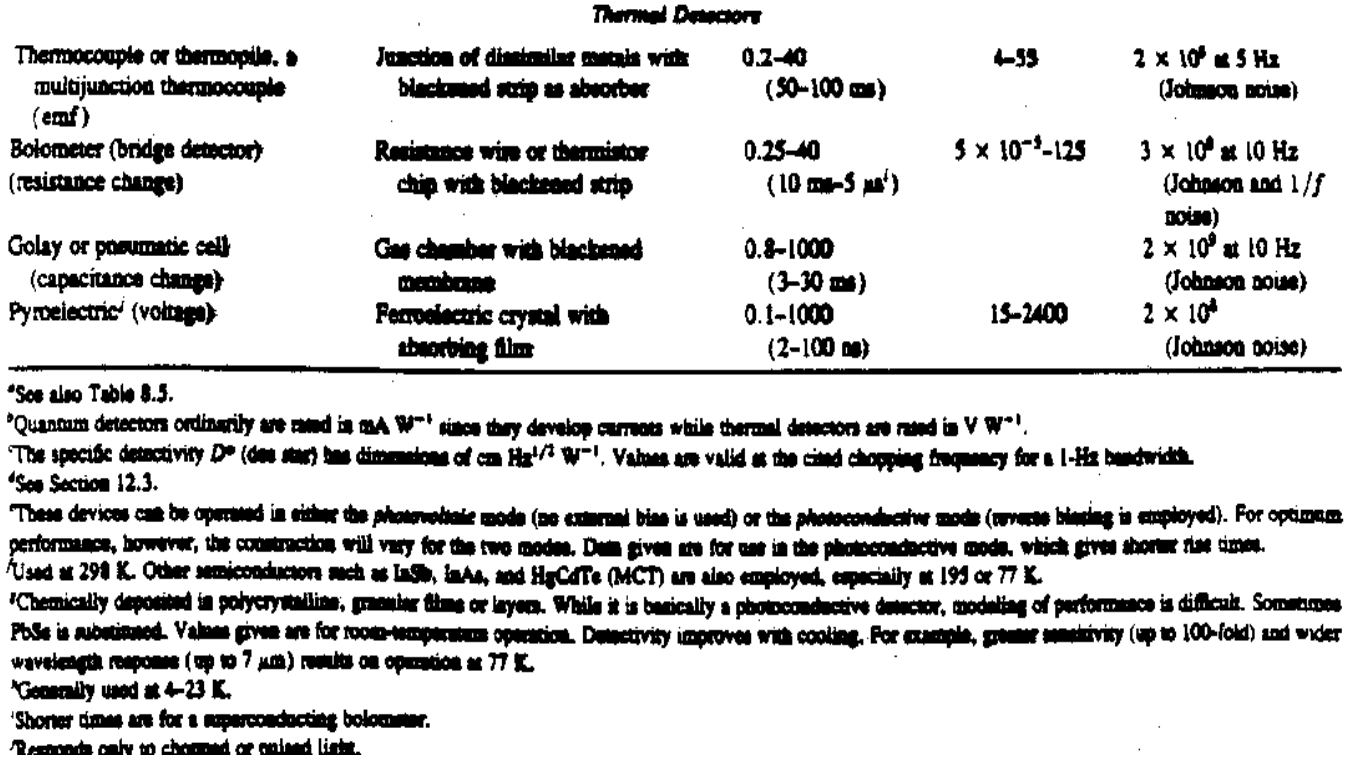
CHEM 524 Course Outline – Detectors - (Part 8)—update 2013

for the 2005 HTML version with linked figures, click here

V. Detectors - Two types Thermal and Photon – see text Table 4-5 (Thermal), 4-6 (photon)

Reading, Chap. 4-4 in text and **handouts** for downloading,

a) PMT operation from RCA and b) infrared detectors from Oriel/Newport



Thermal Detectors

Thermocouple or thermopile, a multijunction thermocouple (emf)	Junction of dissimilar metals with blackened strip as absorber	0.2–40 (50–100 ms)	4–55	2×10^9 at 5 Hz (Johnson noise)
Bolometer (bridge detector) (resistance change)	Resistance wire or thermistor chip with blackened strip	0.25–40 (10 ms–5 μs[i])	5×10^{-3}–125	3×10^8 at 10 Hz (Johnson and $1/f$ noise)
Golay or pneumatic cell (capacitance change)	Gas chamber with blackened membrane	0.8–1000 (3–30 ms)		2×10^9 at 10 Hz (Johnson noise)
Pyroelectric[j] (voltage)	Ferroelectric crystal with absorbing film	0.1–1000 (2–100 ns)	15–2400	2×10^8 (Johnson noise)

[a] See also Table 8.5.

[b] Quantum detectors ordinarily are rated in mA W^{-1} since they develop currents while thermal detectors are rated in V W^{-1}.

[c] The specific detectivity D^* (dee star) has dimensions of cm $Hz^{1/2}$ W^{-1}. Values are valid at the cited chopping frequency for a 1-Hz bandwidth.

[d] See Section 12.3.

[e] These devices can be operated in either the *photovoltaic* mode (no external bias is used) or the *photoconductive* mode (reverse biasing is employed). For optimum performance, however, the construction will vary for the two modes. Data given are for use in the photoconductive mode, which gives shorter rise times.

[f] Used at 298 K. Other semiconductors such as InSb, InAs, and HgCdTe (MCT) are also employed, especially at 195 or 77 K.

[g] Chemically deposited in polycrystalline, granular films or layers. While it is basically a photoconductive detector, modeling of performance is difficult. Sometimes PbSe is substituted. Values given are for room-temperature operation. Detectivity improves with cooling. For example, greater sensitivity (up to 100-fold) and wider wavelength response (up to 7 μm) results on operation at 77 K.

[h] Generally used at 4–23 K.

[i] Shorter times are for a superconducting bolometer.

[j] Responds only to chopped or pulsed light.

