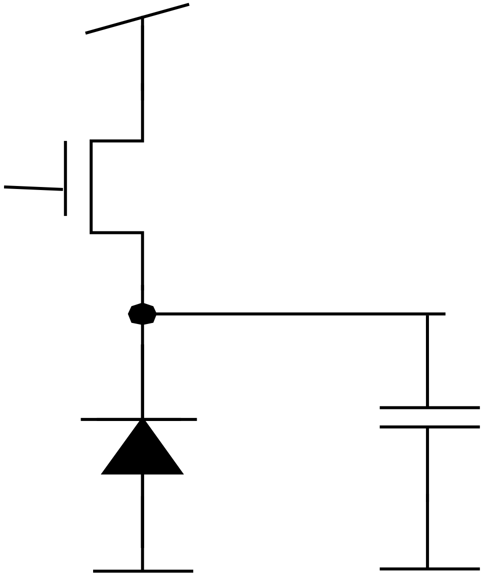
Phototransduction I

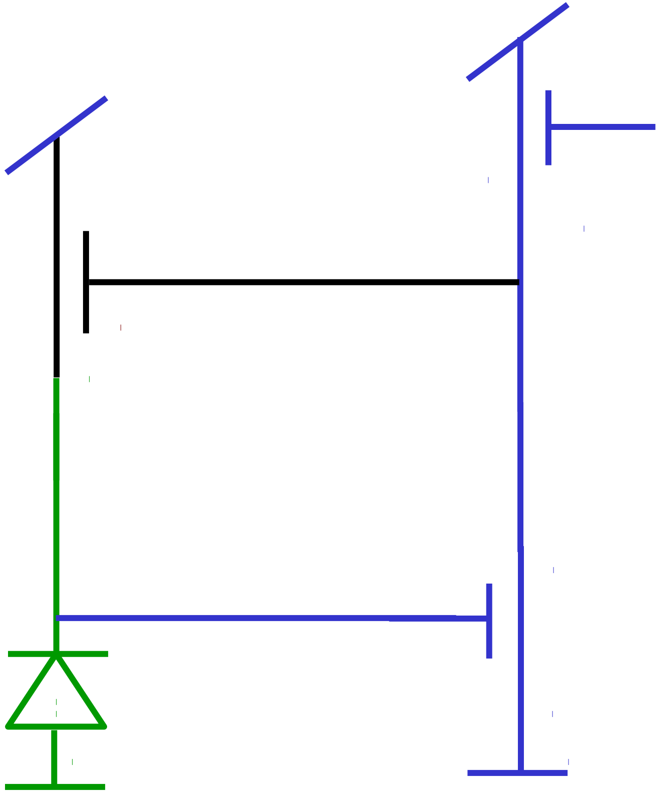
NE1 2021, T. Delbruck

- Biological photosensors
  - The Visual pathway, the Retina, and Photoreceptors
- Silicon photosensors
  - Radiometry and photometry
  - Photoelectric effect
  - Absorption of light by silicon
  - Photodetectors: PN junction
  - Quantum efficiency and spectral response
  - Dark current
  - Estimating actual photocurrent from scene illumination
- Your 3T smartphone pixel with pinned photodiode and correlated double sampling
- Logarithmic photoreceptors (**exercise**)
  - Comparing ***source-follower*** and ***transimpedance*** log photoreceptors
    - DC response
    - Transient large signal response
    - AC small signal analysis

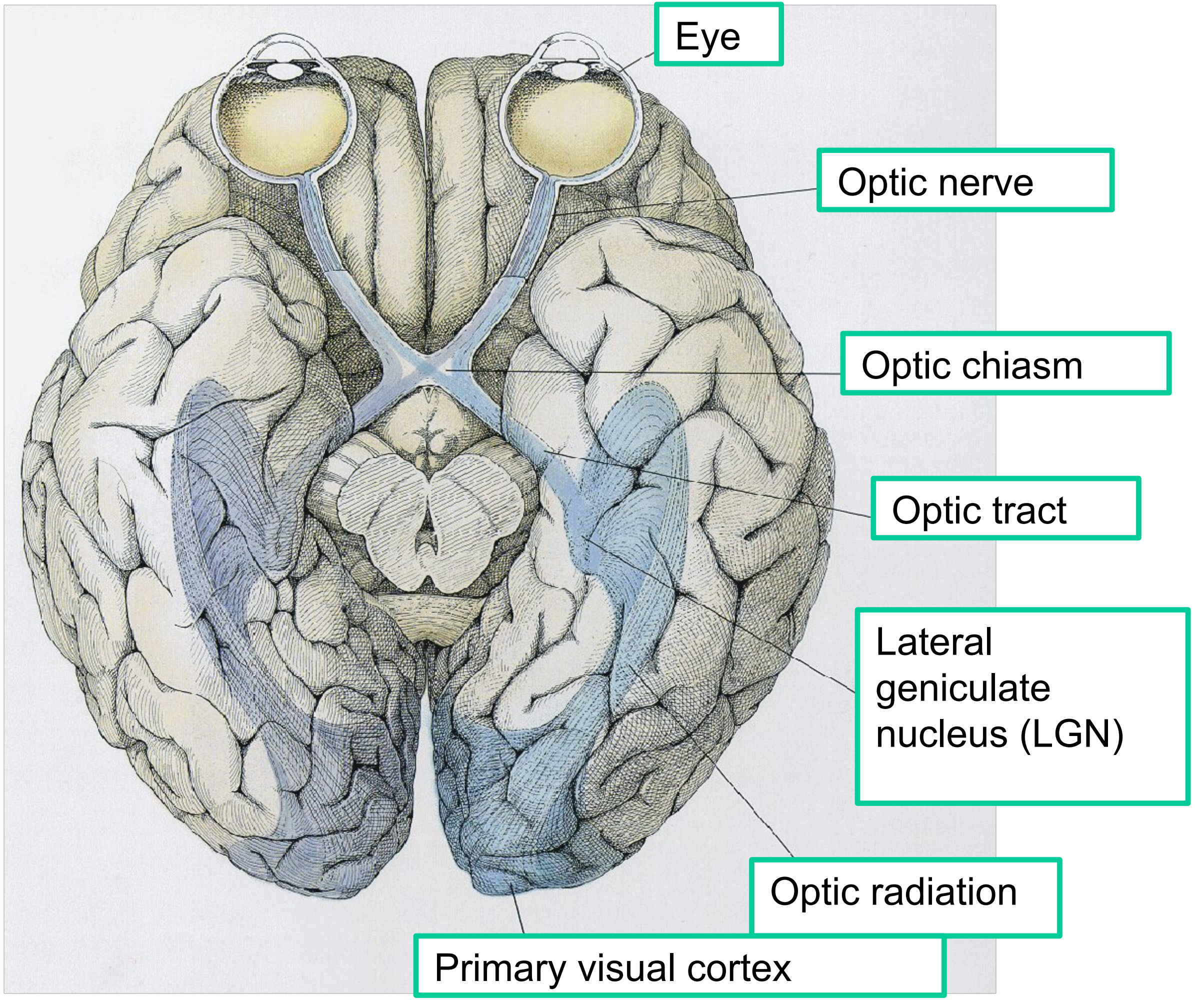
Exercise (in python Jupyter notebook)

Passive ***source-follower*** **(SF)** and active ***transimpedance*** **(TI)** log photoreceptors

