OPTICAL TRANSDUCERS

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MICROMACHINED OPTICAL DEVICES EXAMPLES

- Photosensors/Imagers (IR, visible, UV)
- Spectrophotometers
- Light emitters
- Optical modulators
- Fiber optic interfaces
- Lenses and other optical components
- Other

BASIC OPTICAL TRANSDUCER CONCEPTS

- Electron/hole pair generation in depletion regions of semiconductor junctions generates voltages/currents.
- In photoconductors, but bulk resistance drops due to extra photogenerated carriers.
- Indirect conversion of photons may be used, such as conversion to heat (can measure temperature) or to gas expansion (via heat) as in the Golay cell.
- Photoemission (photons directly releasing electrons from emissive surfaces) can also be used (e.g. photomultipliers), but has not been applied in micromachined devices yet.
- For light emission, lasers, light-emitting diodes (recombination), electroluminescence or incandescence may be used.

BASIC PHOTOSENSOR CONCEPTS

- There are four basic types of photosensors:
  - photoemissive (electron released from metal by sufficiently energetic photon)
  - bulk photoconductive (no junction - photogenerated carriers lower bulk resistance)
  - junction (electron-hole pairs generated in depletion region, can be used as photovoltaics or photoconductors)
  - indirect (conversion of optical to another form of energy that is then sensed)
- The first three are “direct” and the last type is “indirect.”
- Direct photosensors use some or all of the three basic processes that contribute to their final gain:
  - carrier generation by photons
  - carrier transport and/or multiplication
  - interaction with external circuit
- The final gain of indirect photosensors is more case specific.

KEY PHOTOSENSOR SPECIFICATIONS

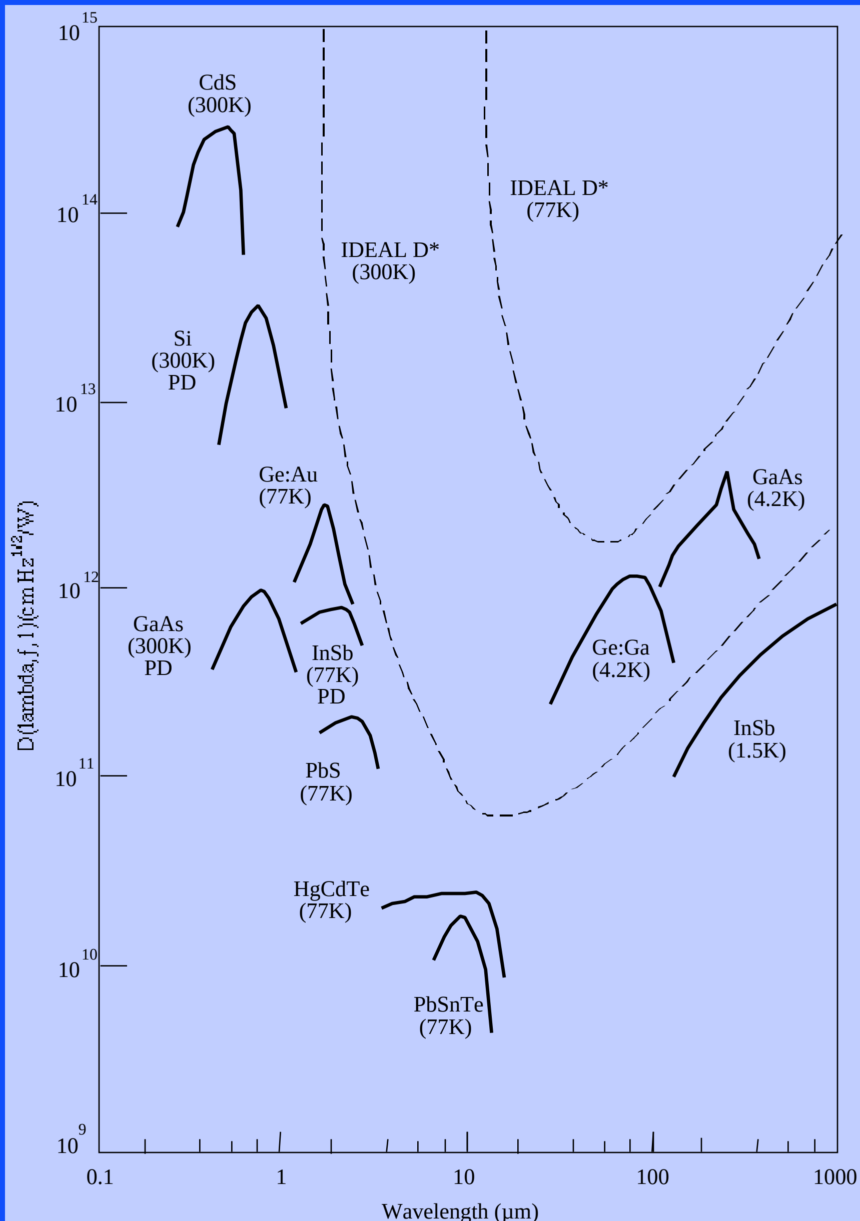
- **Quantum Efficiency (η): number of carriers generated per photon.**
- **Responsivity (R_V or R_I): ratio of output voltage (or current) to the optical input power (V/W or A/W).**
- **Noise Equivalent Power (NEP): amount of light required to yield a signal just equal to the noise floor = noise voltage (V/√Hz)/responsivity (similarly for current)**

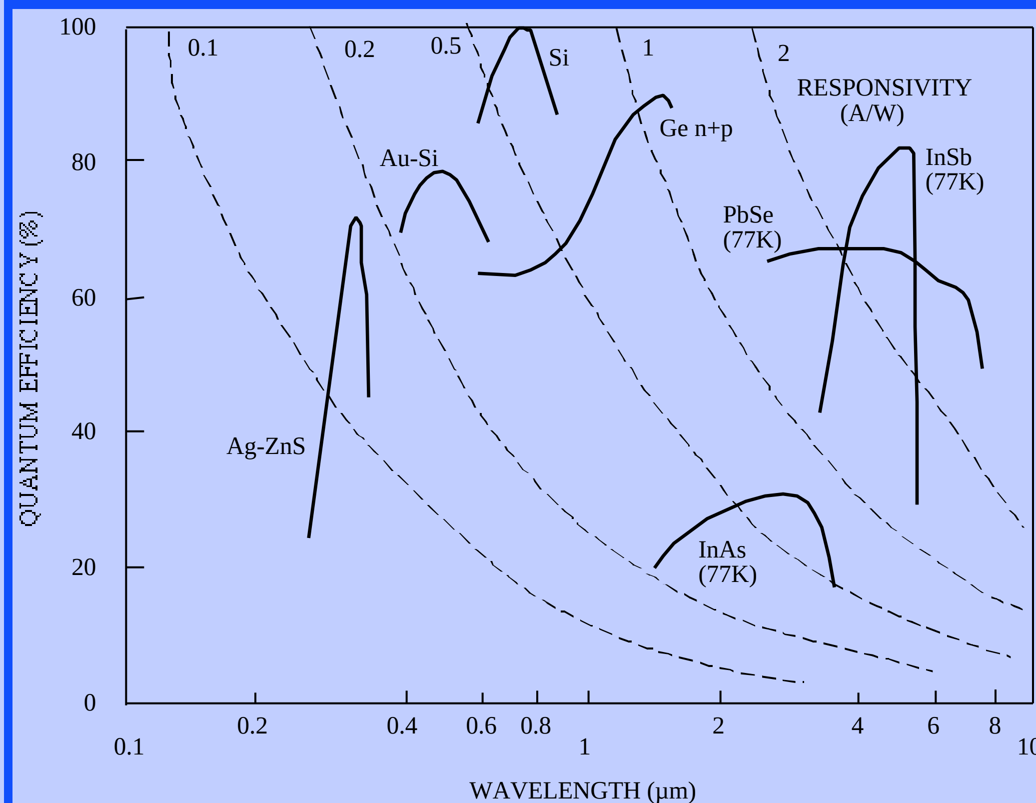
$$\mathrm{NEP} = \frac{\text{RMS Noise Current}\left(\frac{\mathrm{A}}{\sqrt{\mathrm{Hz}}}\right)}{\text{Responsivity}\left(\frac{\mathrm{A}}{\mathrm{W}}\right)} = \frac{\text{RMS Noise Voltage}\left(\frac{\mathrm{V}}{\sqrt{\mathrm{Hz}}}\right)}{\text{Responsivity}\left(\frac{\mathrm{V}}{\mathrm{W}}\right)} \quad \text{in} \left(\frac{\mathrm{W}}{\sqrt{\mathrm{Hz}}}\right)$$

- **Detectivity (D*): (√A√B)/NEP, which takes into account detector area and bandwidth (noise current is proportional to the square root of A and of B). It can be looked at as a signal-to-noise ratio corrected for these effects.**

$$D^* \equiv \frac{\sqrt{AB}}{\mathrm{NEP}}$$

EXAMPLE DETECTIVITIES AND QUANTUM EFFICIENCIES



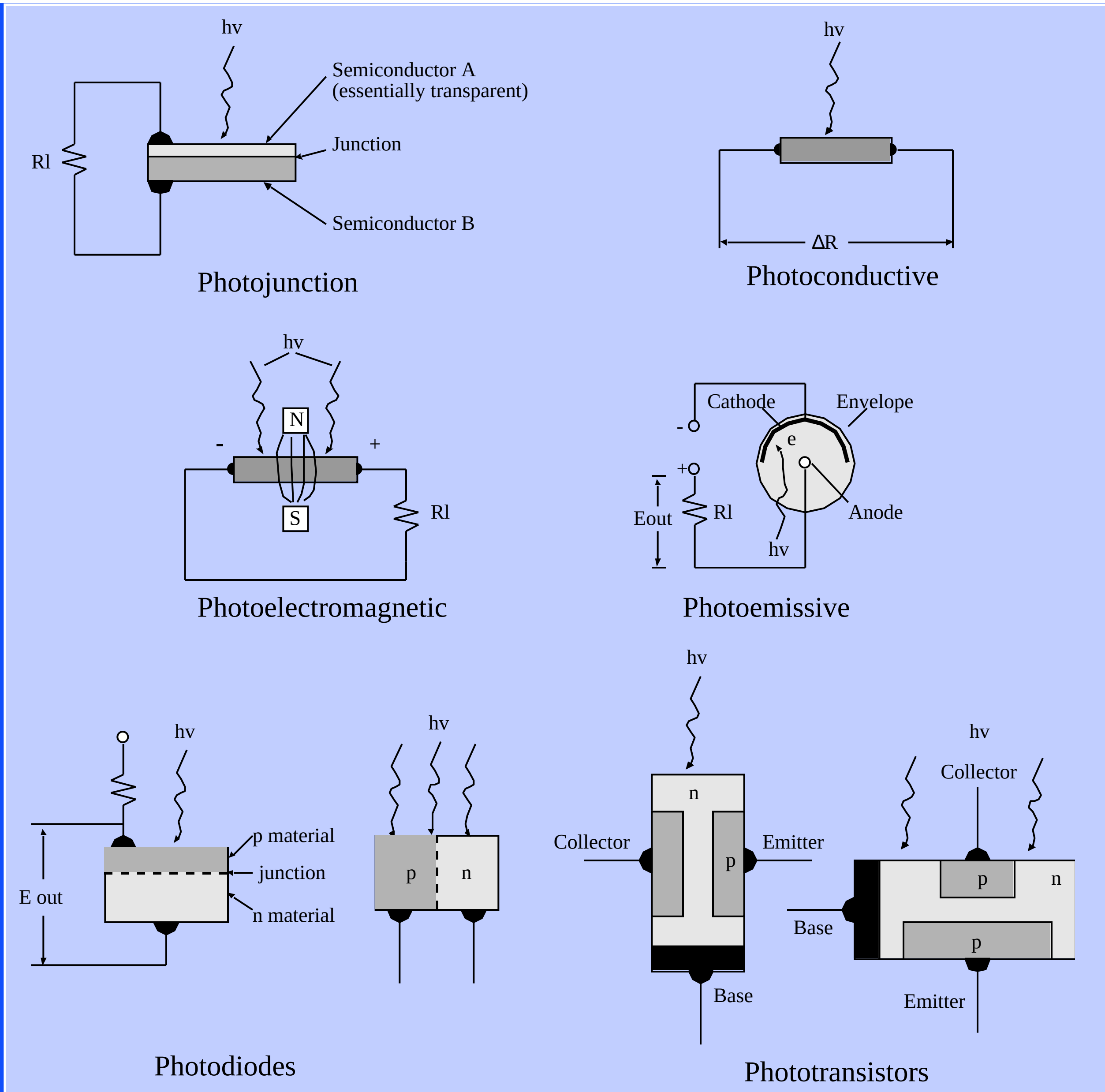


LIGHT ABSORPTION

- A photon flux absorbed into a material falls off exponentially as,

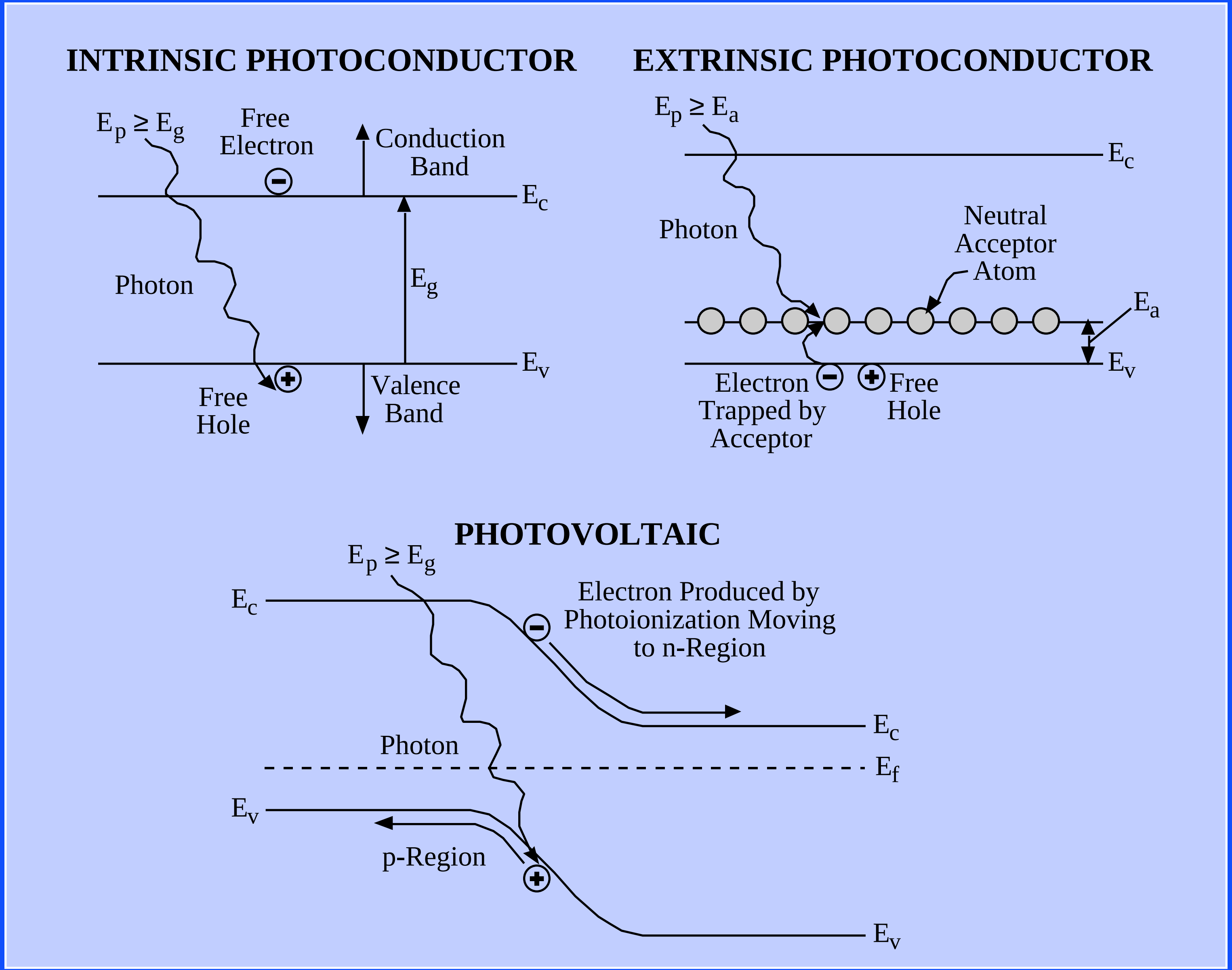
$$\Phi(x) = \Phi_o e^{-\alpha x}$$

- The absorption coefficient, α, is characteristic of each material and is often a strong function of the wavelength.
- Consideration of this effect in the design of photosensors is critical.



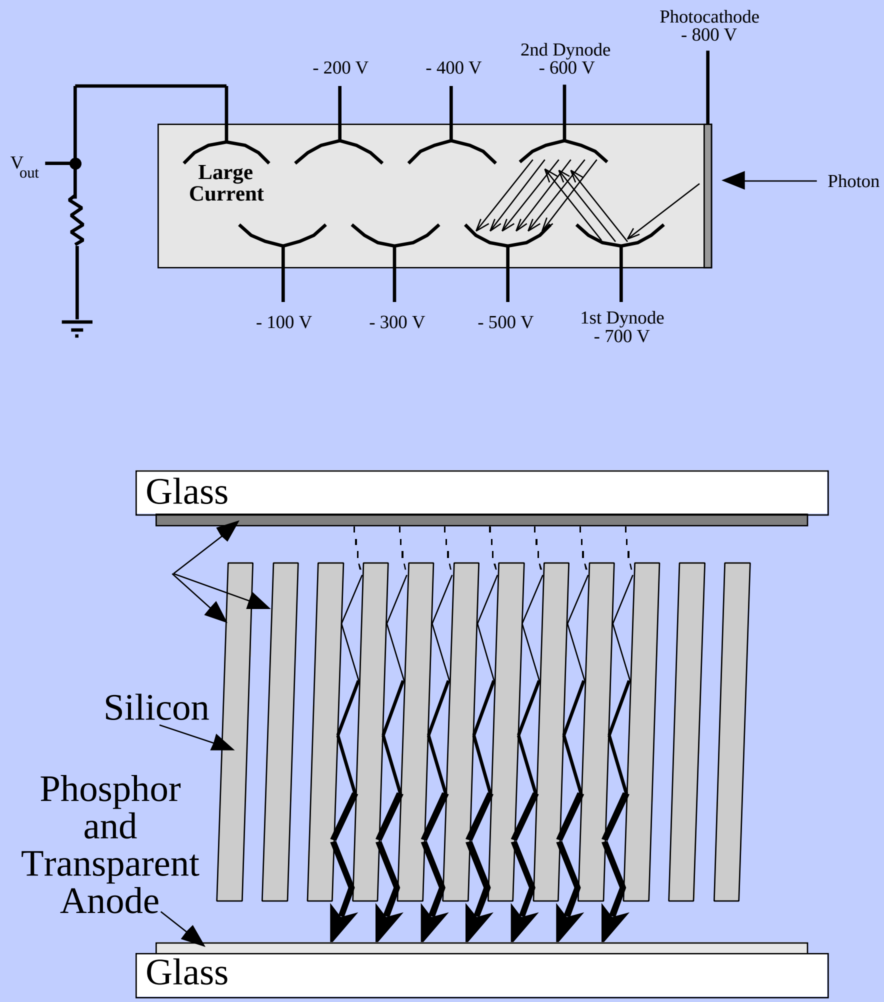
DIRECT OPTICAL SENSORS

Device Type	Gain	Response Time (s)	Typical Operating Temperature
Photomultiplier	> 10^6	10^{-7} to 10^{-9}	300 (sometimes cooled)
Photoconductor	1 to 10^6	10^{-3} to 10^{-8}	4.2 to 300
Metal-Semiconductor-Metal Photodetector	1 or less	10^{-10} to 10^{-12}	300
p-n Photodiode	1 or less	10^{-6} to 10^{-11}	300 (sometimes cooled to 77K)
p-i-n Photodiode	1 or less	10^{-6} to 10^{-9}	300
Metal-Semiconductor Diode	1 or less	10^{-9} to 10^{-12}	300
Avalanche Diode	10^2 to 10^4	10^{-10}	300
Bipolar Phototransistor	10^2	10^{-6} to 10^{-8}	300
Bipolar PhotoDarlington	10^4	10^{-5} to 10^{-6}	300
Field-Effect Phototransistor	10	10^{-7}	300
CCD Cell (Metal-Insulator-Semiconductor Capacitor)	1 or less	10^{-5} to 10^{-8}	300 (sometimes cooled)



INTRINSIC PHOTOCONDUCTOR
$E_p \geq E_g$
Free Electron
Conduction Band
E_c
Photon
E_g
E_v
Free Hole
Valence Band
EXTRINSIC PHOTOCONDUCTOR
$E_p \geq E_a$
E_c
Photon
Neutral Acceptor Atom
E_a
E_v
Electron Trapped by Acceptor
Free Hole
PHOTOVOLTAIC
$E_p \geq E_g$
E_c
Electron Produced by Photoionization Moving to n-Region
E_c
Photon
E_f
E_v
p-Region
E_v

PHOTOEMISSIVE DEVICES



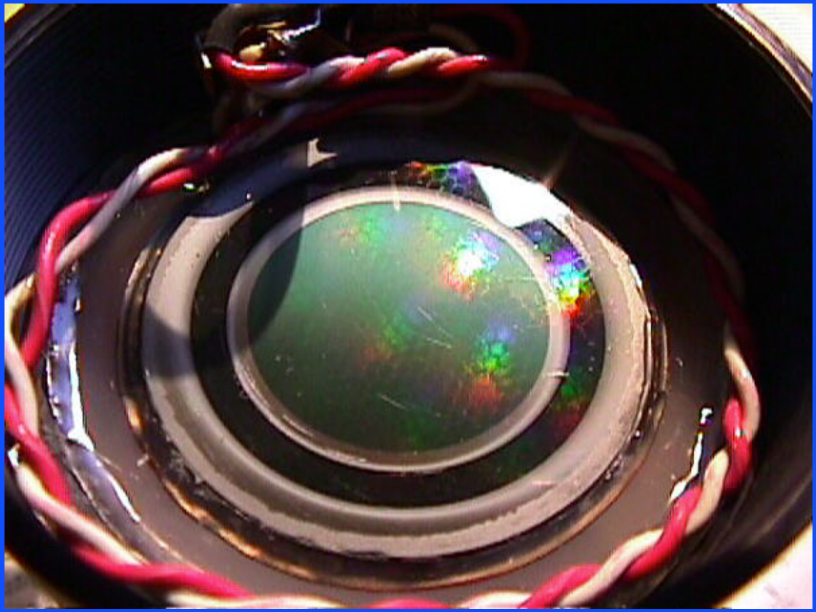
- Photons at wavelengths shorter than the cutoff for the photocathode material release electrons due to elastic collisions.

$$\lambda_{max} = \frac{hc}{\varphi_m}$$

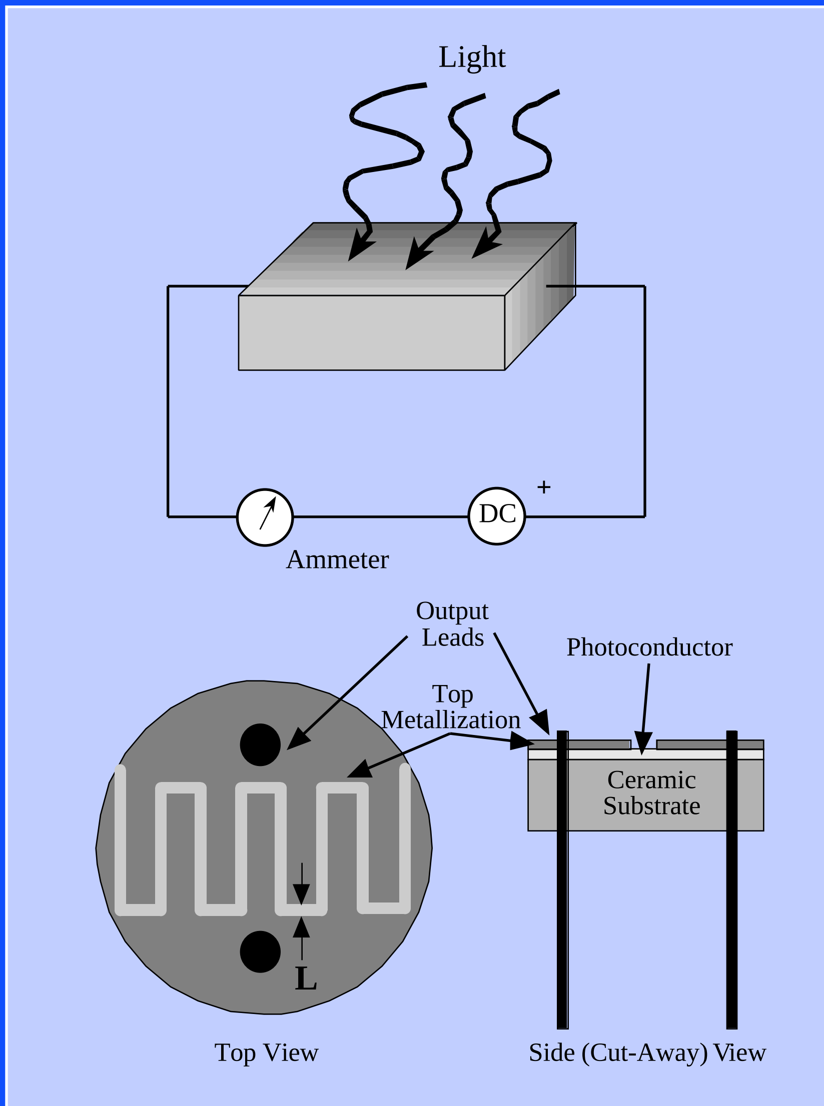
- Multiple secondary low-work-function cathodes ("dynodes") are used to provide gain.
- Can obtain single-photon sensitivity and nanosecond time speed.
- Dark current (thermionic, not photonic emission) is the major limiting factor, and is amplified by the dynodes.
- They are used for night vision, nuclear physics, etc.

Courtesy of Hamamatsu, Inc.

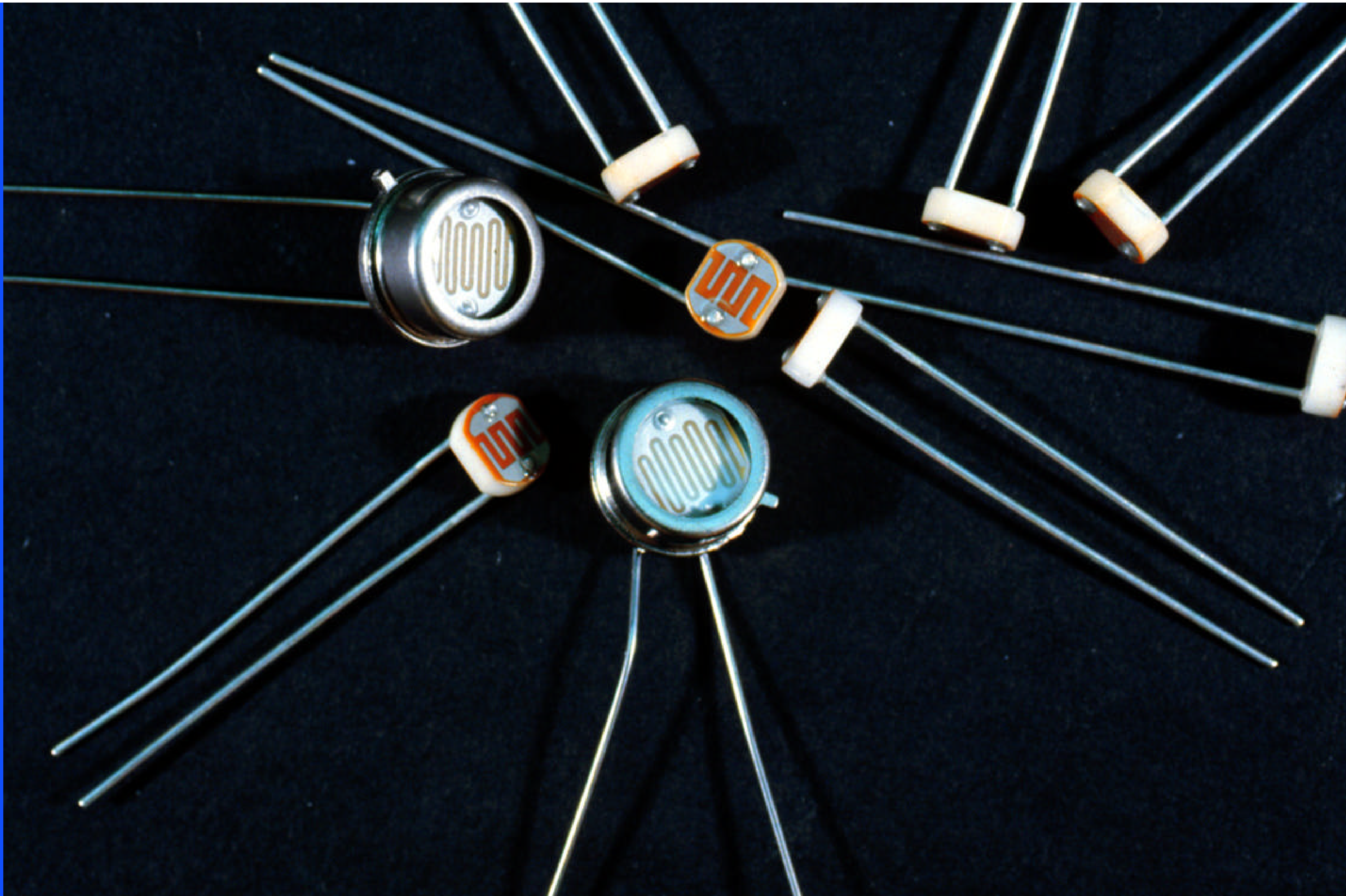
IMAGE INTENSIFIERS

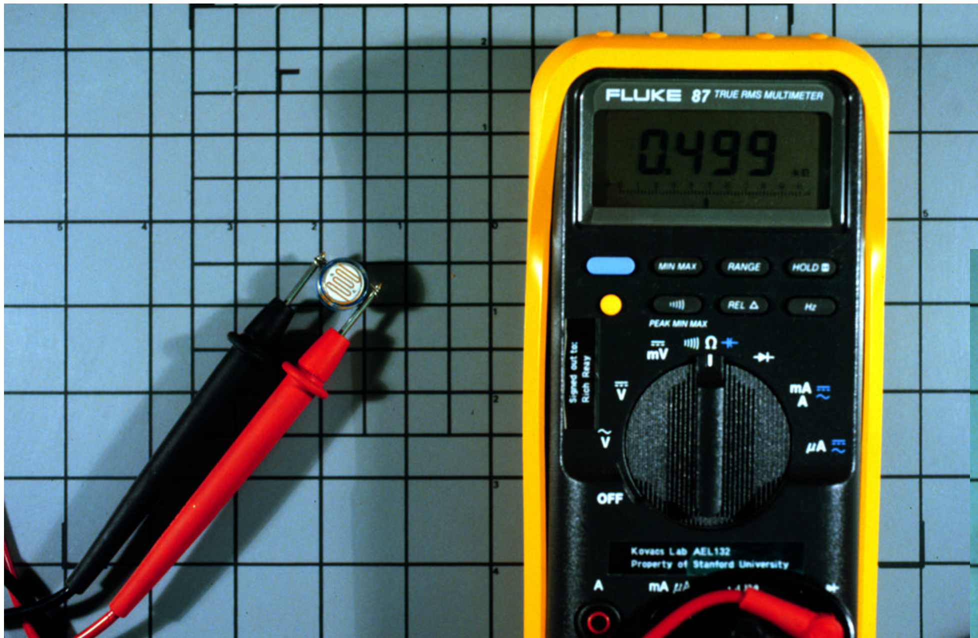


PHOTOCONDUCTORS



- **Photocurrent gain defines the number of carriers than can flow for each photogenerated carrier before it recombines.**
- **Long-lived carriers contribute more to a change in conductivity.**
- **If carriers are not swept out of the photoconductor quickly, they can contribute longer.**
- **Photocurrent gain is simply the carrier lifetime divided by the transit time.**
- **Short transit paths, high mobilities and long carrier lifetimes contribute greatly to increased gain.**
- **Photoconductors can be 1,000X more sensitive than photovoltaics and up to 1,000,000X more sensitive than simple photoemissive devices.**
- **The CdS cell is a classic design (with tremendous sensitivity), and CdS can be applied to silicon devices.**




FLUKE 87 TRUE RMS MULTIMETER
0.499
Kovacs Lab AEL132
Property of Stanford University


FLUKE 87 TRUE RMS MULTIMETER
27.29
Kovacs Lab AEL132
Property of Stanford University


FLUKE 87 TRUE RMS MULTIMETER
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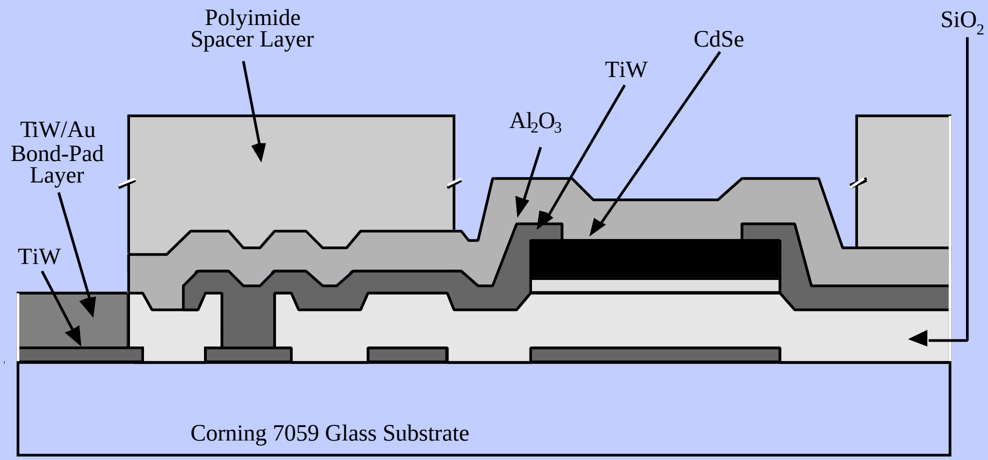
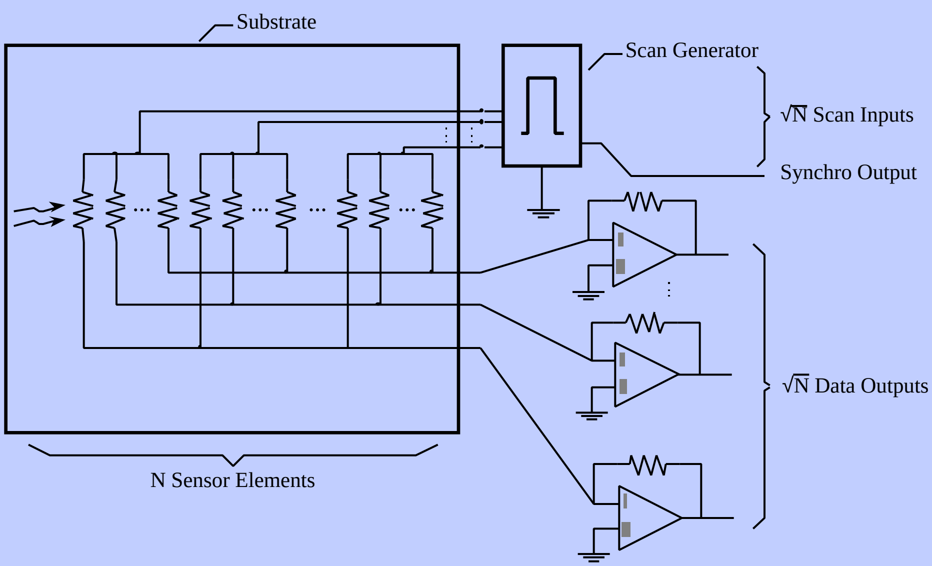