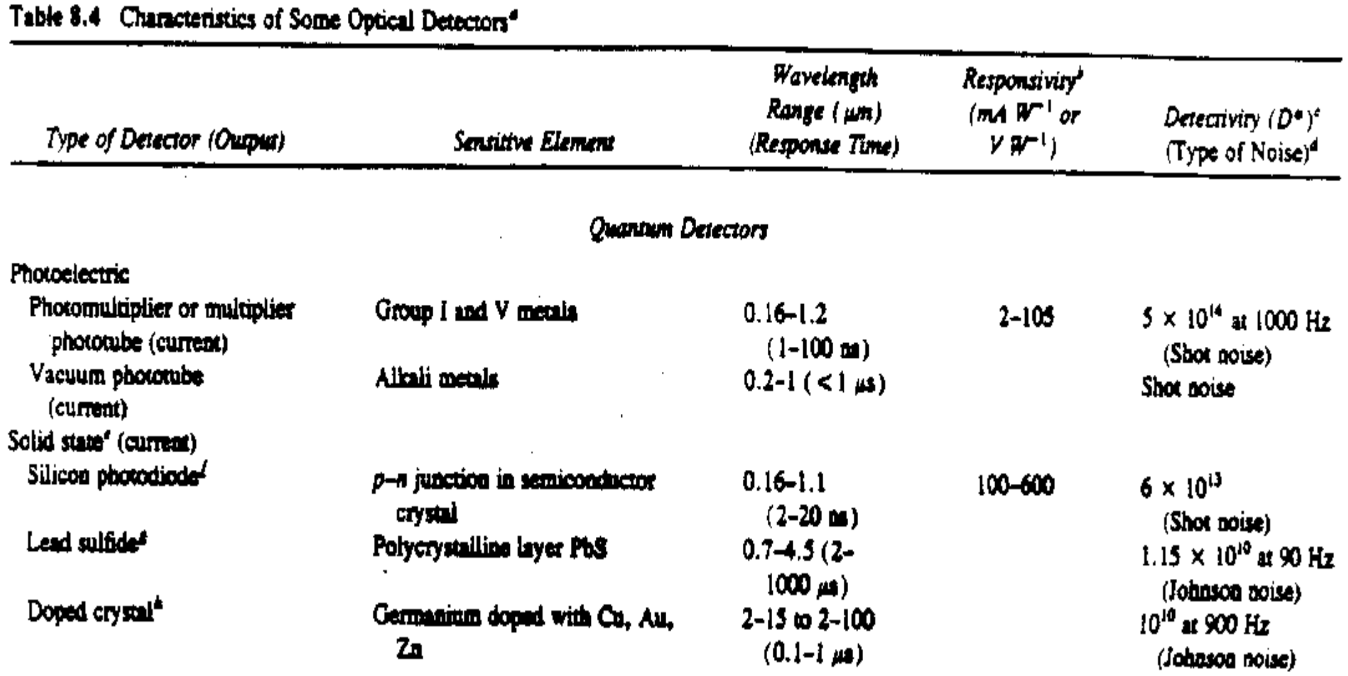


Table 8.4 Characteristics of Some Optical Detectors[a]

Type of Detector (Output)	*Sensitive Element*	*Wavelength Range (μm) (Response Time)*	*Responsivity*[b] *(mA W^{-1} or V W^{-1})*	*Detectivity (D^*)*[c] (Type of Noise)[d]
		Quantum Detectors		
Photoelectric				
Photomultiplier or multiplier phototube (current)	Group I and V metals	0.16–1.2 (1–100 ns)	2–105	5×10^{14} at 1000 Hz (Shot noise)
Vacuum phototube (current)	Alkali metals	0.2–1 (< 1 μs)		Shot noise
Solid state[e] (current)				
Silicon photodiode[f]	p–n junction in semiconductor crystal	0.16–1.1 (2–20 ns)	100–600	6×10^{13} (Shot noise)
Lead sulfide[g]	Polycrystalline layer PbS	0.7–4.5 (2–1000 μs)		1.15×10^{10} at 90 Hz (Johnson noise)
Doped crystal[h]	Germanium doped with Cu, Au, Zn	2–15 to 2–100 (0.1–1 μs)		10^{10} at 900 Hz (Johnson noise)

A. Characterization – where X is current or voltage, what signal generates

- Responsivity ($R = X/\Phi$--signal size for input flux) vs.
- Sensitivity ($Q = \delta X/\delta\Phi$ --change of signal with change of flux)
  - Linearity (region in which $Q =$ const.),
  - Dynamic Range (magnitude of Q variation measurable),
  - Stability (time over which. R, Q are const),
  - Degradation (long term stability),
  - Hysterisis (power dependent change in R,Q)
- Timing:
  - Rise time (10-90% full response) and
  - Time constant $[\tau = (2\pi f_c)^{-1}\ f_c \rightarrow R = 0.7\ R_{max}]$
- Signal to noise ratio:
  - Noise equivalent Power (NEP is signal level needed to obtain S/N = 1)
  - Detectivity ($D^* = DA_d^{1/2}\ (\Delta f)^{1/2}$, $D = (NEP)^{-1}$) – “D-star”
  - Quantum efficiency ($\kappa(\lambda)$ = # electron / # photon)

B. Thermal (energy) detectors -- increase in temperature creates electrical response (table)

1. Typically light irradiates blackened plate, heating it,

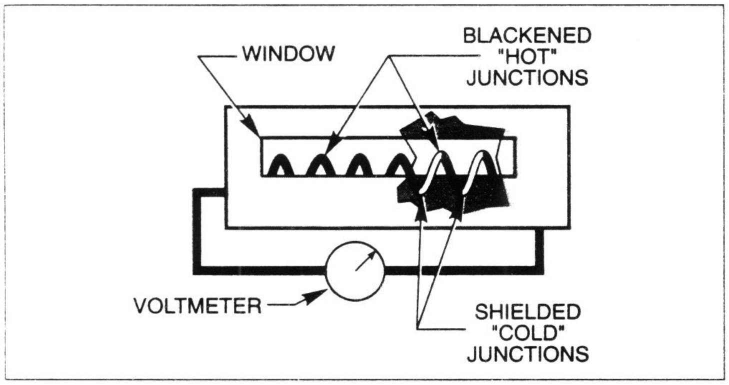
    causes response in the sensor coupled to it

Expect - slow and modest sensitivity, surface heated should be small for sensitivity