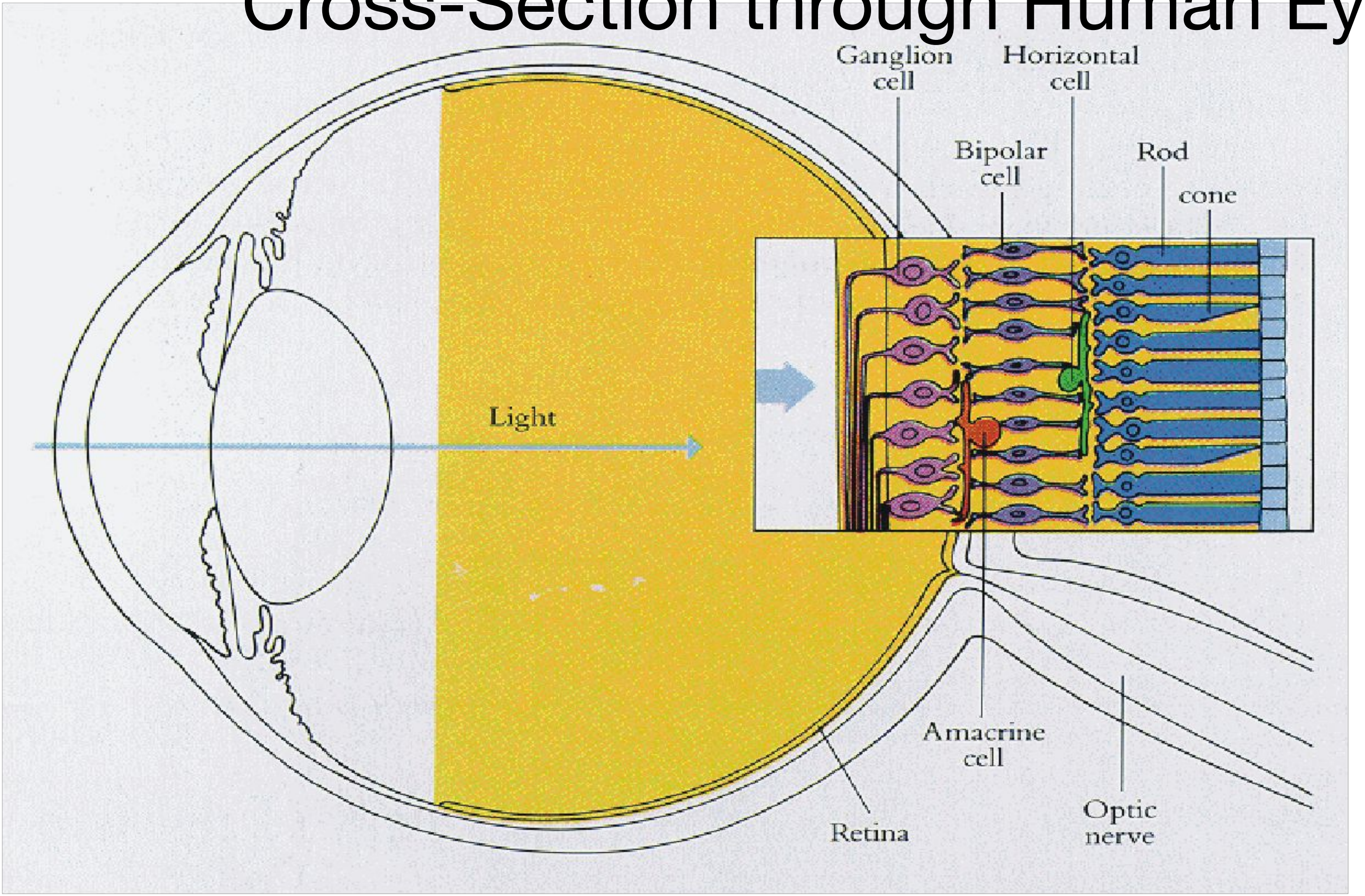




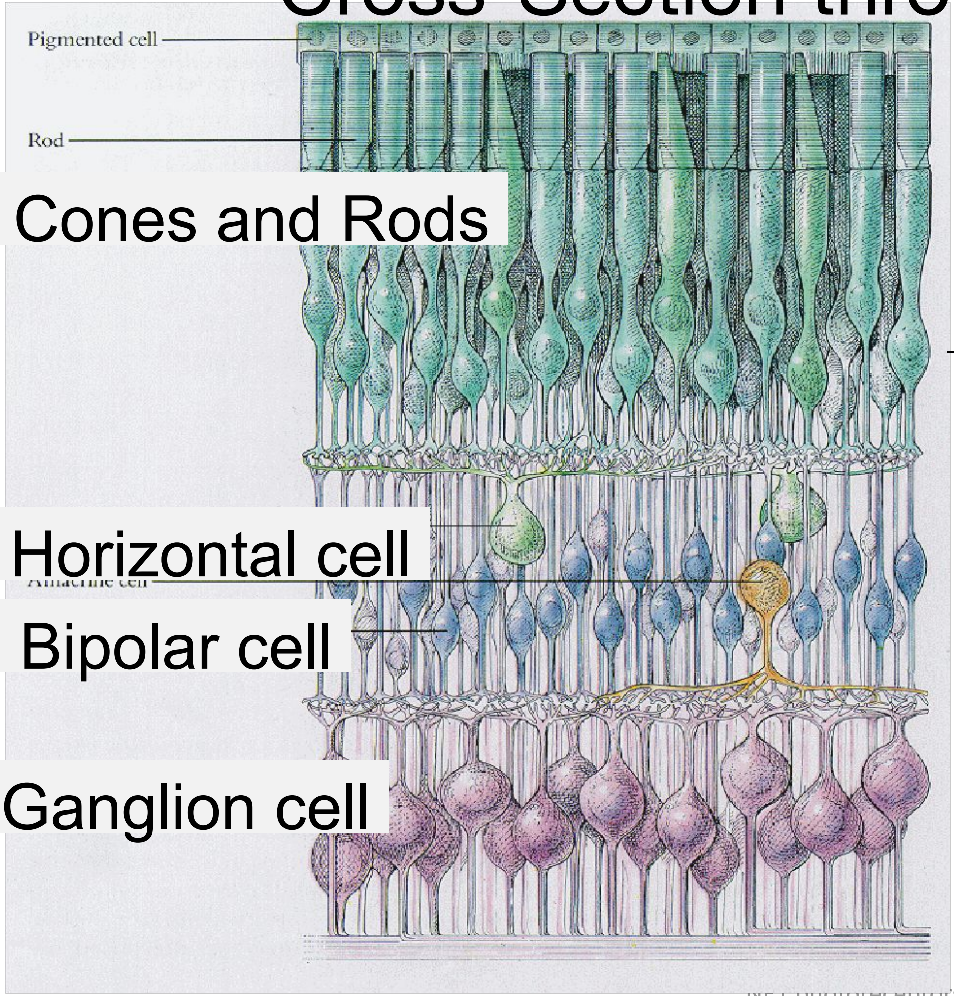
Visual Pathway in Brain (Bottom View)



Cross-Section through Human Eye



Cross-Section through Human Retina



Outer nuclear layer

Outer plexiform layer

Inner nuclear layer

Inner plexiform layer

(Rodieck)

