light sensing & sensors

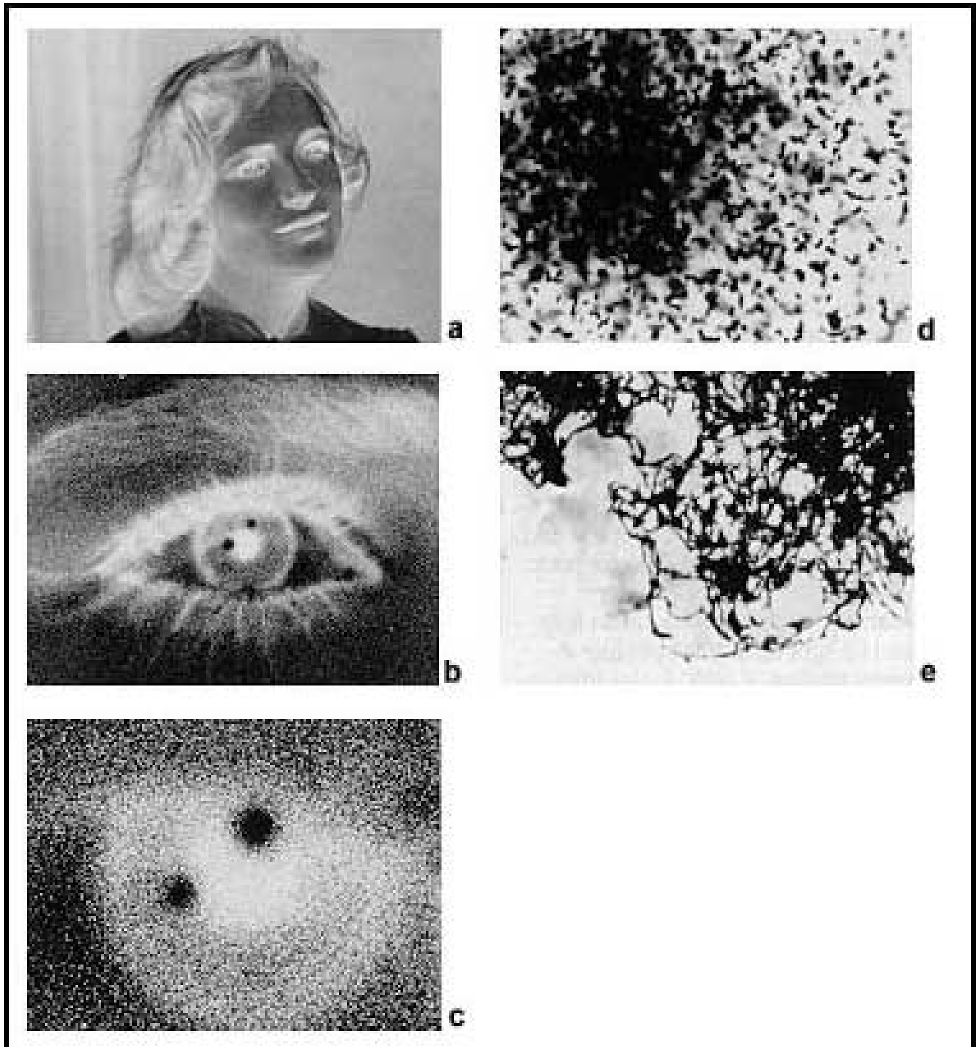
reading

Fraden Section 3.13, Light, and
Chapter 14, Light Detectors

three basic principles of light sensing

- photochemistry:
  light renders silver halide grains in film "emulsion" "developable"
- thermal physics:
  heating effect of incident light heats sensor that basically measures temperature
- photophysics:
  interaction of light with matter frees electrons
  - (more typically, rather than freeing them, it promotes them from valence to conduction band)