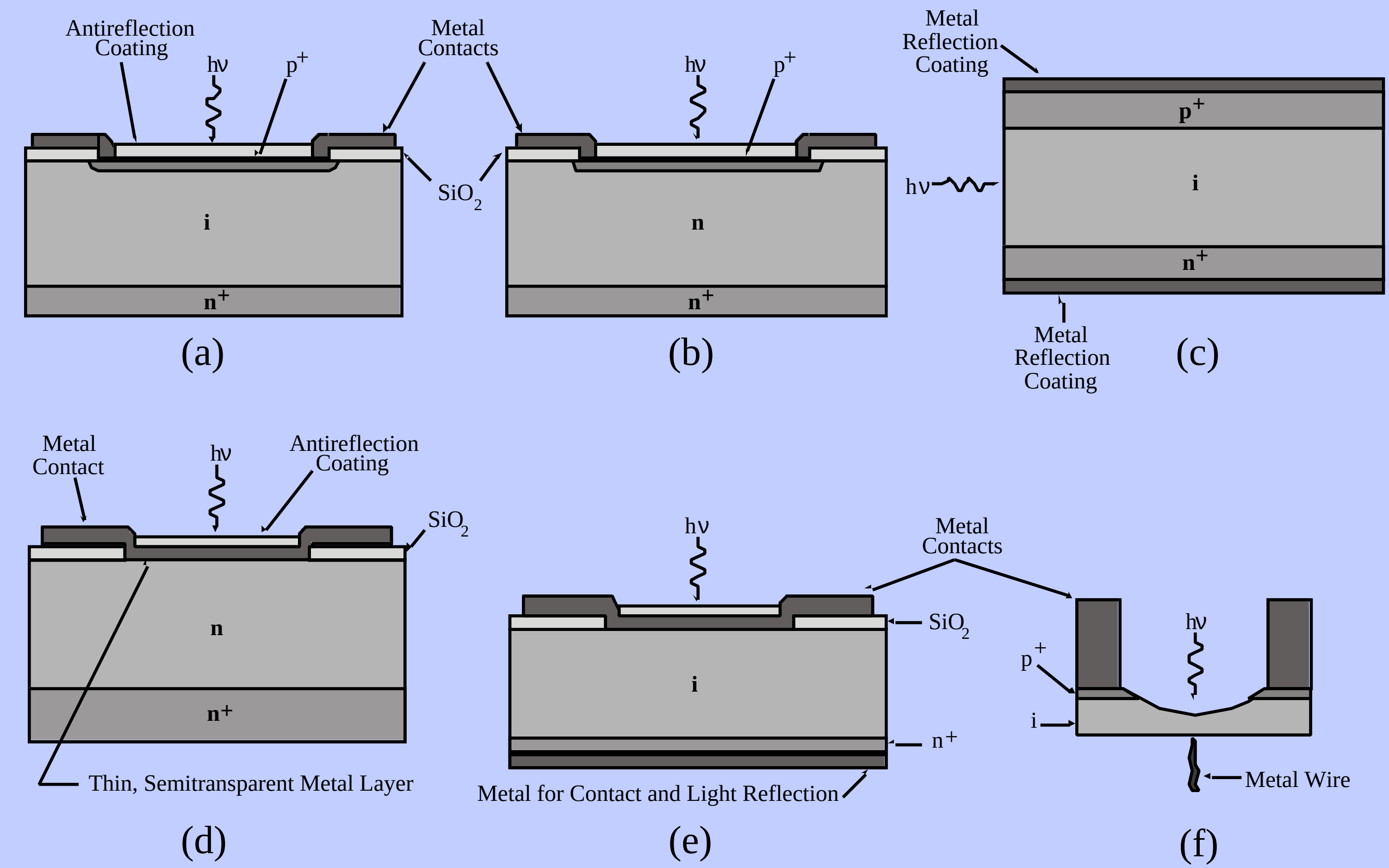
CdSe SENSOR ARRAY

- **Glass substrate used with separate amplifier array to realize a fax machine scanner.**
- **TiW electrodes used for contacts (etched with peroxide).**
- **Evaporated CdSe deposited and HCl etched.**
- **CdSe "activated" (doped) using $CdS/CdCl_2/Cu$)**

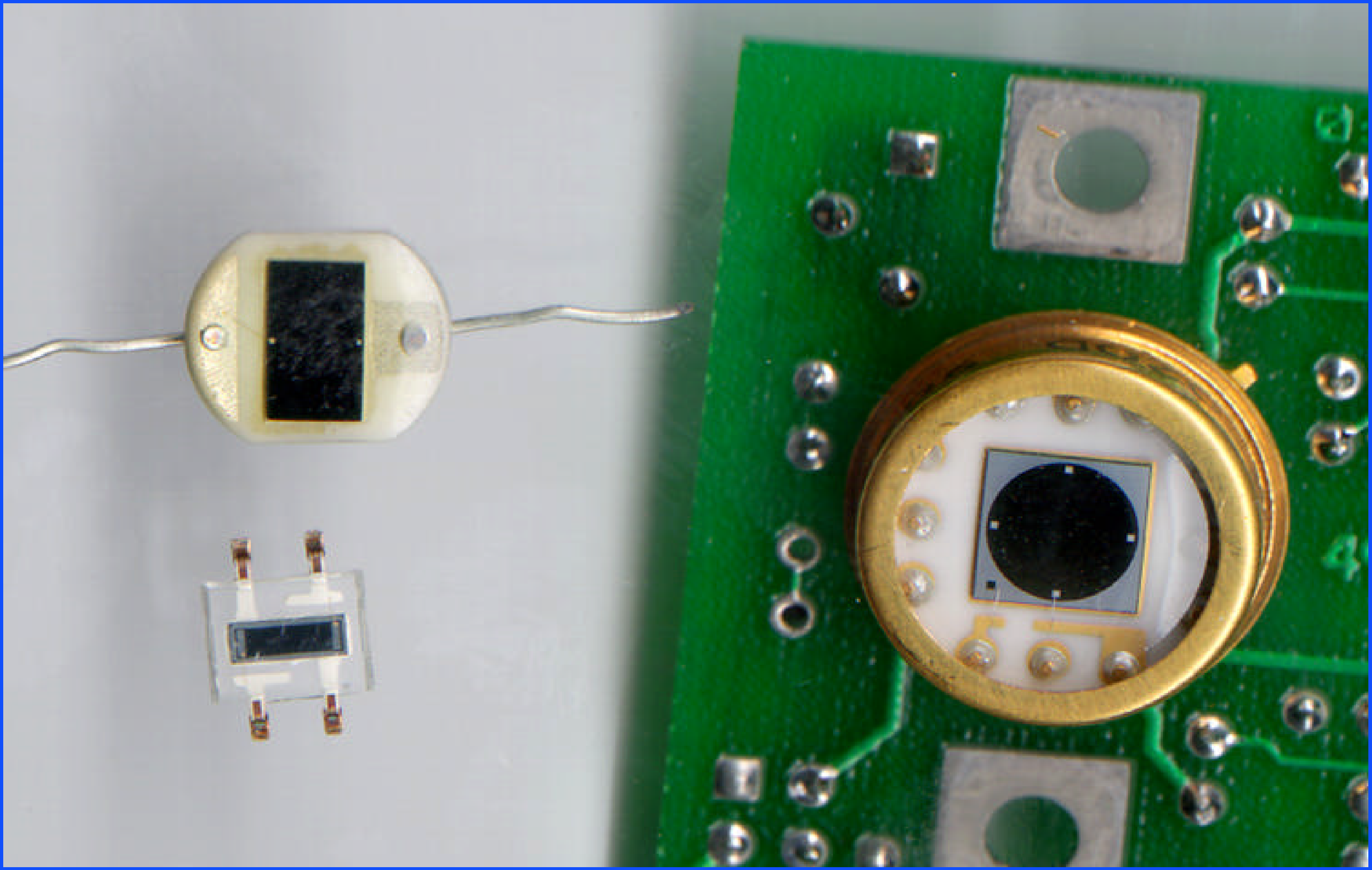
TYPES OF PHOTOJUNCTION DEVICES

- Photodiodes - simple.
- Avalanche diodes - inherent gain, very fast (100 GHz possible), noisy, high voltage.
- PIN diodes - common, wide depletion region, fast.
- Phototransistors - simple, common.
- PhotoDarlingtons - higher gain, lower speed.
- PhotoFETs - not common.
- Others...

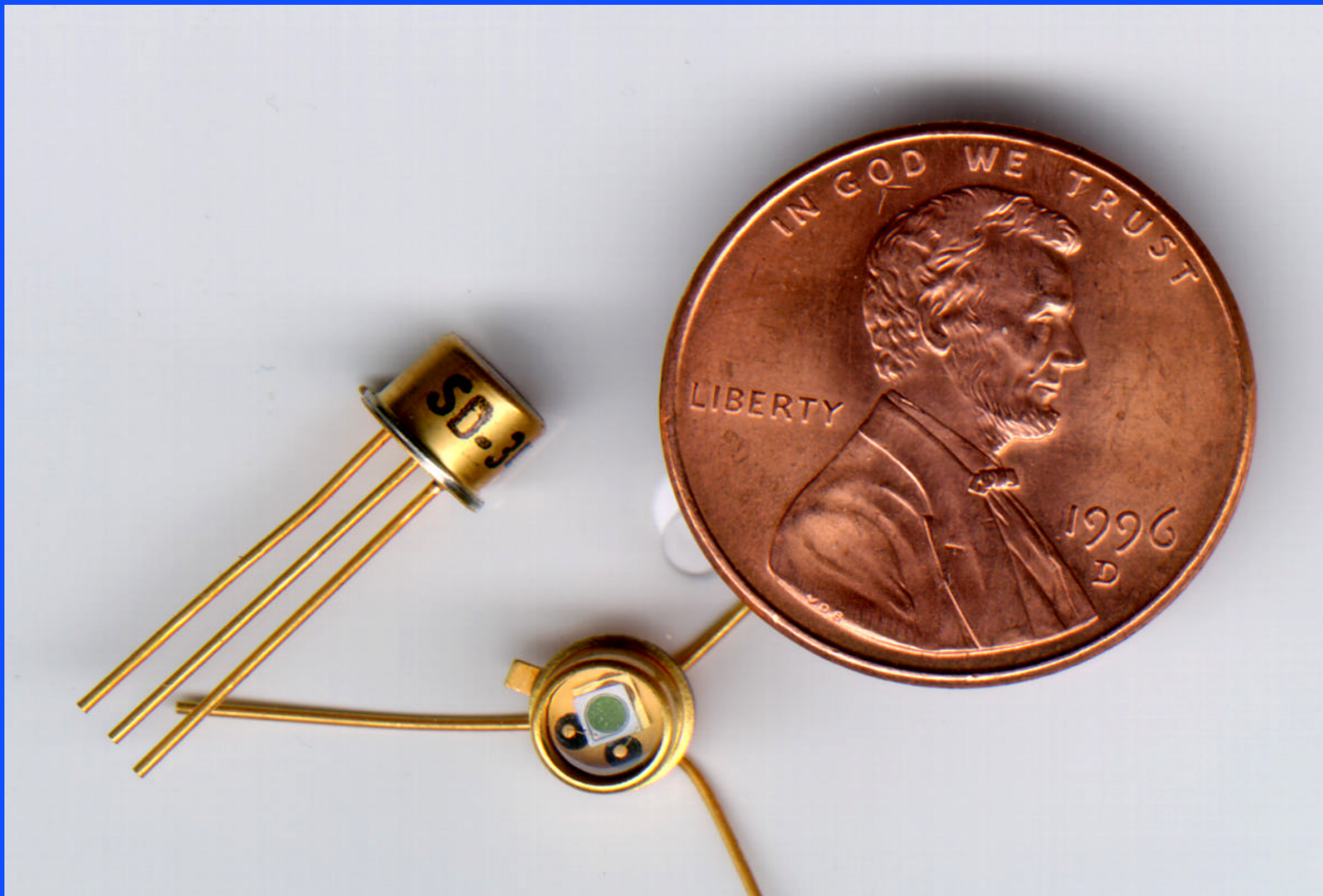
PHOTOJUNCTION DEVICES

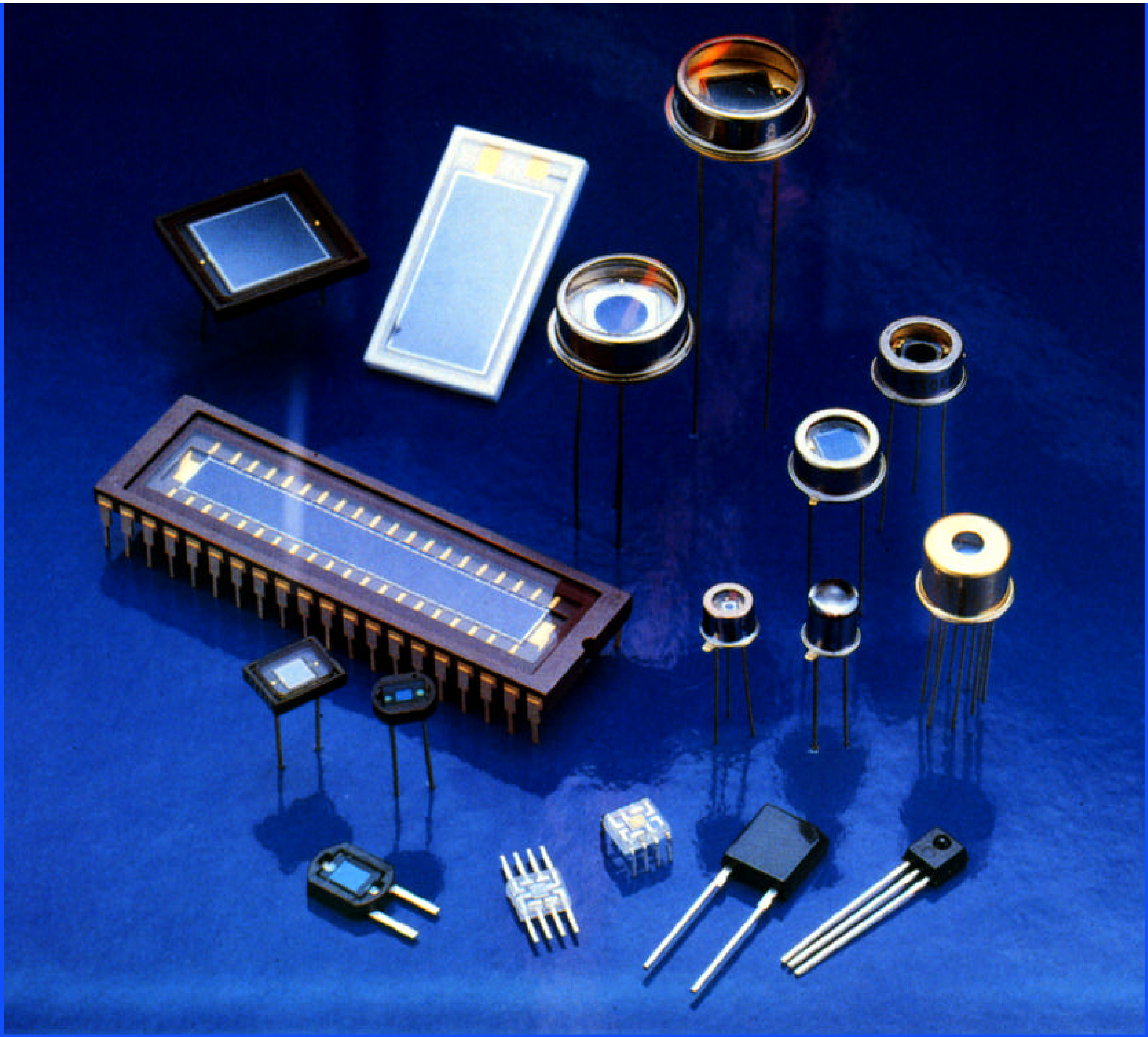


TYPICAL PHOTODIODES



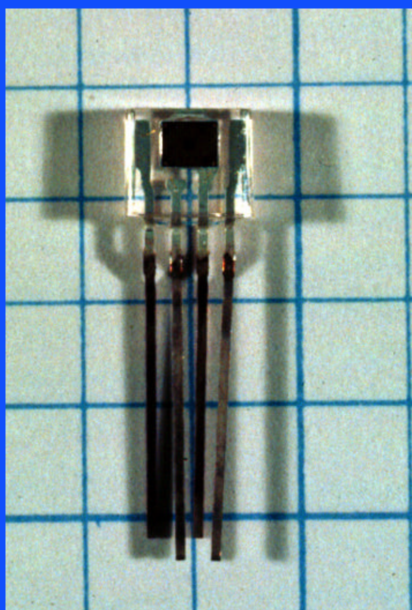
TYPICAL PHOTODIODES

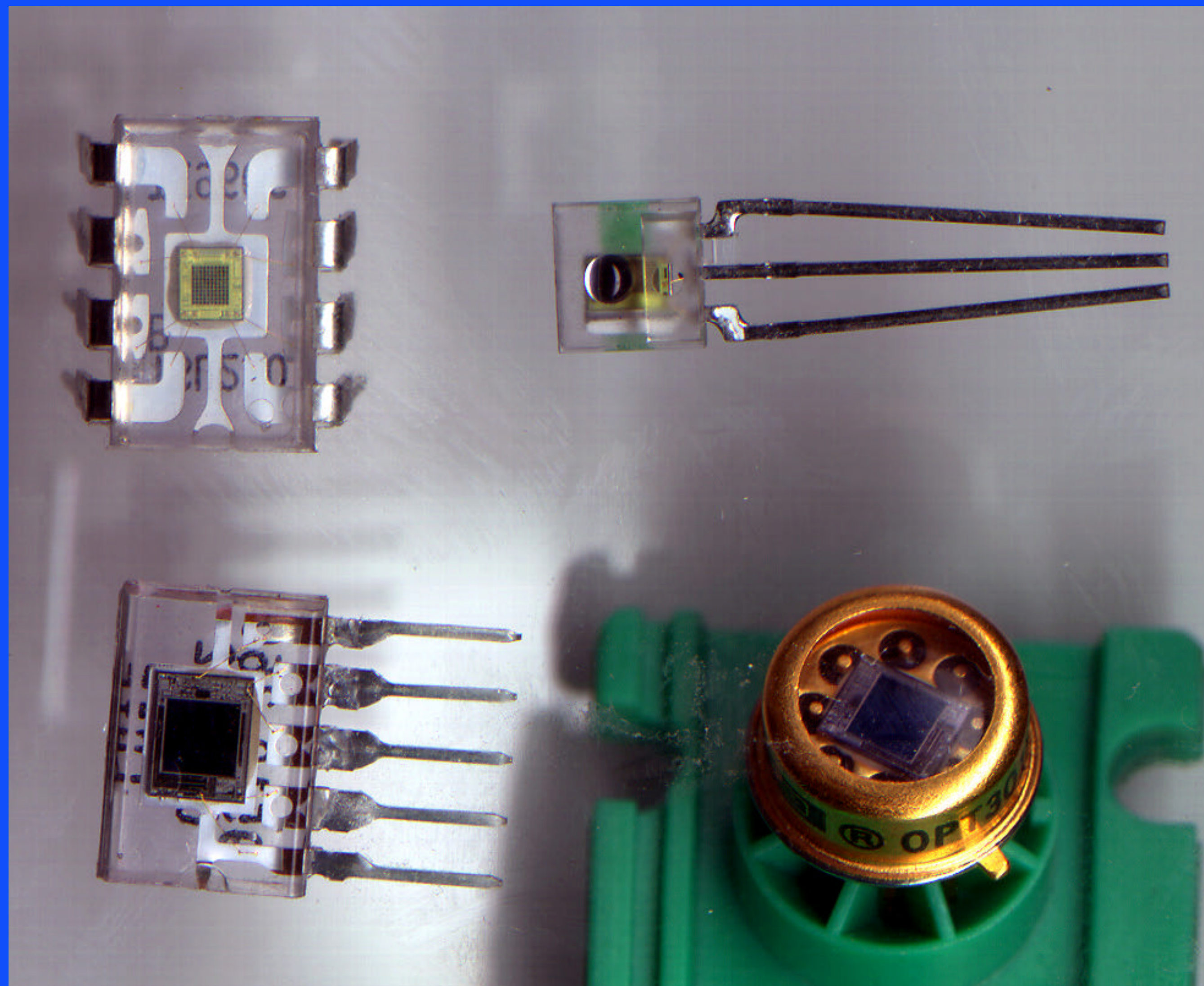




Courtesy of Hamamatsu, Inc.

INTEGRATED PHOTODETECTORS





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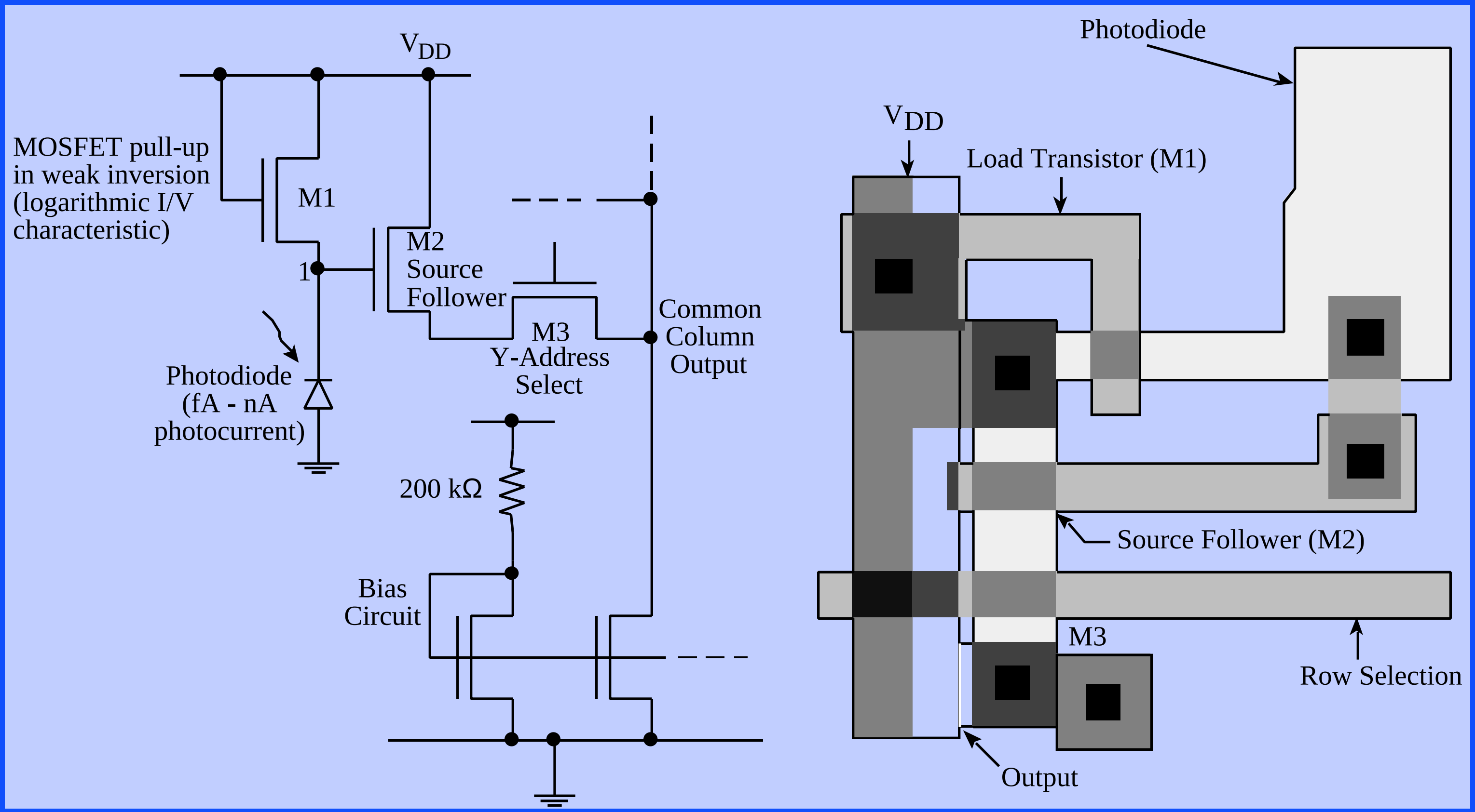
BRIEF SUMMARY OF PHOTOJUNCTION DEVICE ISSUES

- **WIDE DEPLETION REGION**
  - HIGHER quantum efficiency (η) since more likely to get photon interactions....
  - LOWER junction capacitance, C_j
  - LONGER transit time, t_r -> slows response, but high reverse bias helps (you normally use photodiodes in reverse bias and end up with high speed operation)!
- **NARROW DEPLETION REGION**
  - LOWER h
  - LARGER C_j
  - SHORTER t_r -> helps speed response, but capacitance may dominate
- **BOTTOM LINE: speed is determined by three factors:**
  - 1) diffusion of carriers generated outside the depletion region into it (reduced by making the depletion region close to the surface)
  - 2) drift time in the diffusion region (reduced by making it only wide enough to absorb maximally but not too thin so that capacitance goes up)
  - 3) junction capacitance (reduced by strong reverse bias or intrinsic region).

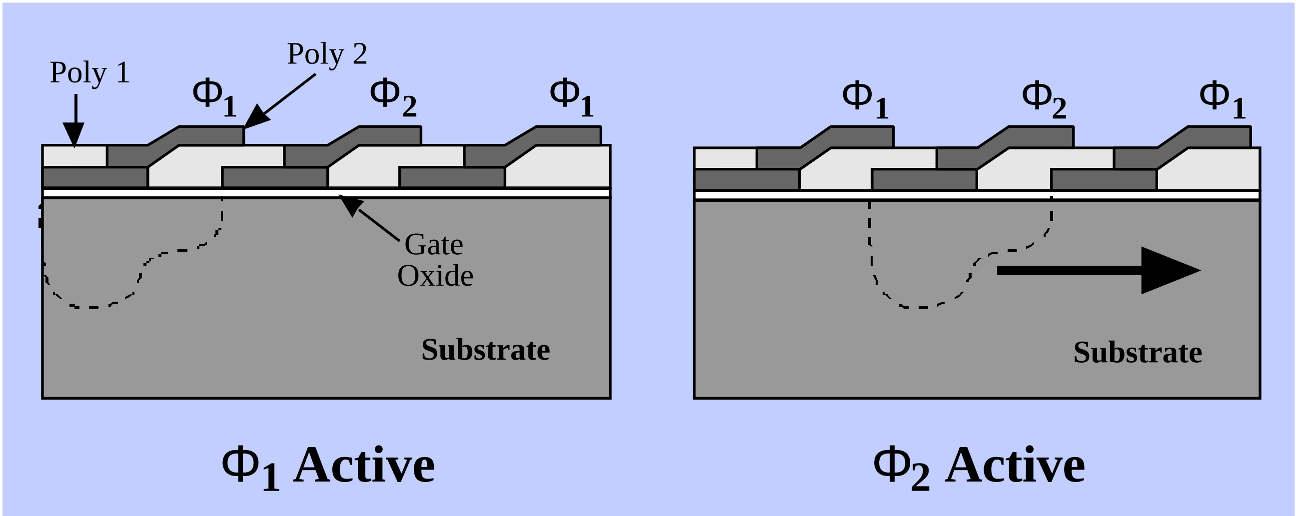
PHOTOSENSORS IN CMOS



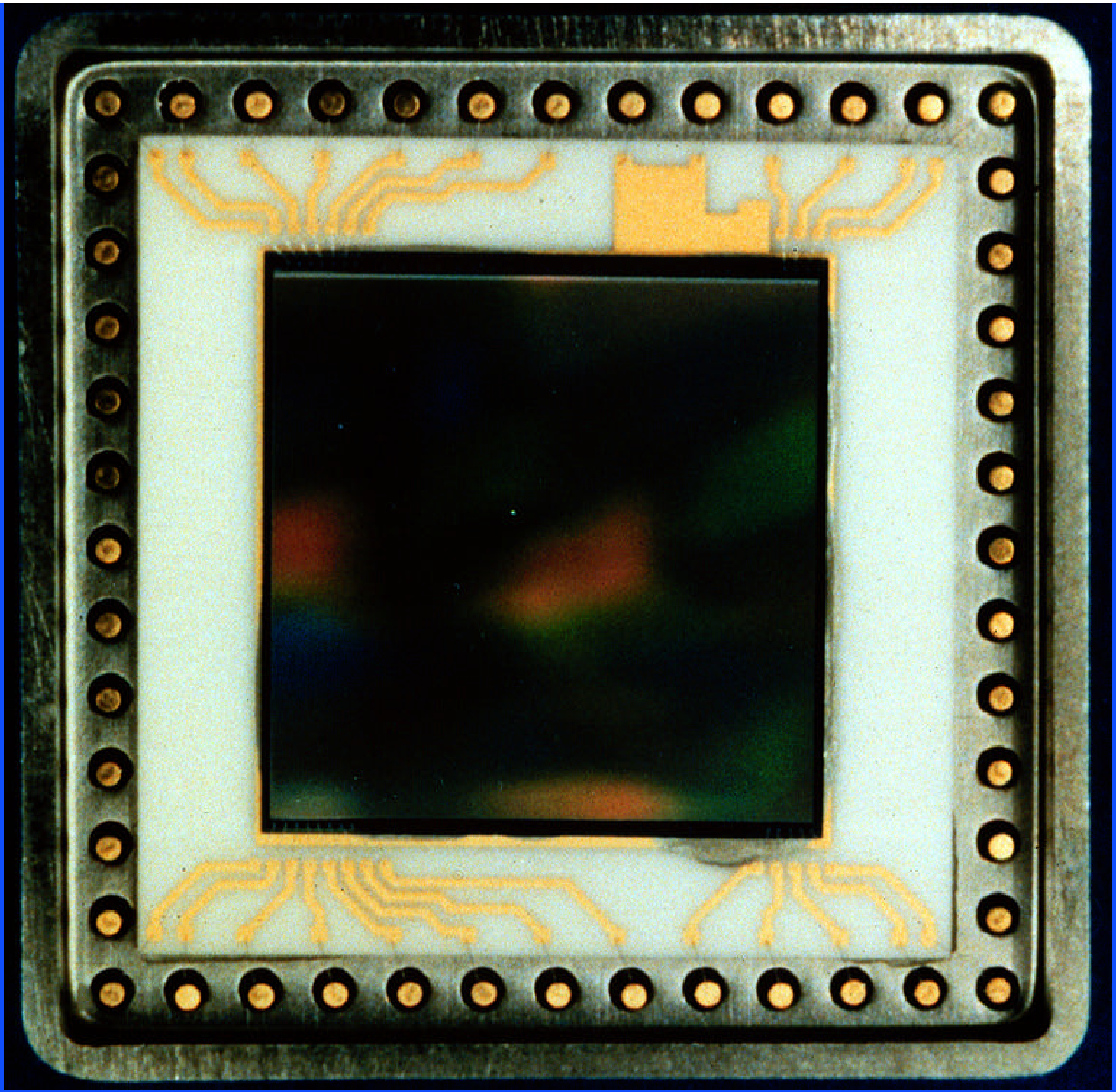
- **Readily achievable, but need V_t insensitive designs!**

Reference: Ricquier, N., and Dierickx, B., “Random Addressable CMOS Image Sensor for Industrial Applications,” Sensors and Actuators, vol. A44, no. 1, July 1994, pp. 29 - 35.

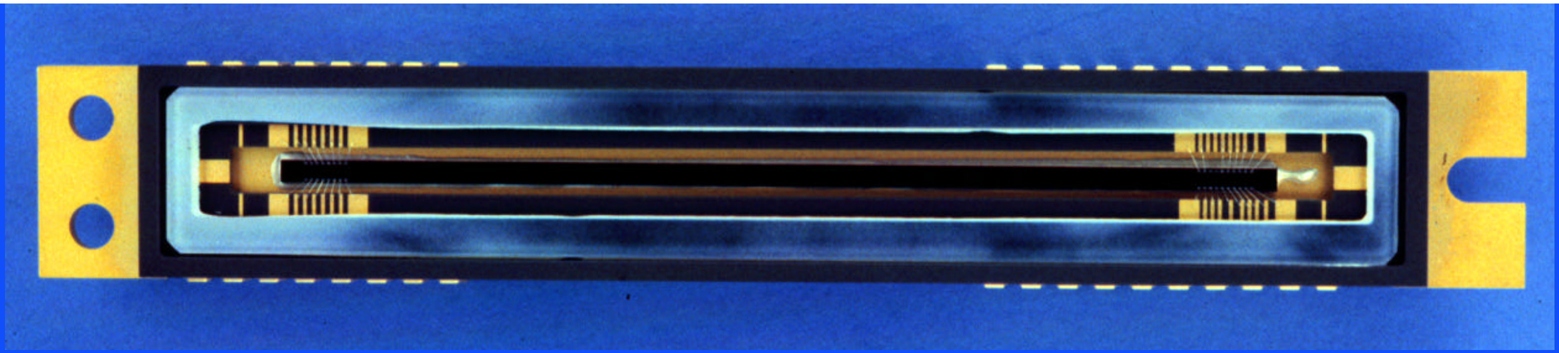
CCD STRUCTURES

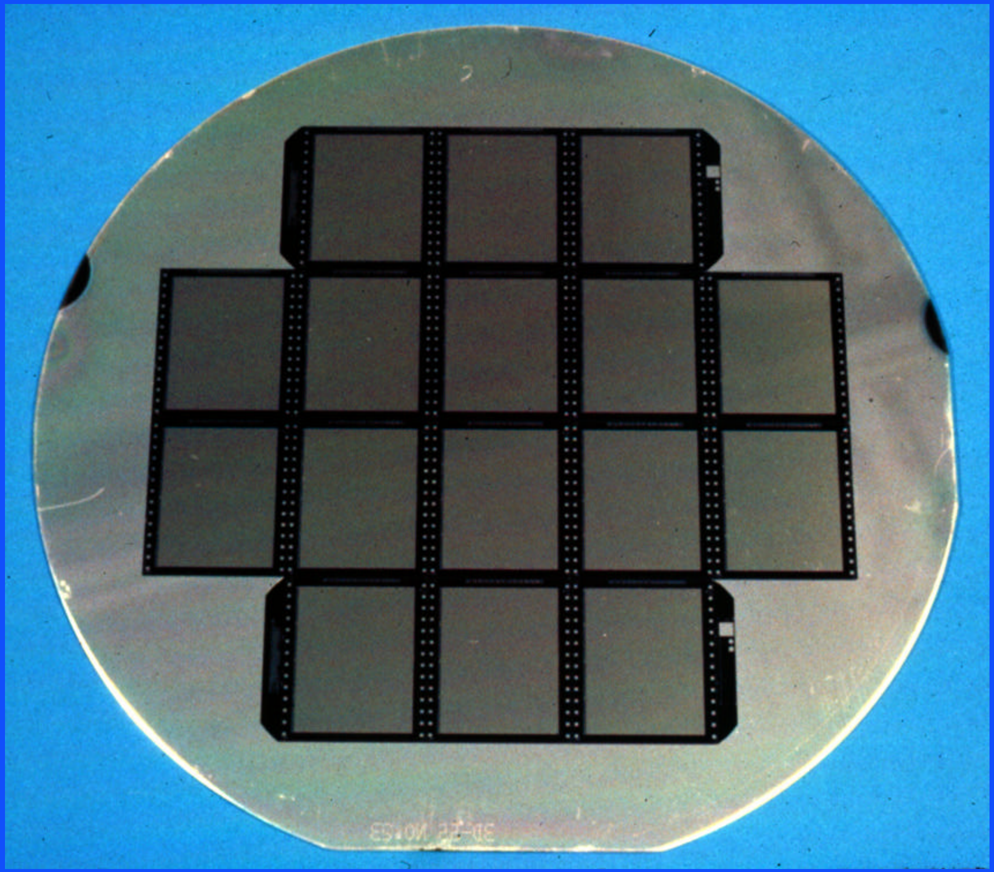


- CCDs are members of the metal-insulator-semiconductor (MIS) class of photodetectors.
- Bias applied to electrode above dielectric causes inversion in substrate so that photogenerated electron hole pairs are separated.
- Multiple electrodes can be used to move charge packets along by changing the applied potentials.
- Can be very sensitive (single photon) and huge arrays can be fabricated.