Two Types of Photoreceptors: Rods & Cones

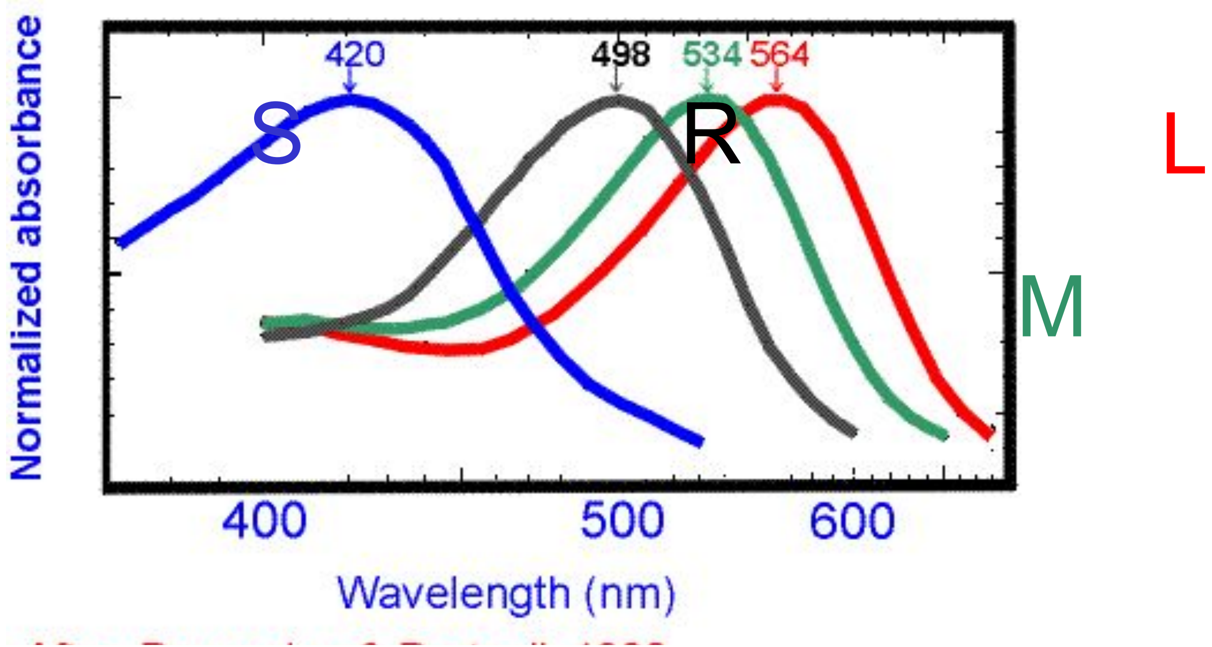
Rods (~126 million)

- Sensitive in very dim light – lowest 3 decades
- Saturate at high illumination
- One light-sensitive pigment in blue-green
- Not present in fovea

Cones (~6 million)

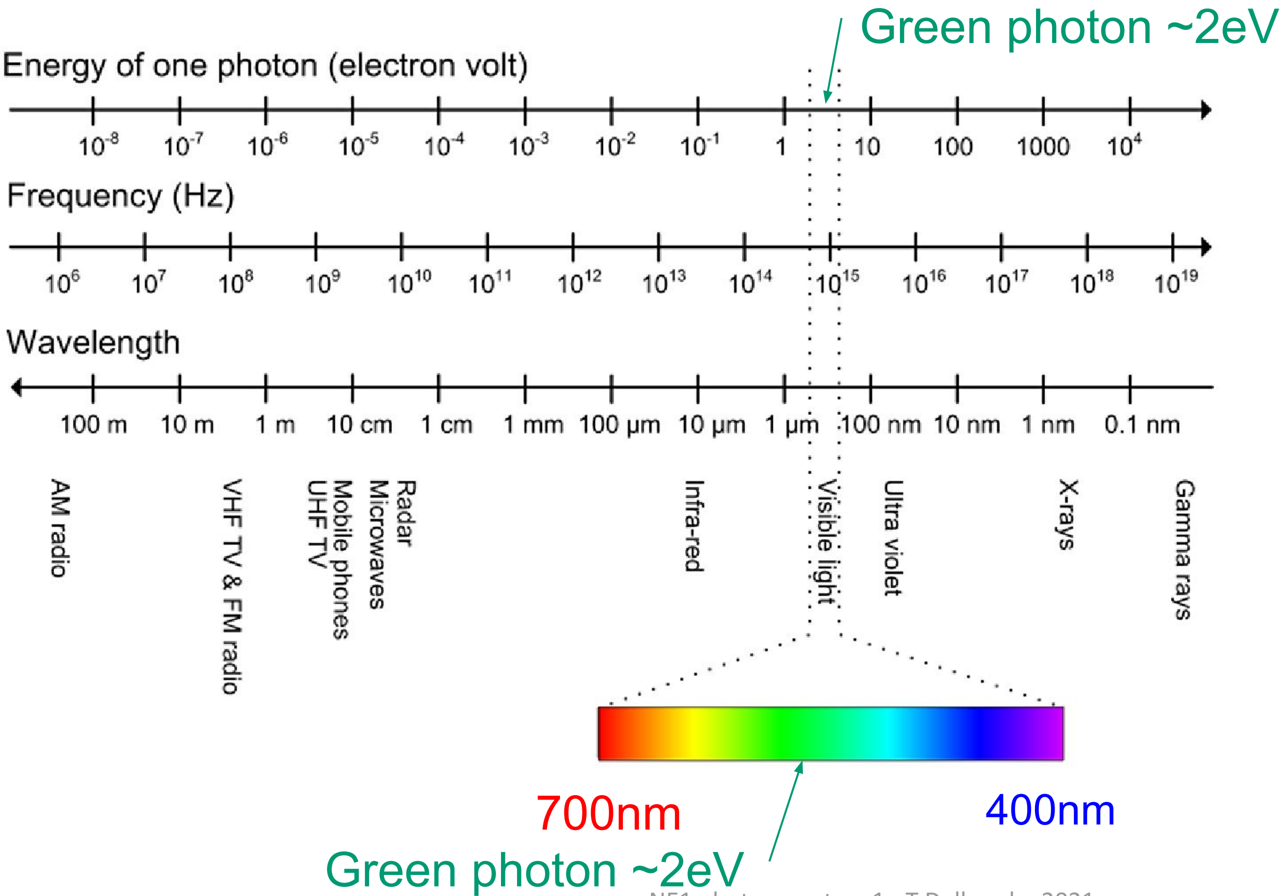
- Only sensitive to brighter light – upper 9 decades
- Three types with pigments with different wavelength sensitivities color vision

Photoreceptor Spectral Sensitivity



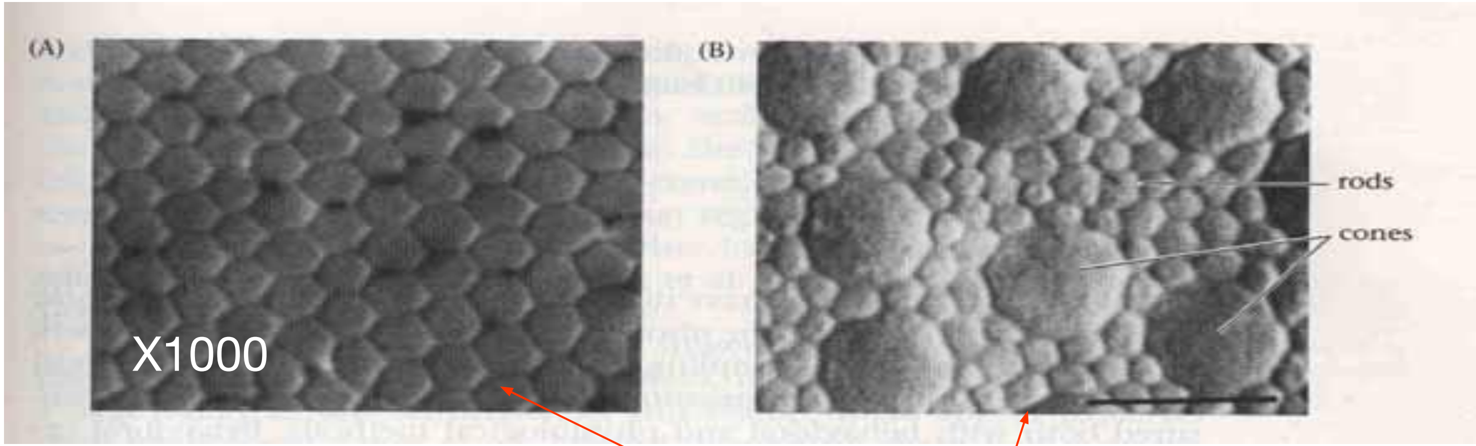
3 types of cones: L cones (sensitive to long wavelengths), **M cones** (sensitive to medium wavelengths), **S cones** (sensitive to short wavelengths) are only 10 % of the total number of cones, and absent from the center of the fovea.
Rods (**R**) are sensitive to intermediate wavelengths.