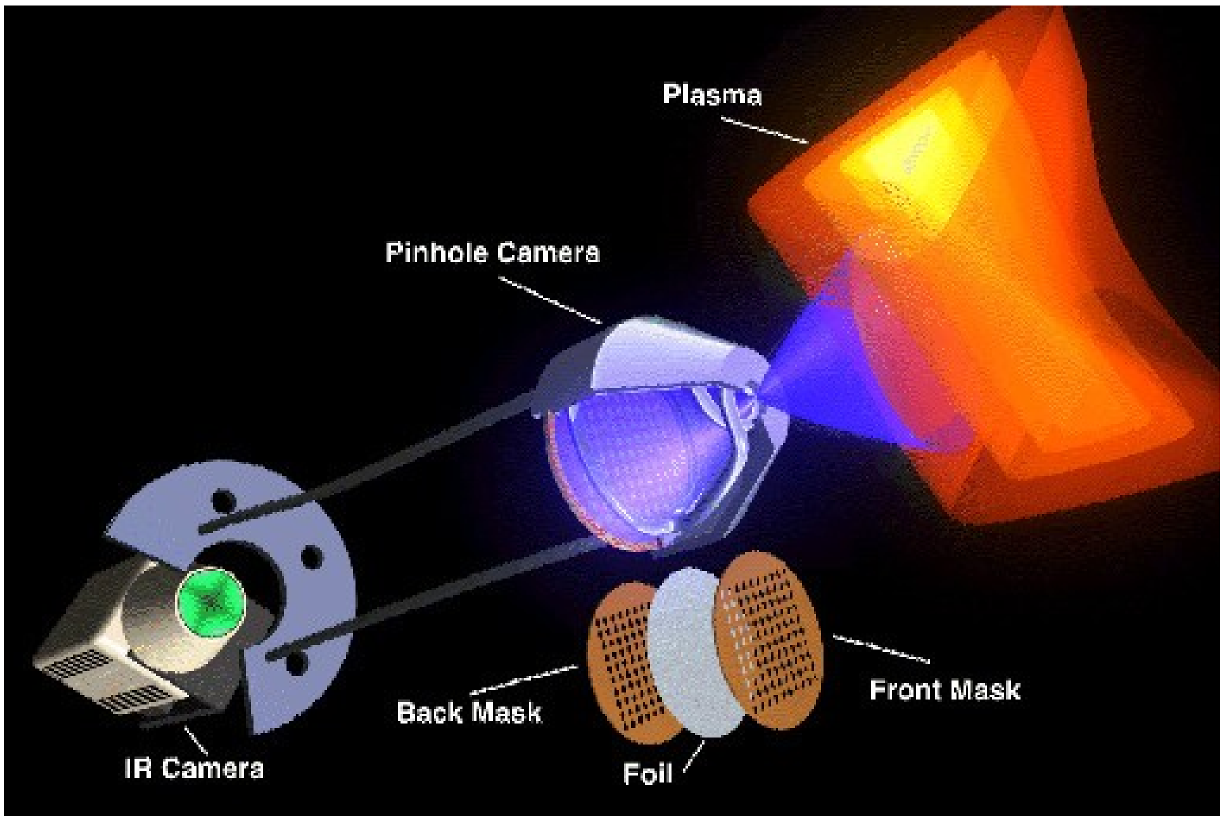
photographic film



(a) A 2.5X enlargement of a negative shows no apparent graininess. (b) At 20X, some graininess shows. (c) When a segment of the negative is inspected at 60X, the individual silver grains start to become distinguishable. (d) With 400X magnification, the discrete grains are easily seen. Note that surface grains are in focus while grains deeper in the emulsion are out of focus. The apparent "clumping" of silver grains is actually caused by overlap of grains at different depths when viewed in two-dimensional projection. (e) The makeup of individual grains takes different forms. This filamentary silver, enlarged by an electron microscope, appears as a single opaque grain at low magnification.

thermal physics (bolometry)

- usually just a simple temperature-sensitive resistor in a Wheatstone Bridge circuit
- but they can get very fancy, as in this NASA camera ...



note that you don't need the IR camera ... you could measure the local resistivity of the foil, or replace the foil with an array of thermocouples, RTDs, etc

photoelectric effect

- light absorbed by metal surfaces causes current to be ejected from them
  - for visible light, it is necessary to use alkali metals – typically cesium – in a vacuum
- light absorbed by semiconductors causes their conductivity to increase (i.e., causes their resistivity to decrease)
  - depending on device structure and measuring approach, signal may be seen as photocurrent, photovoltage, or photoconductance

photoelectric effect: history

- well understood empirically by ~1900:
  - photocurrent proportional to light intensity
  - “stopping potential” inversely proportion to wavelength of light employed
  - generally the more chemically reactive the photocathode metal the longer the maximum wavelength that will cause photoemission
- explained by Einstein in 1905 based on recent quantum hypothesis of Planck: (photon energy) $E = h\, v$ (frequency)

electrons & photons explain it

- optical power = photons/second * energy/photon
- electron current created is proportional to photons/second received
- for any given material (copper, silicon, etc), there is a well-defined minimum energy/photon that can eject any electrons at all
  - minimum photon energy ⇔ maximum wavelength
  - minimum photon energy == "work function" (WF)
- maximum electron energy is $h\nu$ – WF
  - electron energy can be less (due to resistive loss)
  - WF is generally smaller for more reactive materials