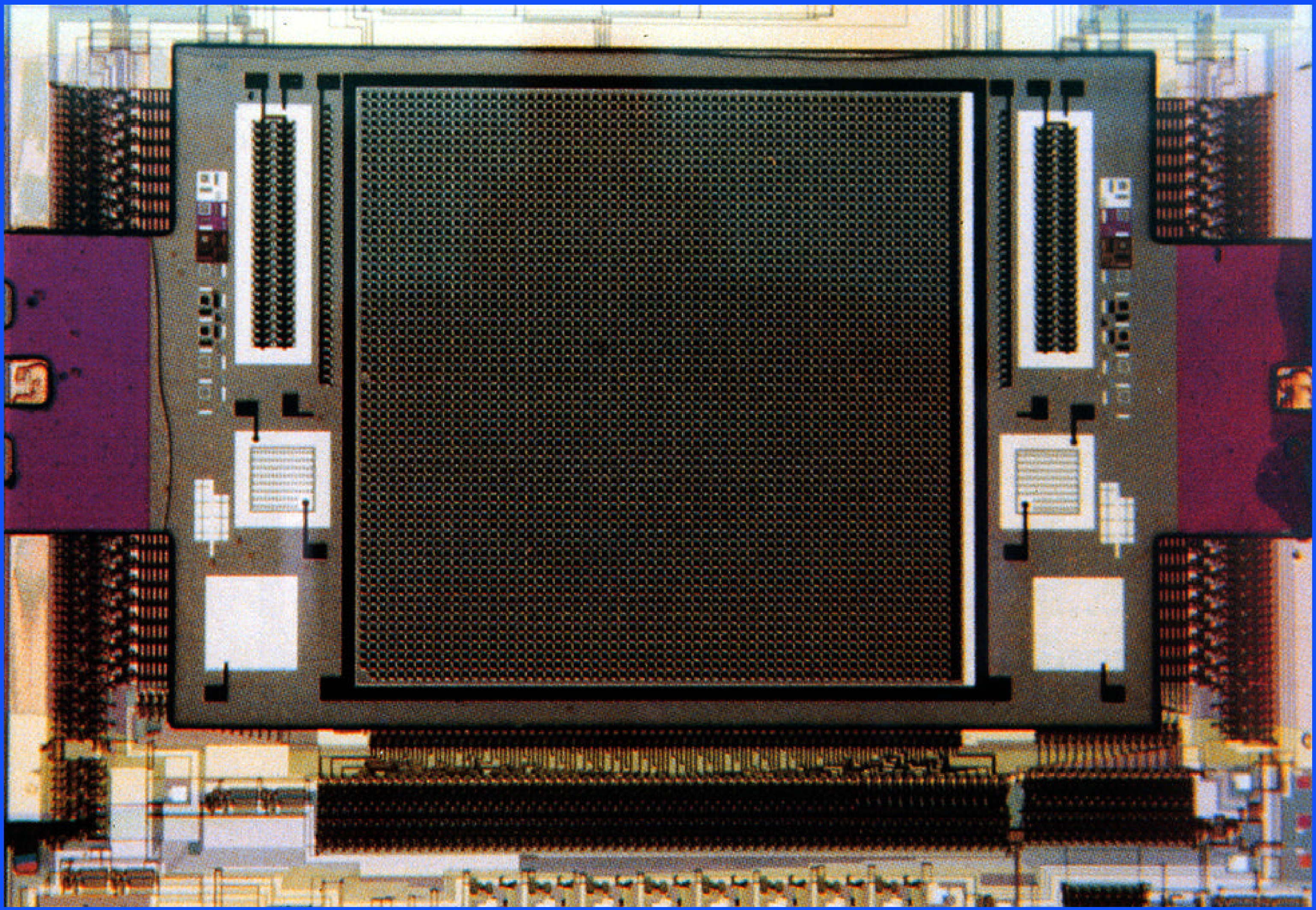
Courtesy of Kodak, Inc., Rochester, NY.





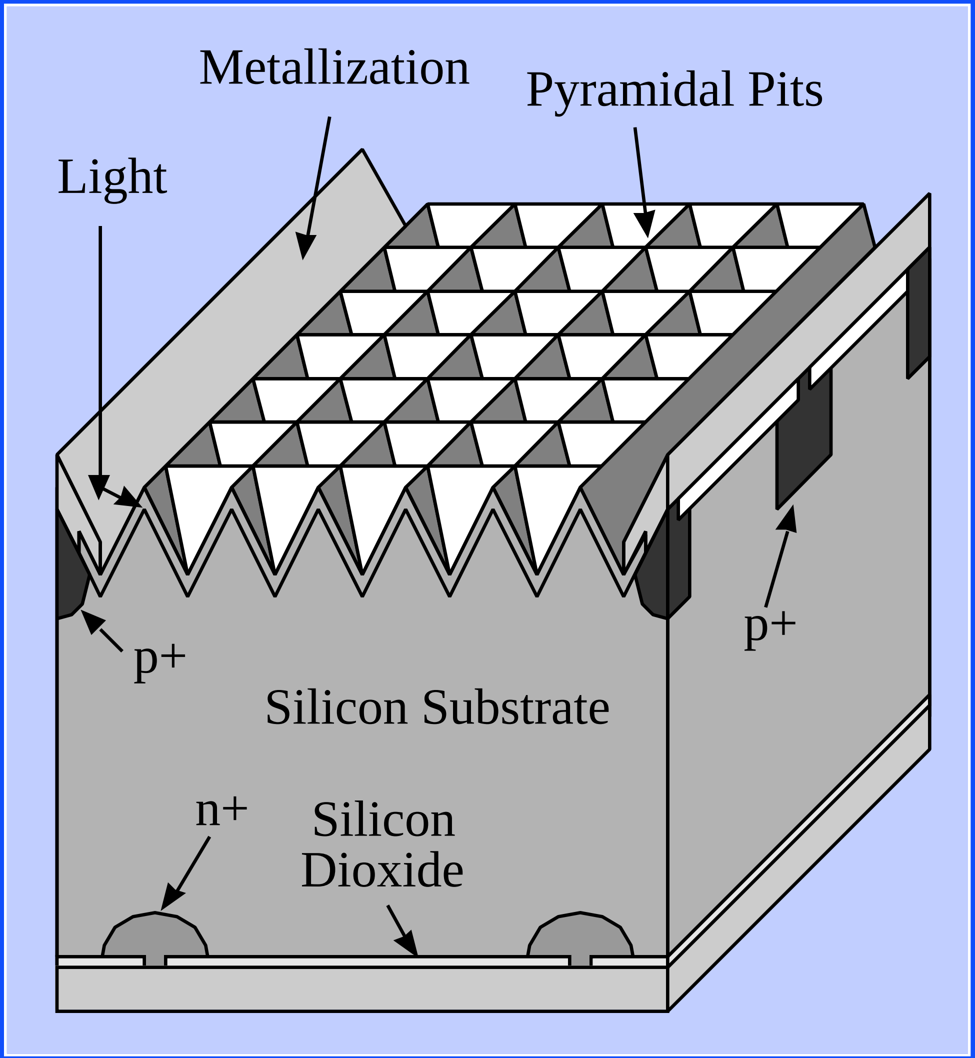
Courtesy of Kodak, Inc., Rochester, NY.

HgCdTe FOCAL PLANE HYBRID

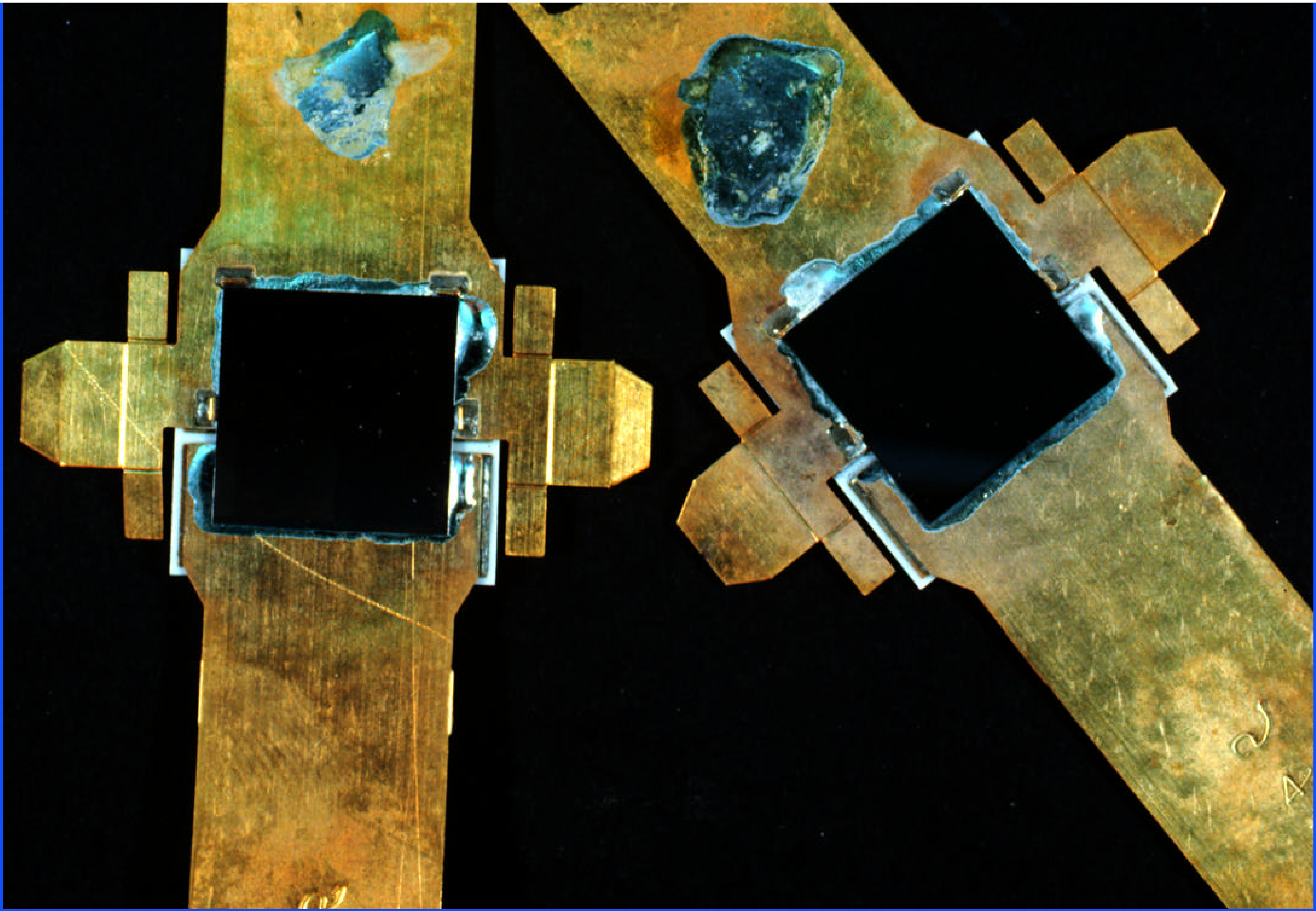


Courtesy of Texas Instruments, Inc., Dallas, TX.

MICROMACHINED SOLAR CELLS

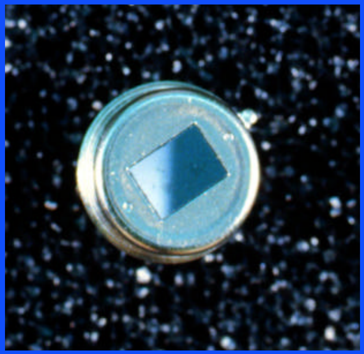


- Solar cells actually seldom pay back the energy required to make them (typically 8 - 10 years!).
- Micromachined versions can be made much more efficient than conventional designs by trapping more photons.
- Sunpower, Inc., manufactures such devices.

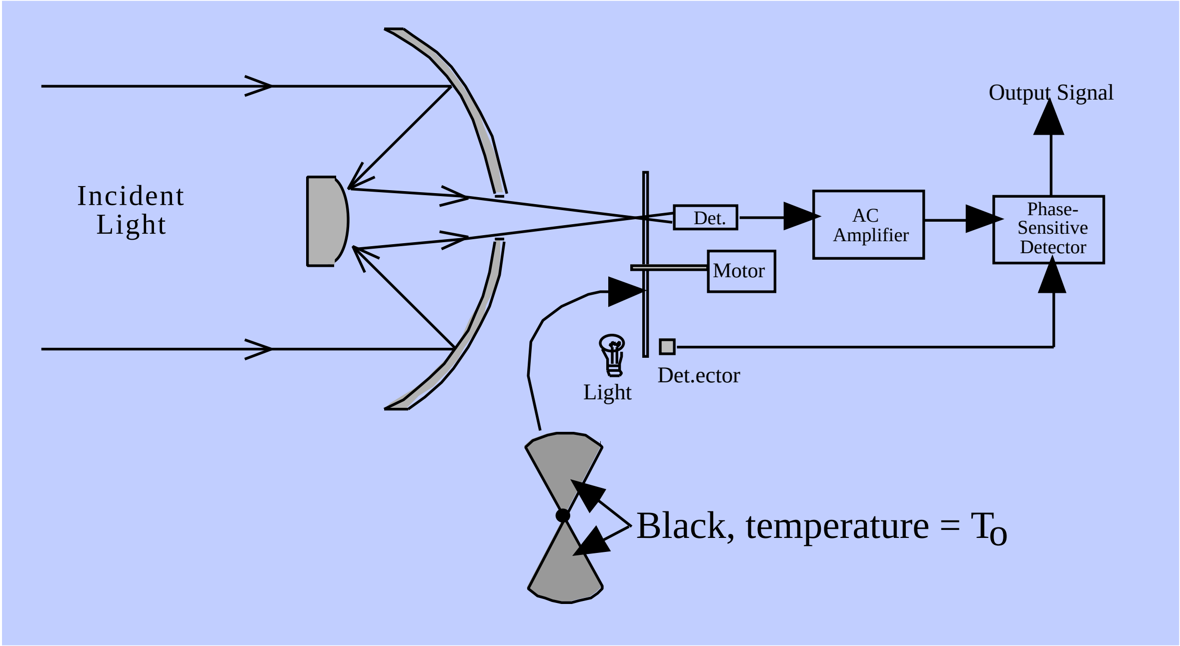


Courtesy Sunpower, Inc.

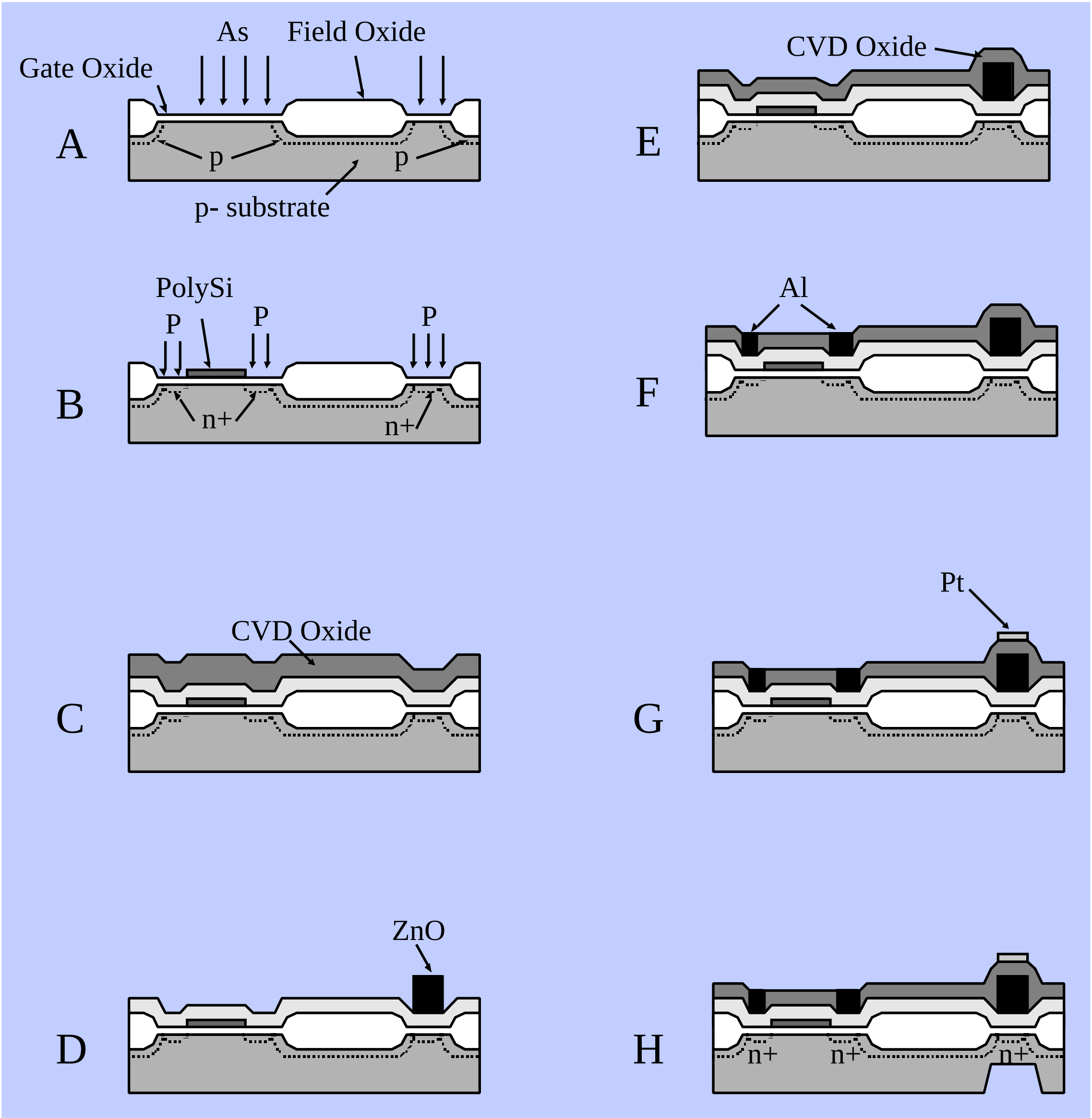
PYROELECTRIC DETECTORS



Example materials: barium titanate, triglycine sulfate, polyvinyl fluoride, lithium tantalate, zinc oxide, etc.



- These devices can be very sensitive to temperature, but have no DC response (light must be chopped... they behave like capacitors with charge generated by photons).
- Want high ratio of pyroelectric to dielectric constant for speed.
- They generally have quite flat responses.

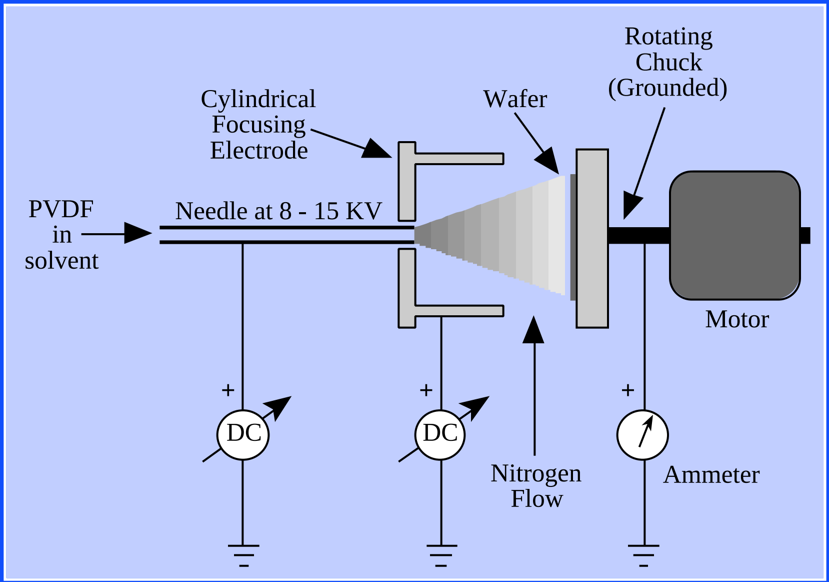


ZnO ON MOS (POLLA)

- Polla used RF-magnetron sputtered ZnO (<250°C) directly above NMOS.
- ZnO easily etched with acetic:phosphoric:water (1:1:30).
- These chips included IR sensors, anemometers, chemical reaction sensor (calorimeters), etc.

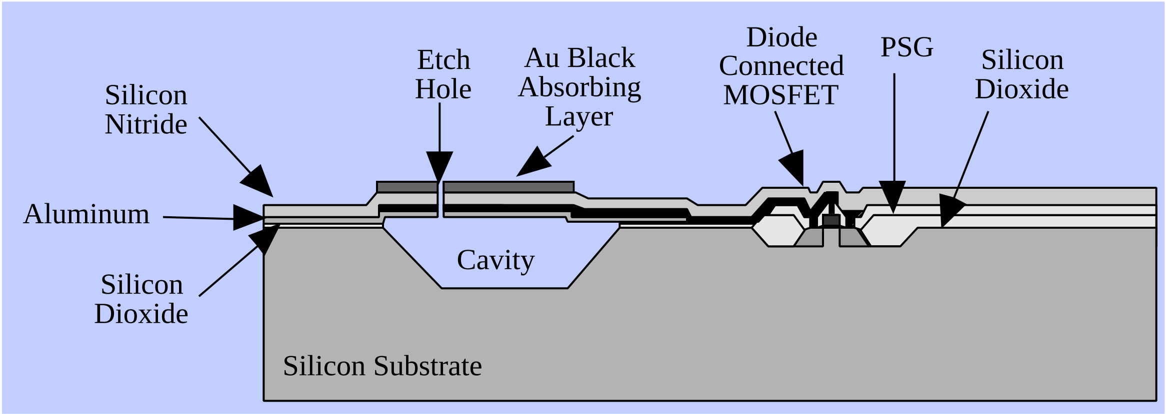
Reference: Polla, D. L., Muller, R. S., and White, R. M., “Integrated Multisensor Chip,” IEEE Electron Device Letters, vol. EDL-7, no. 4, Apr. 1986, pp. 254 - 256.

ELECTRICALLY POLED PVDF

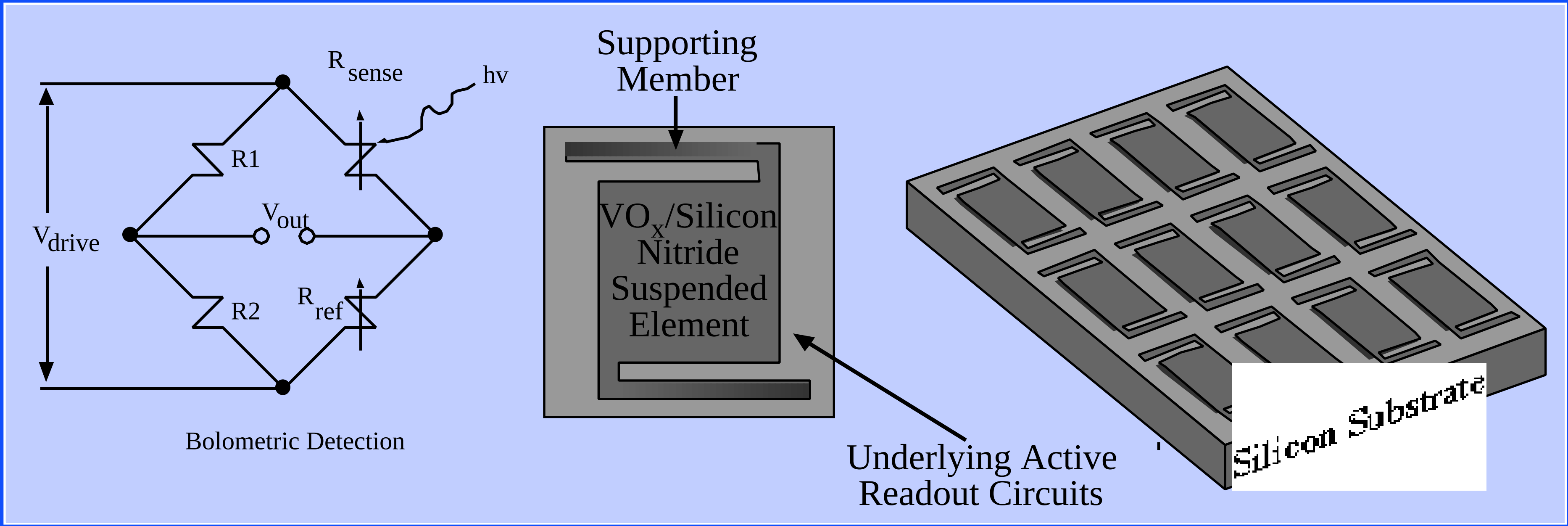


- **PVDF requires poling in an electric field to orient dipoles in the film.**
- **Asahi, et al., demonstrated an electro-spray method wherein the PVDF was poled as it was deposited.**
- **The process is MOS compatible and the PVDF can be O_2 etched.**

Reference: Asahi, R., Sakata, J., Tabata, O., Mochizuki, M., Sugiyama, S., and Taga, Y., "Integrated Pyroelectric Infrared Sensor Using PVDF Thin-Film Deposited by Electro-Spray Method," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 656 - 659.

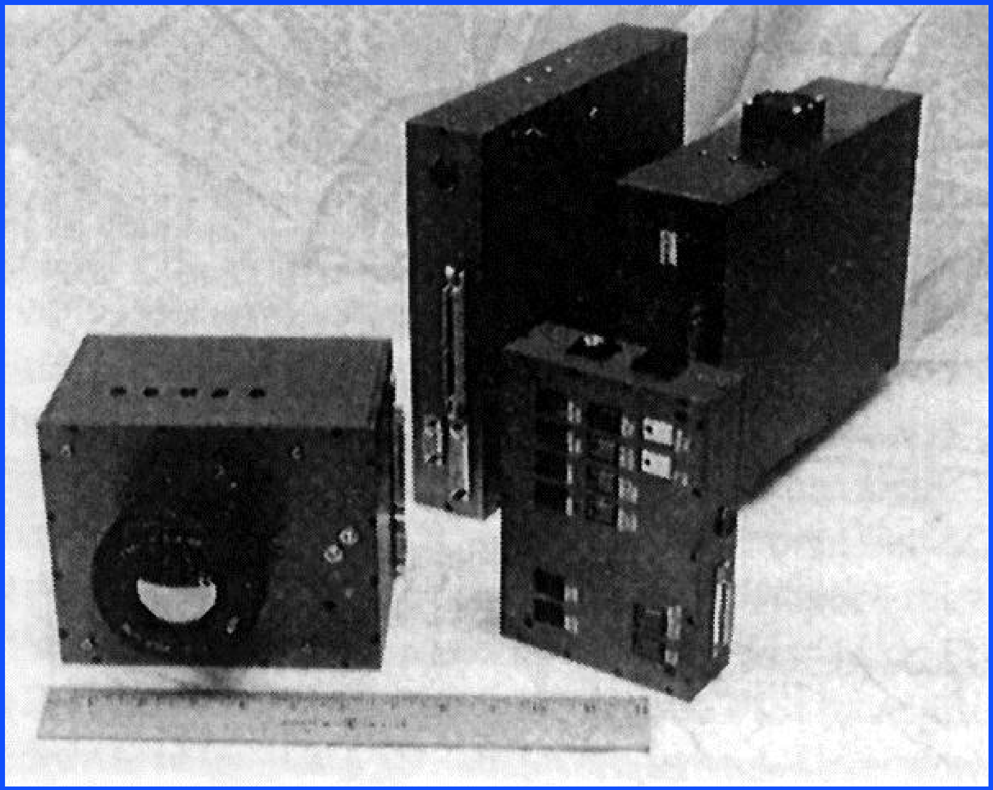


BOLOMETERS



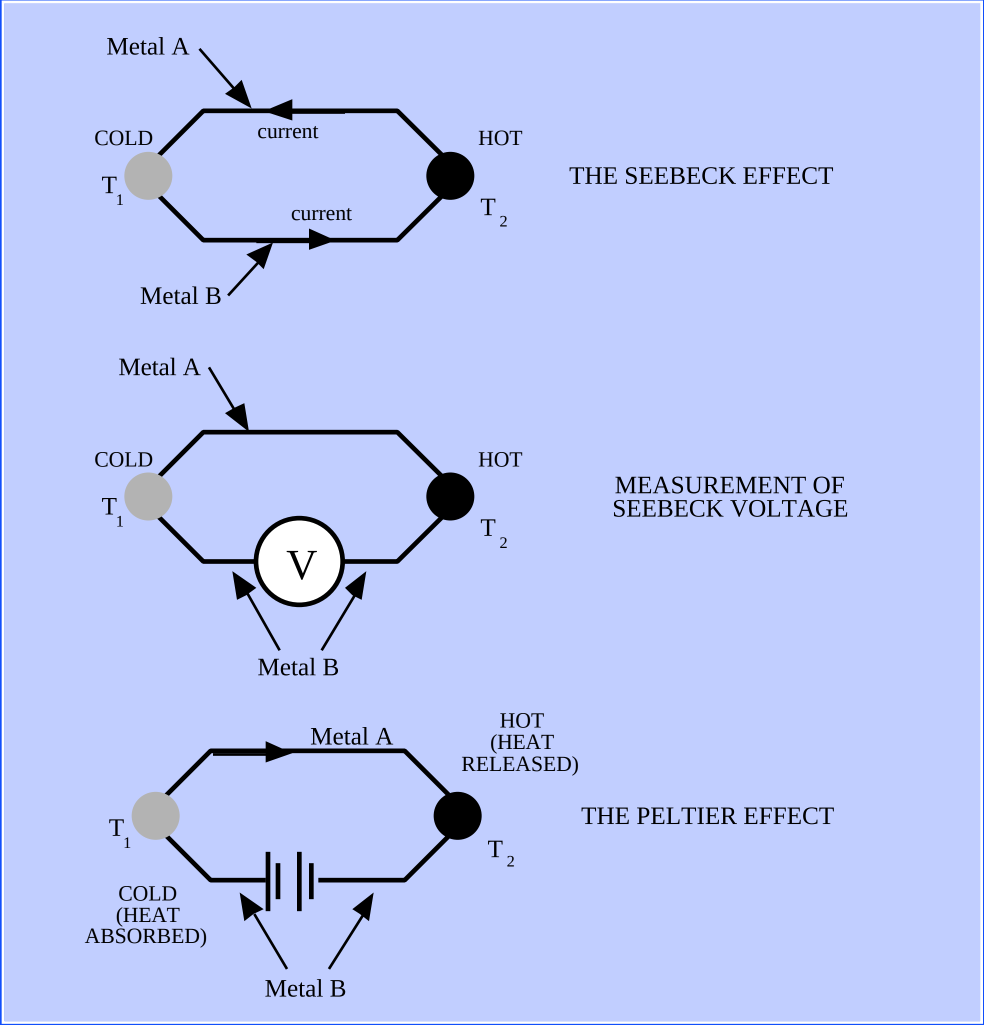
- Thermally sensitive resistors are used as temperature (and hence light) sensors.
- Like pyroelectrics, they have a flat response.
- Bolometers have a DC response (no need for chopper).
- Micromachined examples include Honeywell IR imagers (vanadium oxide thin-film sensors).

HONEYWELL MICROMACHINED UNCOOLED IR IMAGER

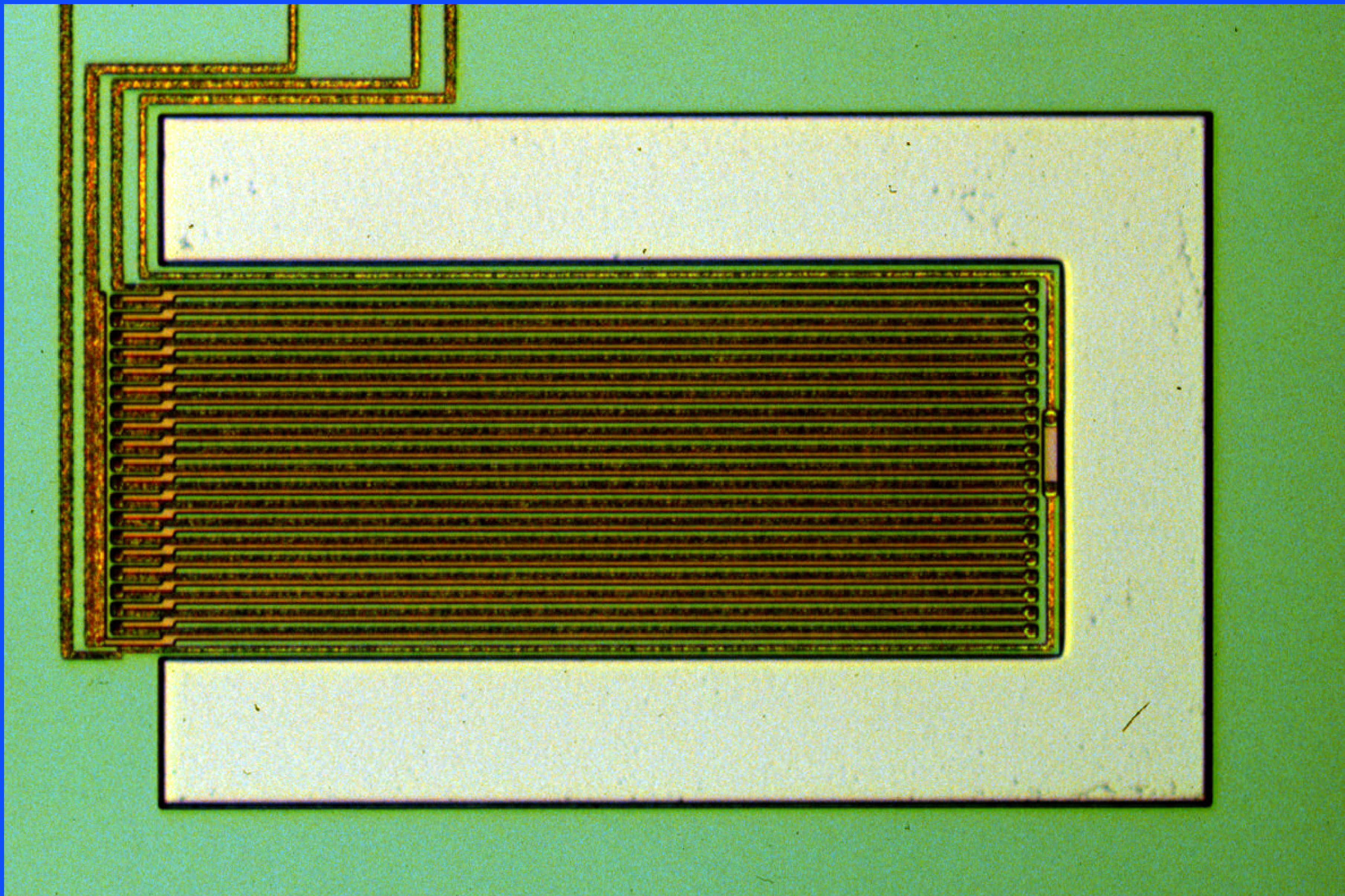


Source: Wood, R. A., Han, C. J., and Kruse, P. W., "Integrated Uncooled Infrared Detector Imaging Arrays," Proceedings of the 1992 Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 22 - 25, 1992, pp. 132 - 135.