Light must heat detector heat capacity, sensor must develop a voltage response

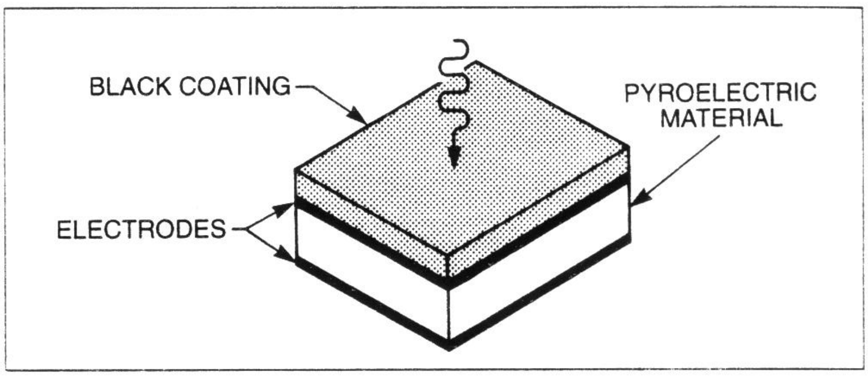
- Thermocouple, thermopile (voltage vs. T), two-metal junctions develop V ~ΔT hot/cold

    Thermo pile uses multiple junctions in series, bigger voltage response



-
- Thermistor bolometer (resistance vs. T), R decrease with T, typ. semiconductor or metal
- Pneumatic Golay (pressure vs. T)— tune to specific gas absorbance (dedicated sensor)

2. Pyroelectric -- e.g. TGS -- responds to dT/dt, change in T – standard FTIR detector



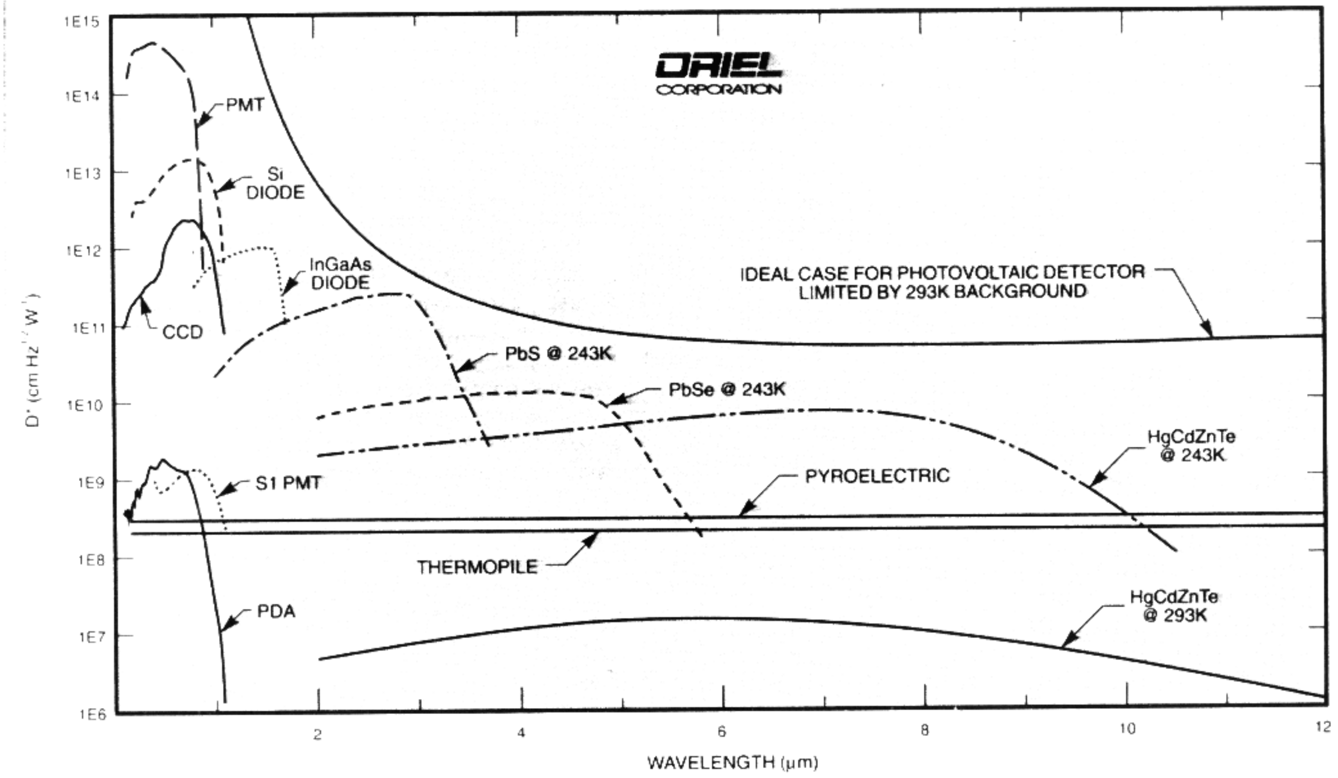
- relatively fast time constant, integrates flux, T-dep. polarized crystal
- flat response with wavelength, relatively inexpensive,

DTGS (deuterated triglycine sulfate), $LiTaO_3$, lead zinc titanate (PZT)

- small chip size, can be made into arrays, allows imaging →
- also used as energy detectors for pulsed lasers – V ~ dT/dt
- perfect for rapid scan FTIR, modulated signal, broad response
- due to handling small signals, 1st stage amplifier typically built in

C. Photon Detectors -- quantum response to # photons above threshold (table)

--D* will be limited by background radiation (BLIP) → room temperature windows, optics



--power response falls off in uv compare to IR, uv more energy/phot., respond to photon

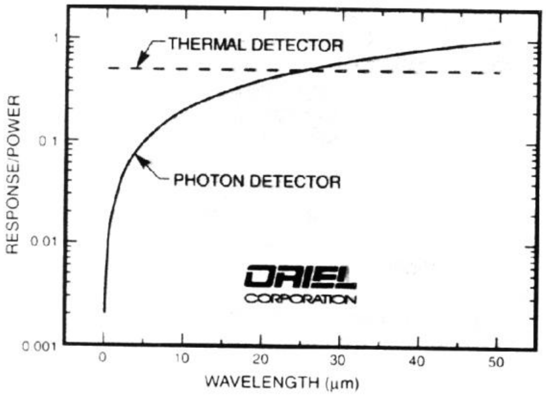


Fig. 7 Relative spectral responsivities of perfect detectors.

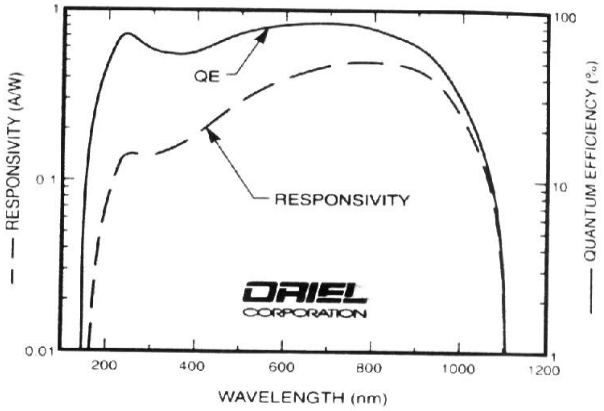


Fig. 8 Silicon responsivity and quantum efficiency.