photocathode responses

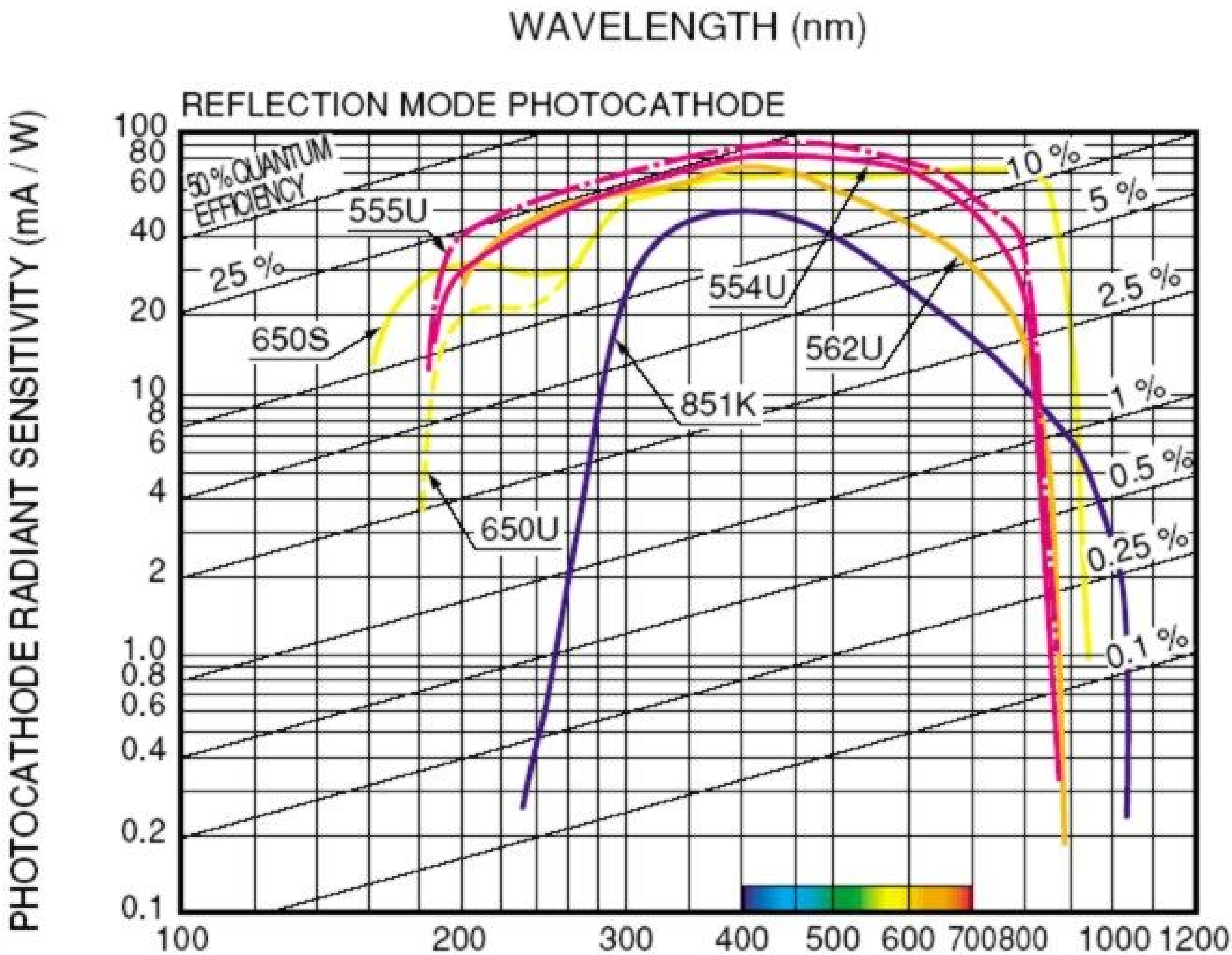


image orthicon: early TV sensor