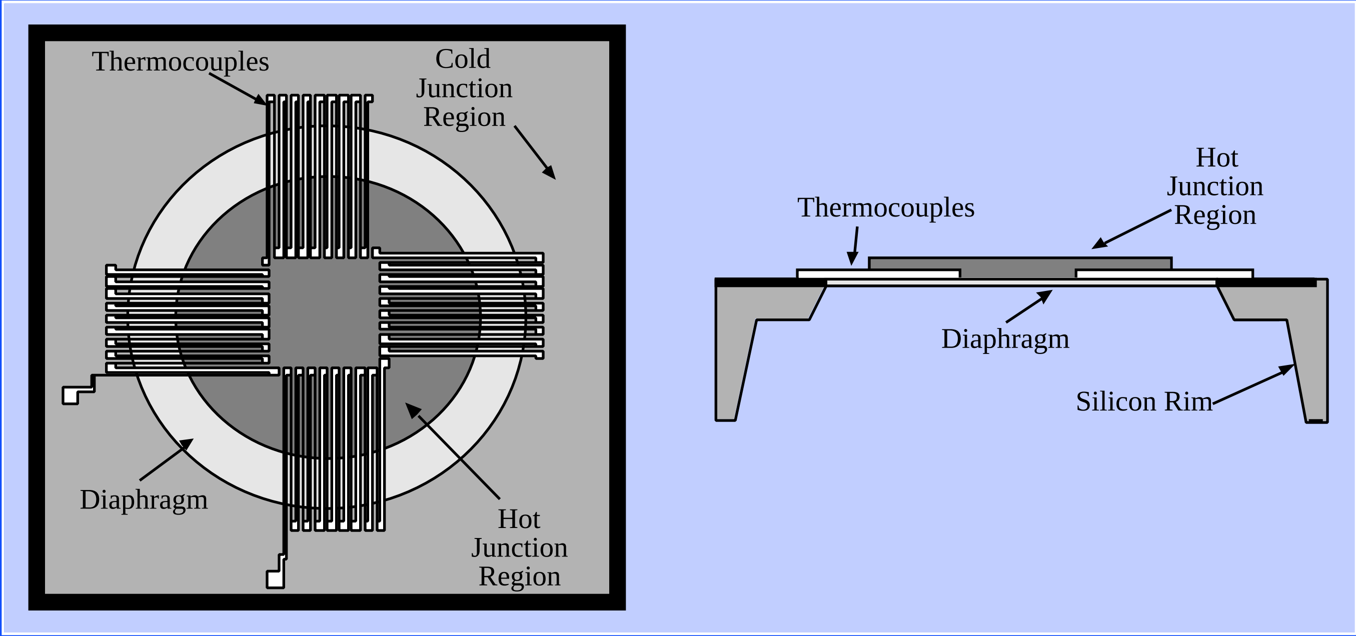
THERMOPILES



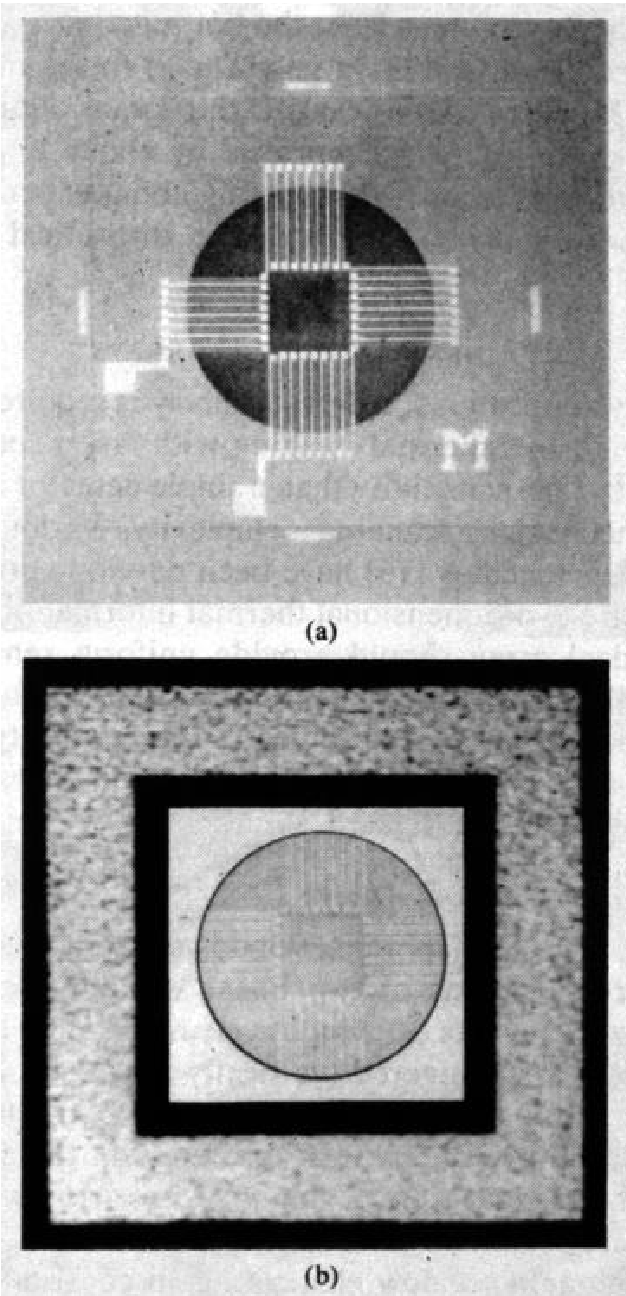
- **Thermopiles directly generate electrical signals through the Seebeck effect.**
- **They have flat wavelength sensitivities and DC responses.**
- **They can readily be fabricated as junctions between thin-films with different thermoelectric powers, such as aluminum and polysilicon (already available in CMOS processes).**

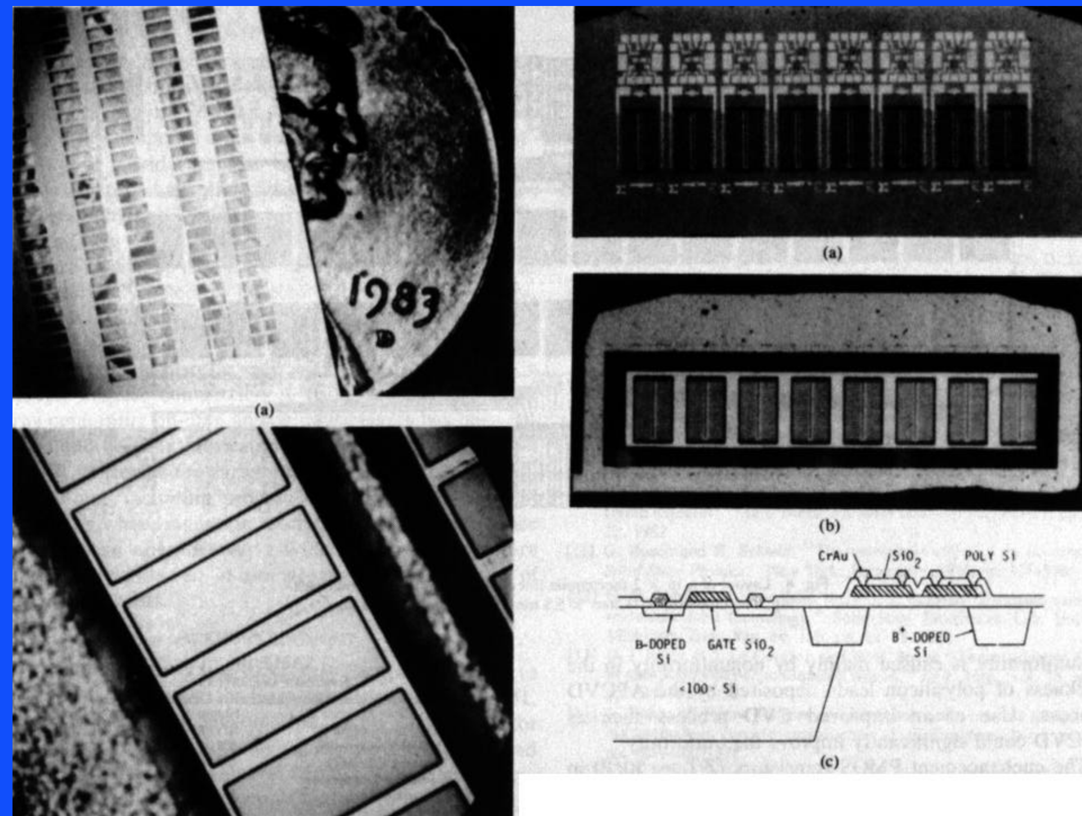


MICROMACHINED THERMOPILES



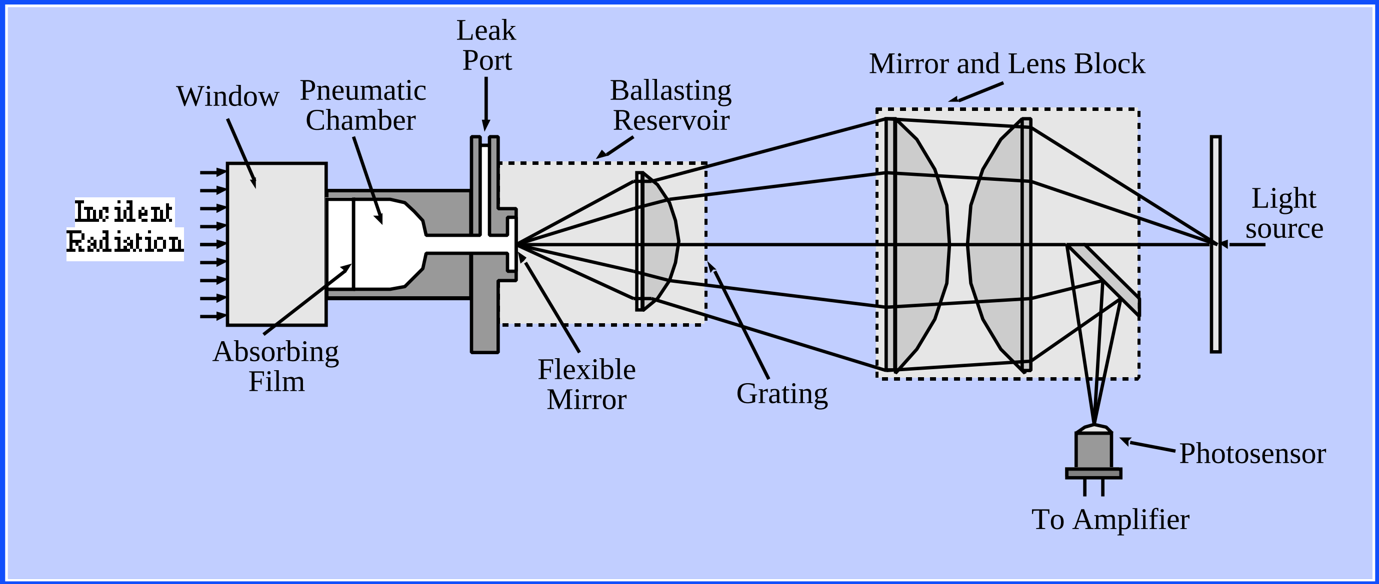
- **Choi and Wise made micromachined arrays of thermopiles on an oxide/nitride membrane.**
- **Absorptivity at hot junctions maximized using bismuth black.**
- **Thermal conductivity of thin films and diaphragm should be minimized.**
- **Many thermocouples in series = thermopile, but as numbers increase, so does noise.**





Source: Choi, I. H., and Wise, K. D., “A Silicon-Thermopile-Based Infrared Sensing Array for Use in Automated Manufacturing,” IEEE Transactions on Electron Devices, vol. ED-33, no. 1, Jan. 1986, pp. 72 - 79.

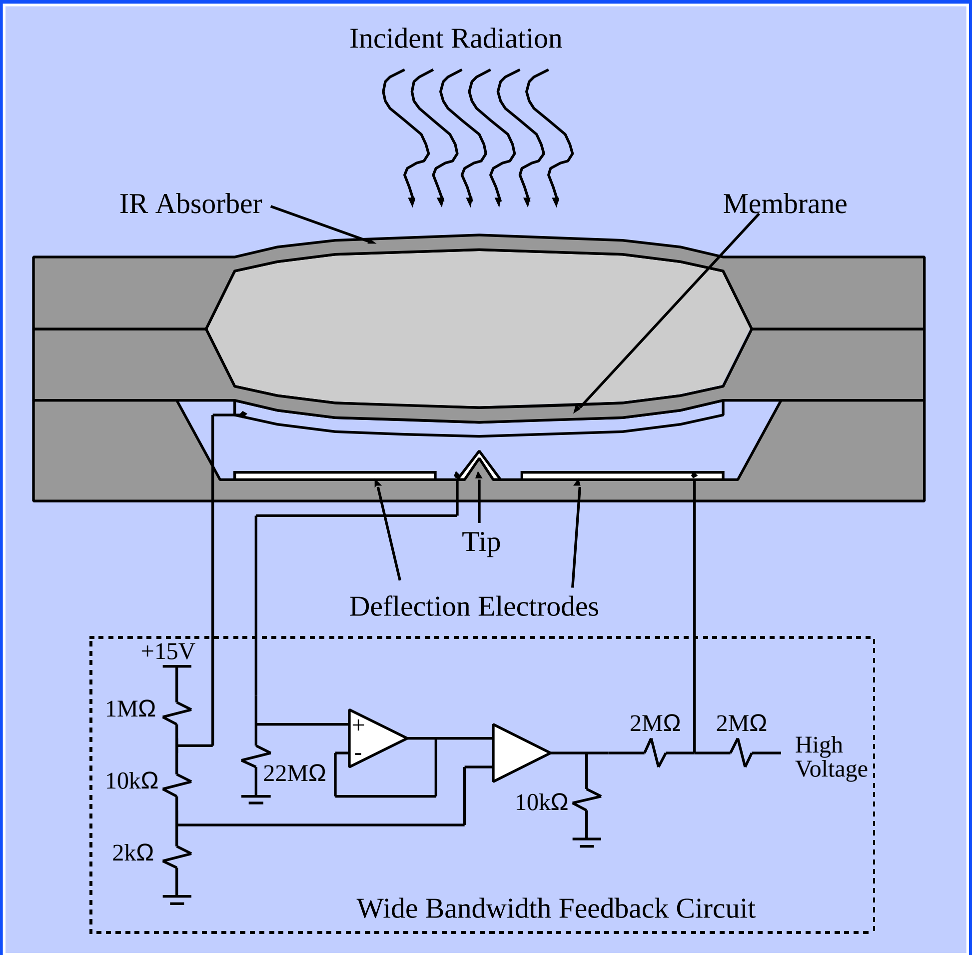
GOLAY CELLS

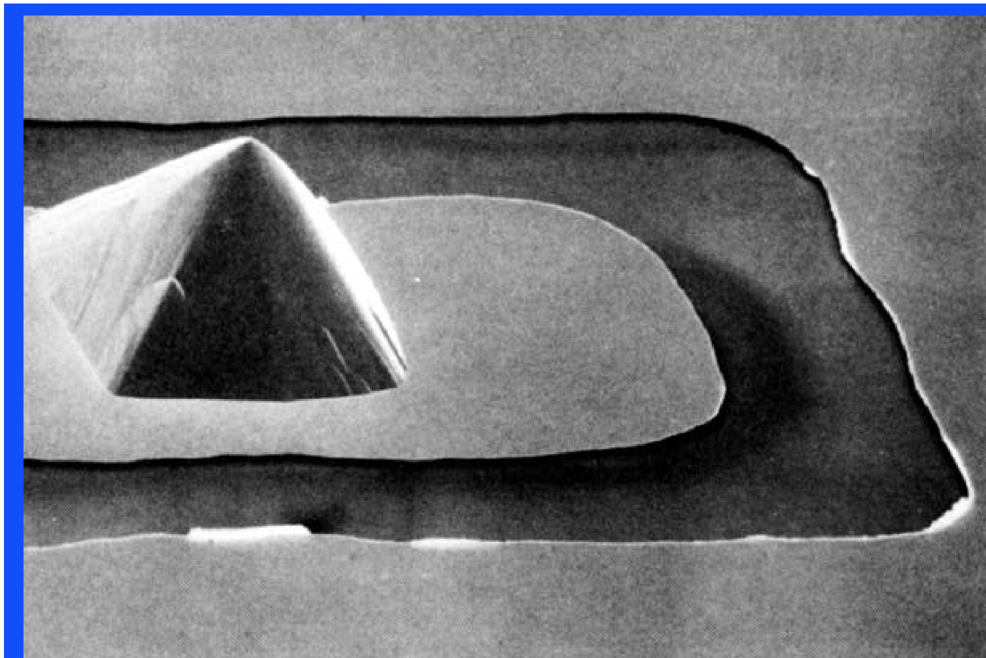


- **Golay cells have flat wavelength responses and high sensitivity.**
- **Despite potential DC responses, they are typically used with choppers to minimize ambient temperature effects.**
- **Impinging light is converted to heat that expands gas trapped beneath a membrane.**
- **Optical or other methods are used to detect deflection of the membrane.**

TUNNELING GOLAY CELL

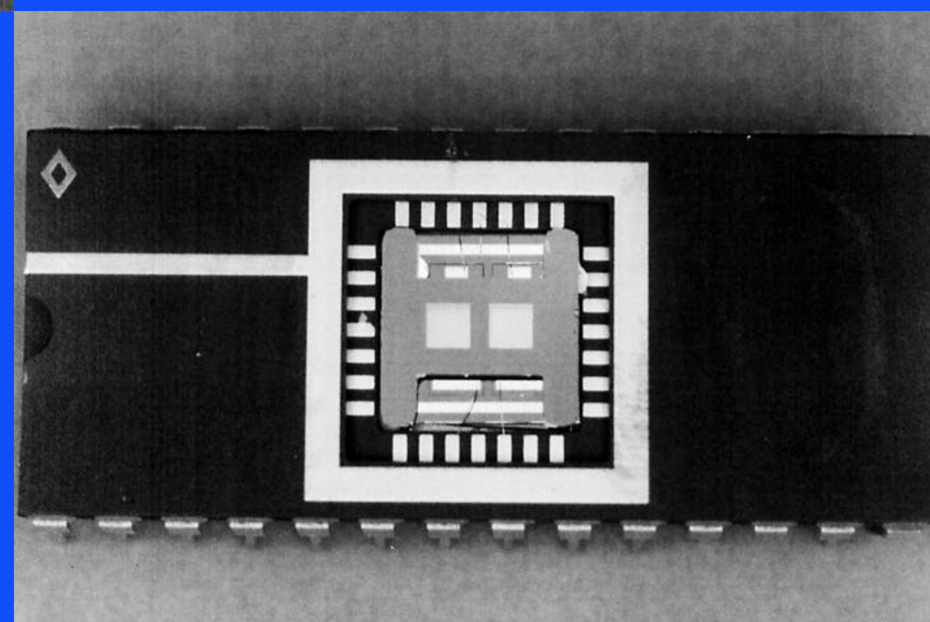
- **Robust tunneling tip with electrostatic feedback.**
- **Gas expansion force measured.**
- **Fabricated as adhesive bonded three-wafer stack, bulk micromachined.**
- **Vented pneumatic chamber blocks DC response and pressure sensitivity.**

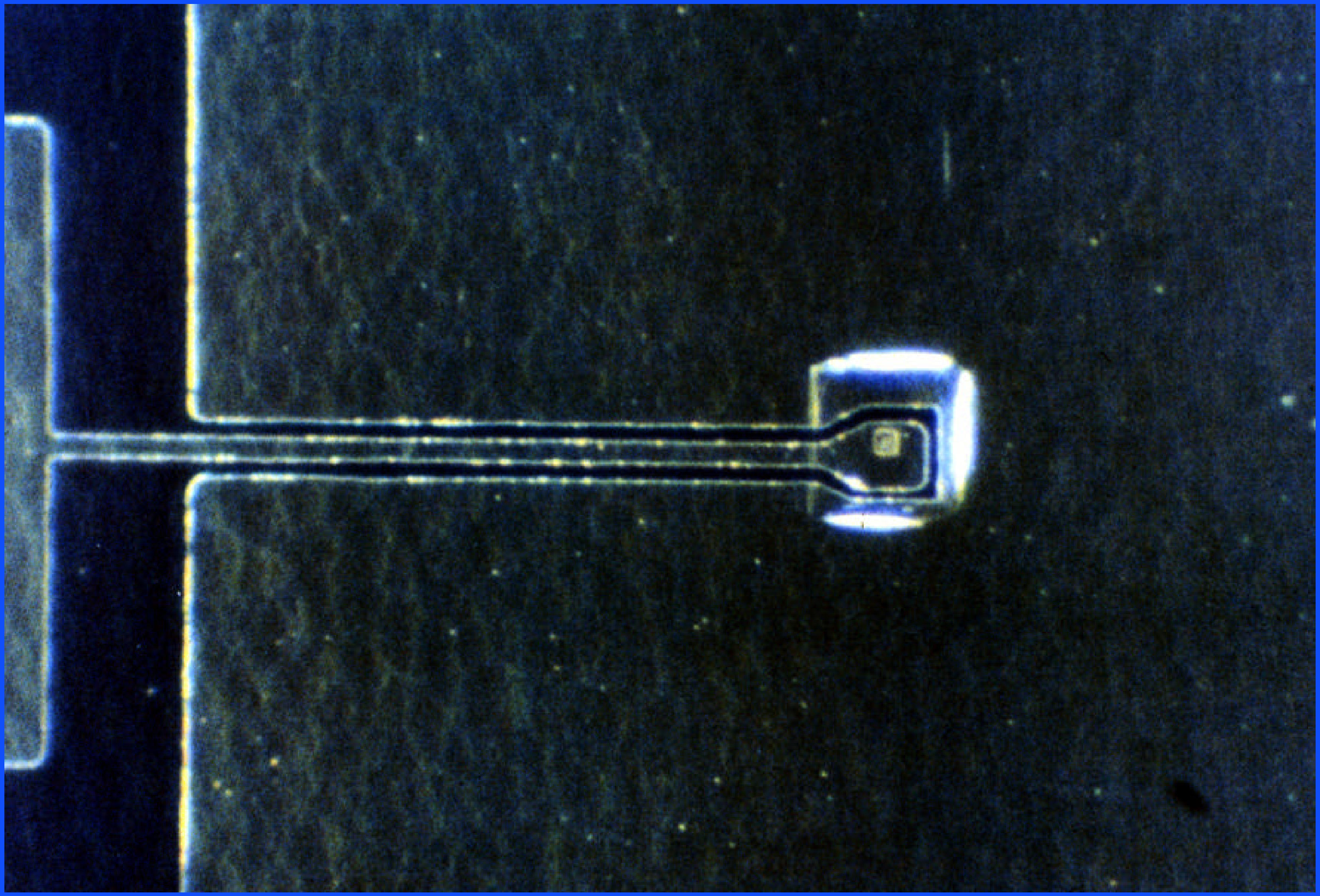




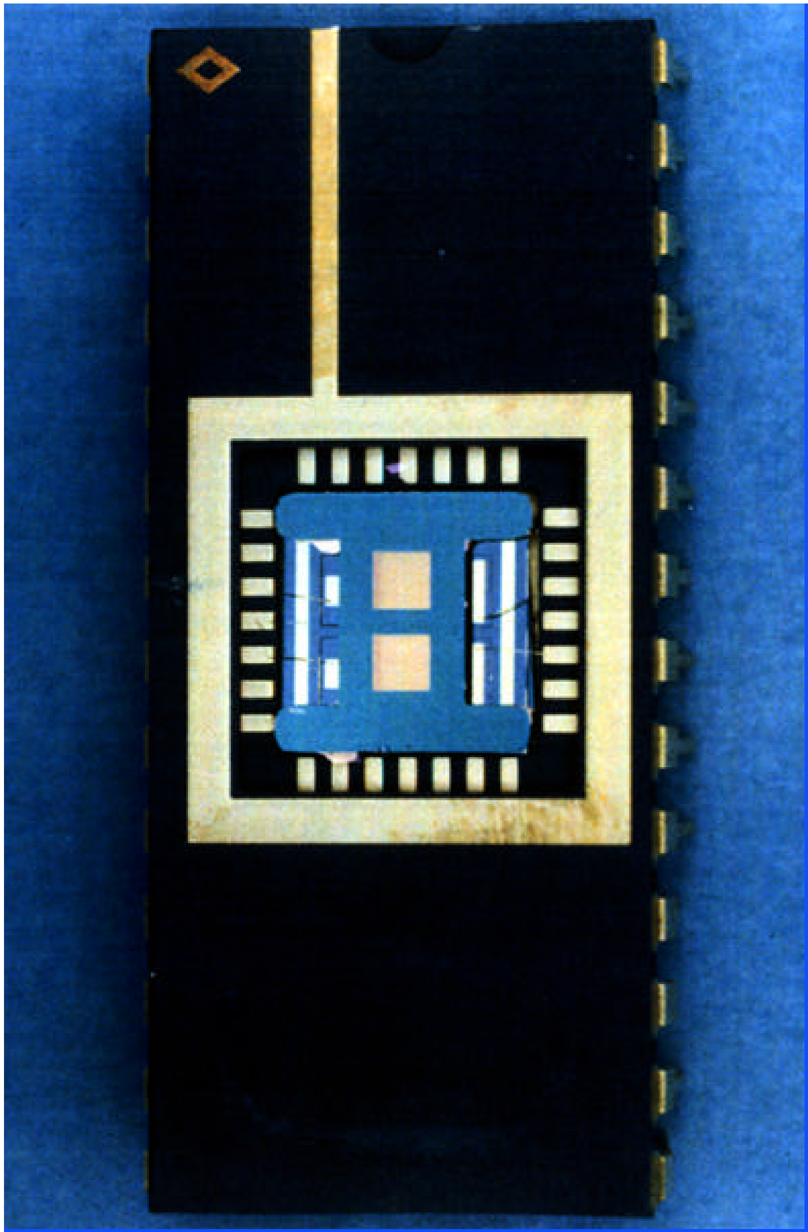
Courtesy Prof. T. Kenny, Stanford University.

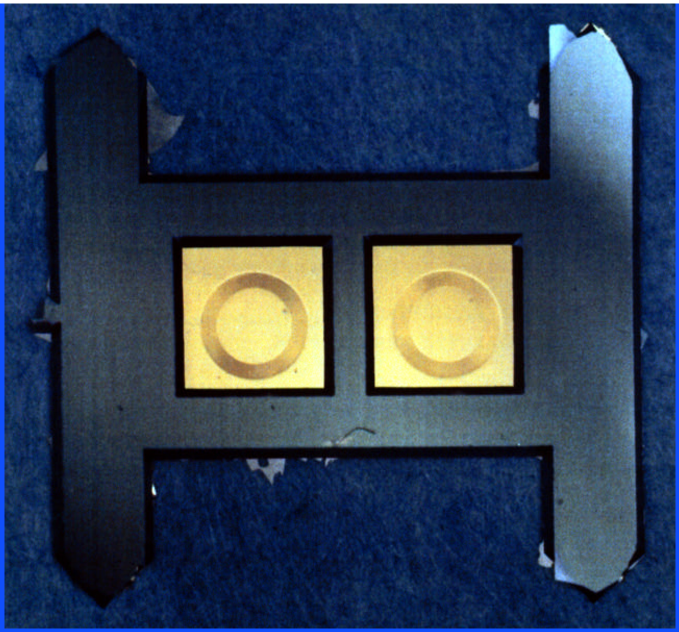
Reference: Kenny, T. W., Kaiser, W. J., Waltman, S. B., and Reynolds, J. K., "Novel Infrared Detector Based on a Tunneling Displacement Transducer," Applied Physics Letters, vol. 59, no. 19, Oct. 7, 1991, pp. 1820-1822.

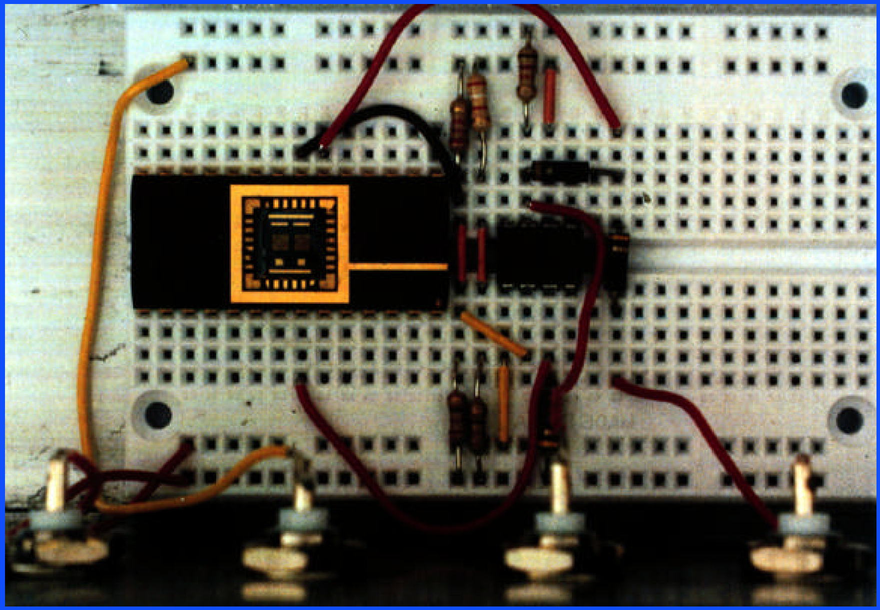




Courtesy Prof. T. Kenny, Stanford University.



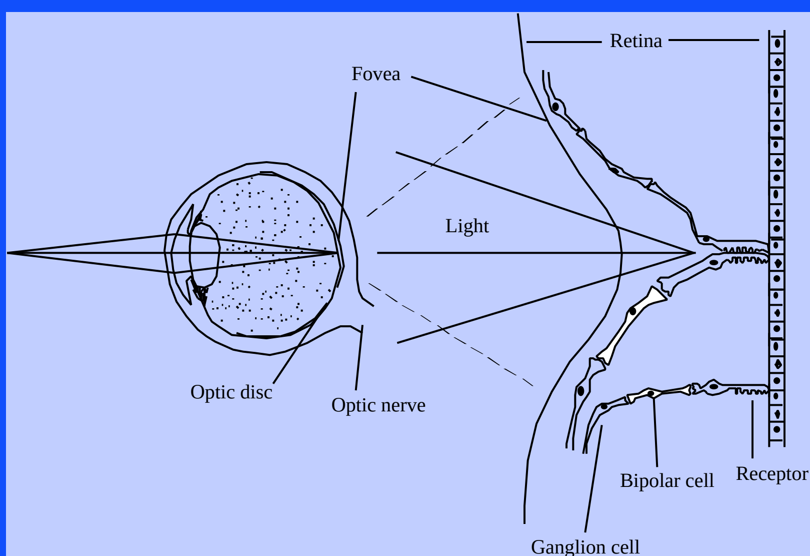


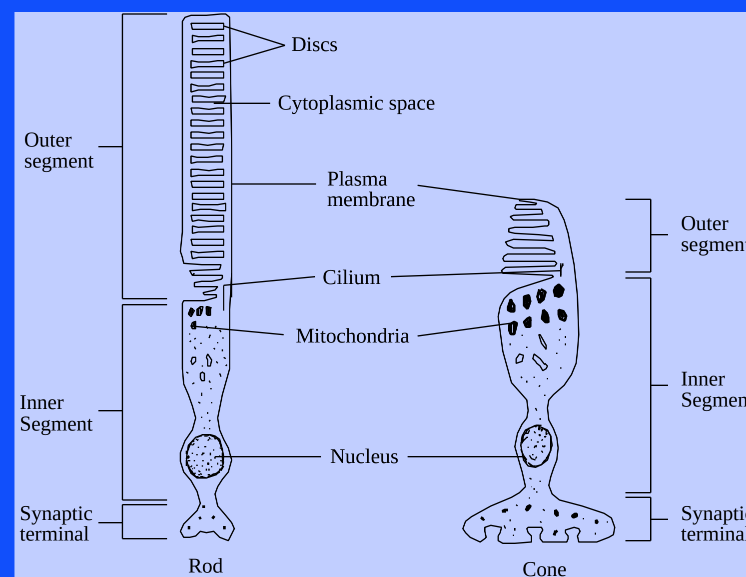


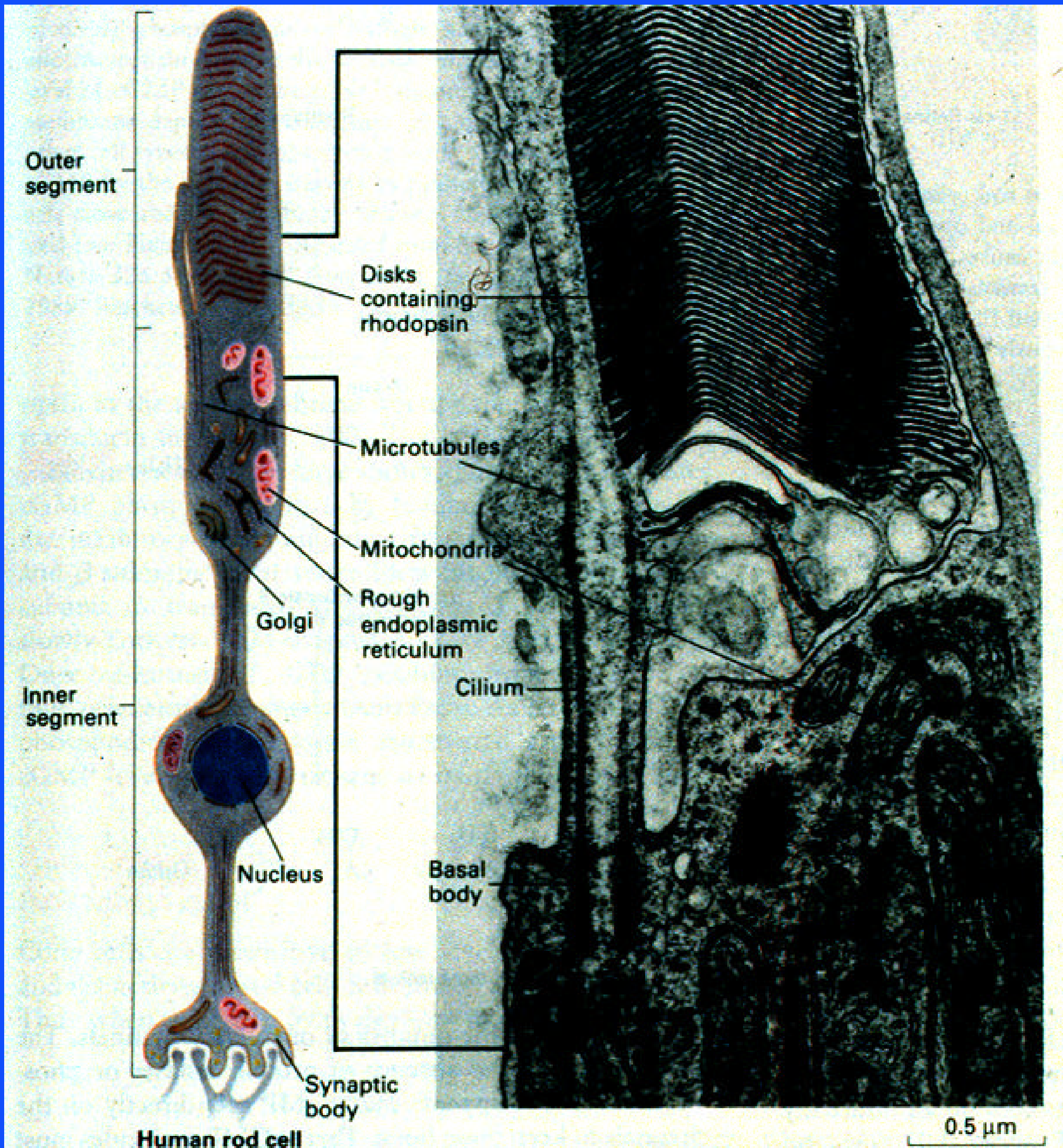
Courtesy Prof. T. Kenny, Stanford University.