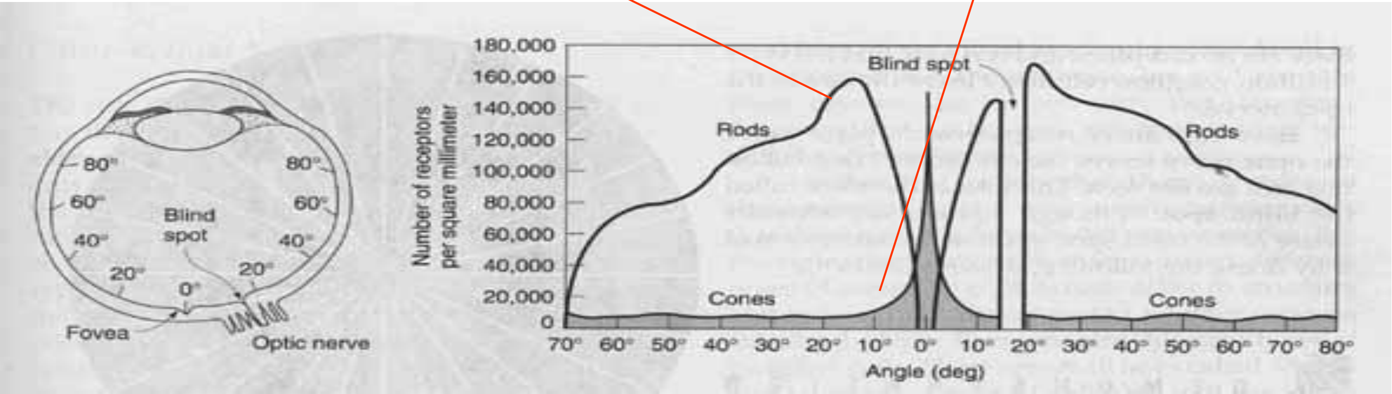
Spectrum of EM radiation



(from web)

Rod/Cone Distribution

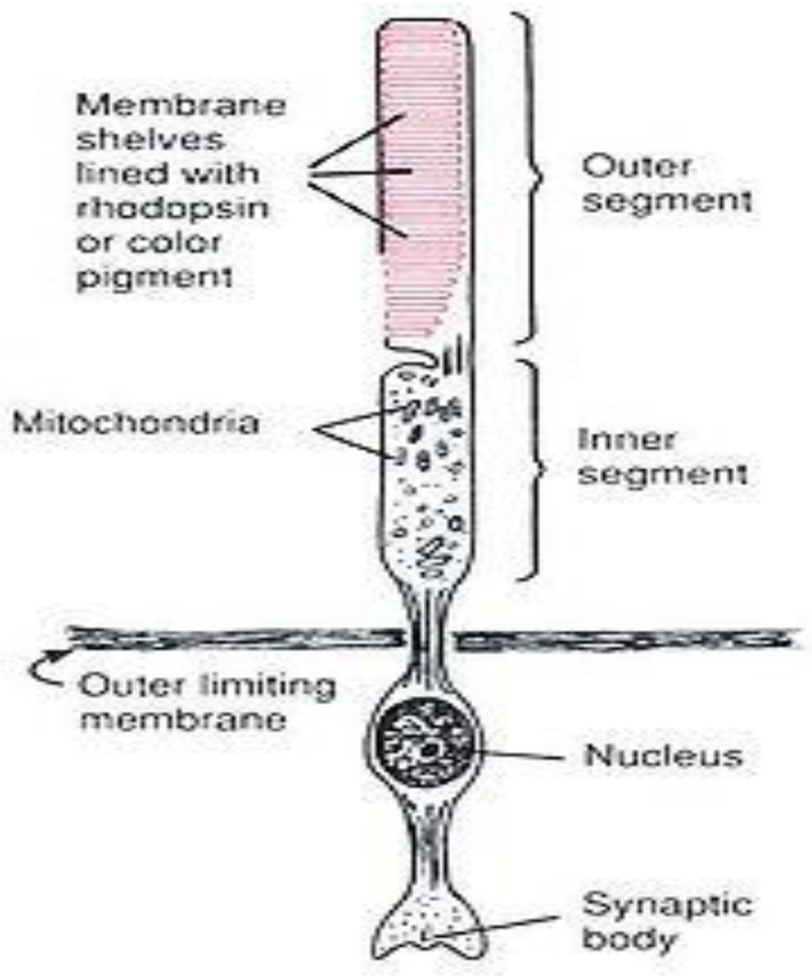




(Rodieck)

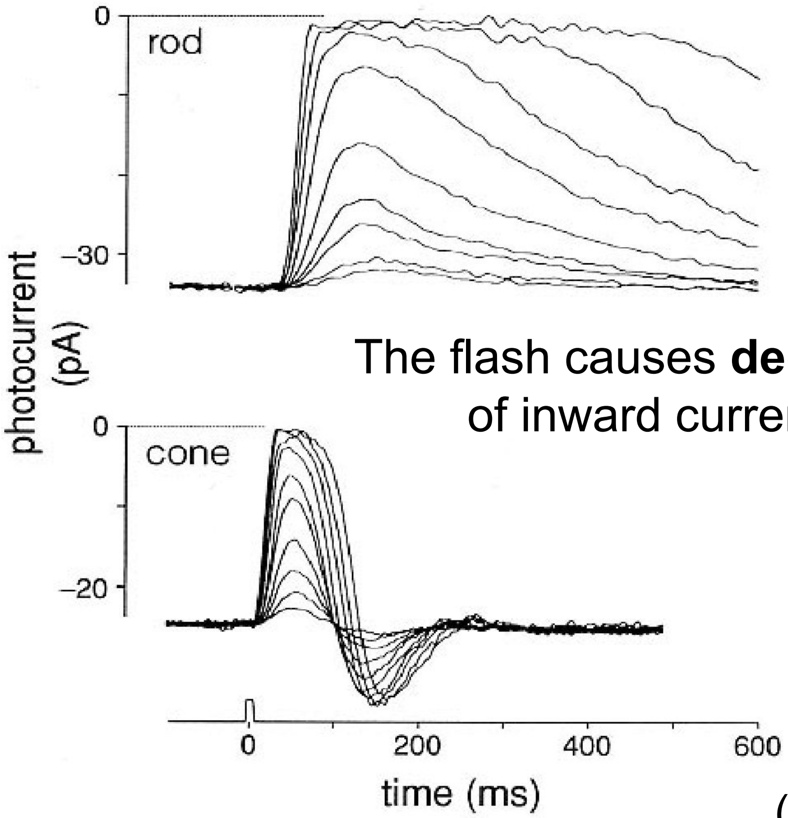
Photoreceptor Structure

- ***Outer segments*** are modified cilia with disks filled with opsin, the molecule that absorbs photons, as well as voltage-gated Na channels.
- The protein opsin contains a pigment molecule called *retinal*. In rods, the opsin+retinal together are called ***rhodopsin***. In cones, there are different types of opsins combined with retinal to form pigments called photopsins.



