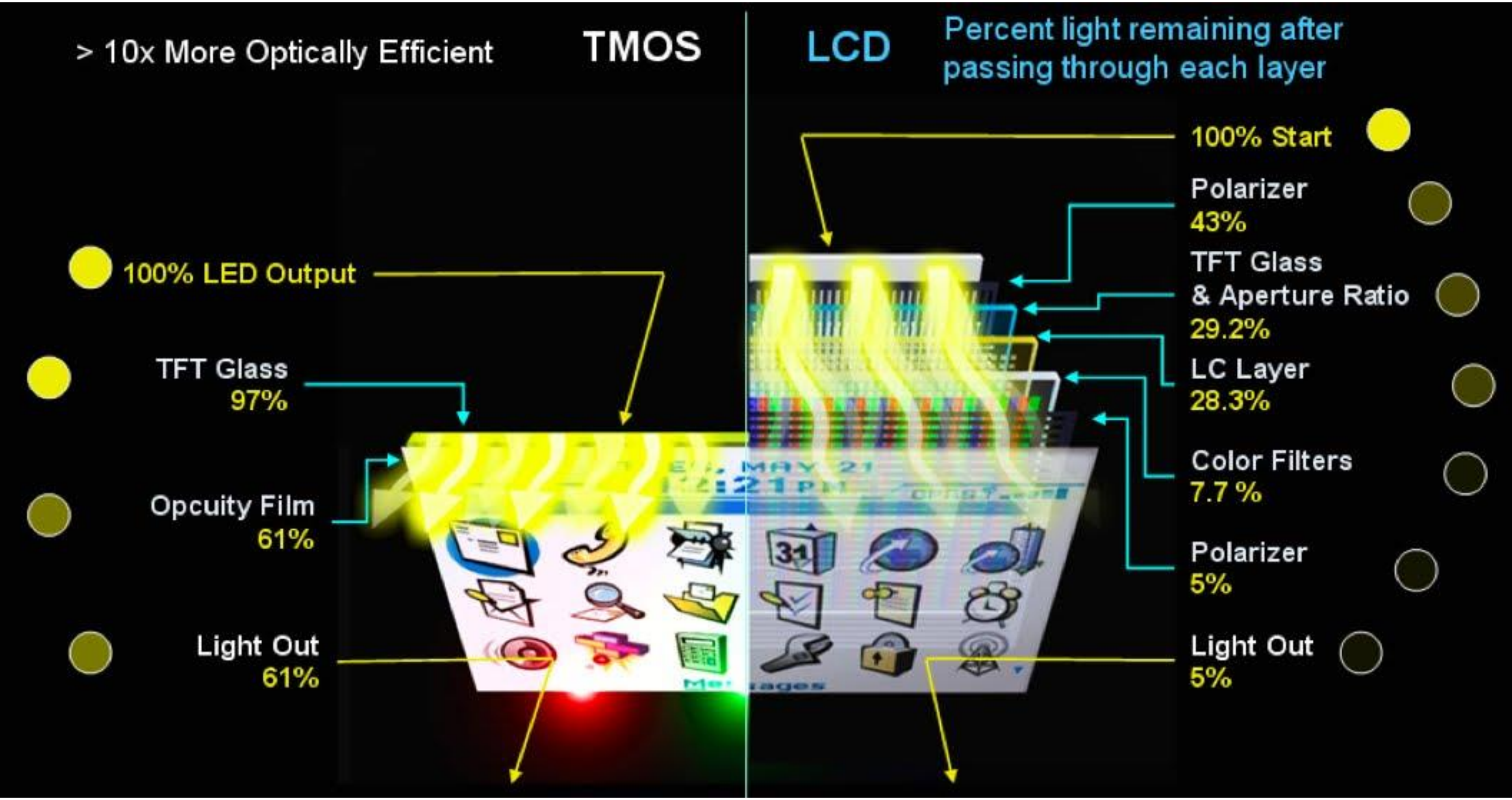






source: Microsyst Technol (2005) 11: 1171–1175

Shutter MEMS Displays



Opcuity™ by unipixel: micro-structured film technology

TMOS = time-multiplexed optical shutter

http://www.gizmag.com/next-gen-tmos-displays-mass-production/13167/

Is there a future for MEMS displays in mobile?

appleinsider

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Breaking

Apple has taken over Qualcomm's IMOD Mirasol display lab in Taiwan

By Daniel Eran Dilger
Monday, December 14, 2015, 10:52 pm PT (01:52 am ET)

Apple is now operating a top secret production laboratory in Longtan, Taiwan, formerly run by Qualcomm to develop a unique, low-power display technology known as IMOD, or Interferometric Modulator Display.

Microscanner for interactive laser projection; any surface can be a UI

February 28, 2017 // By Graham Prophet — 0 Comments

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Transforming any surface into a virtual user interface, Bosch Sensortec's BML050 is an optical MEMS based scanner that promises improved image quality and focus-free projection, creating flexible and intuitive virtual user interfaces.

"Laser projected virtual interfaces are a new fascinating solution in a world of previously undreamed of opportunities," Bosch says. A core component of this solution that enables focus-free laser projection and turns any surface into a virtual user interface (UI) is the high-precision MEMS scanner for interactive laser projection applications.

http://www.edn-europe.com/

See also https://goodereader.com/blog/electronic-readers/the-rise-and-fall-of-qualcomm-mirasol-e-readers

Summary / Take Home Message

- **MOEMS: No 'one solution fits all'**
  (One Application = One MOEMS = One Process)
- **Specific design, fabrication process and packaging development**

- **Review of Electrostatic & Magnetic Actuators**
  (most successful, but many other actuation methods exist)

- **Products can benefit of integrated CMOS electronics**
- **Dedicated processes for MEMS**

- **Specialty Applications with design of MEMS Structures**
- **Engineering Specialties**
- **Performance and Volume Production**

- **Consumer: Display, Projection, 3D Imaging/Gesture Recognition**
- **Mobile Future: Low Power, Miniaturized, Ubiquious, IoT Connectivity**