BIOLOGICAL PHOTOSENSORS

Rods	Cones
More photopigment	Less photopigment
Slow response: long integration time (can detect flickering light up to 12 Hz)	Fast response: short integration time (can detect flickering light up to 55 Hz)
High amplification: single quantum detection	Probably less amplification
Saturating response	Nonsaturating response
Not directionally sensitive	Directionally sensitive
Highly convergent retinal pathways	Less convergent retinal pathways
High sensitivity	Low sensitivity
Low acuity	High acuity
Achromatic: one type of pigment	Polychromatic: three types of pigment

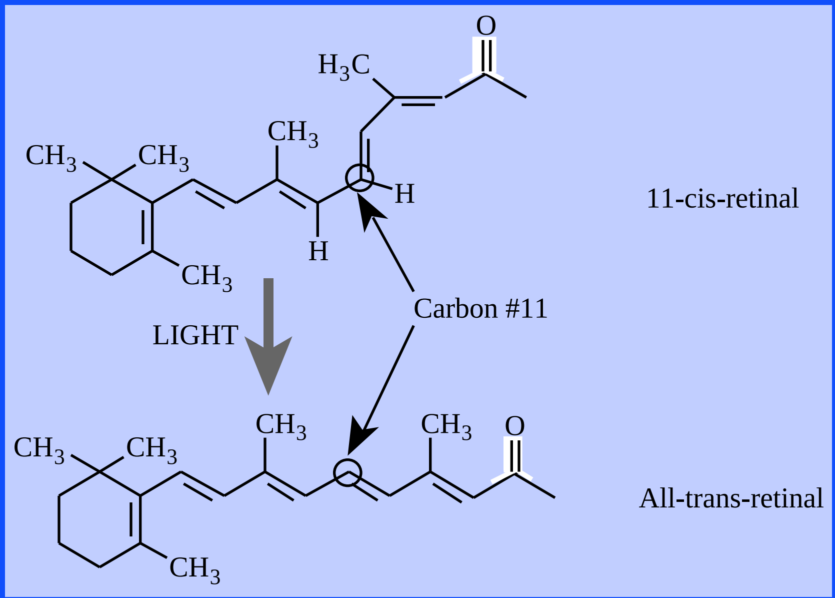


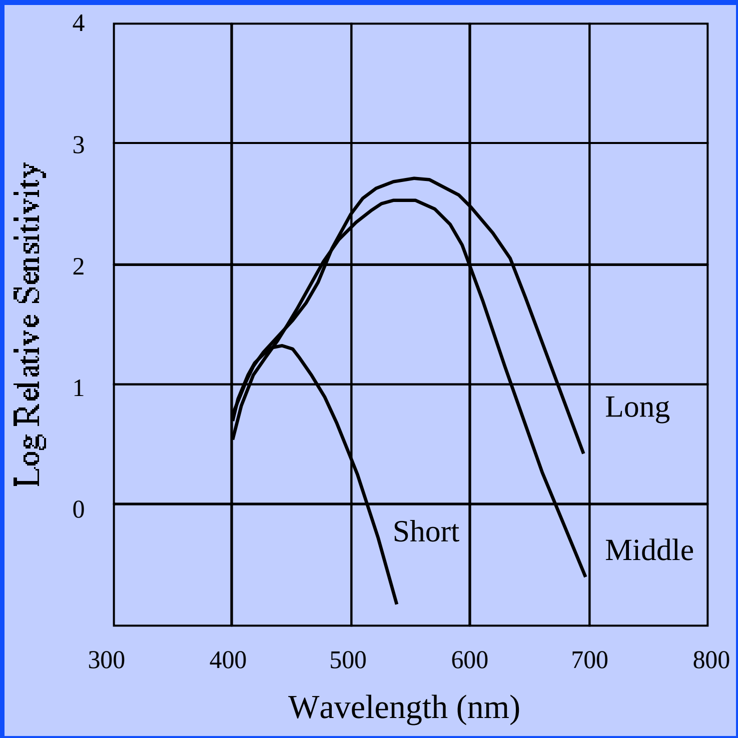




Source: Darnell, J., Lodish, H., and Baltimore, D., "Molecular Cell Biology," Second Edition, Scientific American Books, W. H. Freeman and Co., New York, NY, 1991.

CHEMISTRY OF VISION



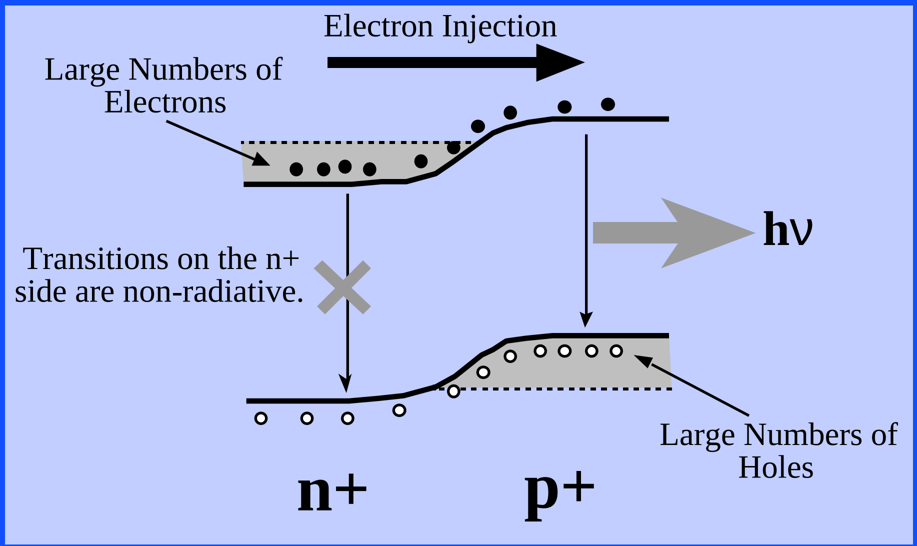


- **Photons change cis- to trans-retinal, and a second messenger mechanism (cyclic GMP) keeps sodium channels open in membranes -> a GAIN stage!**
- **Three types of cones provide color vision.**

LIGHT EMITTERS

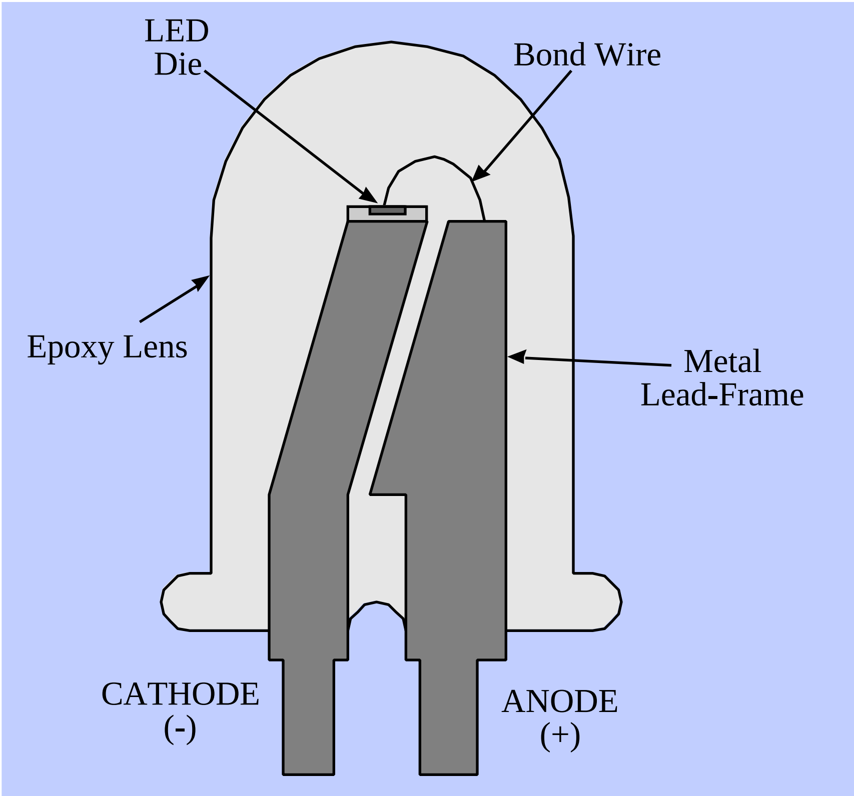
- Light emitting diodes (LEDs)
- Diode lasers
- Organic LEDs
- Incandescent devices
- Plasma sources
- Electroluminescent sources
- Field emitters
- Bioluminescence
- Other...

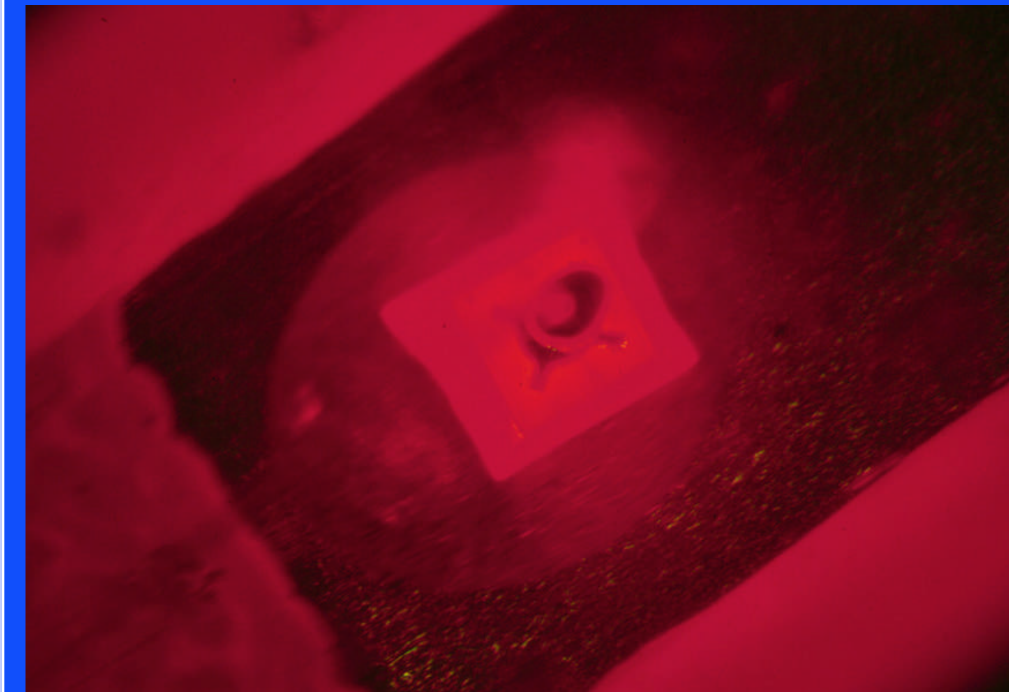
LIGHT EMITTING DIODES

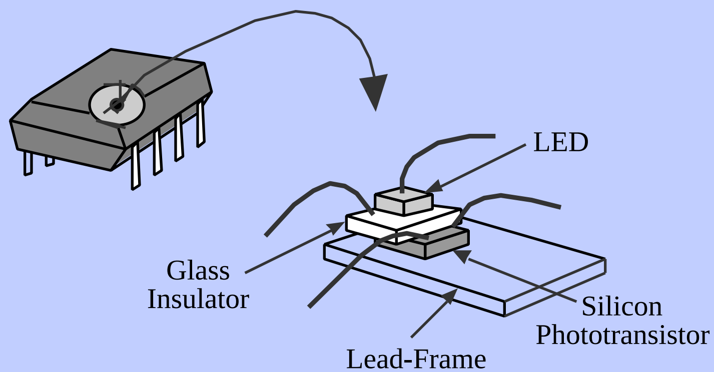


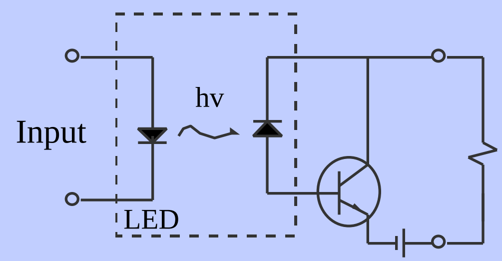
- When a forward bias is applied to an LED, electrons acquire enough energy to cross from the n+ through the depletion region to recombine in the p+ region (similar for holes leaving the valence band).
- Photons are emitted with no phase relationship to each other (incoherent).
- Very bright LEDs are now commonplace (>3 cd).
- Direct bandgap, large quantum efficiency (>80%).

Typical materials: GaP, GaAs, GaAsP, SiC, etc.

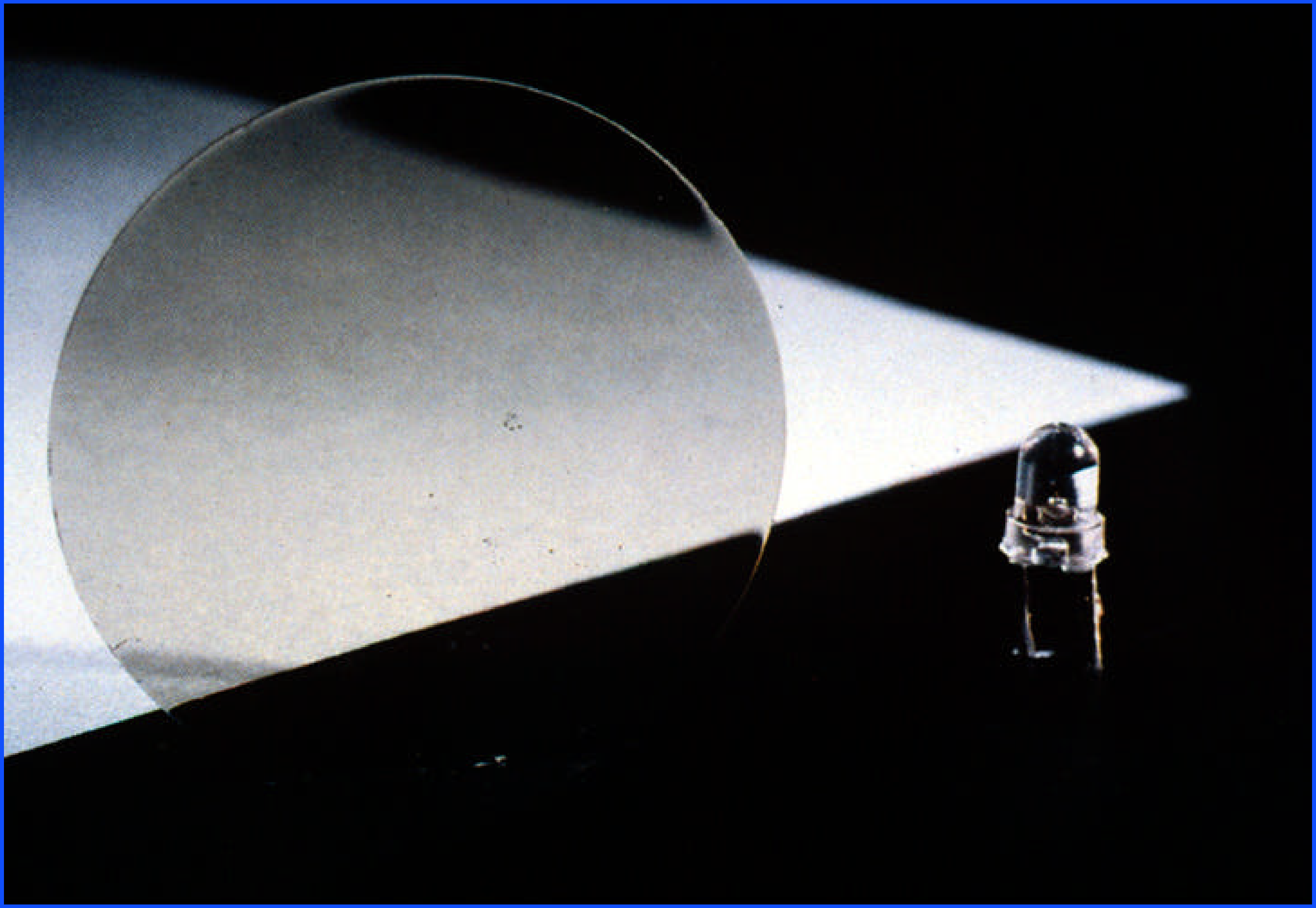

LED
Die
Bond Wire
Epoxy Lens
Metal
Lead-Frame
CATHODE
(-)
ANODE
(+)




LED
Glass
Insulator
Silicon
Phototransistor
Lead-Frame

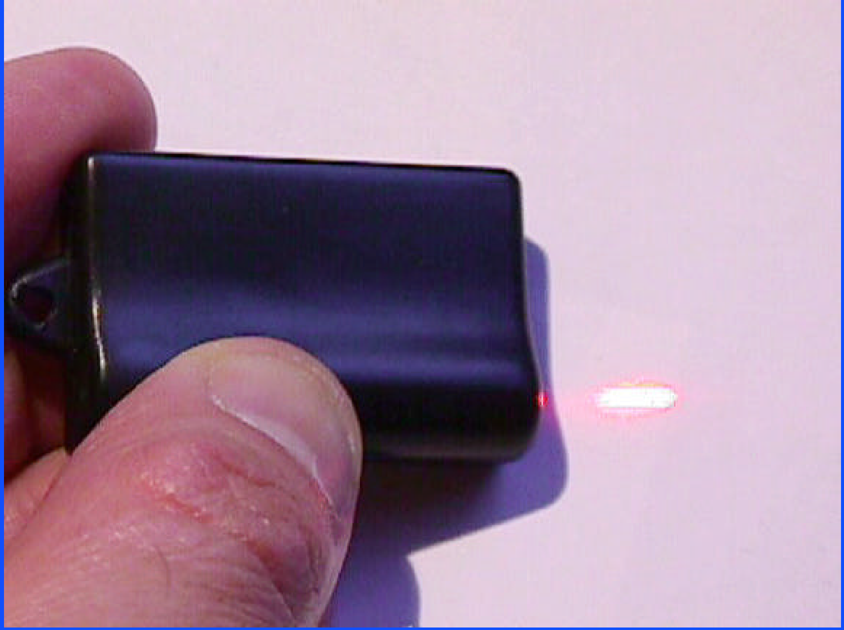

Input
hv
LED

SILICON CARBIDE

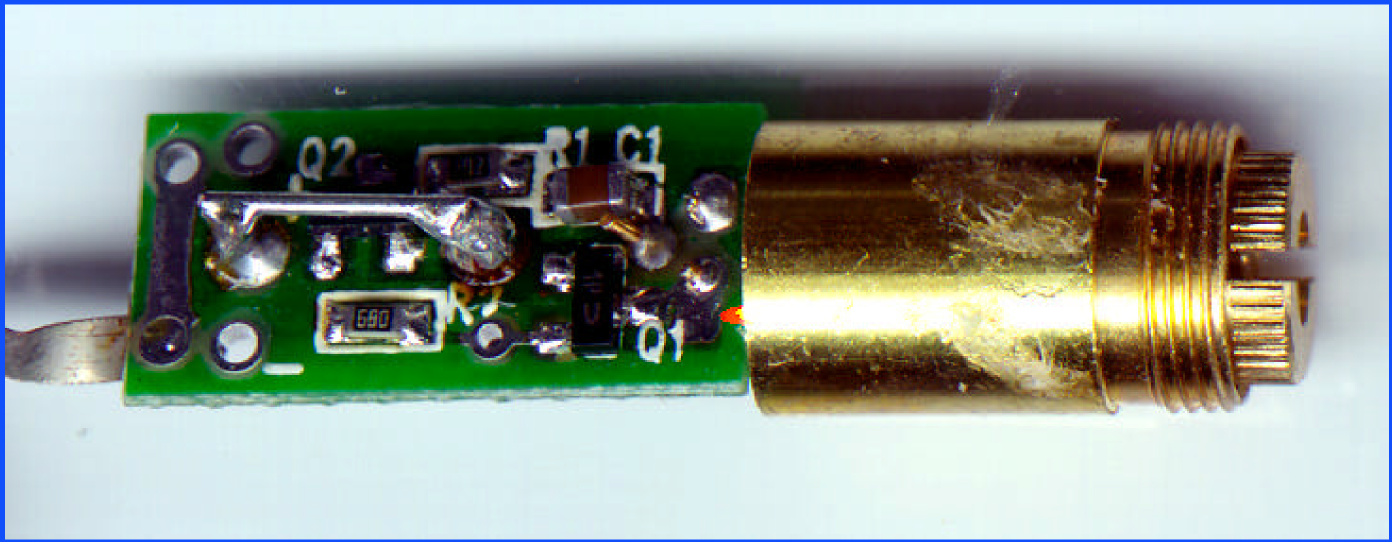


Courtesy Cree, Inc.

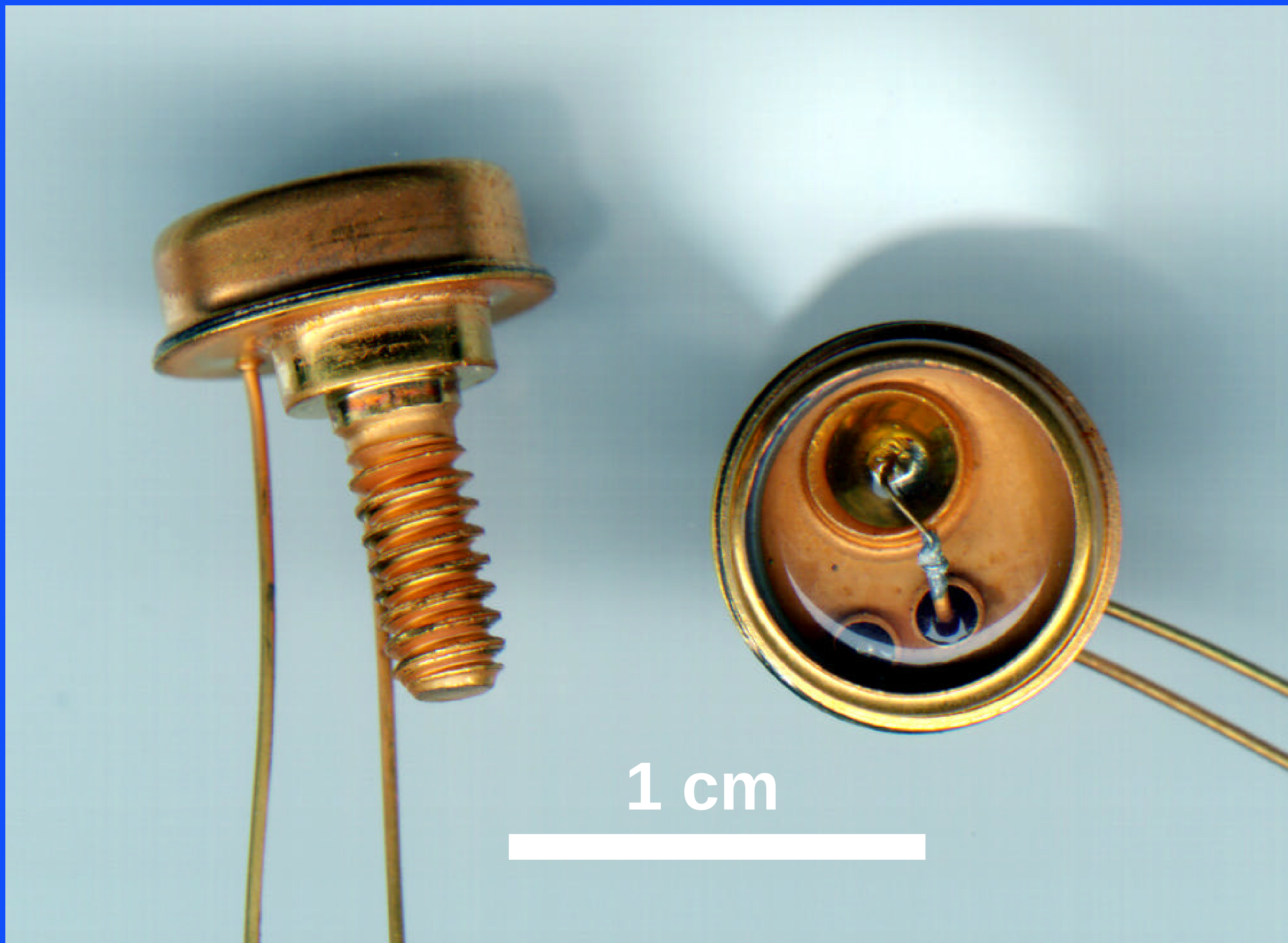
1992

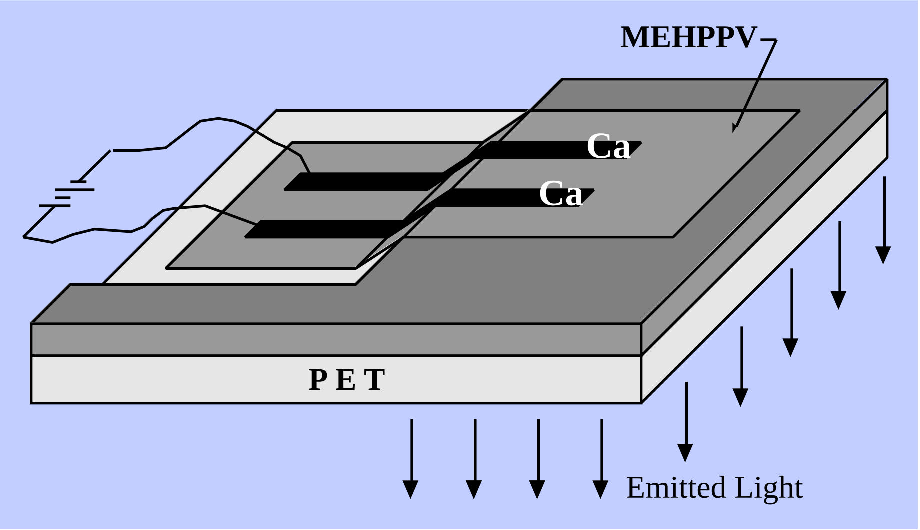


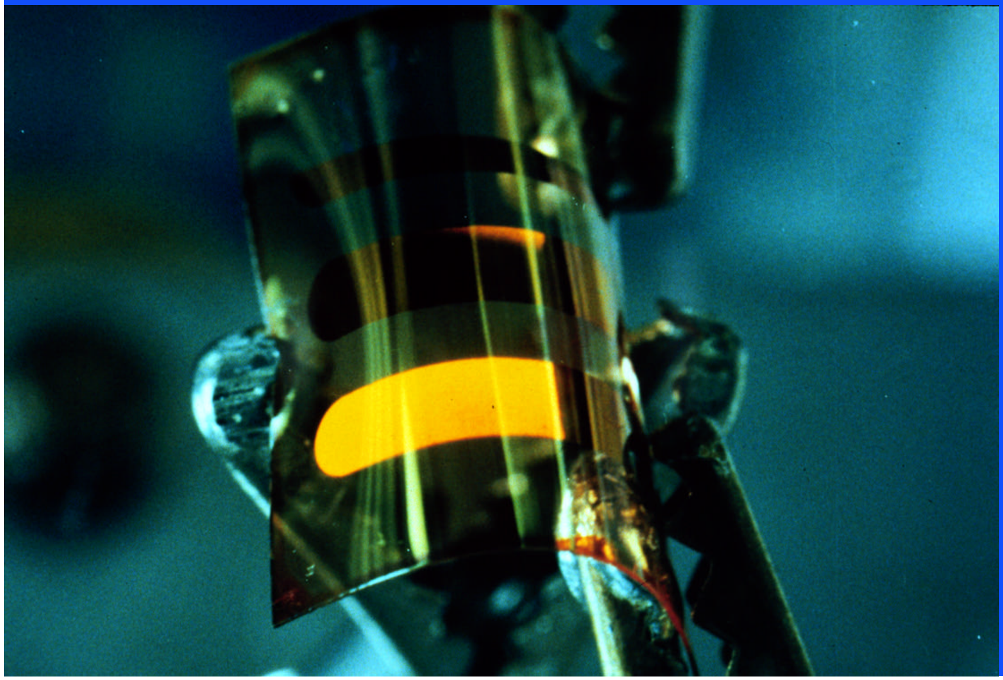
LOW-COST SOLID-STATE LASERS



HIGH-POWER LASER DIODES







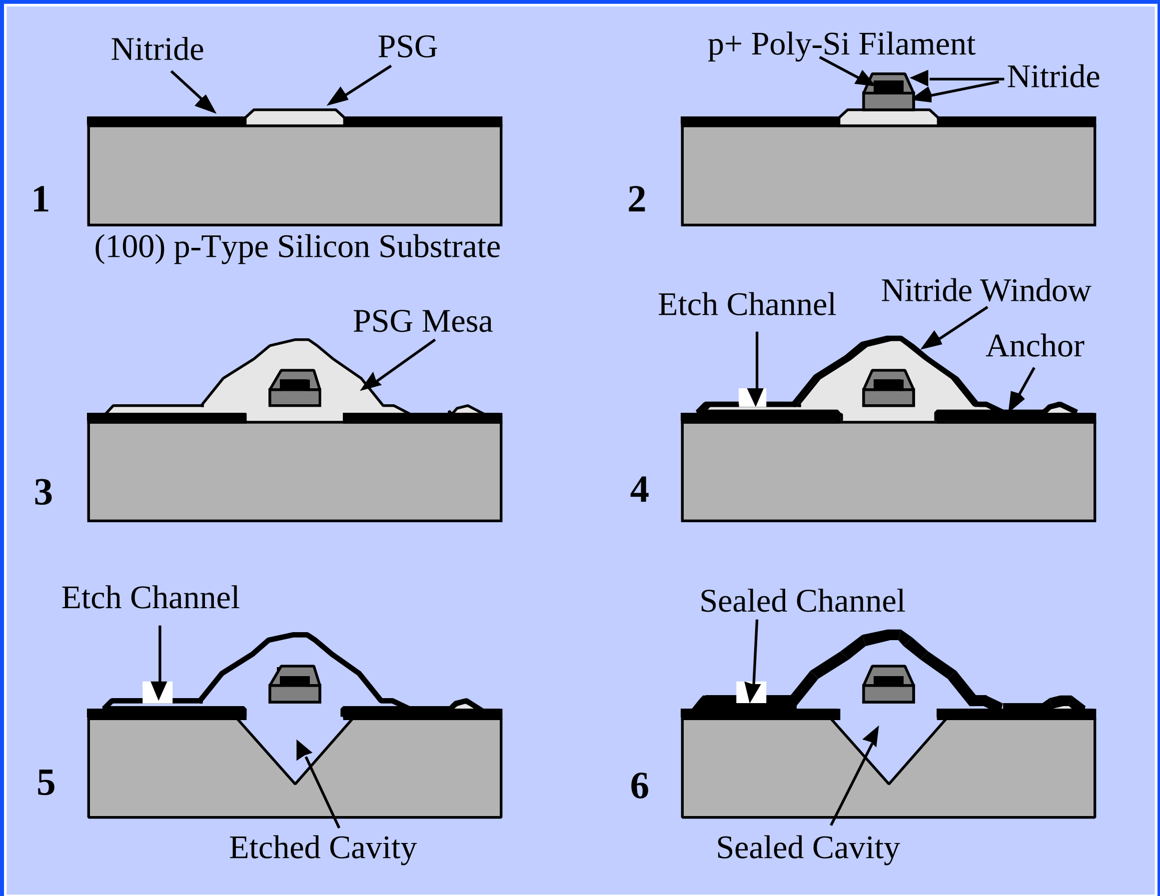
ORGANIC LEDS

- Poly(ethylene terephthalate) substrate + polyaniline anode + substituted poly(1,4-phenylene-vinylene) emitting layer + calcium metal cathode (electron source).
- LED output from devices reported by UNIAX Corp. visible in normal lighting, quantum efficiency ≈ 1%.
- Completed devices are flexible.
- Multiple colors are possible.

Reference: Gustafsson, G., Cao, Y., Treacy, G. M., Klavetter, F., Colaneri, N., and Heeger, A. J., “Flexible Light-Emitting Diodes Made from Soluble Organic Polymers,” Nature, vol. 357, June 11, 1992, pp. 477 - 479.