Photoreceptor response to flash of light

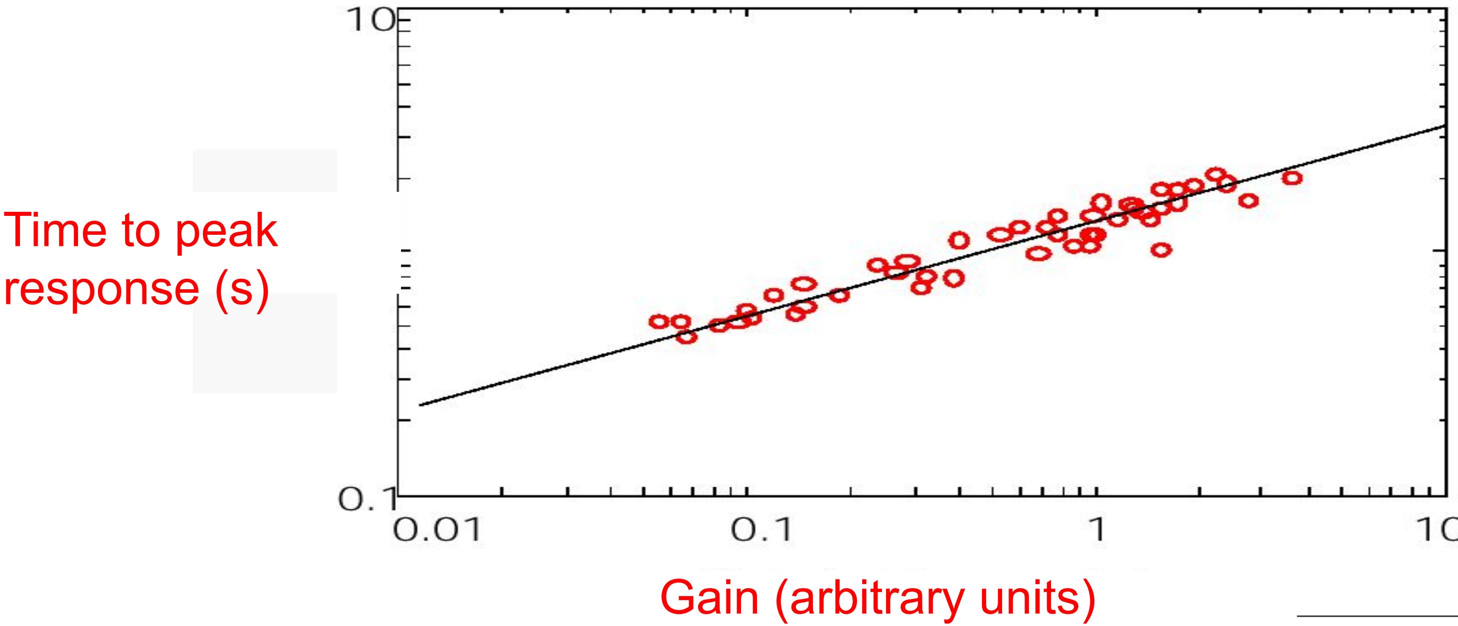
- When a photon absorbed by a rod/cone visual pigment, the retinal undergoes a photoisomerization to all-trans retinal which changes conformation of opsin.
- This conformation change triggers a biochemical cascade that causes ***hyperpolarization*** of the cell and a **decrease** of glutamate release.
- Bipolar cells respond to the subsequent decrease in glutamate.



The flash causes **decrease** of inward current

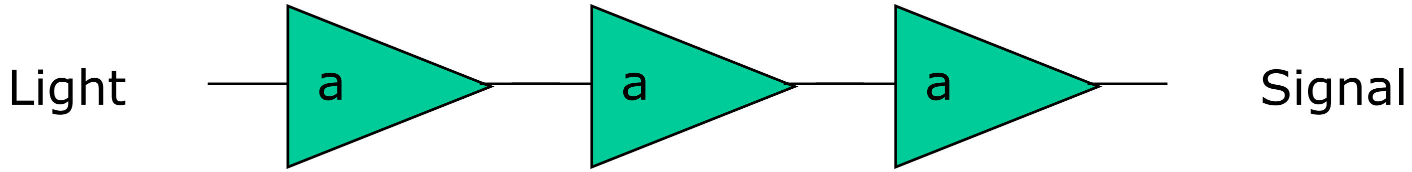
(Baylor, 1987)

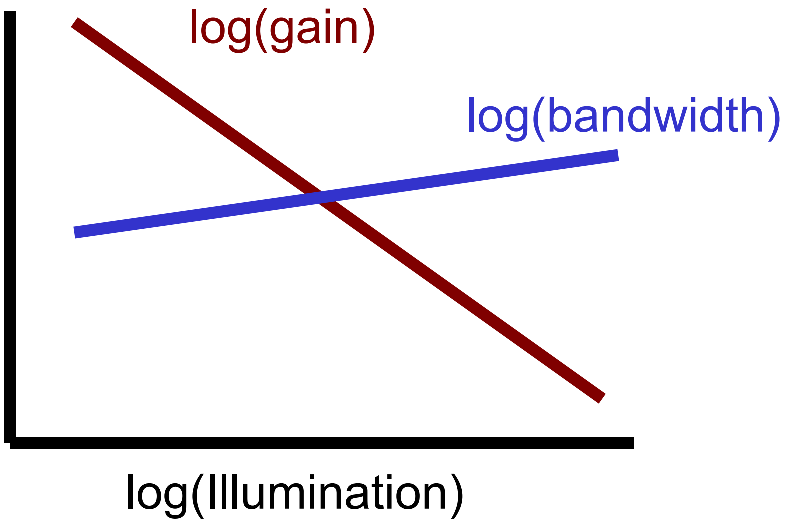
In biological photoreceptors, the rise time is not proportional to the gain