1. Photo multiplier -- current source, based on photo-electric effect – lots of designs

- Photo cathode -- P-E effect -- modest quantum effic. -- spectral response--see curves

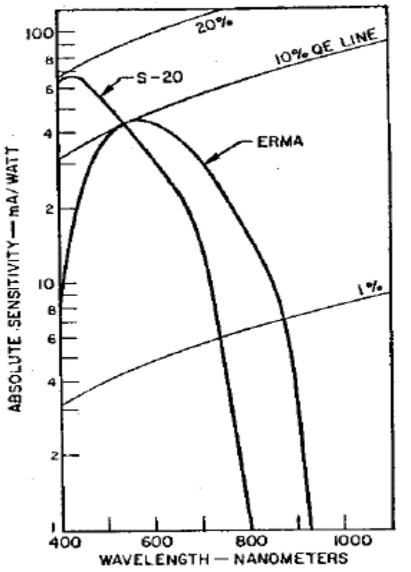


Fig. 7 — Typical spectral-response curve for one of the Extended Red Multi-Alkali (ERMA) photocathodes in comparison with a conventionally processed multialkali photocathode.

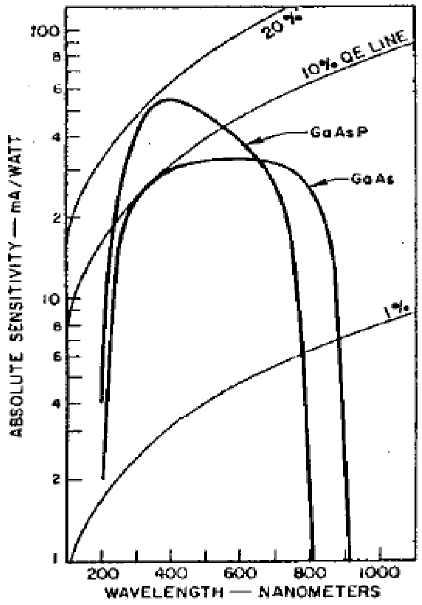


Fig. 8 — Typical spectral-response curves for GaAs(Cs) and $GaAs_xP_{1-x}(Cs)$ *opaque photocathodes.*

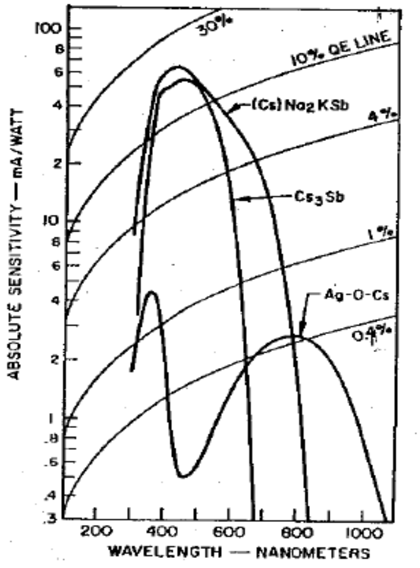
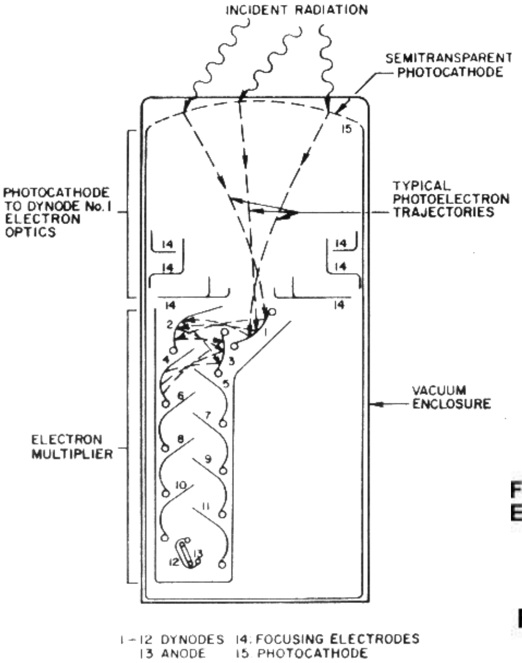


Fig. 6 — Typical spectral-response curves, with 008 lime-glass window, for (a) silver-oxygen-cesium (Ag-O-Cs), (b) cesium-antimony (Cs_3Sb)*, (c) multi-alkali or trialkali* [$(Cs)Na_2KSb$]*.*

- Multiplier -- gives internal gain / results in sensitivity to lowest light levels (photon/sec)
  --based on dynode chain, each with secondary electron emit (book fig. 4-22 diagram)
  --succession of increasing positive (less neg.) voltages accelerate e^- through dynodes



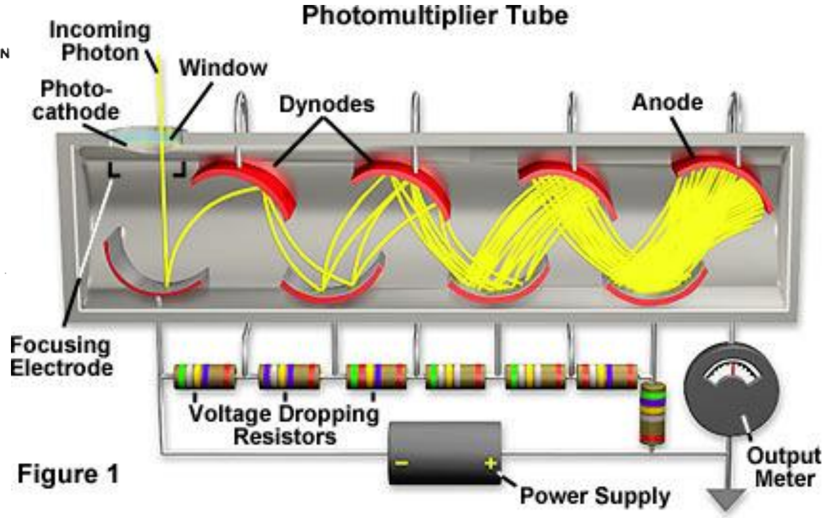
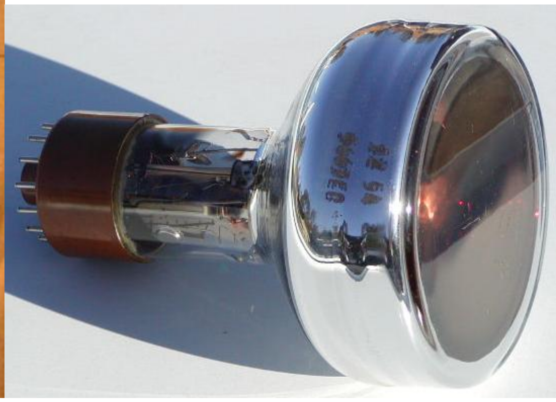