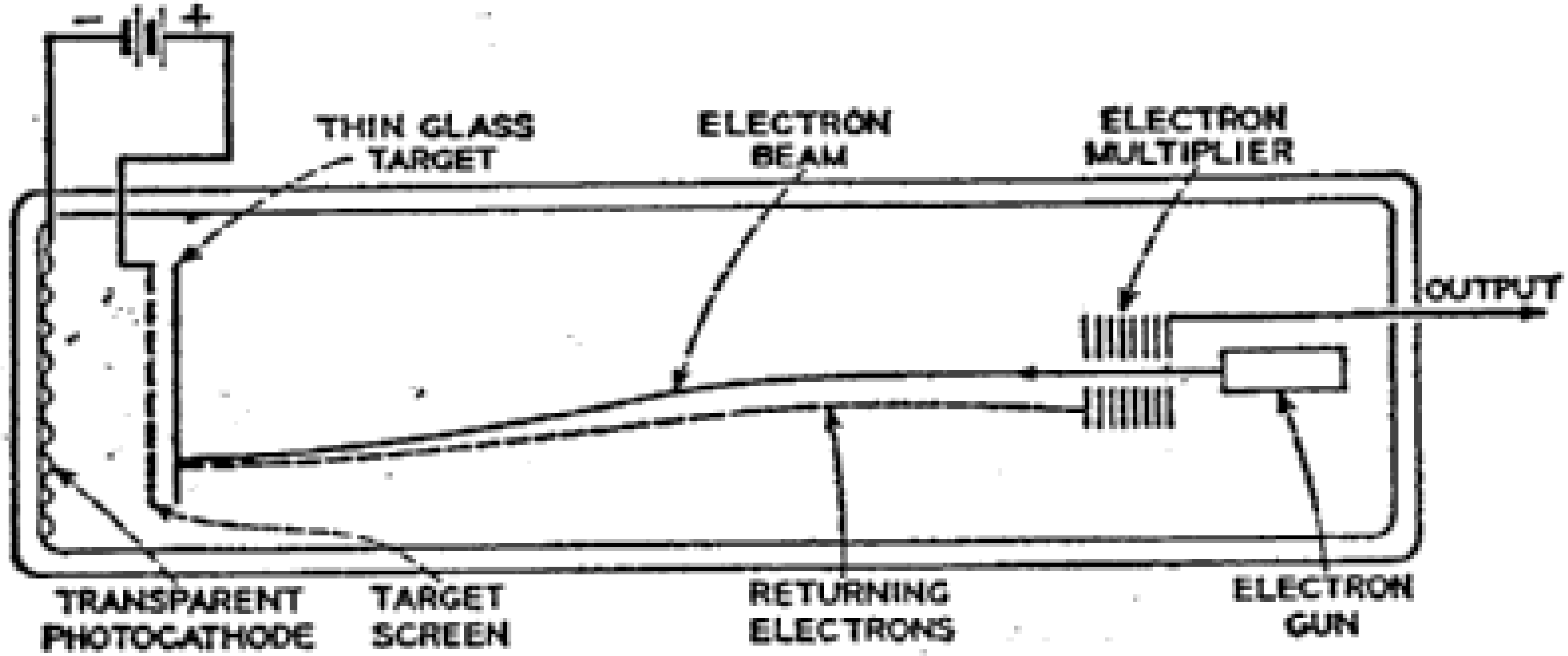
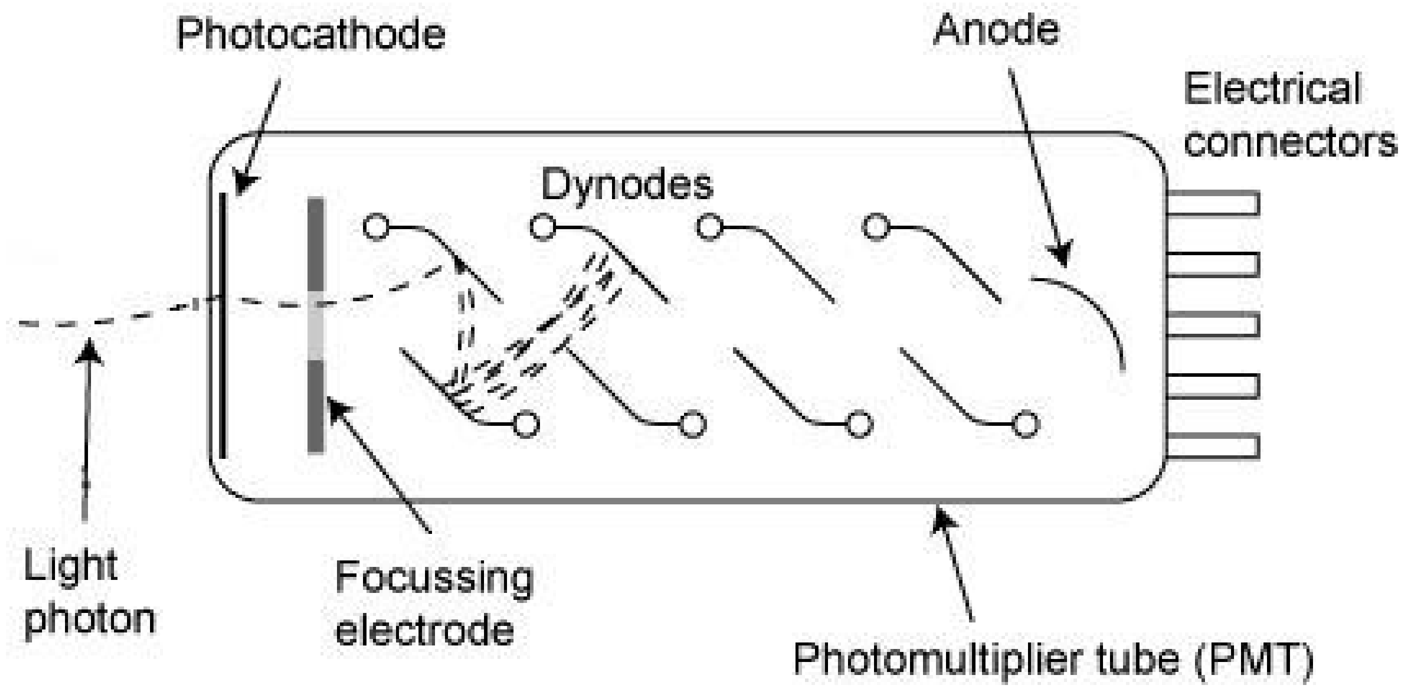