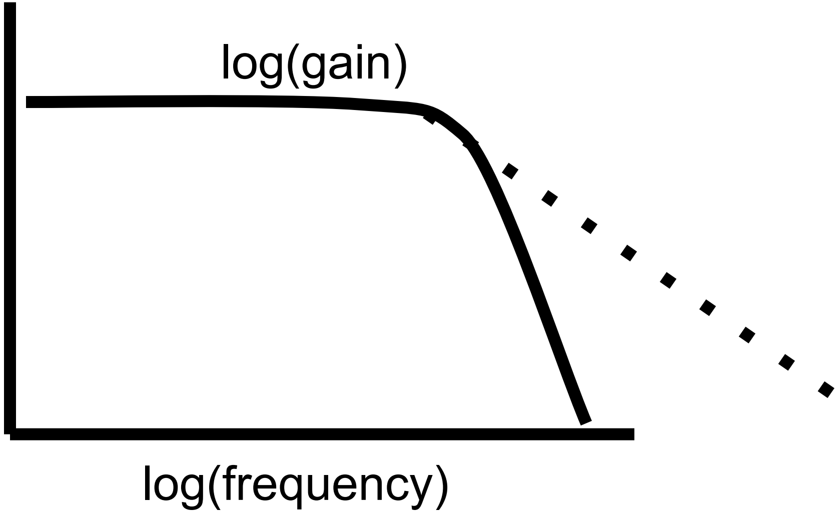


$$\text{Rise time} \sim \text{Gain}^{0.25}$$

The gain is **distributed**



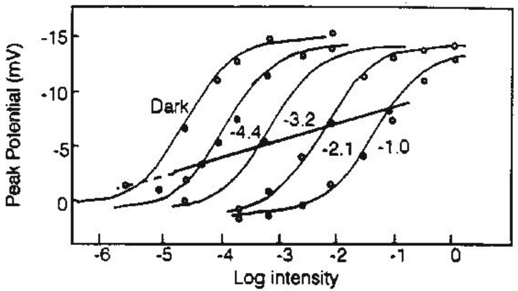




Photosensors in Retina

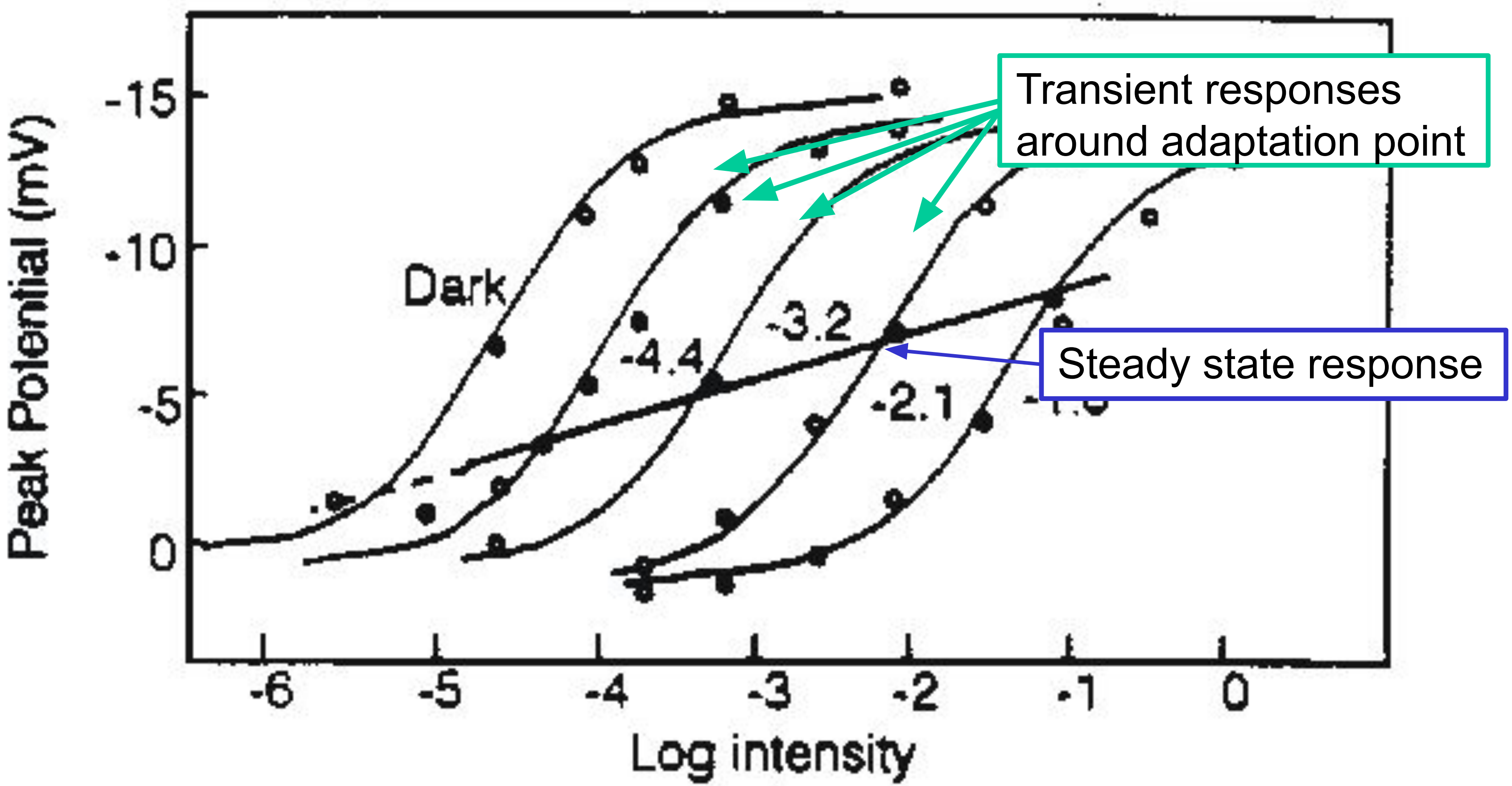
- Logarithmic response characteristics
- Adaptive gain control: transient response amplified with respect to DC response

FIGURE 2.31 Gain adjustment in turtle cones (recorded intracellularly) caused by background illumination. The stimuli are 0.5 s increments or decrements on a steady background (except for the curve for the dark adapted cone which only is for increments). The stimulus spot is 3.2 mm in diameter on the retina. Peak responses measured from the dark-adapted resting potential (dotted line) are plotted as a function of test illumination. The thin curves connect the measured points. The thick curve is the steady membrane potential measured at least two minutes after background onset. The average slope of the transient responses is 9.5 mV/decade, and the slope of the steady-state, adapted response is about 1.8 mV/decade. The ratio of transient gain to the steady-state gain is about 5. The total dynamic range is about 15 mV. The illuminations are given as log attenuation from a baseline value. The unattenuated test stimulus (0 log) is 6.4 10^{15} quanta(640 nm)$(cm^2 s)^{-1}$ on the retina, equivalent to an irradiance of about 20 W/m^2. (Direct office fluorescent lighting is about 1 W/m^2.) The unattenuated background illumination is 9.1 10^{15} quanta(640 nm) $(cm^2 s)^{-1}$. Source: Adapted from [14].



14. R.A. Norman and I. Perlman, "The effects of background illumination on the photoresponses of red and green cones," *J. Physiol.*, vol. 286, pp. 509–524, 1979.

Photoreceptor cone responses in Retina



Visual Phototransduction

- Photoreceptor cells are depolarized in the dark.
- Light hyperpolarizes the cell, this hyperpolarization activates the next cell in the neural pathway.
- In the dark, cGMP levels are high and keep cGMP-gated sodium channels open allowing a steady inward current, dark current. This current keeps cell depolarized around -40mV.
- Depolarization of cell opens voltage-gated Ca channels. An increased Ca2+ intracellular concentration causes release of glutamate neurotransmitter.
- Cone pathway uses glutamate as the neurotransmitter: It
  - **hyperpolarizes** ON-center bipolar cells. Glutamate binds to metabotropic glutamate receptors which, through a G-protein coupling mechanism, causes non-specific cation channels to close, thus hyperpolarizing the bipolar cell.
  - **depolarizes** OFF-center bipolar cells. Binding of glutamate to

Light

Light consists of electromagnetic radiation with a dual particle-wave nature. This was pointed out by Einstein in 1905 who theorized that light is composed of discrete quanta called **photons** with an energy that is inversely proportional to the wavelength of the light, so that

$$E=hc/\lambda$$

A yellow photon with λ=555nm has E=2.1eV.

h=6.6e-34 Js, $c=3*10^8$ m/s, q=1.6e-19 C.