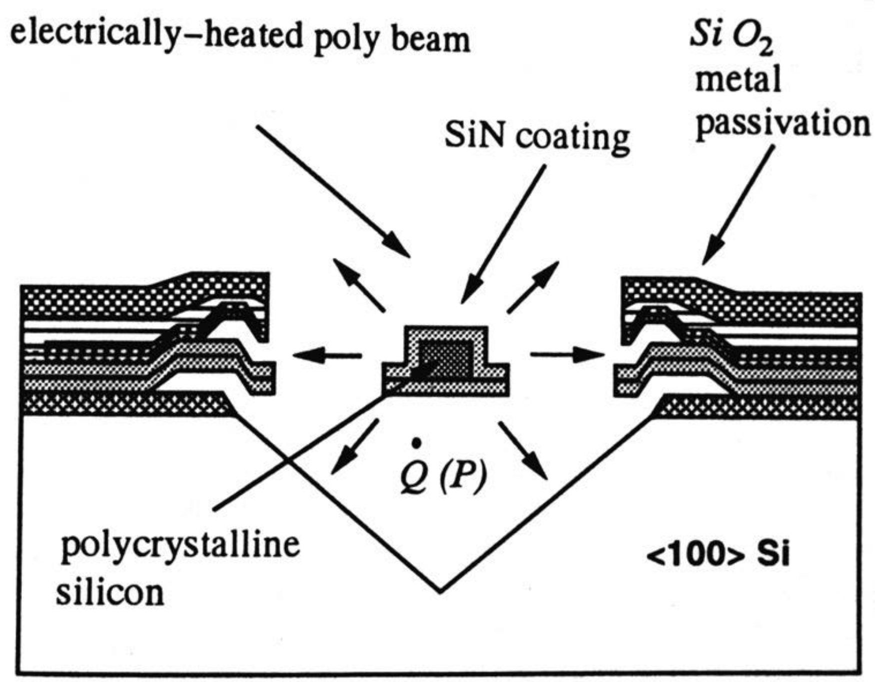
Image courtesy UNIAX Corp.

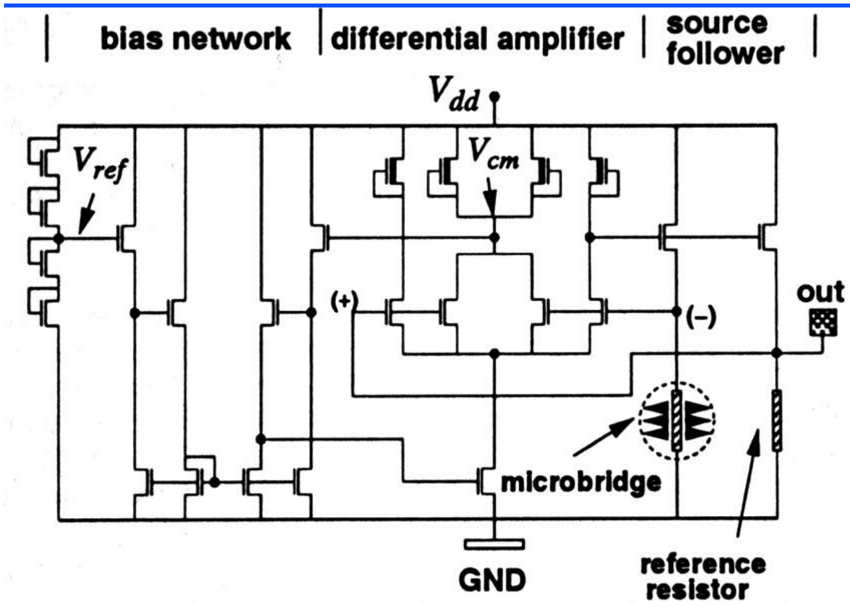
MICROMACHINED INCANDESCENT LAMPS

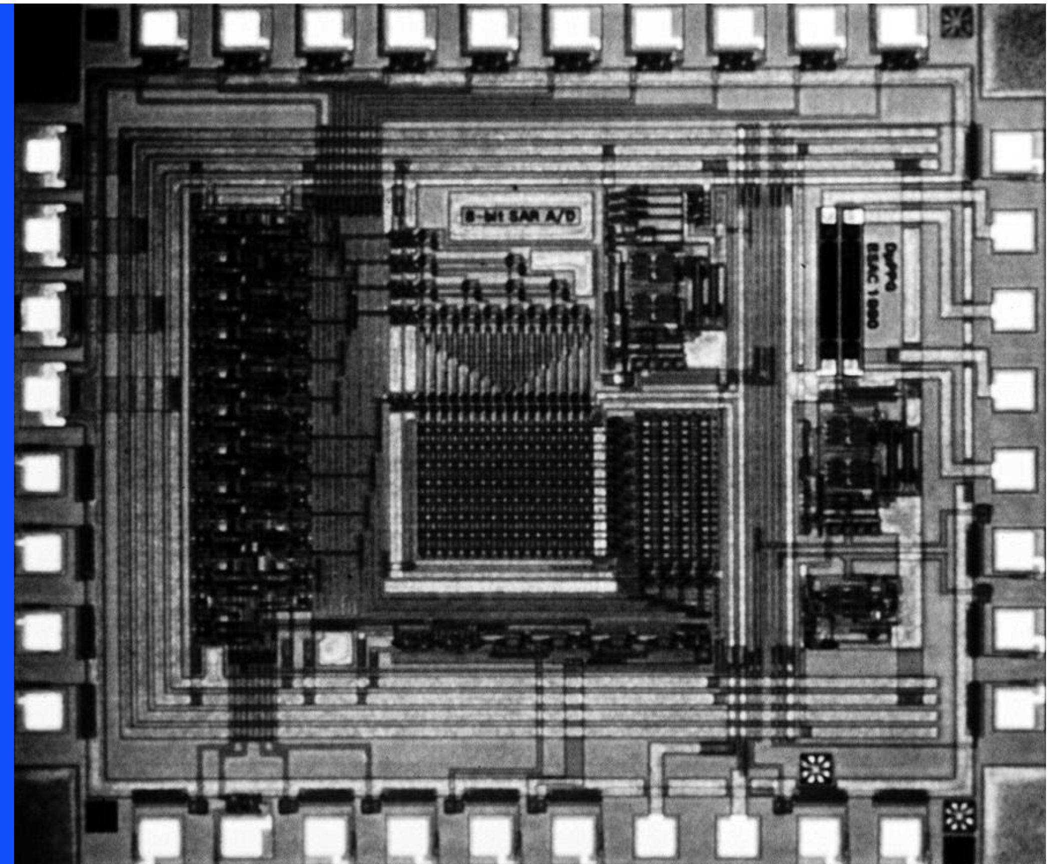


- **Reactive sealed 2.5 µm nitride window with internal vacuum.**
- **Filaments up to 500 µm long, 5 X 1 µm cross section.**
- **Broadband IR emission, 5 mW demonstrated.**

Reference: Mastrangelo, C. H. and Muller, R. S., "Vacuum-Sealed Silicon Micromachined Incandescent Light Source," Proceedings of the IEDM, 1989, pp. 503 - 506.

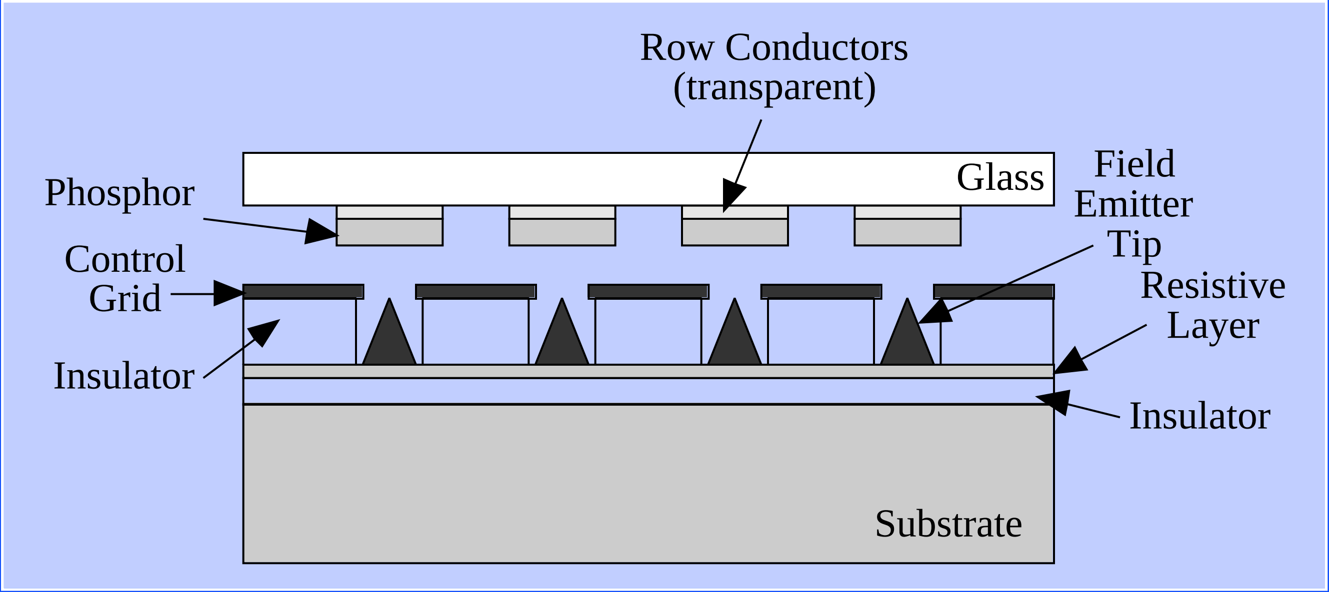






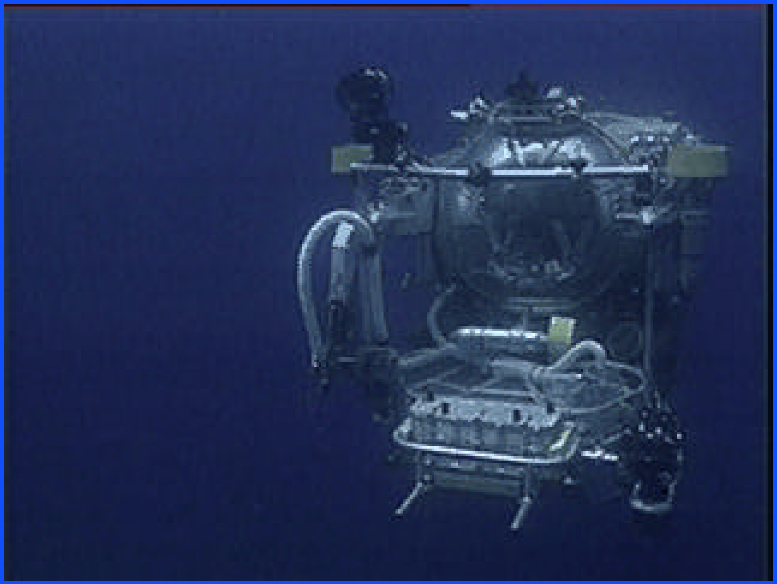
Source: Mastrangelo, C. H. and Muller, R. S., "Vacuum-Sealed Silicon Micromachined Incandescent Light Source," Proceedings of the IEDM, 1989, pp. 503 - 506.

FIELD EMISSION DISPLAYS



- LCDs use 80-90% of their power for backlighting, yet only 4% of the light reaches the viewer.
- FEDs provide electron flux to directly illuminate phosphors (10^7 V/cm easy to generate), with no focusing required due to short gap.
- Should be at least 2X more efficient than LCDs, hence the big push to develop them.

BIOLUMINESCENCE



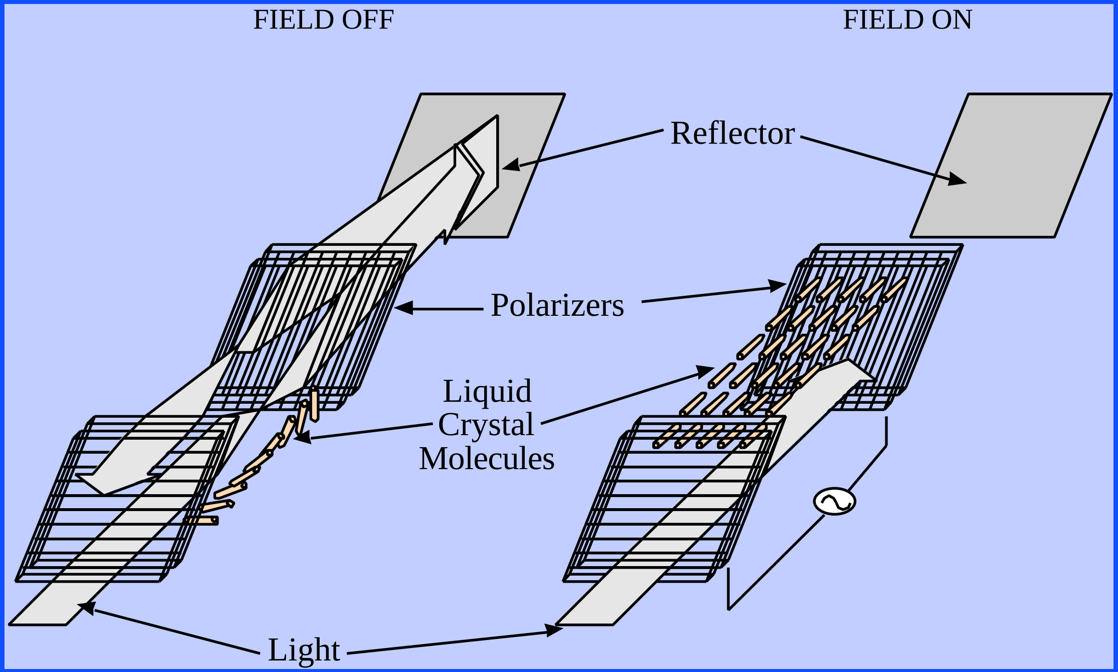
Movie courtesy Prof. H. C. Heller, Stanford University.

Source: Purves, Orians, Heller, and Sadava, “Life: The Science of Biology,” Sinauer Associates/W.H. Freeman & Co., New York, 1999.

LIGHT MODULATORS

- Liquid crystals
- Mechanical modulators
- Other?

LIQUID CRYSTAL DISPLAYS

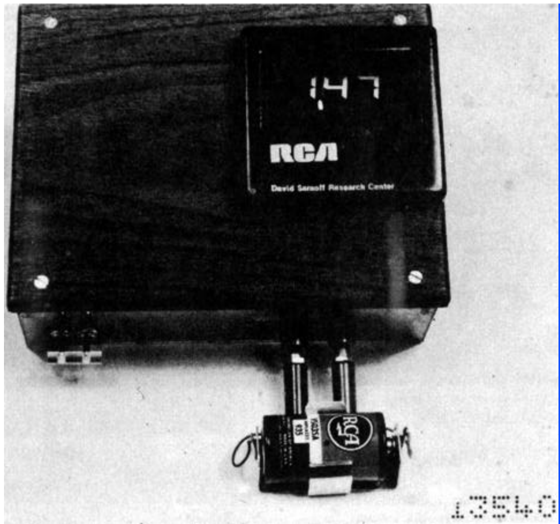


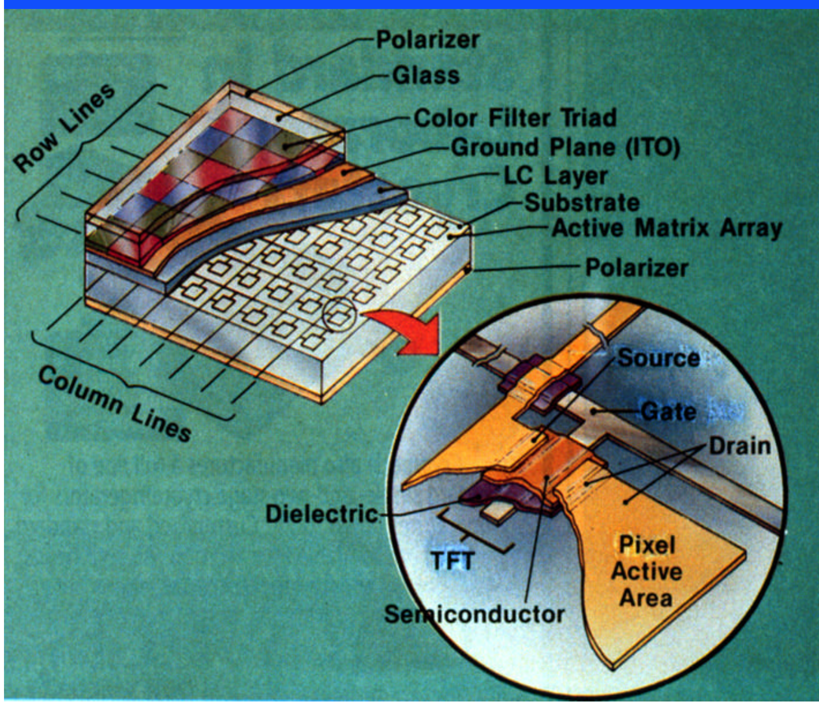
Typical drive: AC squarewave, 3 - 10V PP

Typical speed: 10 - 100 ms

Molecular size: 2nm X 0.5nm diameter

- **Nematic LCDs have a polarizer of buffed glass and ITO coating, a thin layer of LC (≈ 10 μm), an inner polarizer of buffed glass, and a rear reflector (or nothing if transmissive).**
- **LC molecules continuously twist between the buffing orientations and, if "off," allow light to follow the twist and pass back-to-front (electrical drive orients the LC orthogonal to the glass and destroys this effect for a blacked out region).**





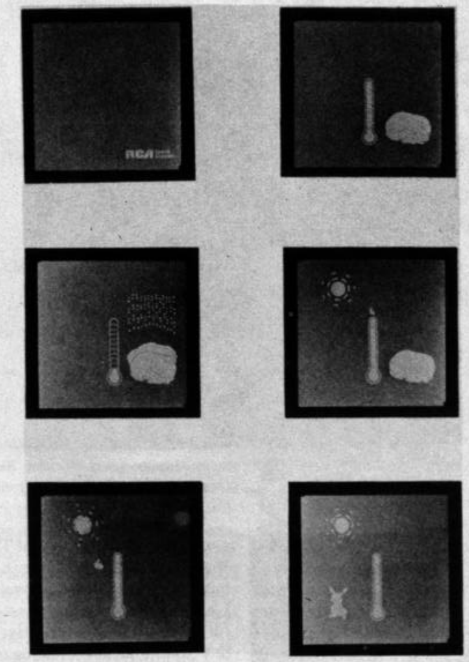


Fig. 6. An animated liquid crystal advertising display.

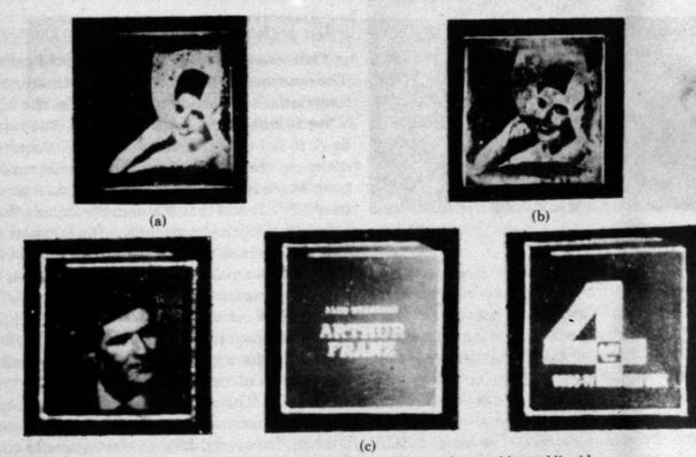
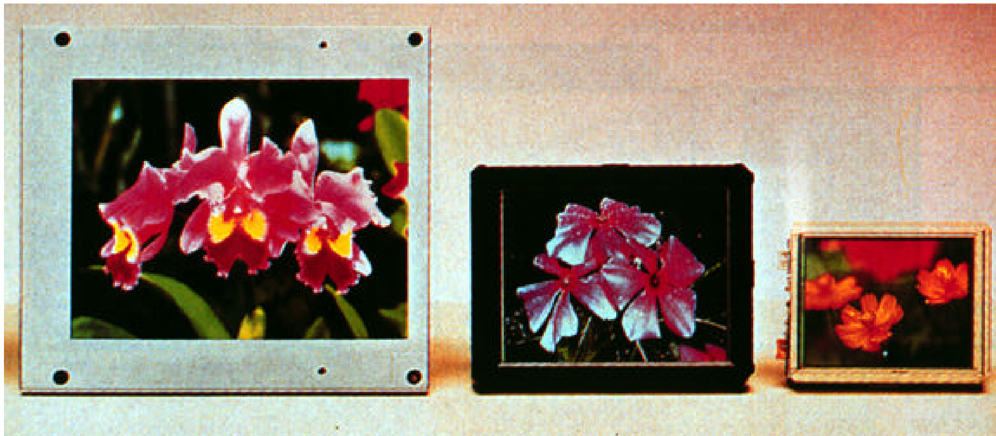
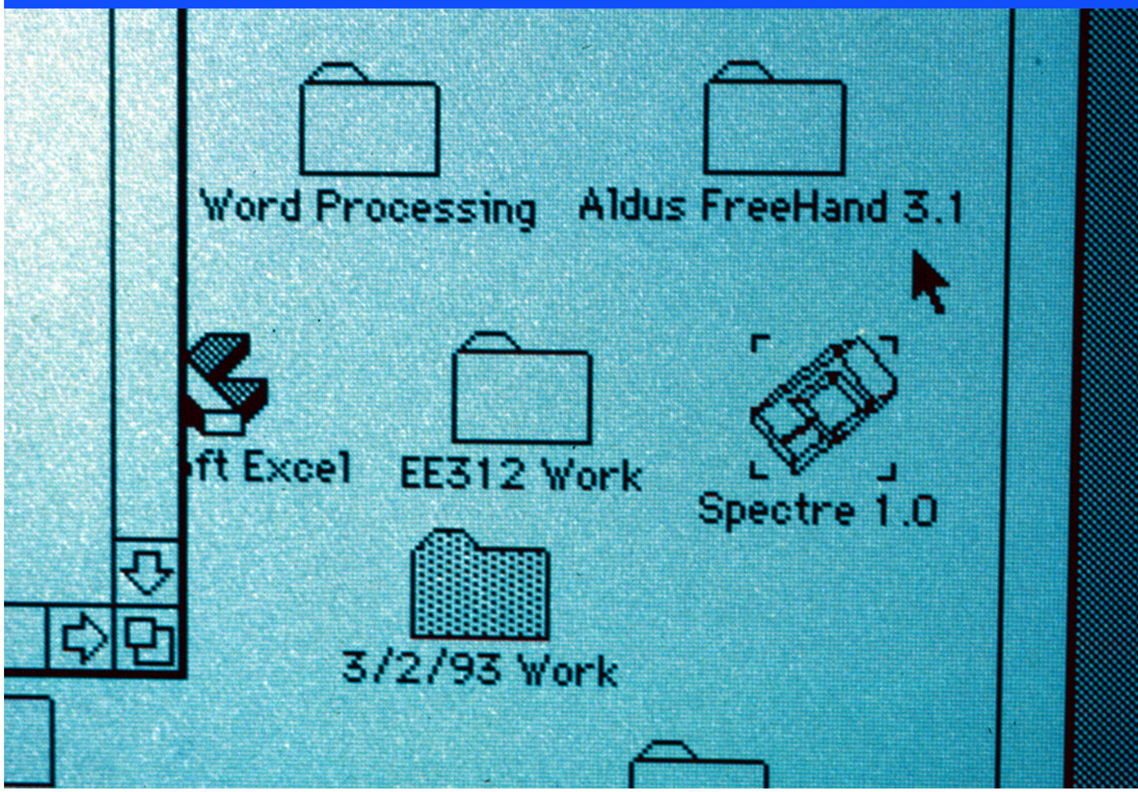


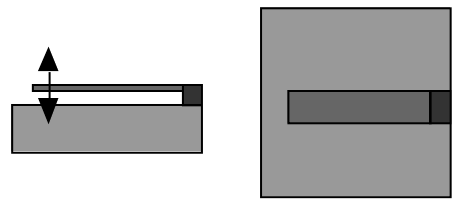
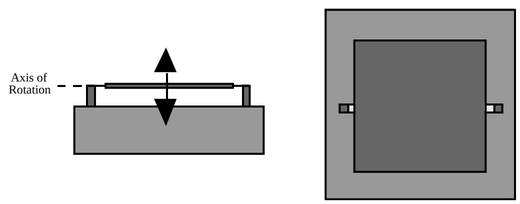
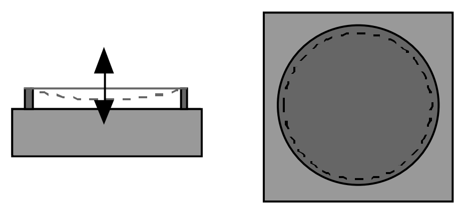
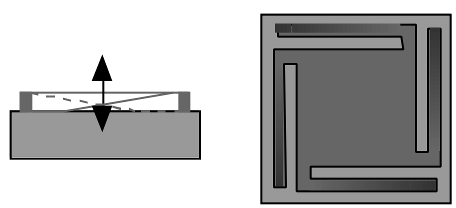
Fig. 7. The first liquid crystal TV—An electron beam addressed liquid crystal display (John VanRaalte, 1969). (a) Lower resolution. (b) Higher resolution. (c) Off-the-air-programming.



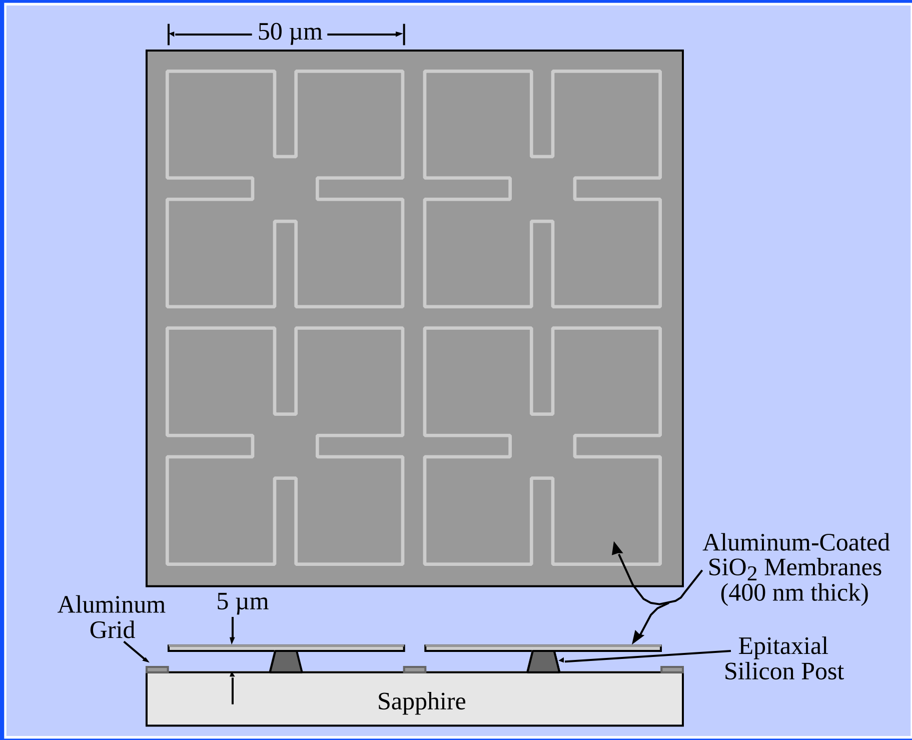


LIQUID CRYSTAL DISPLAYS

MICROMECHANICAL LIGHT MODULATORS

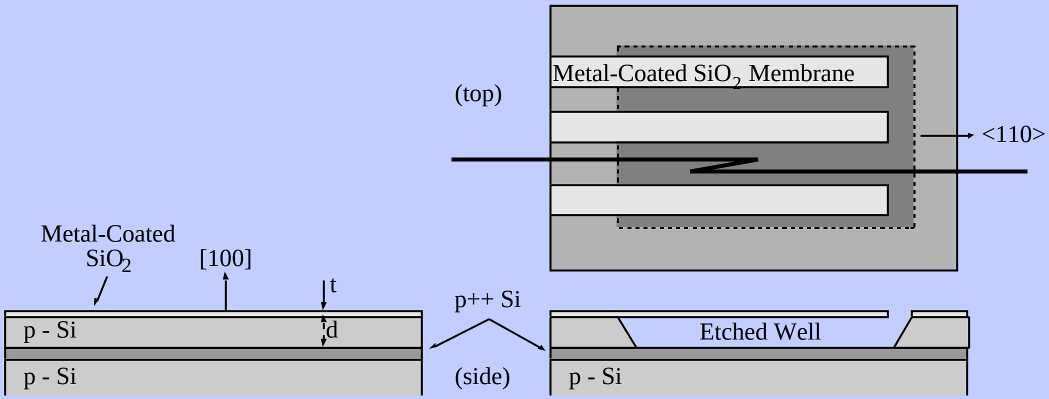
Modulator Type	Motion	Side and Top Views
Cantilever Beam	Bending	
Torsional Plate	Rotation About Torsion Axis	
Membrane	Drumhead	
Suspended Plate	Vertical	

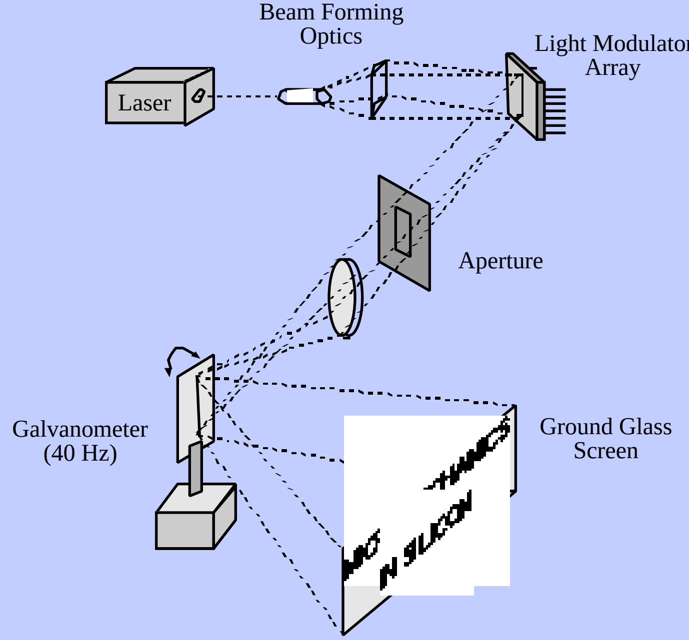
WESTINGHOUSE LIGHT MODULATOR



- An electron-beam deflected micromechanical light modulator was developed by Westinghouse in the mid-1970s.
- Al-coated SiO_2 “flaps” supported by epitaxial silicon posts on sapphire substrates were sealed into a vacuum tube with a CRT-like electron beam.
- Deflection of up to 4° occurred since more secondary electrons were knocked off than the impinging electrons.
- Output viewed through Schlieren optics.
- Images could be refreshed or stored for hours.
- Interestingly, the Al stress was controlled by adjusting the background O_2 level during evaporation.

Reference: Thomas, R. N., Guldberg, J., Nathanson, H. C., and Malmberg, P. R., “The Mirror-Matrix Tube: A Novel Light Valve for Projection Displays,” IEEE Transactions on Electron Devices, vol. ED-22, no. 9, Sept. 1975, pp. 765 - 775.

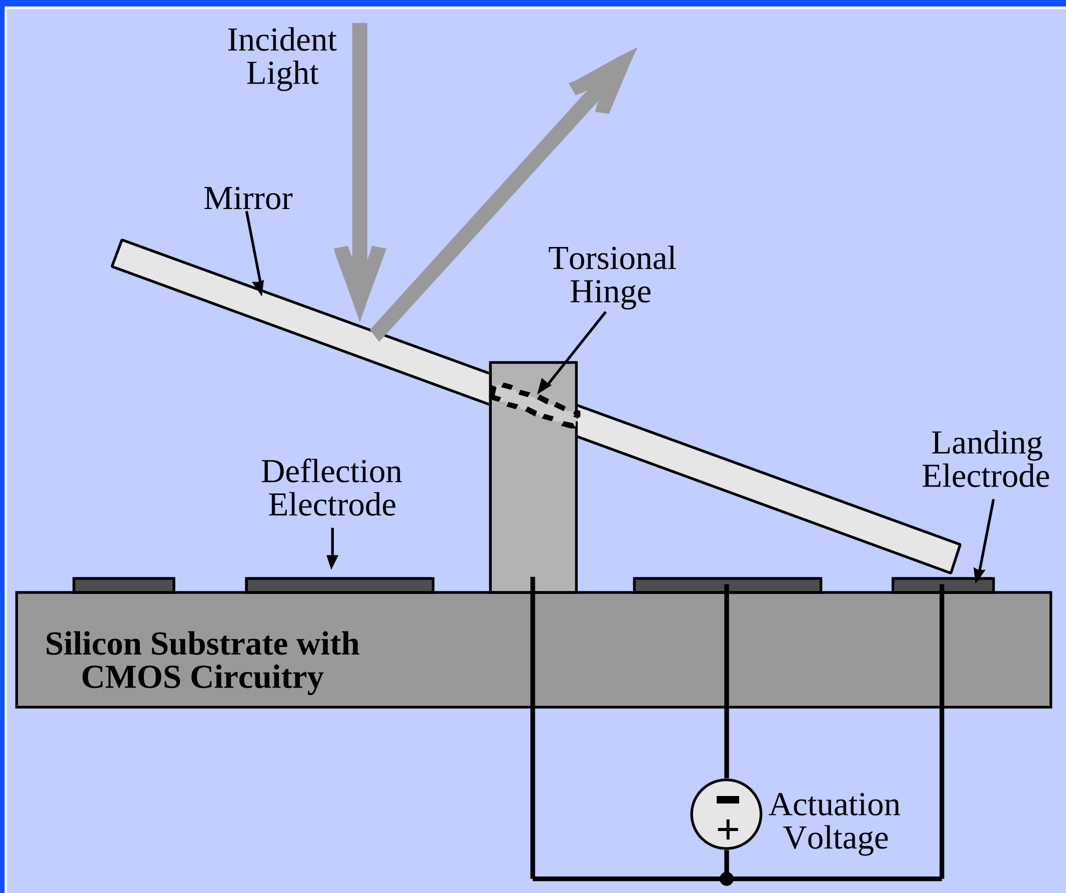




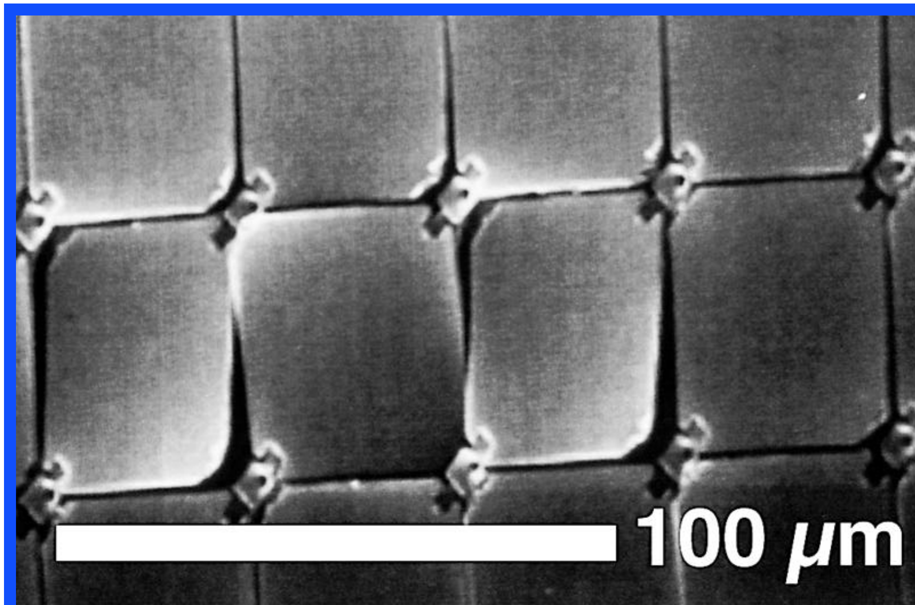
- **Several mechanical optical modulators were developed at IBM for computer display applications.**

Reference: Petersen, K. E., "Micromechanical Light Modulator Array Fabricated on Silicon," Applied Physics Letters, vol. 31, no. 8, Oct. 1977, pp. 521 - 523.

