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

### Table 8.4 Characteristics of Some Optical Detectors

<table>
<thead>
<tr>
<th>Type of Detector (Output)</th>
<th>Sensitive Element</th>
<th>Wavelength Range (μm)</th>
<th>Responsivity (mA W⁻¹ or V W⁻¹)</th>
<th>Detectivity (D*) (Type of Noise)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantum Detectors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photomultiplier or multiplier phototube (current)</td>
<td>Group I and V metals</td>
<td>0.16-1.2 (1-100 ns)</td>
<td>2-105</td>
<td>$5 \times 10^{14}$ at 1000 Hz (Shot noise)</td>
</tr>
<tr>
<td>Vacuum phototube (current)</td>
<td>Alkali metals</td>
<td>0.2-1 (&lt; 1 μs)</td>
<td></td>
<td>Shot noise</td>
</tr>
<tr>
<td><strong>Solid state</strong> (current)</td>
<td>$p-n$ junction in semiconductor crystal</td>
<td>0.16-1.1 (2-20 ns)</td>
<td>100-600</td>
<td>$6 \times 10^{13}$ (Shot noise)</td>
</tr>
<tr>
<td>Silicon photodiode²</td>
<td>Polycrystalline layer PbS</td>
<td>0.7-4.5 (2-1000 μs)</td>
<td></td>
<td>$1.15 \times 10^{10}$ at 90 Hz (Johnson noise)</td>
</tr>
<tr>
<td>Lead sulfide³</td>
<td>Germanium doped with Cu, Au, Zn</td>
<td>2-15 to 2-100 (0.1-1 μs)</td>
<td></td>
<td>$10^{10}$ at 900 Hz (Johnson noise)</td>
</tr>
</tbody>
</table>
A. Characterization – where X is current or voltage, what signal generates

- **Responsivity** \((R = \frac{X}{\Phi})\) – signal size for input flux) vs.
- **Sensitivity** \((Q = \frac{\delta X}{\delta \Phi})\) -- change of signal with change of flux
  - Linearity (region in which \(Q = \text{const.}\)),
  - Dynamic Range (magnitude of Q variation measurable),
  - Stability (time over which R, Q are const),
  - Degradation (long term stability),
  - Hysteresis (power dependent change in R,Q)

- Timing:
  - Rise time (10-90% full response) and
  - Time constant \(\tau = (2\pi f_c)^{-1} f_c \rightarrow R = 0.7 R_{\text{max}}\)

- Signal to noise ratio:
  - Noise equivalent Power (NEP is signal level needed to obtain S/N = 1)
  - Detectivity \((D^* = DA_d^{1/2} (\Delta f)^{1/2}, D = (\text{NEP})^{-1})\) – “D-star”
  - Quantum efficiency \((\kappa(\lambda) = \# \text{ electron} / \# \text{ photon})\)

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 \(V \sim \Delta T\) hot/cold
  - Thermo pile uses multiple junctions in series, bigger voltage response

![Thermocouple diagram](#)

- 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 \( \frac{dT}{dt} \), 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 \( \sim \) \( \frac{dT}{dt} \)
- perfect for rapid scan FTIR, modulated signal, broad response
- due to handling small signals, 1\(^{\text{st}}\) 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

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**
• **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
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)**
   - c. Intensifier has photo cathode to create electrons, then accelerate straight at plate,
     - **Multiplier** – increased num. electrons ($\sim 10^3$) through channels - comes off back of plate
     - then accelerated (straight again) into phosphor, and use CCD or other detector to sense phosorescence 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 $\lambda$ 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.

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: $(I \rightarrow V)$
- **Spectrum depends on material,** Si-vis to 1.1 $\mu$, Ge to 1.8 $\mu$, InSb (near IR to 5 $\mu$), MCT (Hg$_x$Cd$_{1-x}$Te, mid IR, varies with x, normally to 12 $\mu$) -- see response curve above (Judson)
- **Time response depends on material,** diode capacitance $\tau_r = 2.2C_tR_L$ where $C_t = AV_b^{-1/2}$
Si can be ns, InGaAs even faster, but InSb ~ $\mu$s, 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 \( \mu \)m, 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://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 \((V > \text{breakdown})\)

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.

- **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

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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 10^8, why is this? All are mounted in liquid N₂ 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

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)

Another (in Spectroscopy) from Bruker

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/

Hamamatsu—wide range of photodiode detectors and photomultipliers

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

CalSensors—PbS and PbSe detectors
http://www.calsensors.com/

EOC many different detectors including pyroelectrics
http://www.eoc-inc.com/

IR Labs—bolometers

Avalanche photodiodes—background form Hamamatsu Corp

Perkin-Elmer background brochure
http://optoelectronics.perkinelmer.com/content/whitepapers/AvalanchePhotodiodes.pdf

Newport—High gain Geiger mode

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)