Photon

- Photon is a basic unit of all forms of electromagnetic radiation including light.
- It has no mass, no electric charge, does not decay spontaneously in vacuum.
- In vacuum, it moves at c, the speed of light. Its energy E and momentum P are related by E=cp. (p is magnitude of P)

$$E_{ph} = \hbar\omega = \frac{h}{2\pi}2\pi\nu = \frac{hc}{\lambda};$$

$$p_{ph} = \hbar k = \frac{h}{2\pi}\frac{2\pi}{\lambda} = \frac{h}{\lambda}$$

(h/2π): Dirac's constant

κ: Wave vector

ω: Photon frequency

h: Planck constant

ν: Photon frequency

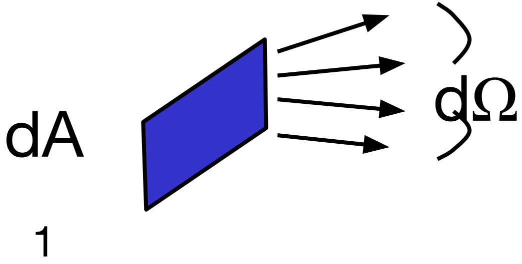
λ: Photon wavelength

Radiometry and photometry

- Unit of visible light is ***lumen=lm*** (total from source), lux (lm/m^2 on surface), and nit=cd/m^2 (brightness). cd=candela=lm/steradion. Sphere has 4π ster.
- Moonlight=0.1lux, Full sun=100klux
- 1lux sunlight ≈ 4mW/m^2≈10^4 photons/um^2/s
- Light falling on sensor plane through a lens is reduced by factor $R/4f^2$ compared with falling on scene with reflectance *R*. f=f# aperture ratio of lens.
- Average scene reflectance R≈18% (Kodak gray)

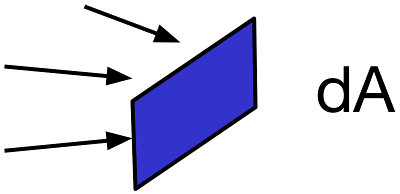
Radiometry

- An ideal sensor has equal sensitivity to all wavelengths of light being measured. The basic unit of light is ***Watts*** measured by photon energy.



Radiance
(Strahledichte)

$W/m^2.sr$



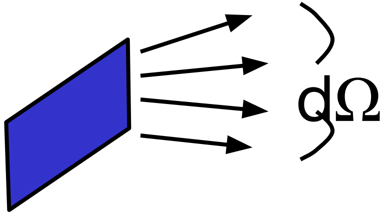
Irradiance
(Bestrahlungs-starke)

W/m^2

Photometry

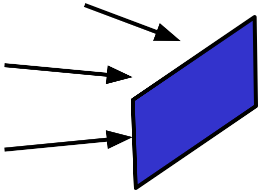
- In photometry, the spectral sensitivity of the sensor is matched to the average human eye with a peak at 555 nm. A ***lumen*** is the basic unit of light.

dA



Luminance
(Leuchtdichte)

cd/m^2
(cd=candela)
(lumen/sr=cd)



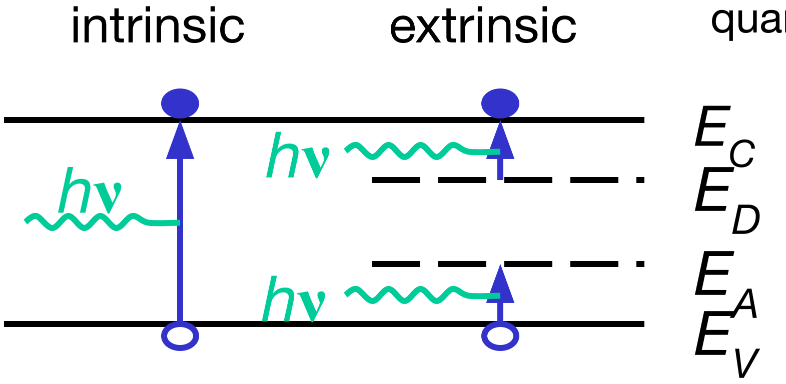
dA

Illuminance
(Beleuchtungs-starke)

lux
(lumens/m^2)

Photoelectric Effect (in Semiconductors)

quantum detectors



Photon energy

$$E_\lambda = h\nu = \frac{hc}{\lambda} = 1.24\text{eV}/\lambda(um)$$

h: Planck constant
ν: Light frequency
c: Speed of light
λ: Light wavelength

Photoelectric Effect

Intrinsic photoelectric effect (the normal one used for sensors)

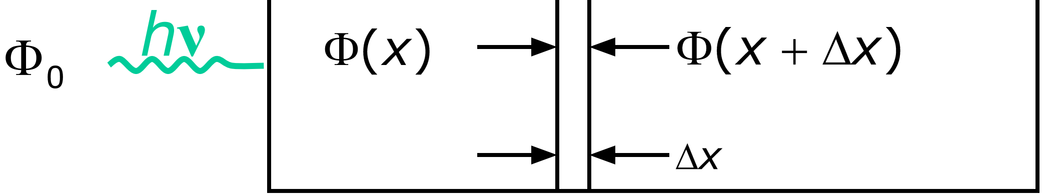
- Interband transitions (electrons elevated from valence to conduction band)
- Generation of electron-hole pairs
- Maximum possible photon wavelength: $\lambda_{max}=hc/E_g=1.24(\mu m)/E_g$ at room temp.
- ($1eV=1.6*10^{-19}J$, $h=6.62*10^{-34}Js$, $c=3*10^8\ m/s$)
- I.e. longest possible silicon wavelength is about 1.1um

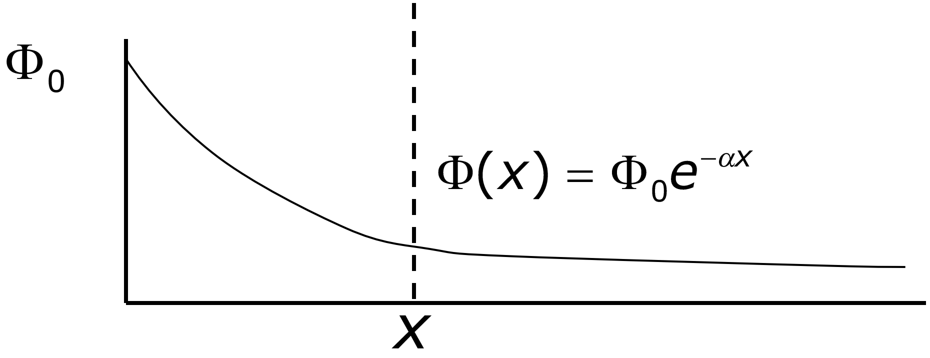
Extrinsic

- Transitions involve impurity energy levels in bandgap
- Generation of only one carrier type
- λ_{max} depends on position of energy levels

Optical Absorption

Φ_0 :Photon flux
(in units of photons/sq.cm/sec)





The number of photons absorbed within Δx is given by $\alpha\varphi(x)\Delta x$ where α is called the absorption coefficient.