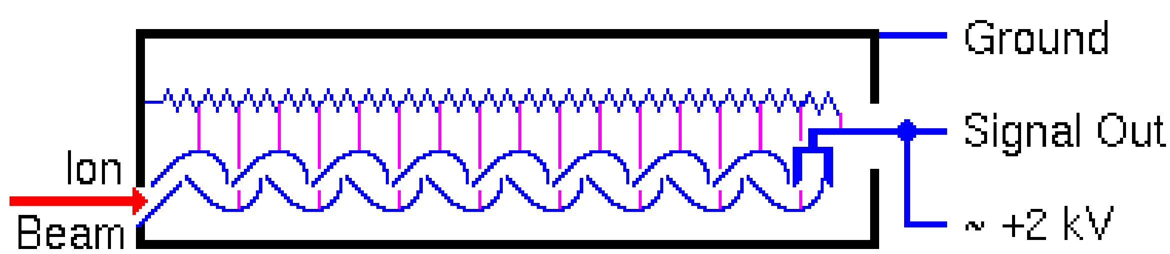
Image Orthicon 5280

microchannel devices

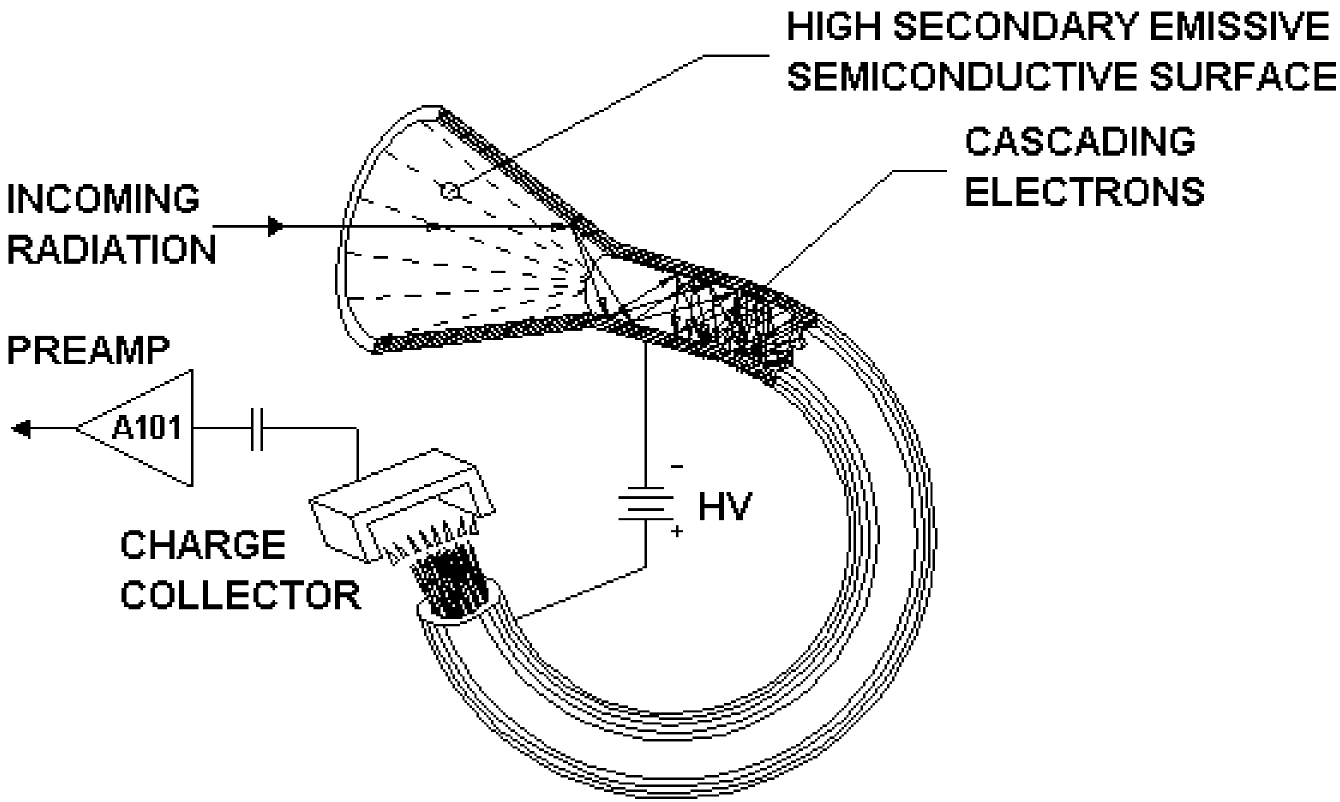
- historical origin in “electron multiplier”
  - for detecting photons (e.g., in orthicon)
    - and electrons, positive and negative ions, fast neutral particles, etc
  - first with discrete “dynodes”
  - later as “continuous dynode”
- continuous dynode version ...
  - miniaturized to capillary dimensions
  - bundle of capillaries fused into “microchannel imaging plate”