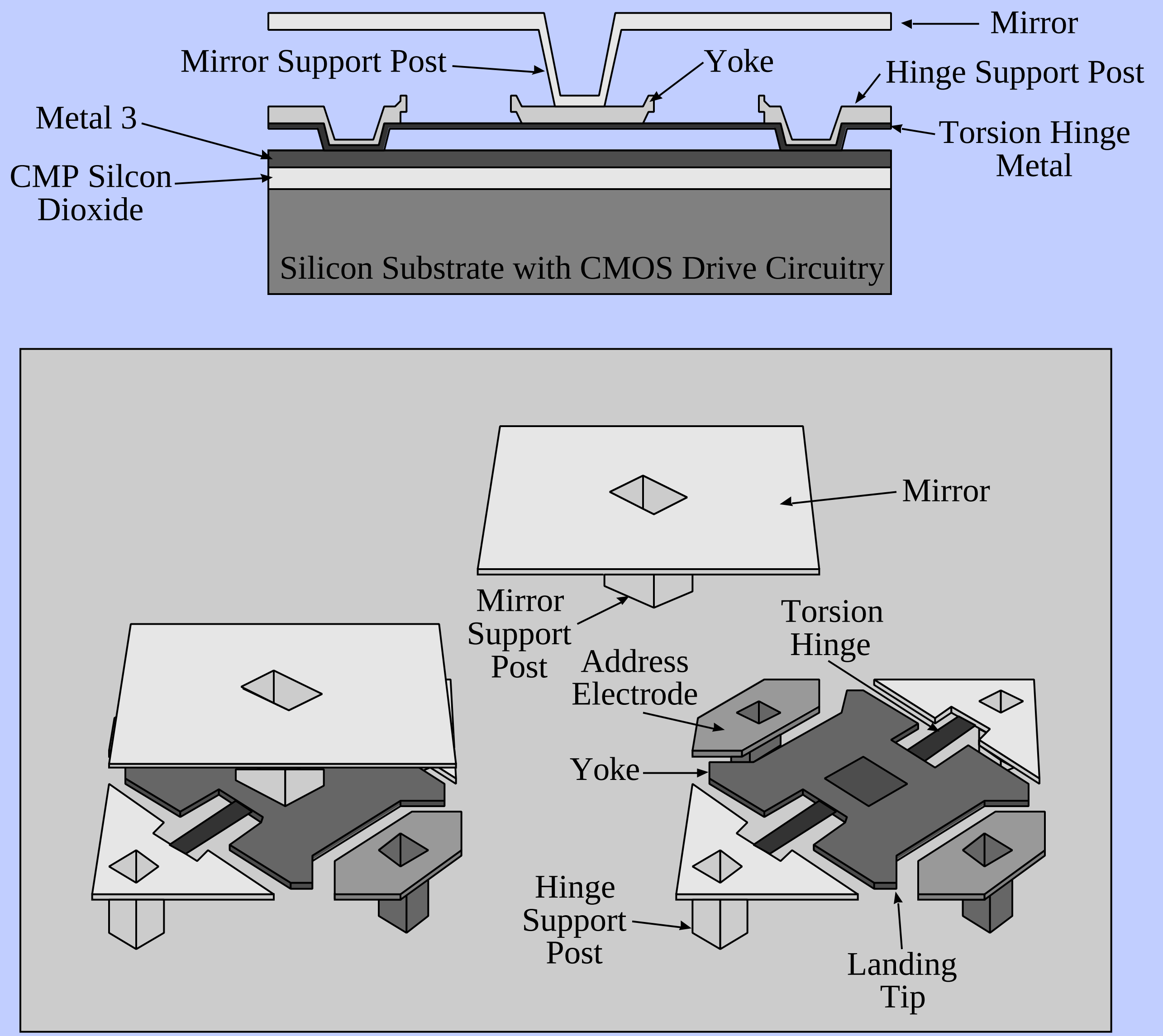
TORSIONAL LIGHT MODULATORS

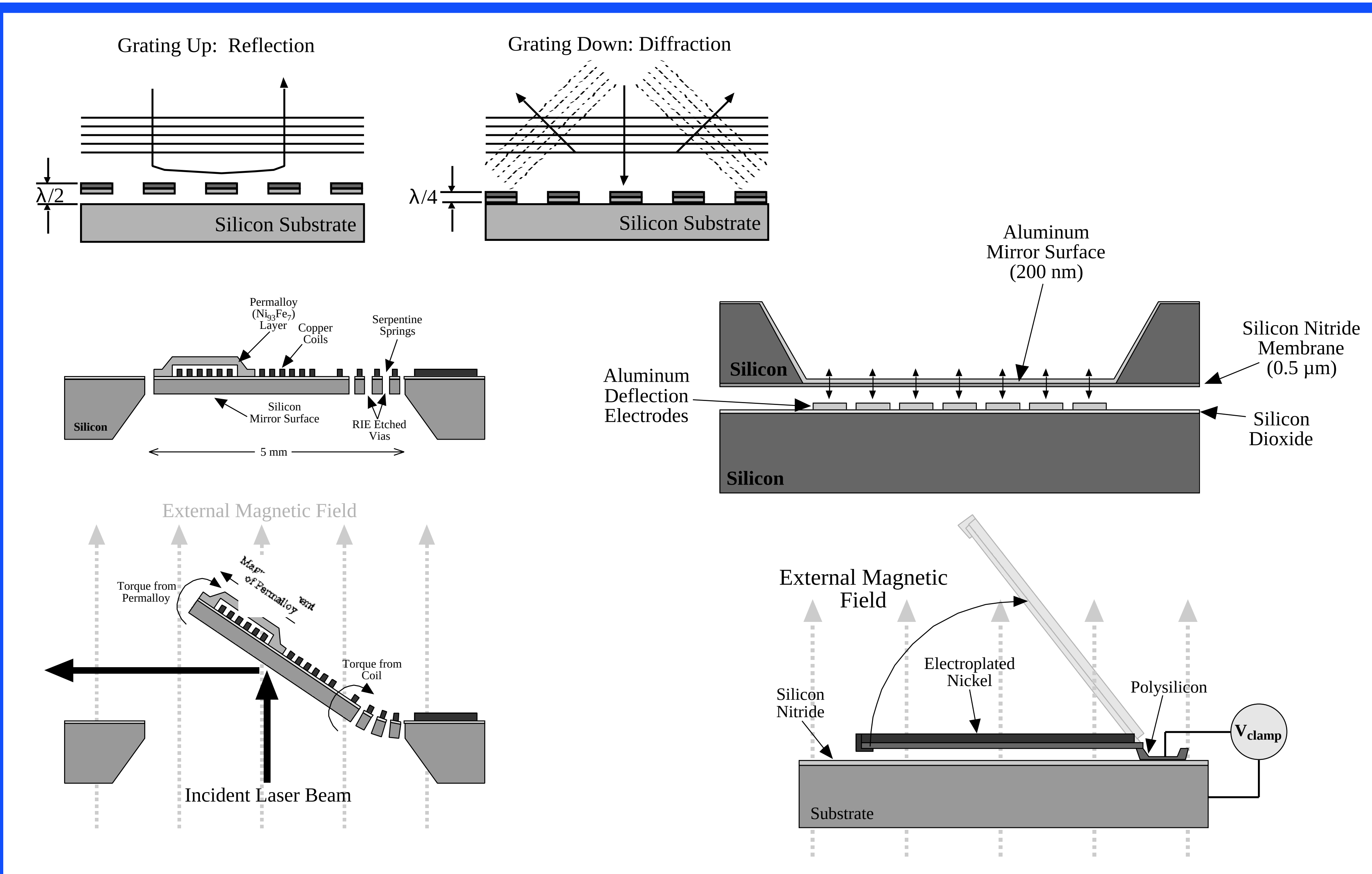


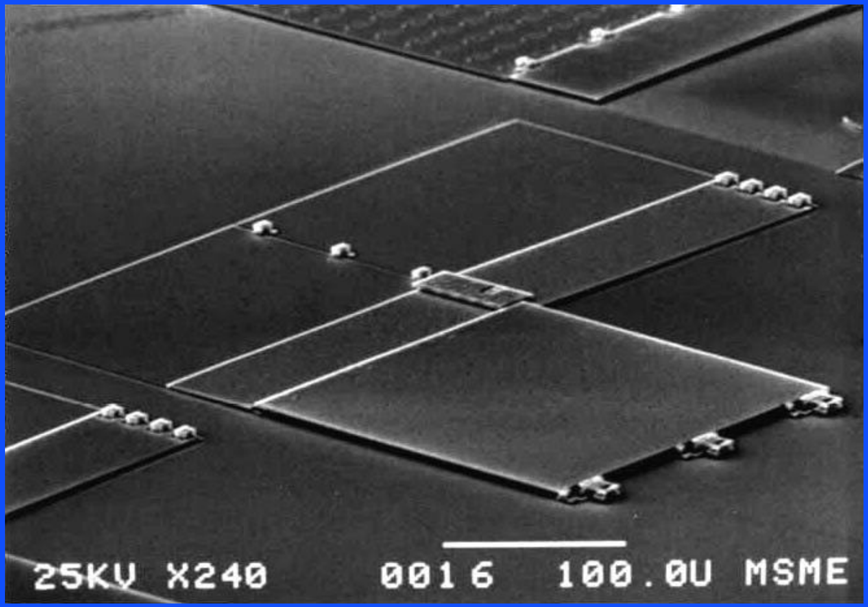
- Texas Instruments has been developing micromechanical optical modulators for over a decade.
- Sacrificial photoresist is used as a spacer, and underlying circuits are derived from a DRAM process.
- Very thin (≈60 nm) Al torsional members are used and have survived 1 trillion cycles.

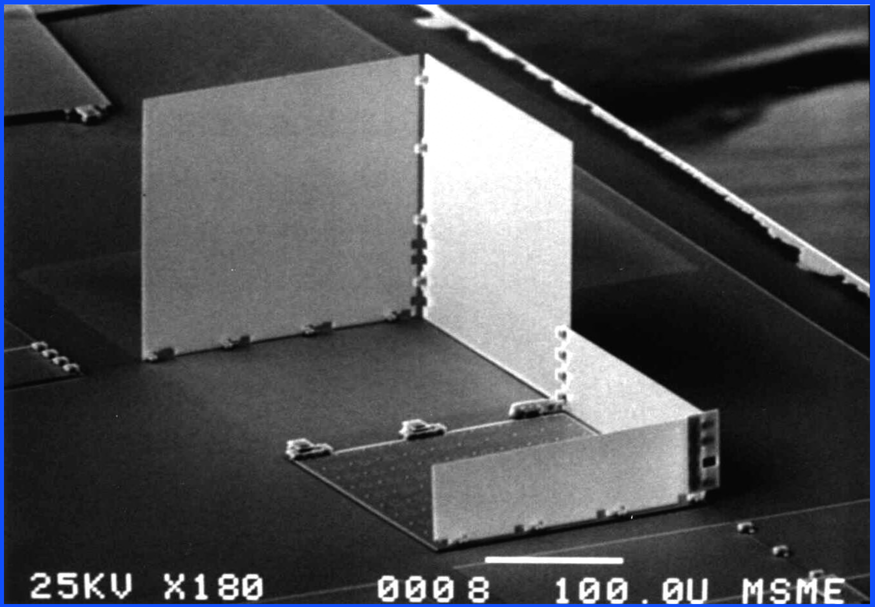


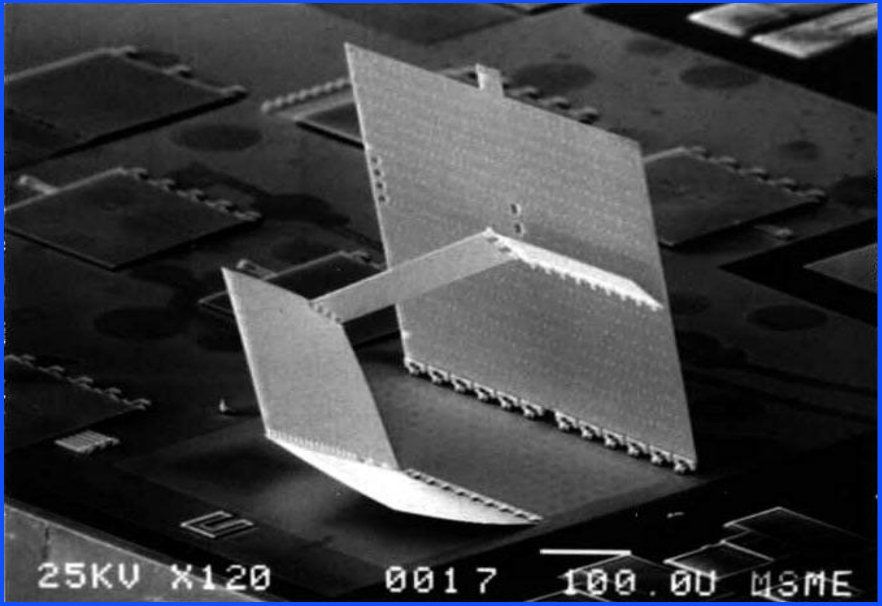
Images courtesy Texas Instruments, Inc.


Mirror
Mirror Support Post
Yoke
Hinge Support Post
Metal 3
Torsion Hinge Metal
CMP Silcon Dioxide
Silicon Substrate with CMOS Drive Circuitry
Mirror
Mirror Support Post
Torsion Hinge
Address Electrode
Yoke
Hinge Support Post
Landing Tip


Grating Up: Reflection
λ/2
Silicon Substrate
Grating Down: Diffraction
λ/4
Silicon Substrate
Permalloy
(Ni$_{93}$Fe$_7$)
Layer
Copper
Coils
Serpentine
Springs
Silicon
Silicon
Mirror Surface
RIE Etched
Vias
5 mm
Aluminum
Mirror Surface
(200 nm)
Silicon
Silicon Nitride
Membrane
(0.5 μm)
Aluminum
Deflection
Electrodes
Silicon
Dioxide
Silicon
External Magnetic Field
Torque from
Permalloy
Torque from
Coil
Incident Laser Beam
External Magnetic
Field
Electroplated
Nickel
Polysilicon
Silicon
Nitride
V$_{clamp}$
Substrate





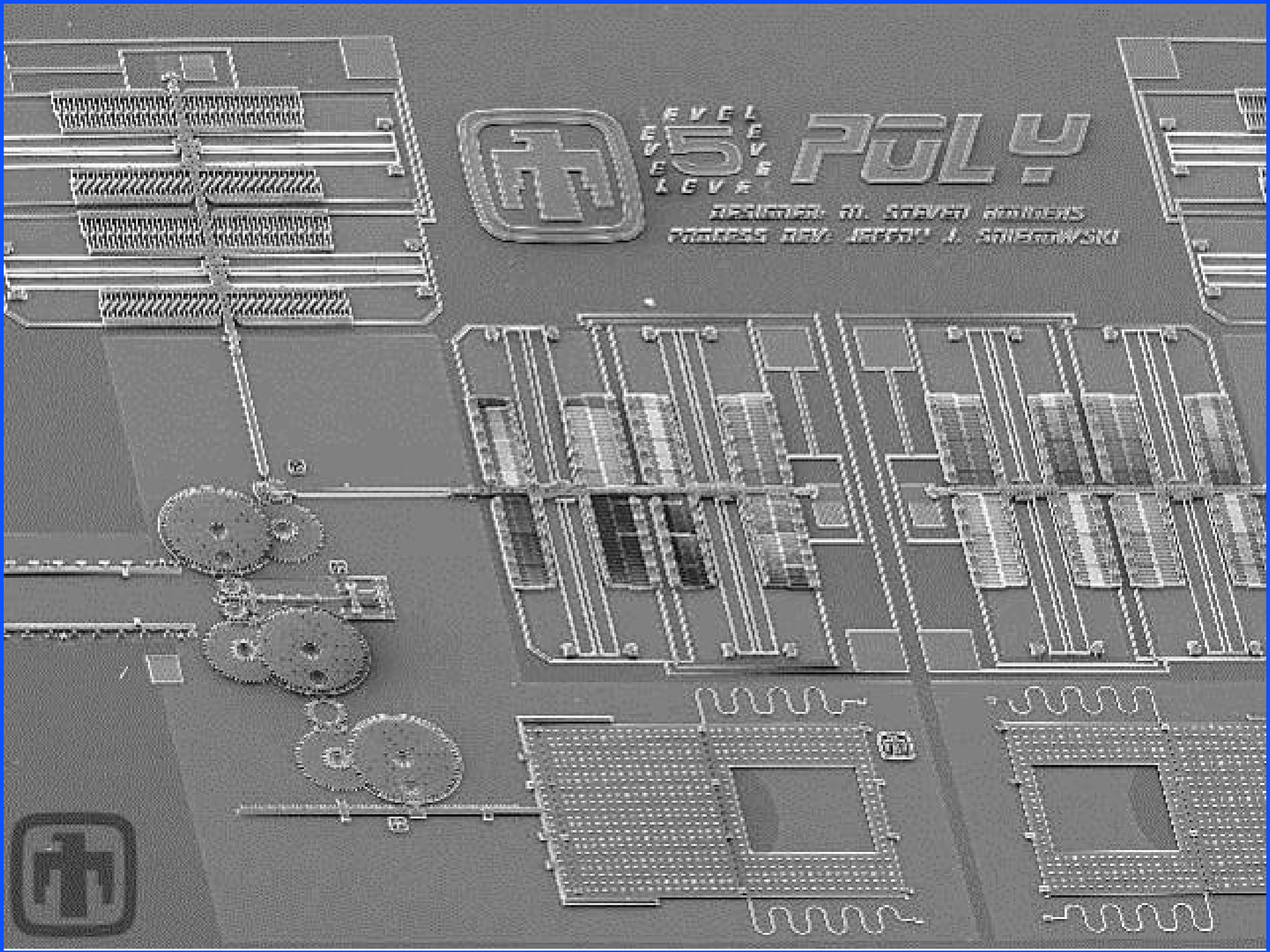


Clockwise: A) Unassembled "pop-up" corner-cube reflector. B) CCR after assembly. This CCR is not actuated. The assembly was accomplished in a single flipping step, using tweezers provided by MEMS Precision Instruments. C) A similar but not identical CCR structure is shown in the partially-assembled state.

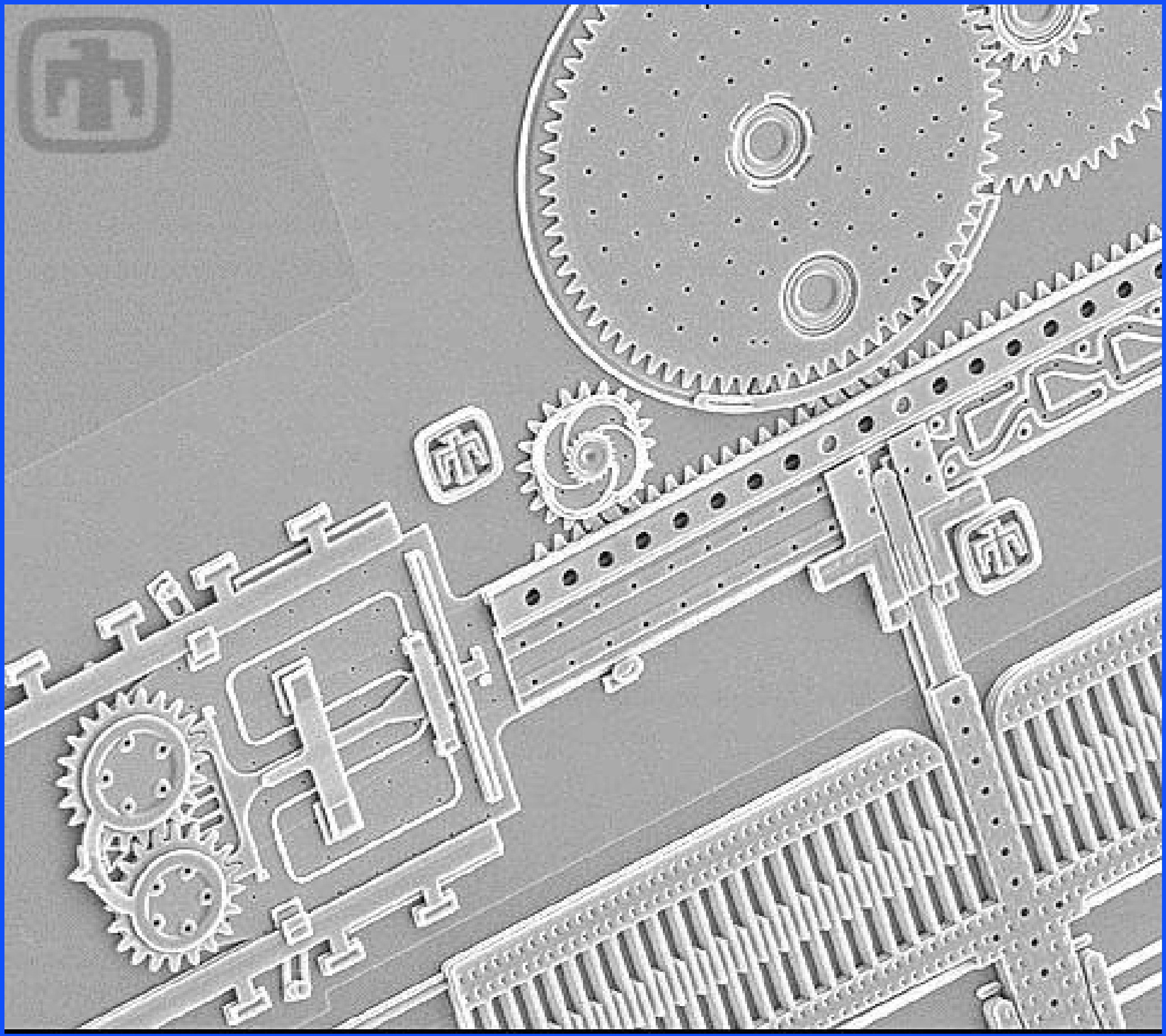
Designed in the Sandia SUMMiT 4-level process
Elliot Hui, 7/22/99

Courtesy E. Hui, U. C. Berkeley.

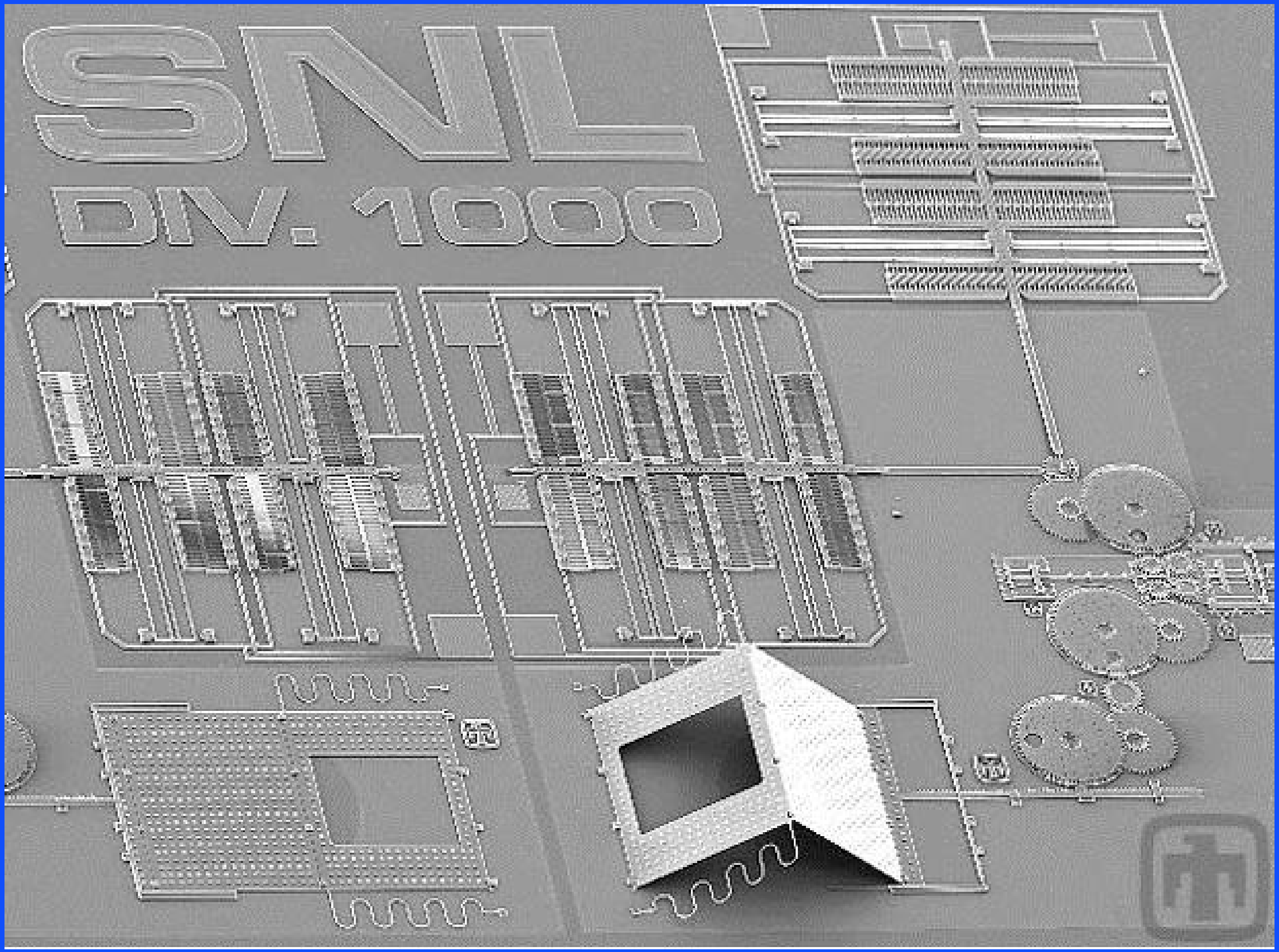
24-BIT LOCK



http://www.mdl.sandia.gov/Micromachine/images.html



http://www.mdl.sandia.gov/Micromachine/images.html



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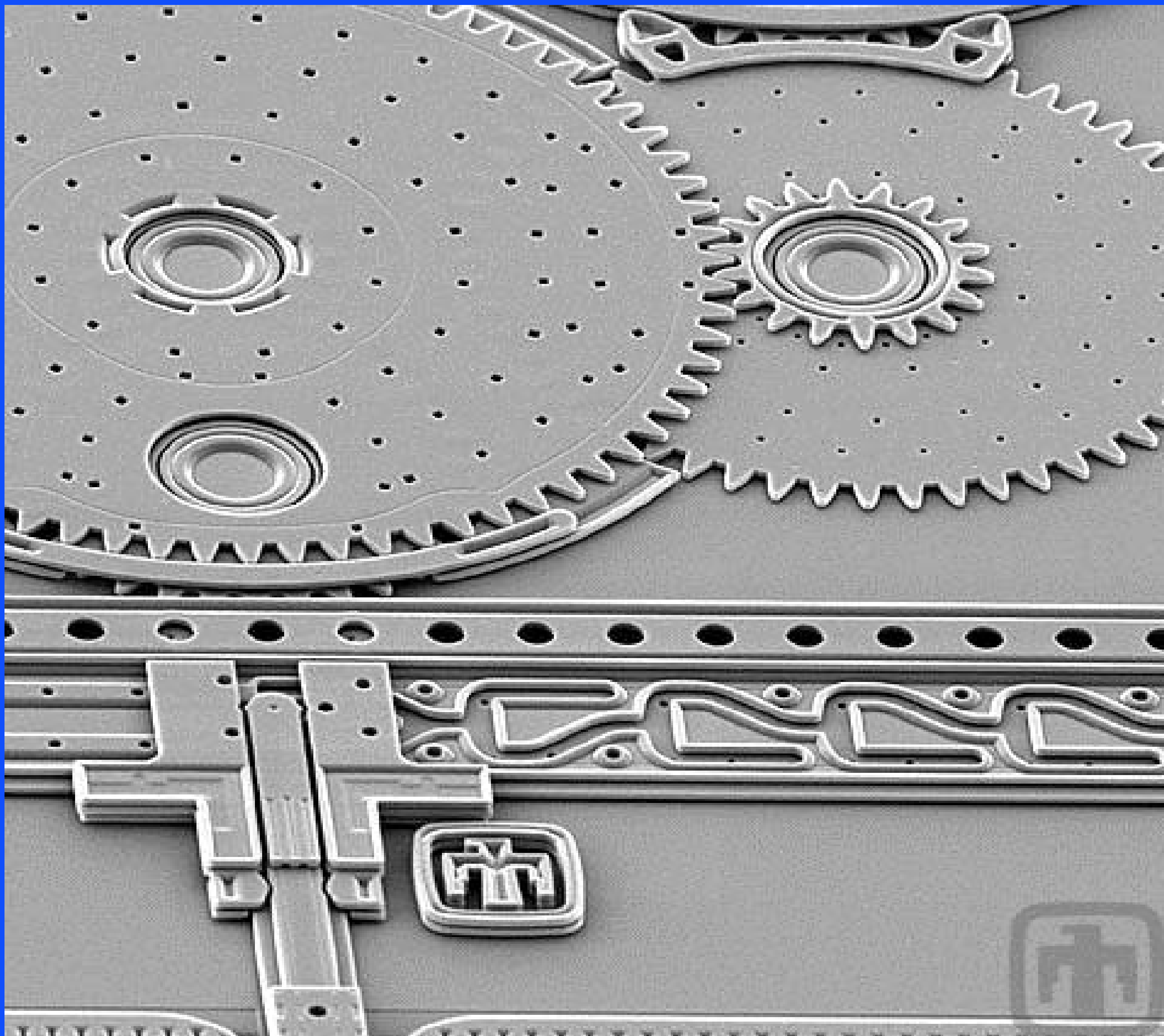