Figure 1



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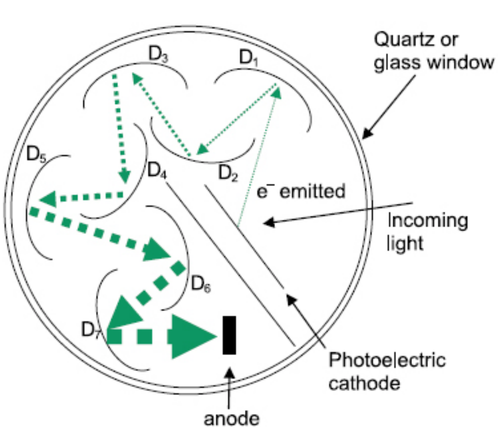
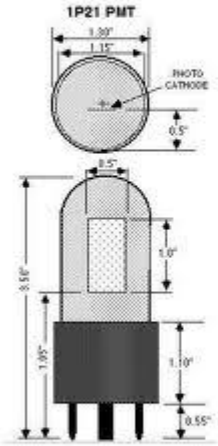




or side illuminated

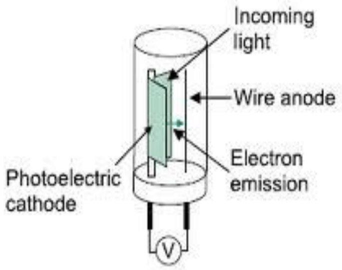
PMT S/N and operation parameters:

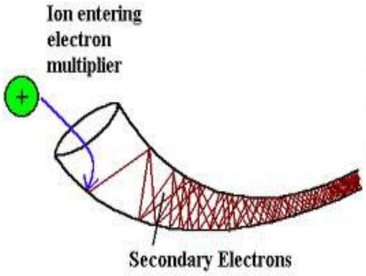
- Dark current -- main source of noise at high temperature, can cool to improve S/N
- Shot noise-- proportional to $\Phi^{1/2}$ -- more light better S/N – just statistics, fundamental
- Can be pulse-counted -- best S/N at low light level, discriminate against thermal noise

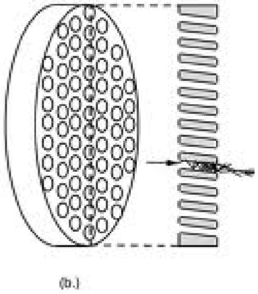
2. Variants: a. photodiode – photocathode + anode, no multiplier, no gain, but inexpensive det.

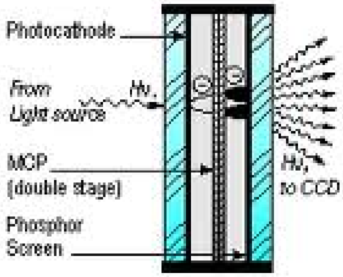
b. Channeltron, micro channel plate, intensifier

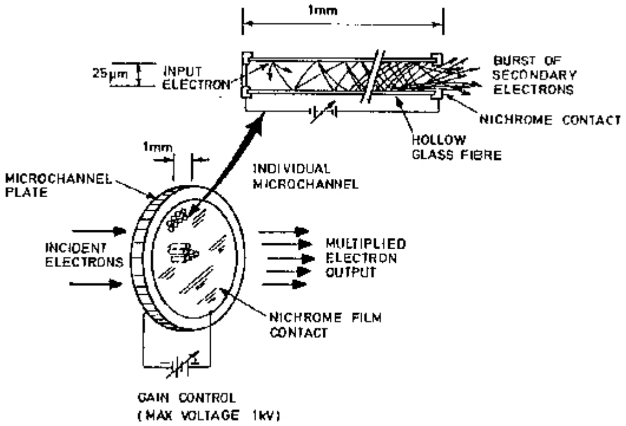
Concept is a tube with surface that creates secondary electrons upon e^- impact
Continual voltage gradient over length of tube, channeltron shaped like cone,
Alternate - multi-micro-channel sloped but maintain spatial separation (intensifier/image)











Proximity-Focused Image Intensifier

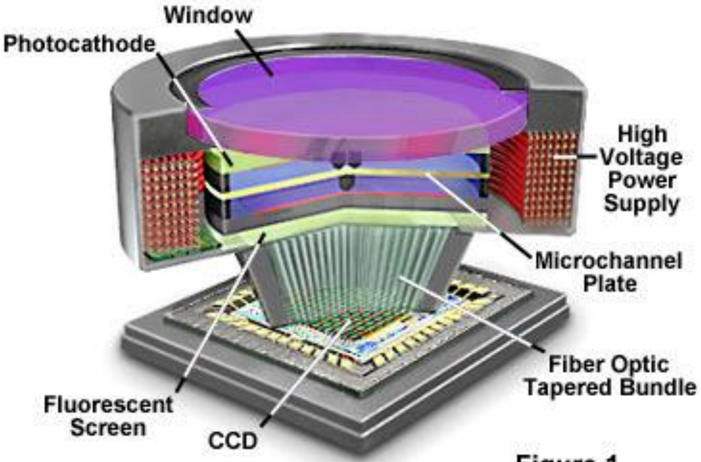
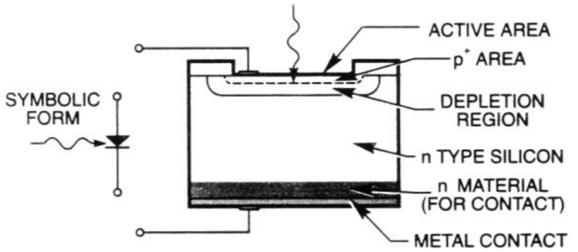