discrete dynode multiplier

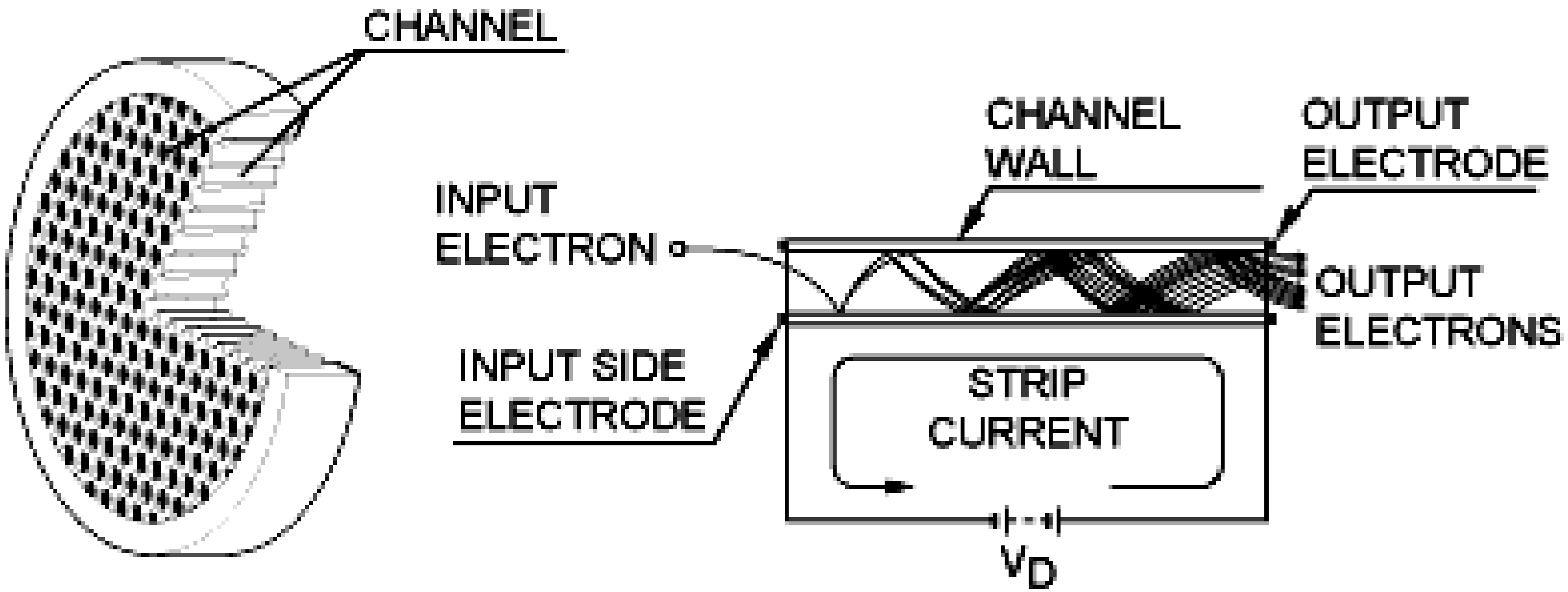




continuous channel multiplier



microchannel imaging plate



physical basis of television

is television based on the photoelectric effect possible?

- typical sunlight ~200 W/m^2 (1350 W/m^2 max)
- typical pixel $(15\text{x}10^{-6})^2$ m^2 [that's big today!]
- pixel dwell time typically 1/500 (lines/pixel) 1/500 (frames/line) 1/30 (second/frame)
- so sunlight shining directly on a pixel gives 200 W/m^2 $(15\text{x}10^{-6})^2$ m^2 2.5x10^{18} photons/(W s) (1/500 1/500 1/30) s
  → ~17000 photons in one pixel dwell time

assignment

(24) Where did the (approximate) conversion factor 2.5×10^{18} photons/(W s) come from?

hint: the number is (approximately) the number of (approximately green) photons whose combined energy is 1 joule; do you remember how do you find the energy of one photon of a given color?

so TV seems to be impossible!