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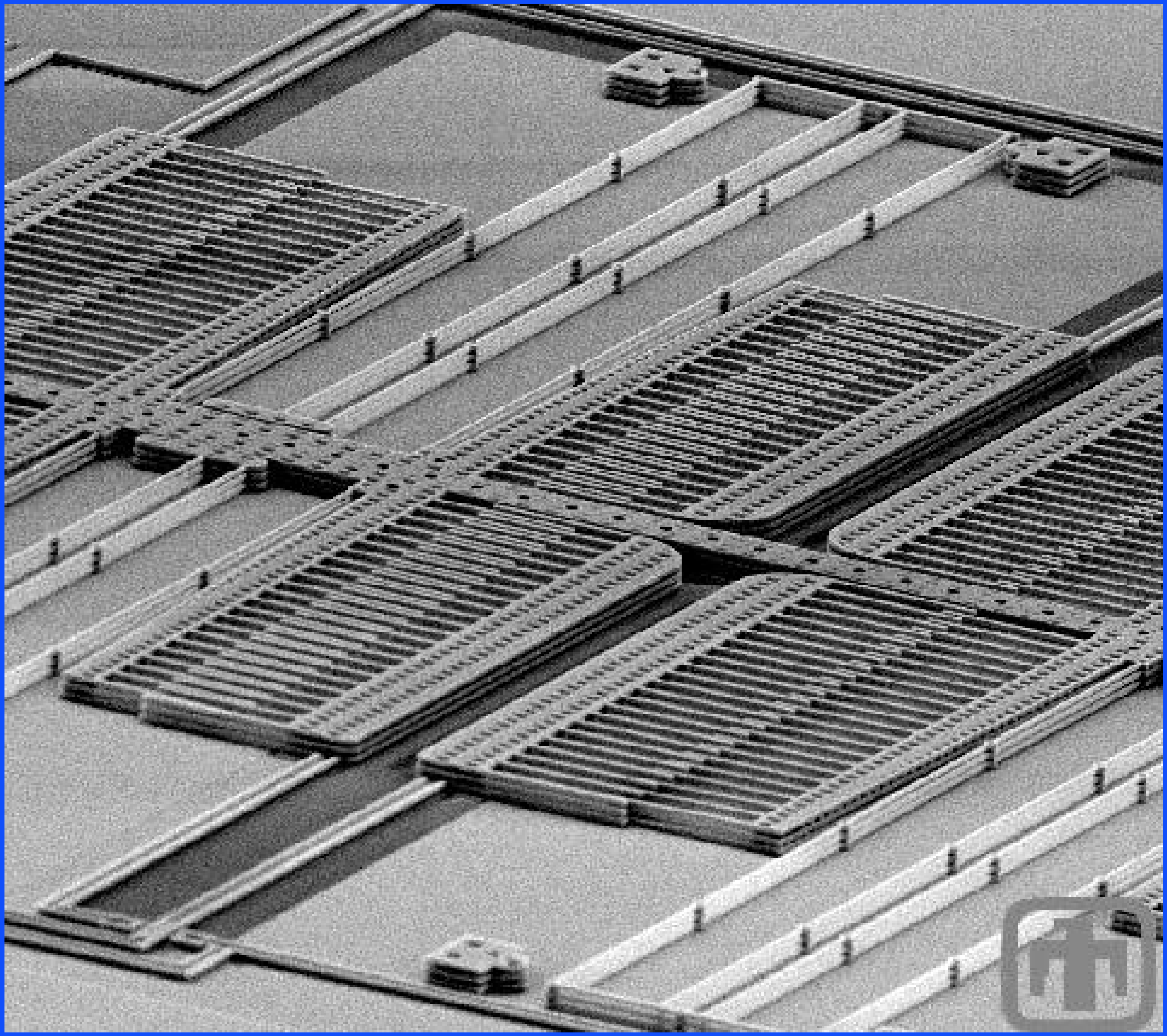
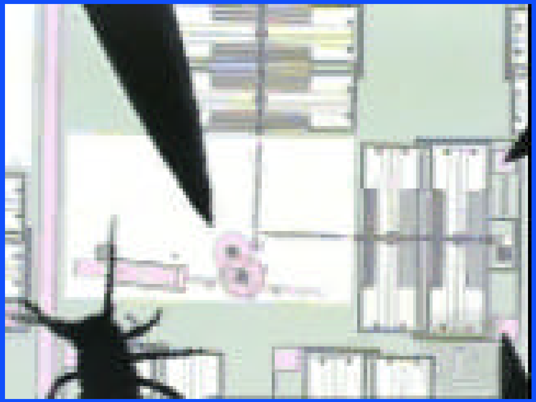
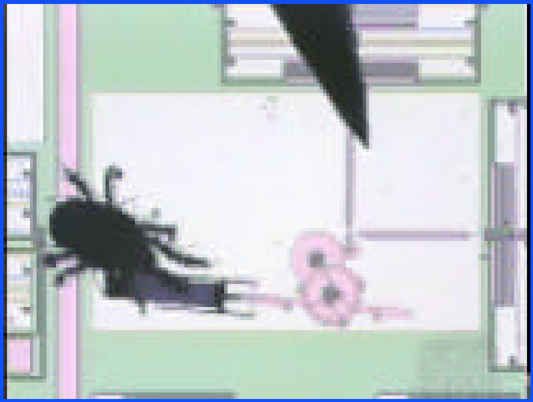
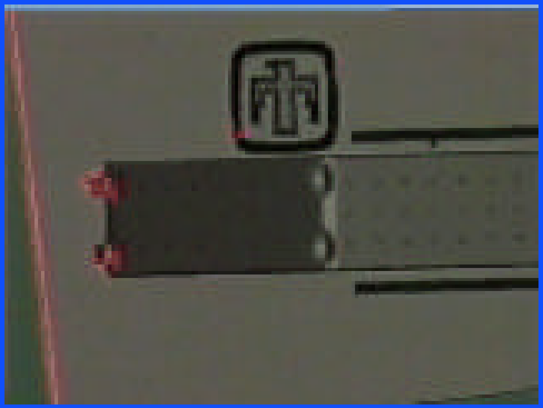


http://www.mdl.sandia.gov/Micromachine/images.html



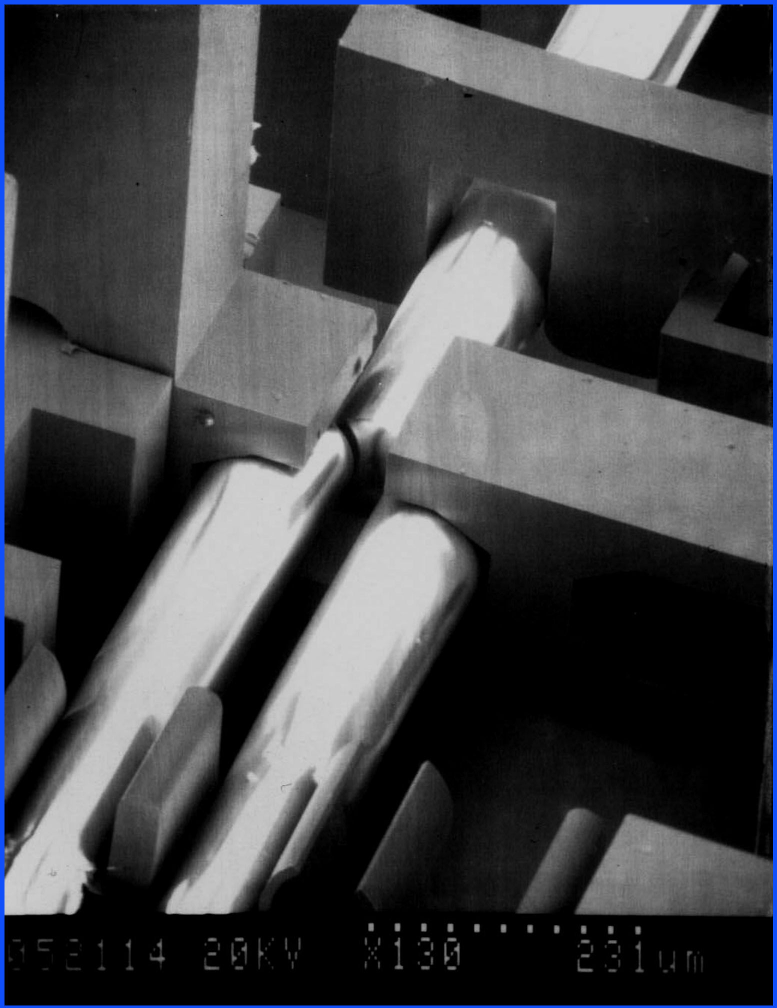


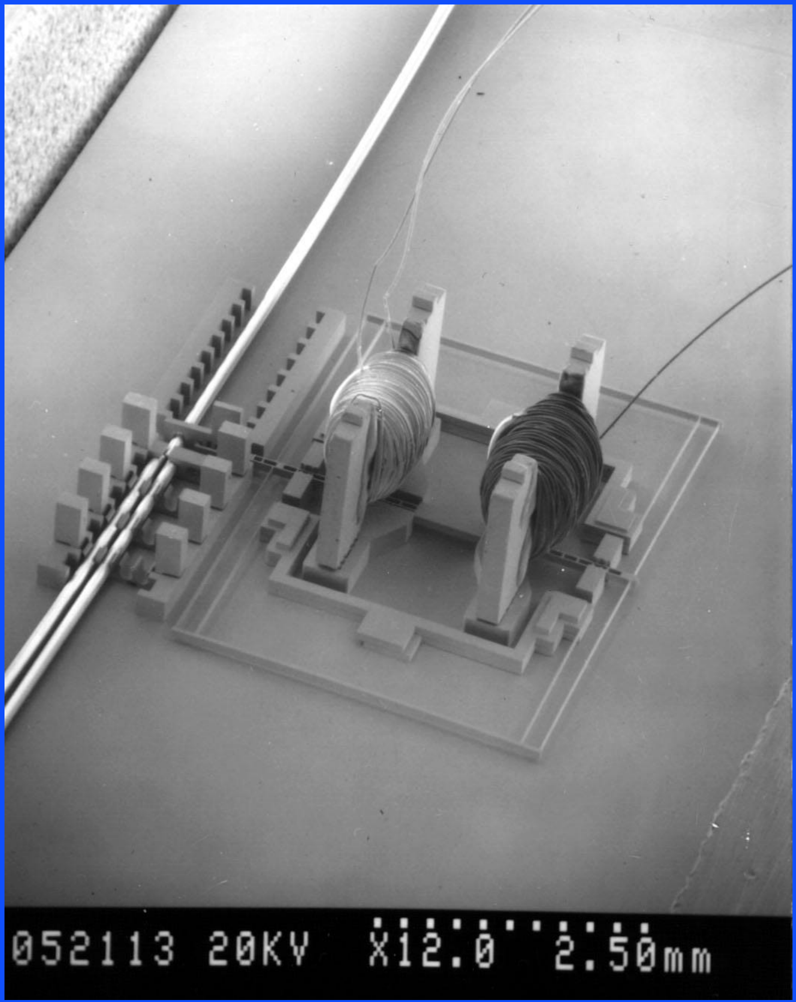


MICROMACHINED OPTICAL STRUCTURES AND SYSTEMS

- **Optical surfaces**
- **Lenses**
- **Waveguides**
- **Optical Switches**
- **Interferometers**
- **Variable filters**
- **Optical “benches”**
- **Integration with CMOS**

FIBER-OPTIC SWITCH

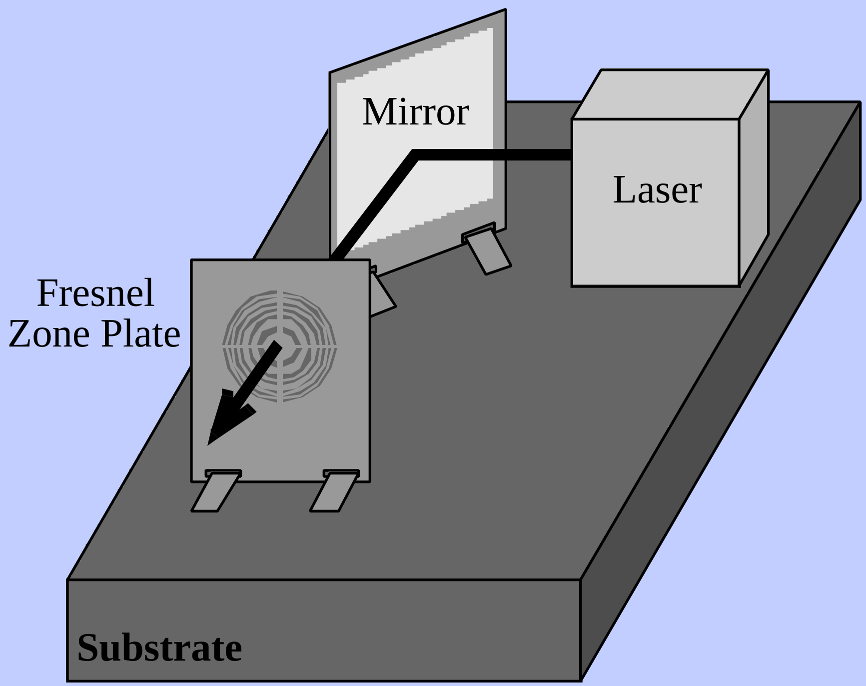


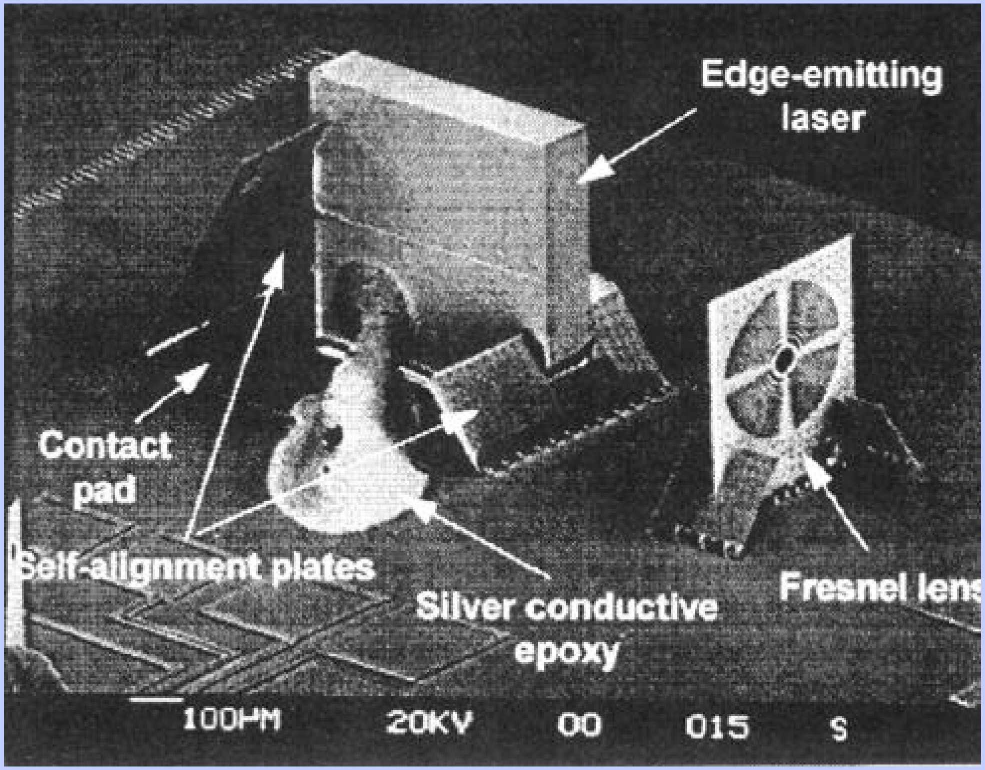


Reference: H. Guckel, K.Fischer, B.Chaudhuri, E.Stiers, S.McNamara, "Single Mode Optical Fiber Switch," HARMST'99, Tokyo, Japan, June 1999.

Courtesy Prof. H. Guckel, University of Wisconsin.

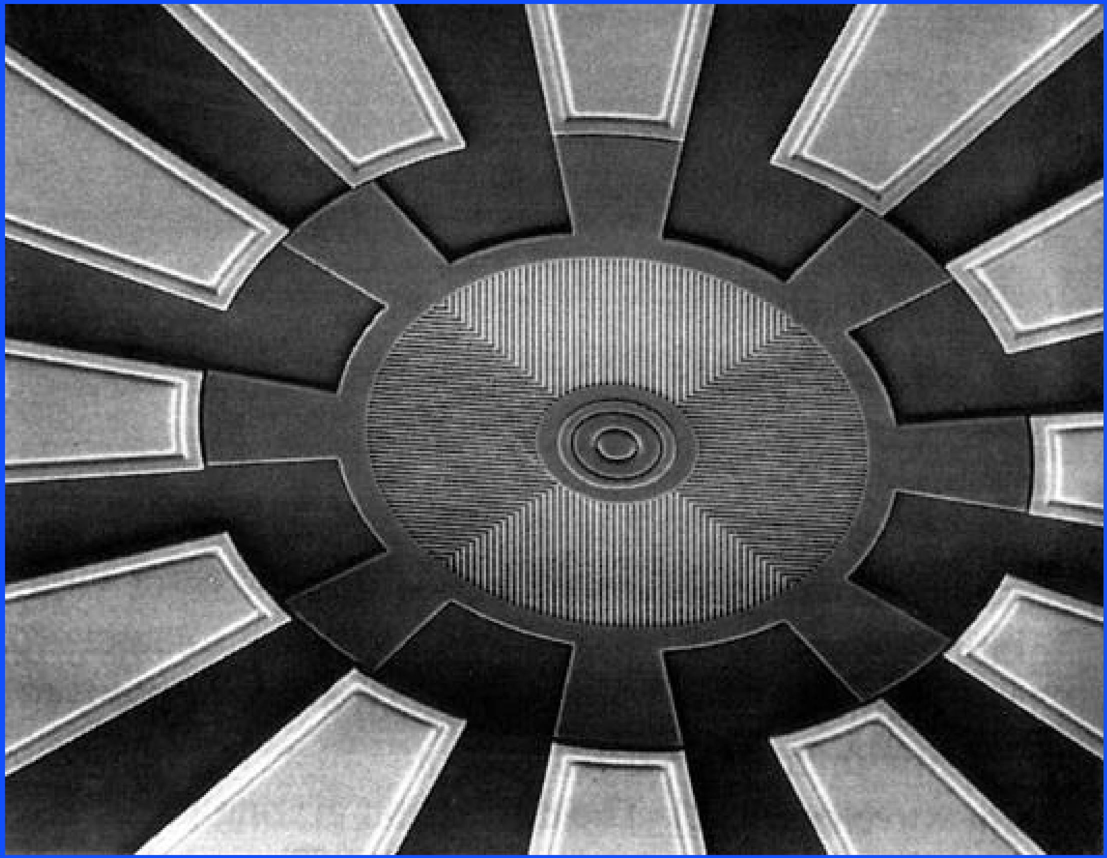
MICROMACHINED "OPTICAL BENCH"





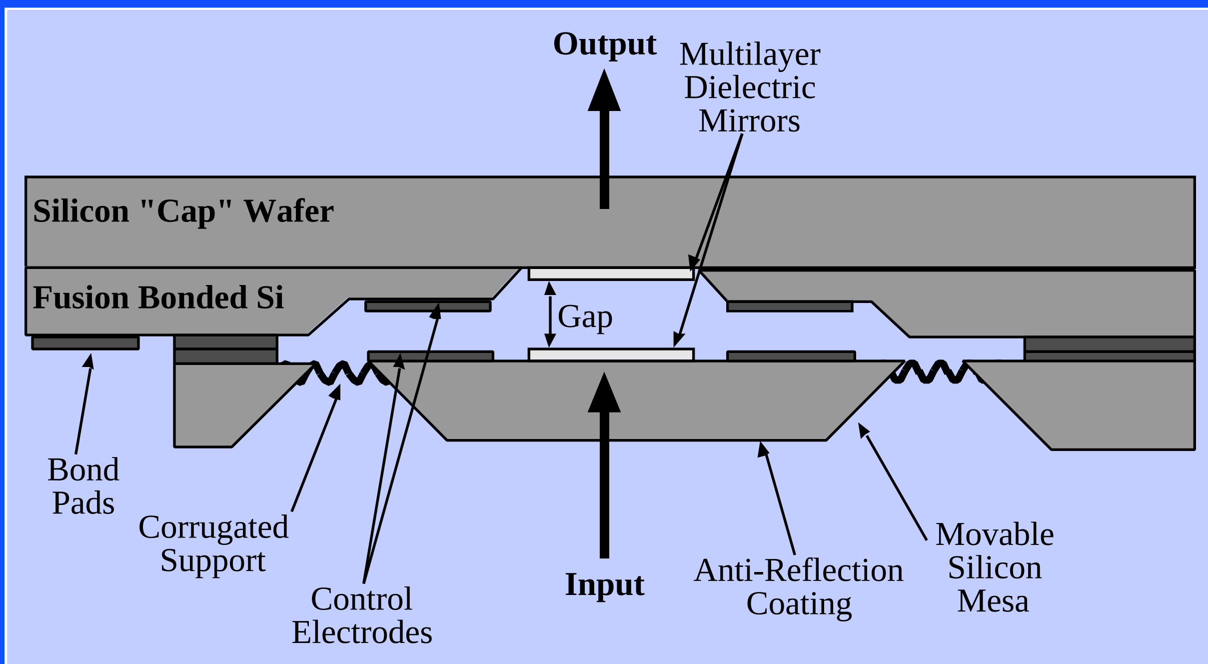
Source (Image): Lee, S. S., Lin., L. Y., and Wu, M. C., "Surface-Micromachined Free-Space Micro-Optical Systems Containing Three-Dimensional Microgratings," Applied Physics Letters, vol. 67, no. 15, Oct. 9, 1995, pp. 2135 - 2137.

MICROMOTOR SCANNED GRATINGS



Courtesy Prof. M. Mehregany, Case Western Reserve University.

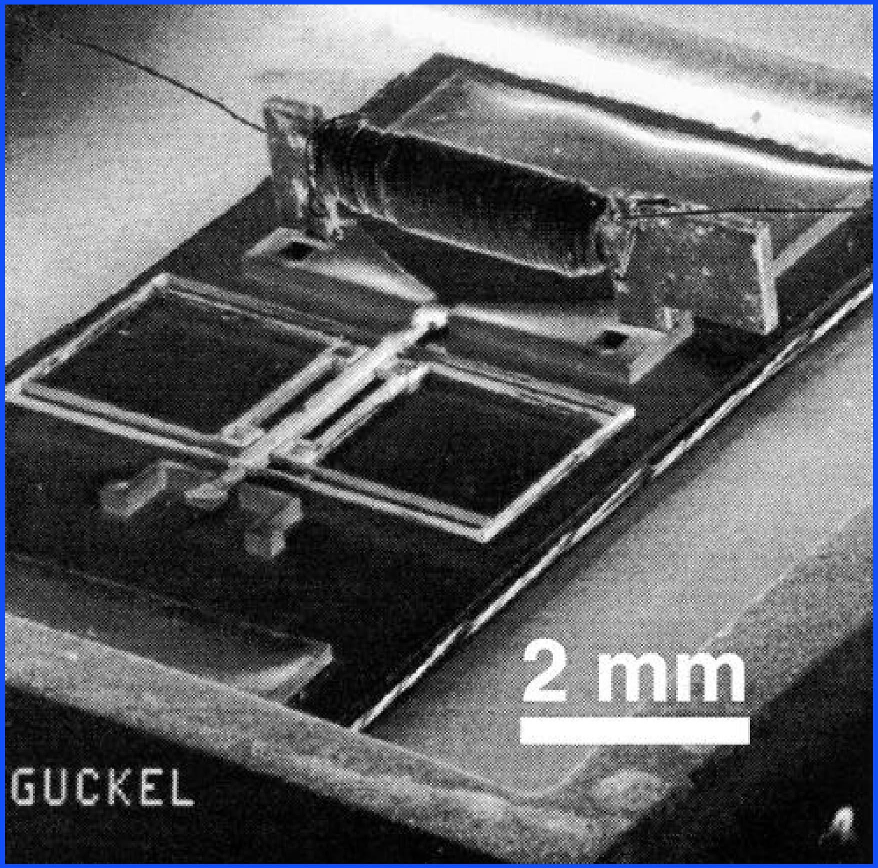
SPECTROPHOTOMETERS

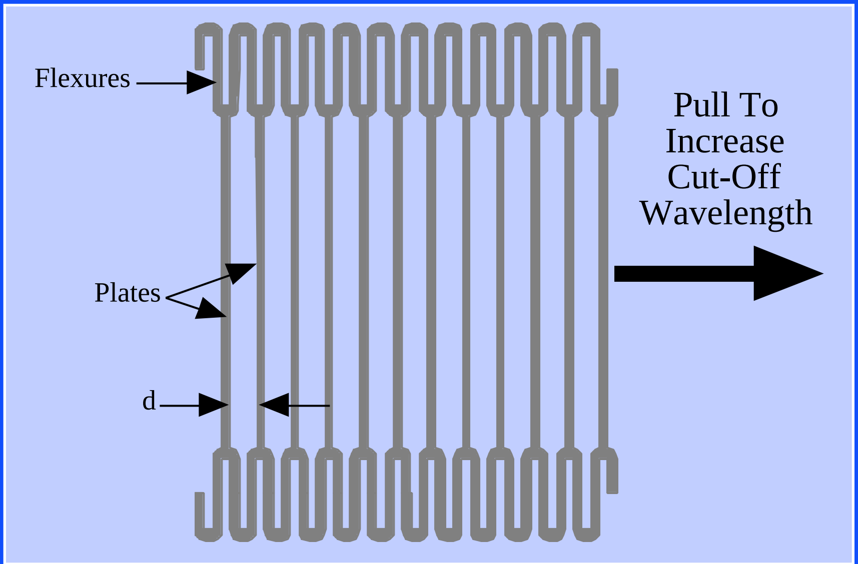


Reference: Jerman, J. H., Clift, D. J., and Mallinson, S. R., "A Miniature Fabry-Perot Interferometer with a Corrugated Silicon Diaphragm Support," Sensors and Actuators A, vol. 29, 1991, pp. 151 - 158.

- **Several groups are working on micromachined spectrophotometers.**
- **Tunable Fabry-Perot interferometers are being developed.**
- **Computed-gratings spectrophotometers have been demonstrated.**

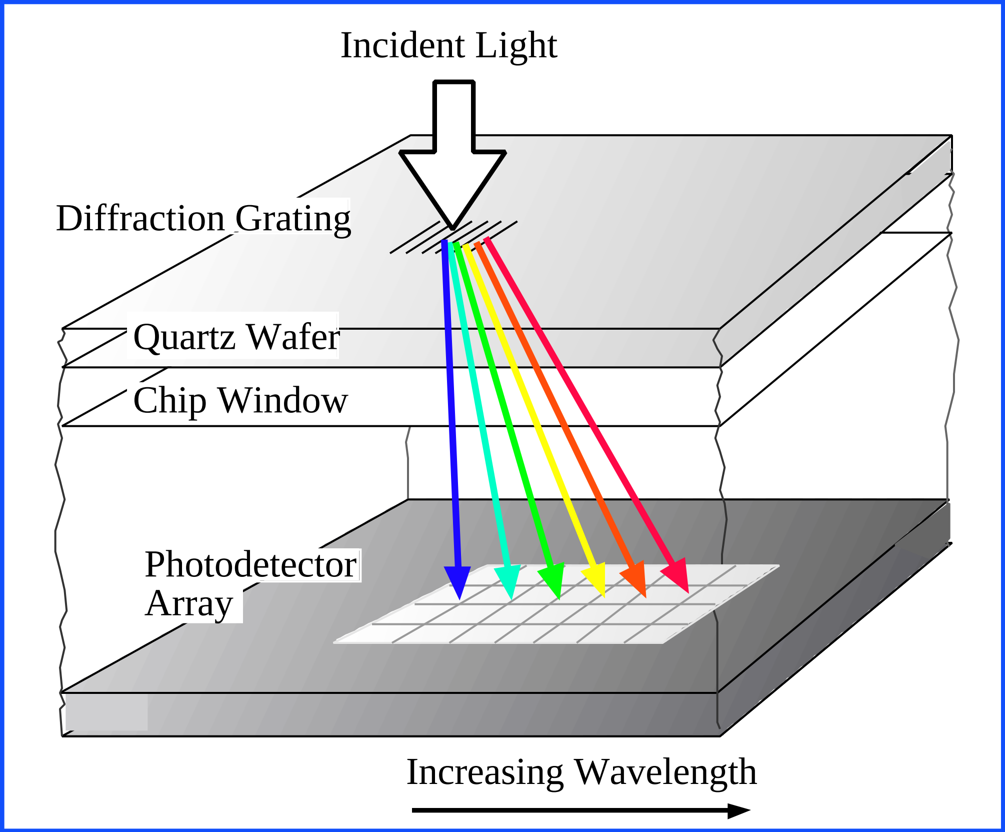
TUNABLE SLIT FILTER





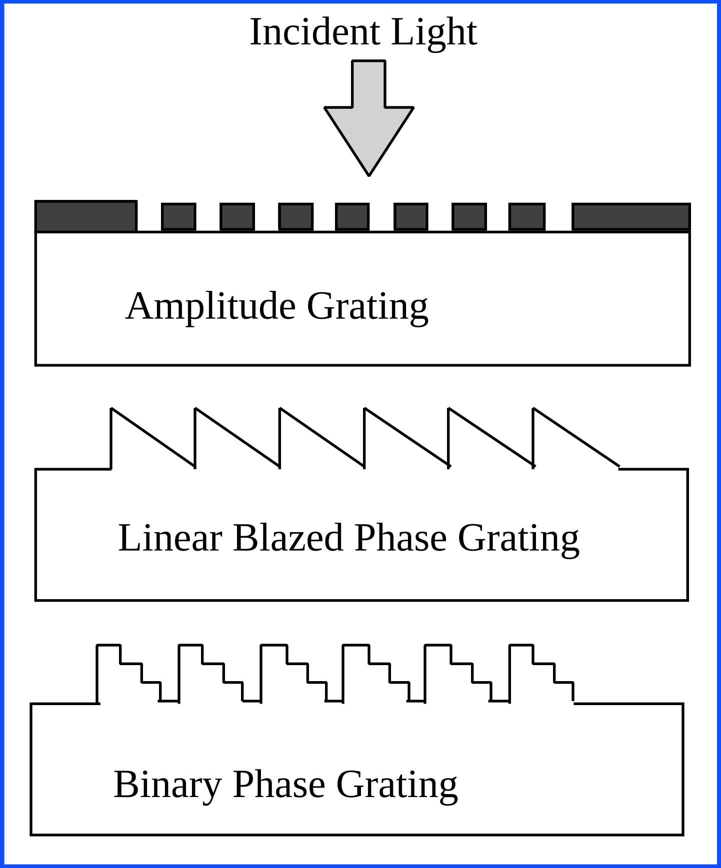
Source: Ohnstein, T. R., Zook, J. D., Cox, J. A., Speldrich, B. D., Wagener, T. J., Guckel, H., Christenson, T. R., Klein, J., Earles, T., and Glasgow, I., "Tunable IR Filters Using Flexible Metallic Microstructures," Proceedings of the IEEE Micro Electro Mechanical Systems Conference, Amsterdam, Netherlands, Jan. 29 - Feb. 2, 1995, pp. 170 - 174.

GRATING SPECTROMETER OPERATION



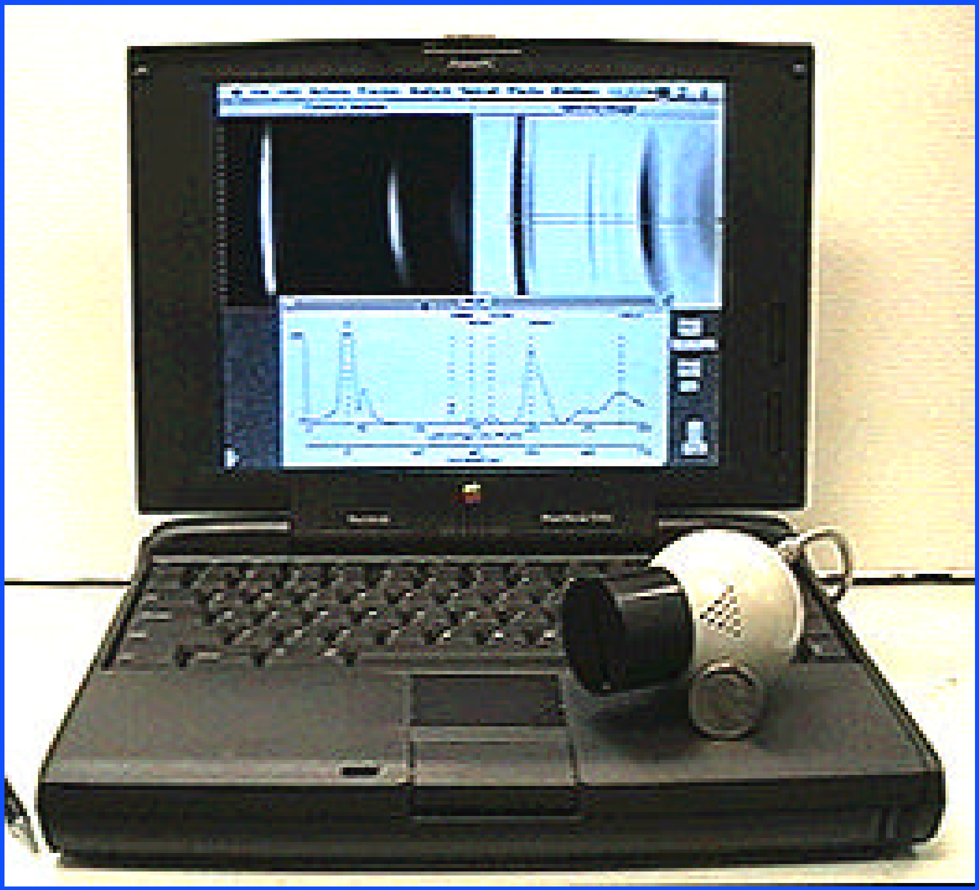
- Light disperses according to its wavelength.
- Fine grating pitch of 0.8 µm allows for short projection distance of ~1cm.
- Micromachining is used to create the gratings.

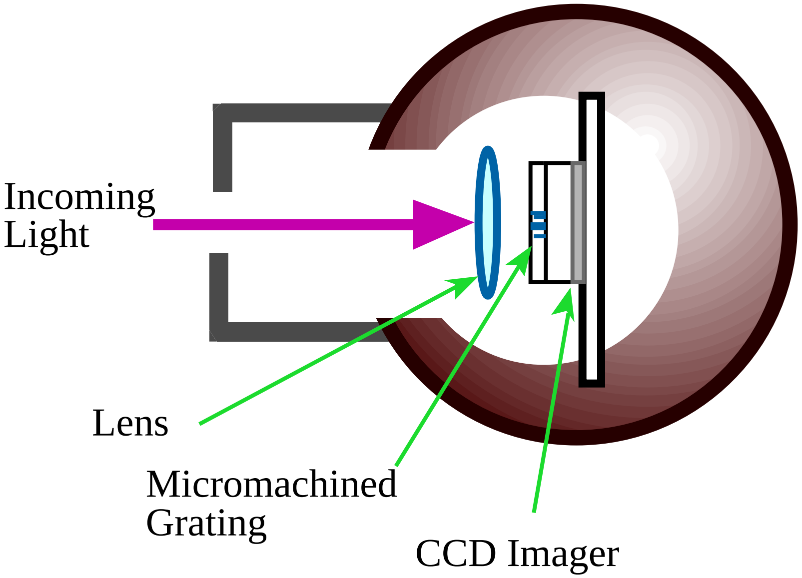
GRATING FABRICATION



- Blazed gratings are more efficient than binary.
- Feasible to approximate blaze in a series of mask steps.
- Quartz wafers are exposed using an electron beam system. A chromium layer acts as a mask for the successive RIE etching.

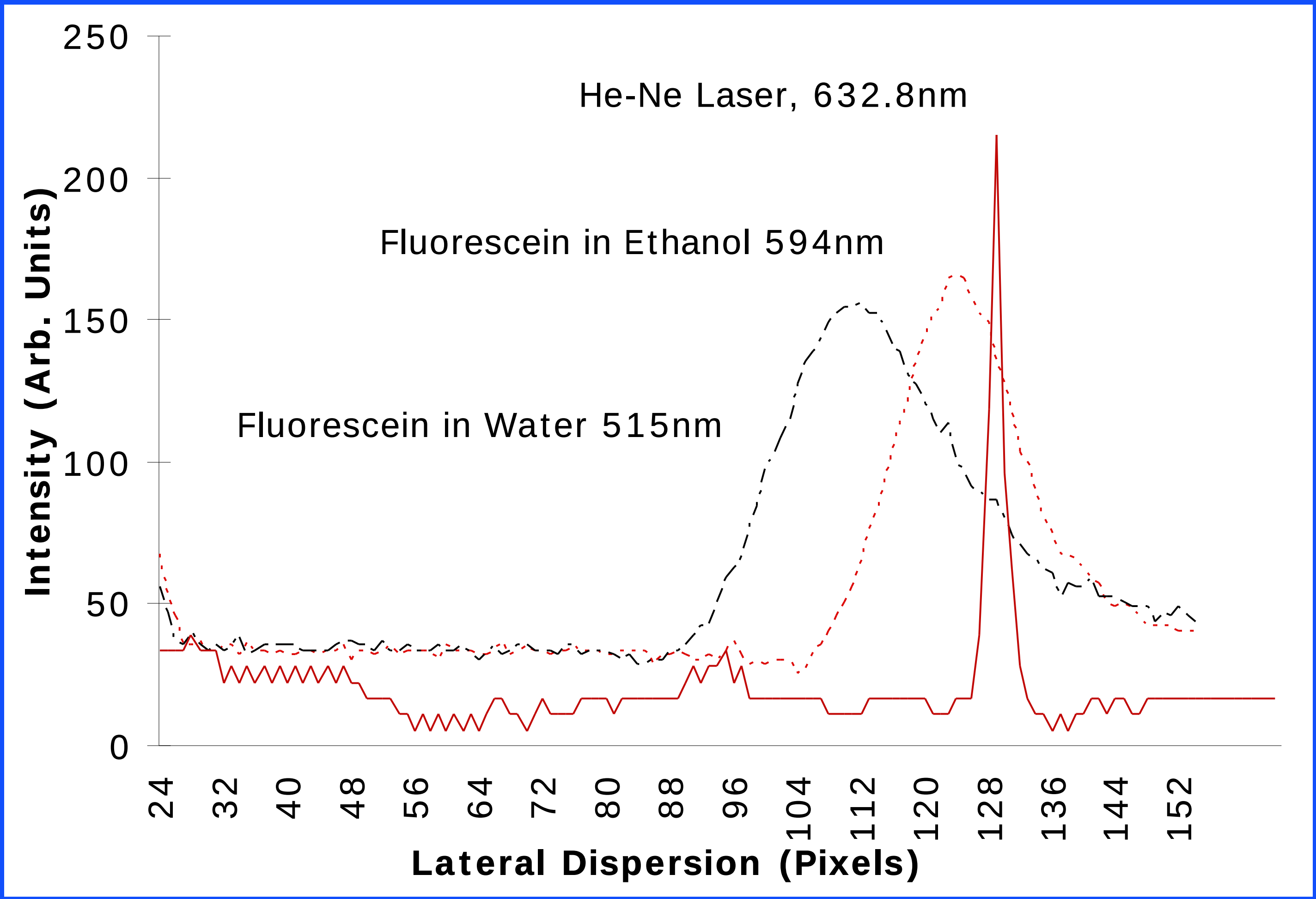
LOW-COST SPECTROMETER SYSTEM





Courtesy G. Yee, Stanford University.

LOW-COST SYSTEM RESPONSE



Courtesy G. Yee, Stanford University.