Figure 1

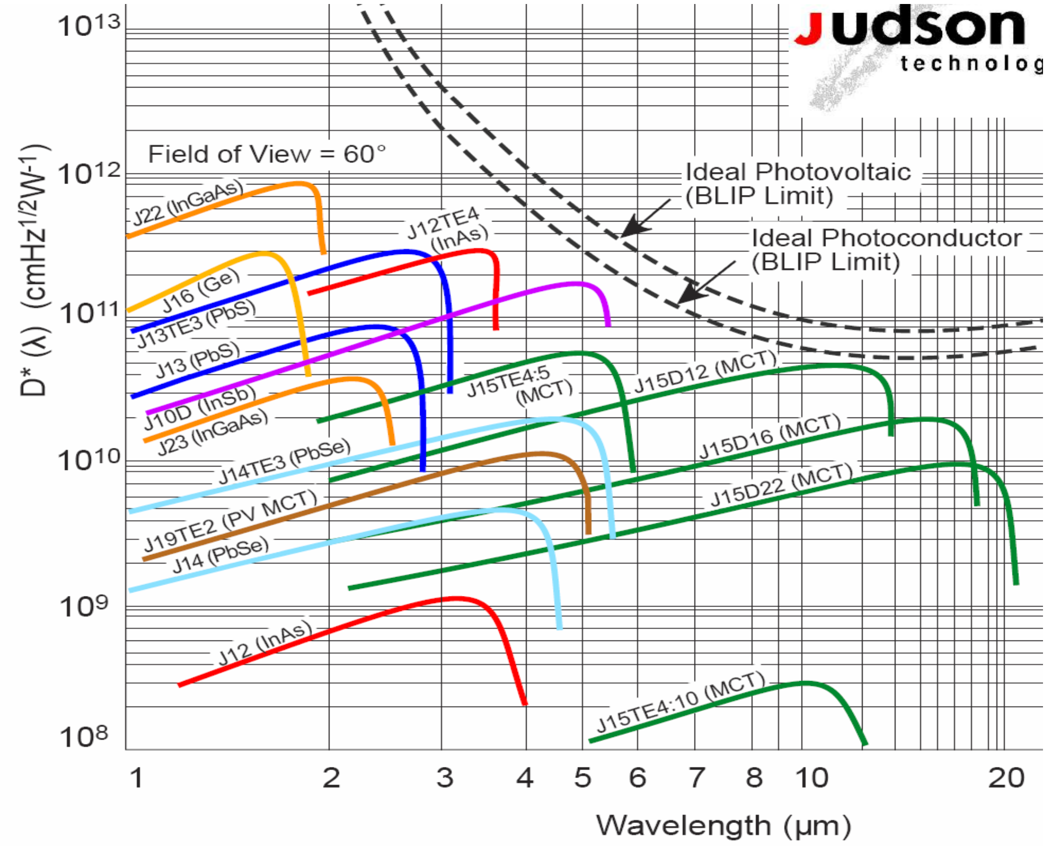
c. Intensifier has photo cathode to create electrons, then accelerate straight at plate, Multiplier – increased num. electrons (~10^3) through channels - comes off back of plate then accelerated (straight again) into phosphor, and use CCD or other detector to sense phosphorescence which maintains spatial distribution of original light –image possible

3. Vacuum UV, since glass window on PMT will not transmit in VUV – can make quartz, but only minor λ improvement. Crystal windows possible but expensive, usual - coat a fluorophore on glass window (outside), let photocathode detect the fluorescence and create photoelectrons (signal). Losses – fluorescence directionality and quantum yield

4. Photodiodes -- photo-voltaic (P-V) -- excite e^- to conduction band, act as current source



10 Model of a silicon photodiode. The junction between the p^+ and depletion regions give this detector its name.



For comparison, PMT can have $D^* > 10^{14}$

BLIP curve is limit for D* with black body illumination at room temp. theoretical limit if detector looks out at window/optics in lab

Cooler detectors have higher D*
Can also cold-shield detector, limit its field of view (FOV)

- Sensitivity: quantum efficiency high but no internal gain, need external amplification
- Zero bias operation, less sensitive to drift, current source – amp: (I →V)
- Spectrum depends on material, Si-vis to 1.1 μ, Ge to 1.8 μ, InSb (near IR to 5 μ), MCT ($Hg_xCd_{1-x}Te$, mid IR, varies with x, normally to 12 μ)--see response curve above (Judson)
- Time response depends on material, diode capacitance $\tau_r = 2.2 C_t \bullet R_L$ where $C_t = AV_b^{-1/2}$

Si can be ns, InGaAs even faster, but InSb ~ μs, others slower, MCT can be fast if small

- Applied voltage - reverse bias and reduce area - speed up response, adds complications

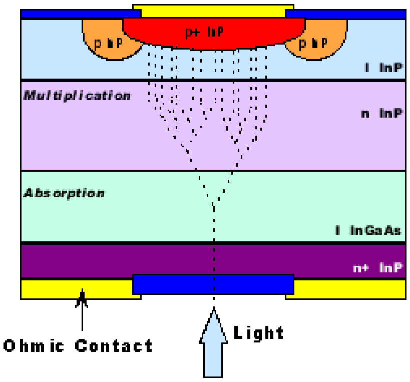
Avalanche photodiodes (APDs) are photodiode detectors that have *internal gain* like photomultipliers. High reverse bias voltage (typically 100-200 V in silicon), gives internal current gain (around 100) due to impact ionization (avalanche effect). Higher values are possible in alternate designs. In general, the higher the reverse voltage the higher the gain.

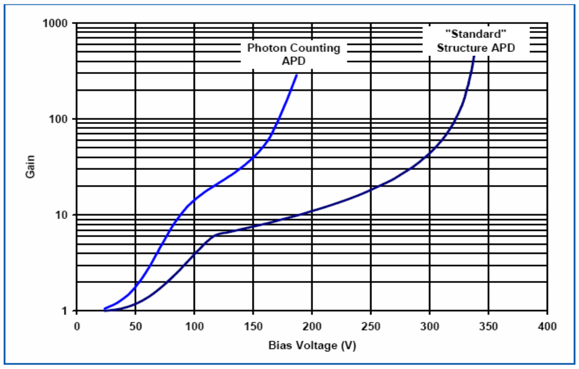
Lower voltages than PMT, but less gain, advantage, *now* simpler, compact, stable

Si have largest gain, work in 200-1000 nm region, usually optimized for one part, Ge go to 1.7 μm, tend to be noiser, and InGaAs offers a lower noise alternative, (both have gains in 10s) -- There are reports of MCT based avalanches for the IR