- only get ~17000 photons in pixel dwell time
- shot noise on this is almost 1%
- and it assumes …
  - sunlight vs. lighting that could be 10^6 times less
  - illumination falling directly on the pixel
    - no aperture
    - no optics

the answer is integration …

culated. The image dissector is much more sensitive than the Nipkow disk device, but it is still not good enough for practical TV.

What is the real secret of TV pickup devices? It is the *storage principle*, a contribution of Vladimir K. Zworykin. This principle was first used in a device called the iconoscope. I shall not describe the iconoscope because its operation is inherently complicated and somewhat faulty. Instead, I shall describe a very good as well as an easily understandable pickup tube, the image orthicon.

write slow, read fast …

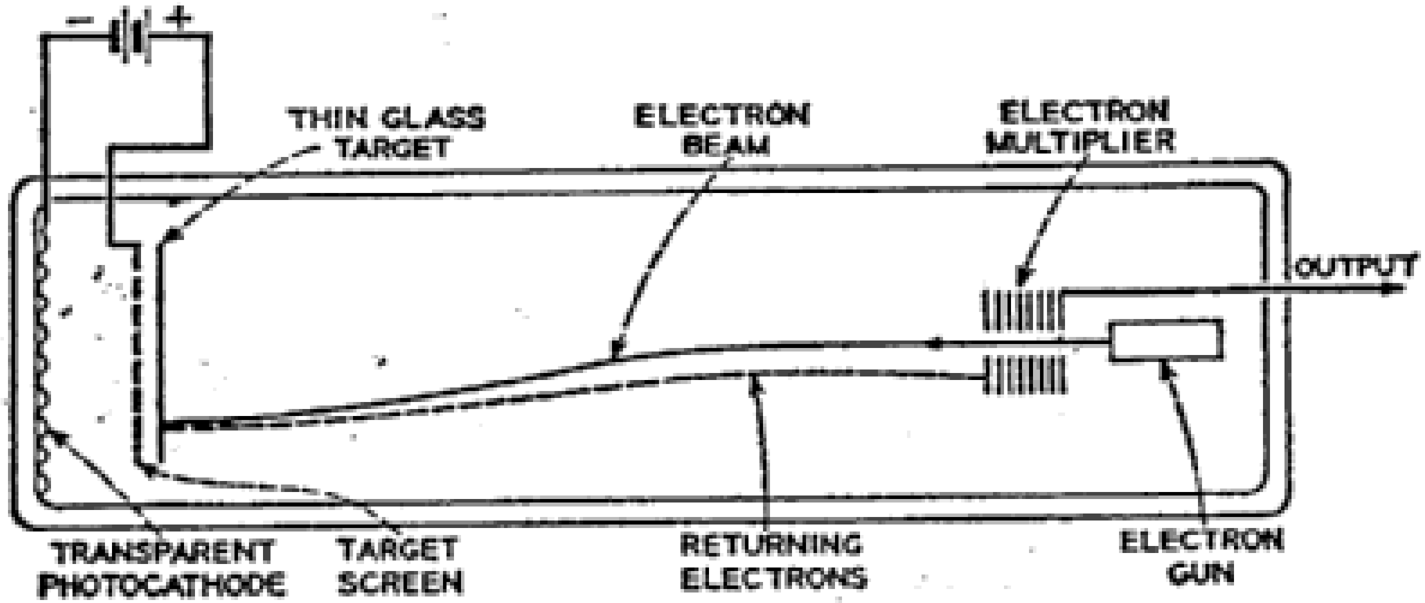


image charge accumulates continuously;
readout is accomplished in the much smaller “pixel dwell time”
(previous text and this picture from Pierce, *Waves and Messages*)

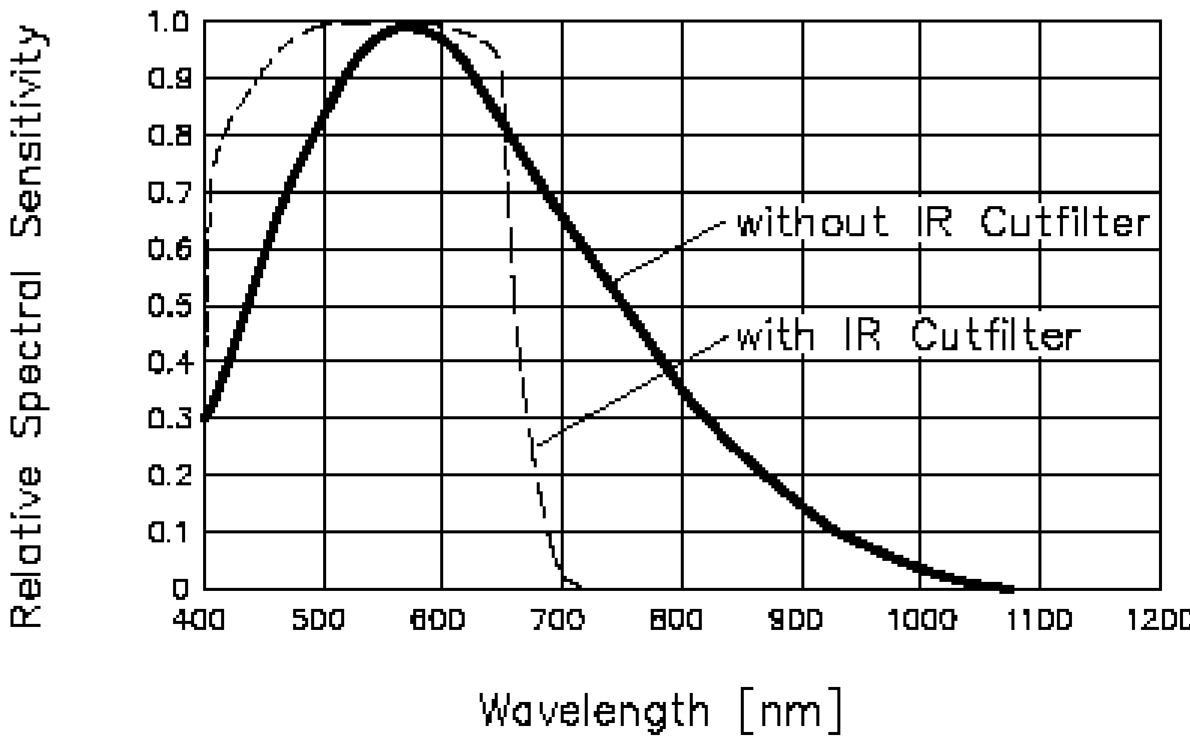
image sensors: physical principles

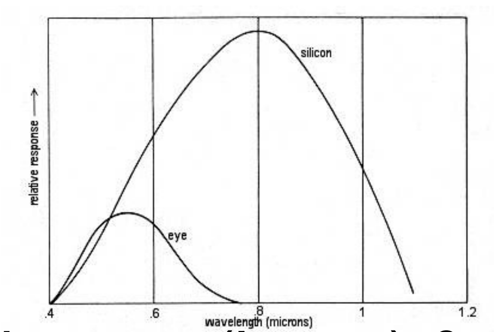
evolution of image sensors

- photographic film
- photoelectric effect + electron beam scanning
- semiconductor screens + electron beam scanning
- *(+ hybrid technologies, e.g., image intensifiers)*
- semiconductor technologies
  - CCD (“charge coupled device”)
  - CMOS (“complementary metal oxide semiconductor”)
    - originally: naked memory chips
    - currently: “camera on a chip” designs
  - special purpose, emerging, or evolving
    - CID (“charge injection device”)

silicon sensor (& IR cut-off filters)

- see *readings* directory: *removing_IR_blocking_filter.htm*





human (lower) & silicon (upper) wavelength sensitivity

note …

- silicon sensitivity extends to “near infrared”
  - i.e., wavelength ~ 1μm
  - “body heat” radiates very little in this regime
  - so “infrared photography” using Si requires a source of illumination, e.g., IR LED illuminators
- some other semiconductor materials, e.g., GaAs, are sensitive to “far infrared”
  - i.e., wavelength ~ 10 μm
  - “body heat” radiates significantly in this regime
  - so “thermal photography” can be done using this self-luminous regime of people & animals

Kodak KAF-400 CCD specs

PARAMETER	NOMINAL FIGURE
Optical form factor	100%
Sensitivity @ 550 nm	740000 e^-/µJ/cm2
"	37000 e^-/µW/cm2
"	146 mA/W
"	44.5 ke^-/lux
Output Charge to Voltage Conversion Factor (CVF)	10 µV/e^-
Blue quantum efficiency @ 400 nm	0.03
Green quantum efficiency @ 550 nm	0.33
Red quantum efficiency @ 700 nm	0.40
Near IR quantum efficiency @100 nm	0.08
Reading noise	13 electrons
Dark current density @ 25°C	10 pA/cm^2
Dark signal	50 e^-/pixel/s
Signal level at saturation	0.11 µJ/cm2
Dynamic range	76 dB
Non-linearity	1%

must mean for
1/20 second
exposure time

assignment

(25) Your camera uses a Kodak KAF-400 CCD. Produce a table that gives the exposure times required to produce ½ full-scale exposure when the lens aperture (f#) is {1, 1.4, 2,…, 8, 11, 16}, the illumination at the scene is sunlight on a nice day in Pittsburgh, and the average reflectivity of the scene is Kodak's "middle gray".