Some background info:

http://sales.hamamatsu.com/assets/applications/SSD/Characteristics_and_use_of_SI_APD.pdf
http://optoelectronics.perkinelmer.com/content/whitepapers/AvalanchePhotodiodes.pdf

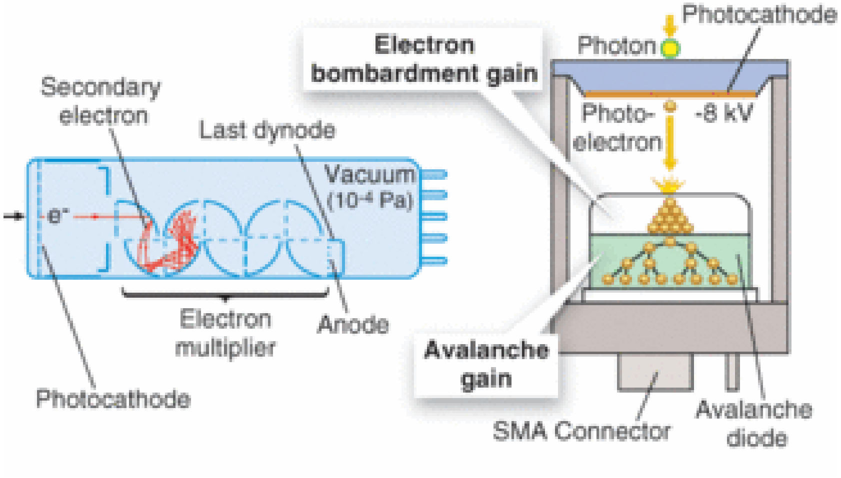




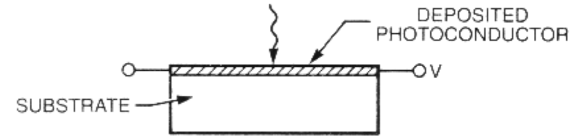
The Gain as a function of the bias voltage varies with the structure of the APD

High gain (10^6) by cooling and operation in Geiger mode (V > breakdown)

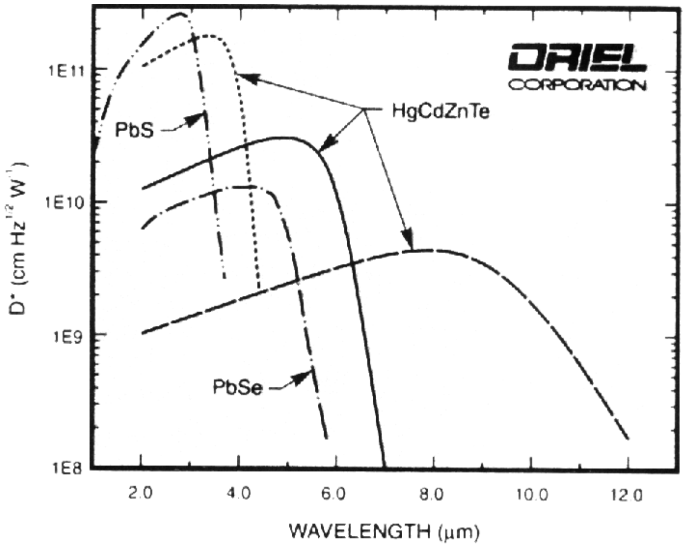
Hybrid detectors, use photocathode plus avalanche technology, gain ~10^5, better time resolut.



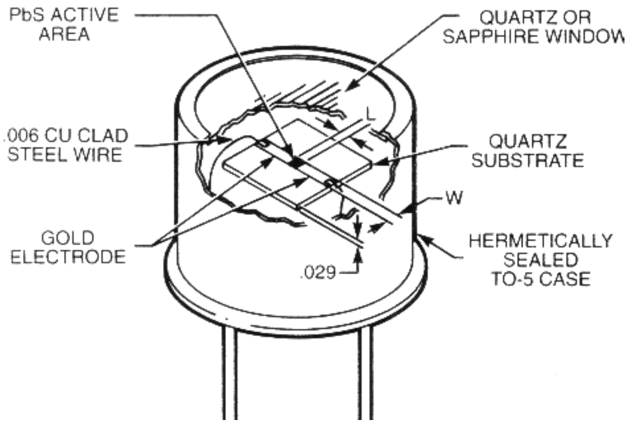
4. Photoconductors -- dominate IR market -- effectively variable resistance of semi-conductor, change by push electrons into the conduction band, spectral sensitivity down to band gap, needs bias voltage, together act as voltage source



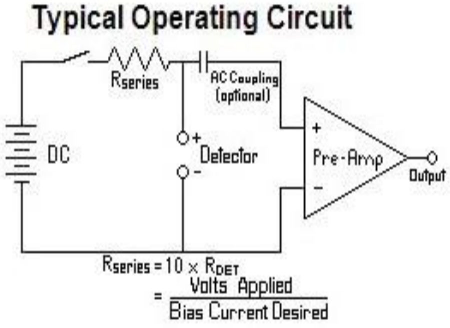
g. 13 Schematic of a photoconductive detector.

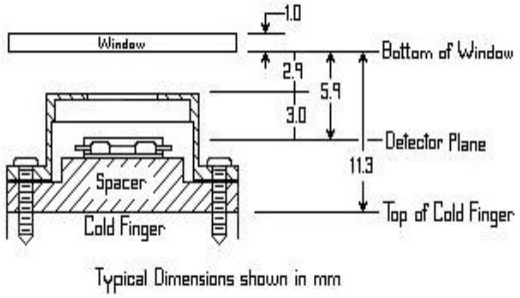


ig. 16 Typical detectivities of some of our cooled IR detectors



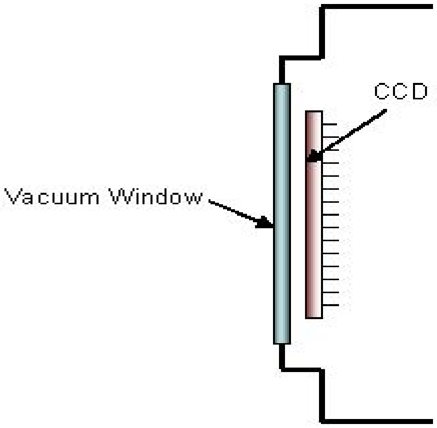
- PbS, PbSe, --near IR, cheap, room temperature, slow
- InAs (to 3+ µ), InSb (to 5.5 µ) -- faster response, but lower noise if P-V and/or 77K cool
- MCT -- $Hg_x(Cd)_{1-x}Te$ -- variable spectral range, highly popular
    1. due to band gap, varies with stoichiometry (x), vis to mid IR,
    2. 8-20 µ long wave limit are available, narrow band vs. wide band
    3. liquid N_2 cooling (77K) needed for nearly BLIP limited D*
- PbSeTe – nearly the same sort of properties as MCT
- Doped Ge—dopants (e.g. Au, As, Cu, Ga) vary Ge band gap—Ge:Ga far-IR sensitivity
    1. typically need more cooling, more bias (can be fast)
    2. specialized applications, not routine
    3. some need more cooling (10-20 K)





D. Multichannel Detectors—*growth area, imaging*-- See Multichannel Detector links (below)

- older technologies: Film, Vidicon, Diode Array (1-D, Si based, PDA)
- **CCD** (charge coupled device) - Si based, 2D, high quantum yield –dominate field
  - Can be “square” ~1024x1024 pixels, or 2048x2048, or more in cameras
    - “pixel” - each detector element, typical 26 μ size, or smaller
  - or rectangle with e.g. 100x1300 or 256x1024 for spectra from monochromator
  - Speed and sensitivity can tradeoff, back-thinned have high quantum efficiency
    - or back illuminated and special coated for UV or other spectral need
  - Cooling can reduce dark current approximately to digitization level



Spectroscopic CCD: Device size is primarily for cooling and control, chip in vacuum, at focus

- Intensifier can increase sensitivity (not generally needed with top CCD), useful for PDA
- Particular interest are “focal plane array detectors” of InSb or MCT where pixels are IR detectors, but array sizes range form 64x64 up to 256x256 (more?) – FTIR imaging
- Room temperature arrays are available made from GaAs/AlGaAs materials with a Quantum Well IR photodetector (QWIP) array technology – near IR application, extend to IR with InGaAs/InP, InGaAs/InAlAs, and AlGaInAs/InP – may over take MCT

diode arrays—linear line of detectors for spectrum

Focal plane array for imaging

Homework— part of Set #3

Read Chap. 4, transducers, Sect. 4-4, and links below for: PMT and IR detectors

Discuss: Chap 4- #5, 6, 10, 17

a. I have several PMTs. Two nice ones are both cylindrical end-on designs, one has a transparent multi-alkalai photocathode (S-20) which covers most of the diameter of the tube (~50 mm) and the other has an InGaAs solid photocathode with an opening of ~10 x 15 mm. Why would I have two of them? What are the design advantages of each?

b. I have several MCT detectors, one is wide band and detects out to about 16 μ, two are narrow band and cut off at ~ 8 μ. Most are medium band cutting off at ~12 μ. They all vary in D*, but the narrow band ones are >4 x 10^{10} while the wide band is ~5 x 10^9, why is this? All are mounted in liquid N_2 dewars, why? These are photoconductors, why do they need a bias voltage?

c. I have an InSb detector, P-V design. Where would I use this (i.e. what kind of spectroscopy)? What kind of preamp would this need?

d. We have a photodiode array (PDA) and a CCD both based on Si chips and for use in a Raman Spectrometer. The CD can make an image of the spectrum at the exit plane, but the PDA cannot, why is this?

Problems to hand in: Chapter 4: #3, 15, 16

Links

Two handouts are linked in the list of notes as pdf files for downloading,

one on PMT operation from RCA and

one on infrared detectors from Oriel

Korean site with PMT tutorial
http://elchem.kaist.ac.kr/vt/chem-ed/optics/detector/pmt.htm

Wikipedia PMT site
http://en.wikipedia.org/wiki/Photomultiplier

Online tutorial: from Acreo with a point of view (QWIP)
http://www.acreo.se/templates/Page____226.aspx

A dated review of detectors, by E H Putley
http://ej.iop.org/links/q03/ICDDvZ5nWNmcFKO2WL8dEA/ptv4i3p202.pdf

Focal plane array article use of FTIR of chemical imaging (Digilab)
http://www.aip.org/tip/INPHFA/vol-9/iss-5/p29.html

Another (in Spectroscopy) from Bruker
http://www.brukeroptics.com/downloads/SP1001Schultz.pdf

Summary discussion of various focal plane array detection systems--Sierra Pacific Infrared
http://x26.com/infrared/images/fpa.htm

Detector companies:

Judson Technologies, range of IR detectors for spectroscopy
http://www.judsontechnologies.com/
Infrared Associates, good line of MCT and InSb etc. including multielement arrays
http://www.irassociates.com/
Hamumatsu—wide range of photodiode detectors and photomultipliers
http://www.sales.hamamatsu.com/en/products/solid-state-division.php
http://www.sales.hamamatsu.com/en/products/electron-tube-division/detectors.php
EMI and RCA used to be big PMT manufacturers, but all sites I find are resale/reconditioning
Products for Research makes PMT housings with cooling
http://www.photocool.com/
PTI seems to have a system for PMT housings also, and gives background on the topic
http://www.pti-nj.com/obb_8.html
CalSensors—PbS and PbSe detectors
http://www.calsensors.com/
EOC many different detectors including pyroelectrics
http://www.eoc-inc.com/
IR Labs—bolometers
http://www.irlabs.com/irlabs%20pages/irlabs_frameset.html
Avalanche photodiodes—background form Hamamatsu Corp

http://sales.hamamatsu.com/assets/applications/SSD/Characteristics_and_use_of_SI_APD.pdf
Perkin-Elmer background brochure
http://optoelectronics.perkinelmer.com/content/whitepapers/AvalanchePhotodiodes.pdf
Newport—High gain Geiger mode
http://www.newport.com/Avalanche-Photodiode-Detectors-High-Gain-SPM-Seri/828083/1033/catalog.aspx?gclid=CM6Oh8LxjpkCFQ0NDQodDBArZQ#
Multichannel sites:
Photometrics Germany Roper Scientific
http://www.photometrics.de/
Princeton Instruments/Acton div. of Roper (pixis detectors)
http://www.princetoninstruments.com/products/pixis/
Princeton Instruments- Acton
http://www.piacton.com/spectroscopy/
Andor Technology==ccd camera
http://www.andor-tech.com/products/brand.cfm?marketsegment=2&brand=6
Sensors Unlimited inc focal plane arrays, (InGaAs)
http://www.sensorsinc.com/arrays.html
Northrup Grumman IR Electro-optic Div--night vision etc (military)
http://www.es.northropgrumman.com/es/eos/ir_products.htm