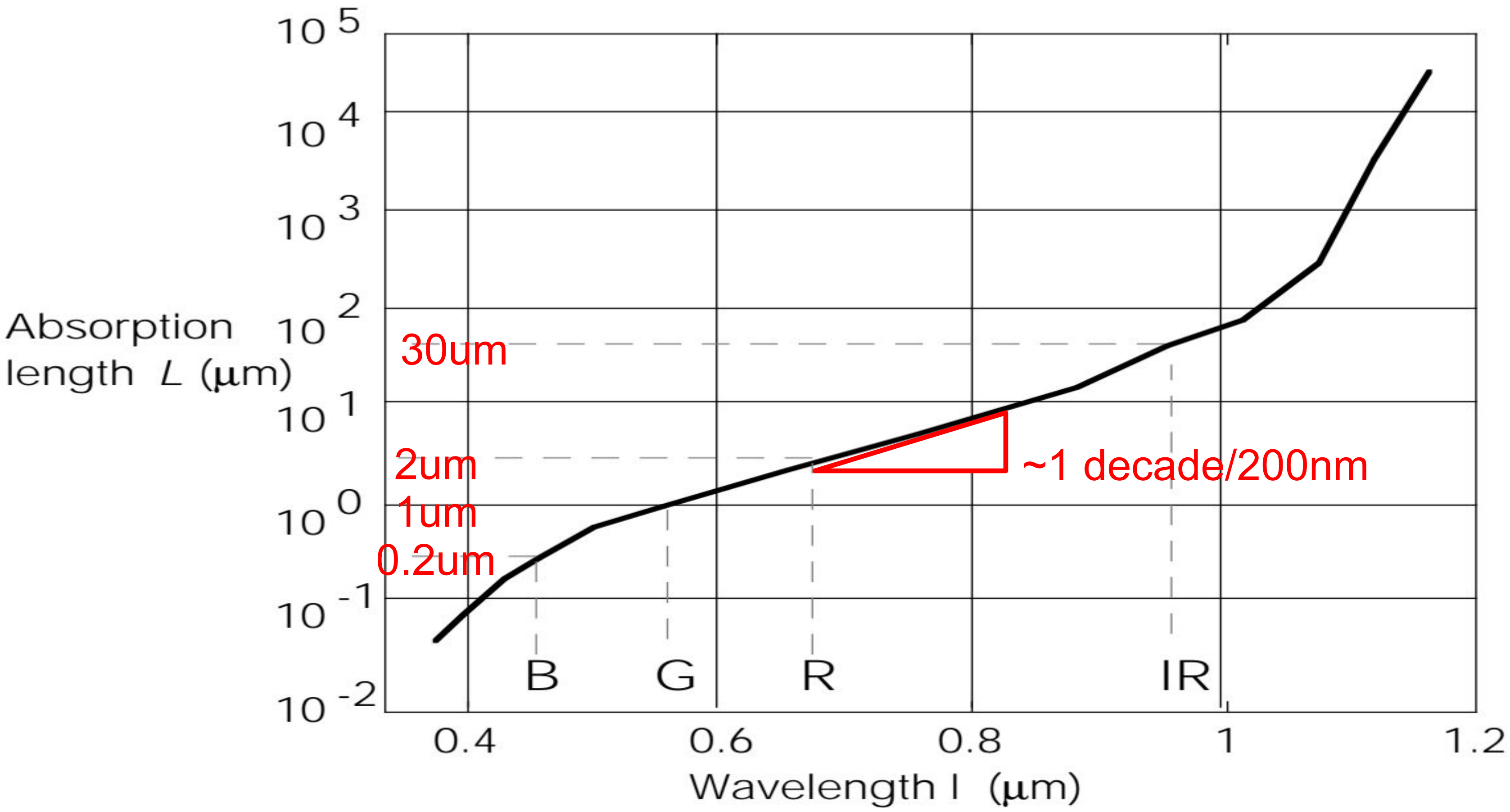
$$\frac{d\Phi(x)}{dx} = -\alpha\Phi(x)$$

$$\Phi(x) = \Phi_0 e^{-\alpha x}$$

$$\Phi_0 = \frac{1-R}{A} \cdot \frac{\lambda}{hc} \cdot P_{opt}$$

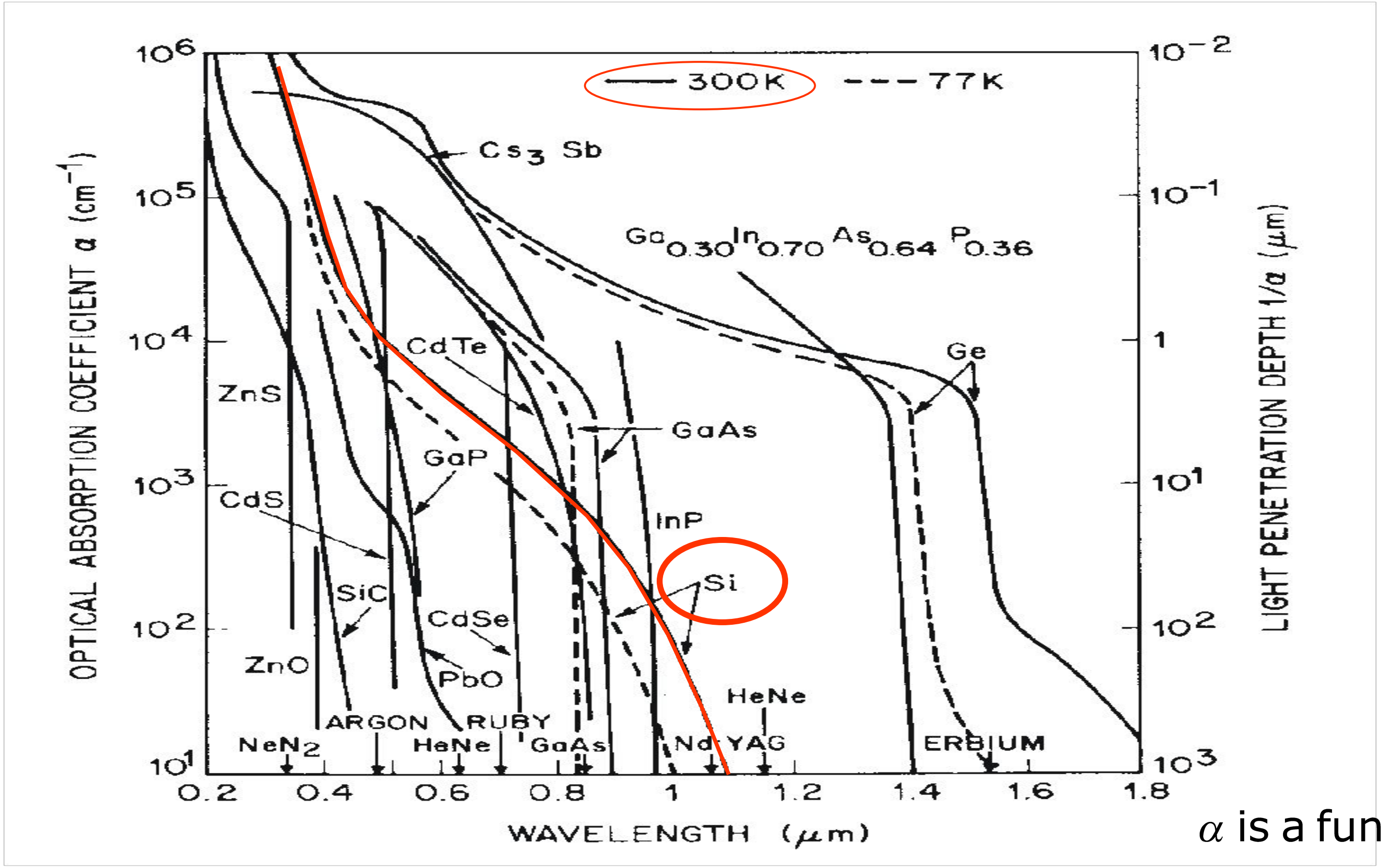
R: Reflection
A: Cross-section
P_{opt}: Incident optical power

Silicon photon absorption length vs. wavelength



Delbruck, 1995

Optical Absorption Coefficients of Different Semiconductor Crystals



α is a function of $h\nu$

Silicon Photodetectors

1) Photoconductor
2) **Photodiode – practically only device used in CMOS**
3) Phototransistor
4) Photogate

Quantum Efficiency

Quantum efficiency, η (or QE) is defined as the number of electron-hole pairs generated for each incident photon (always <=1 !!)

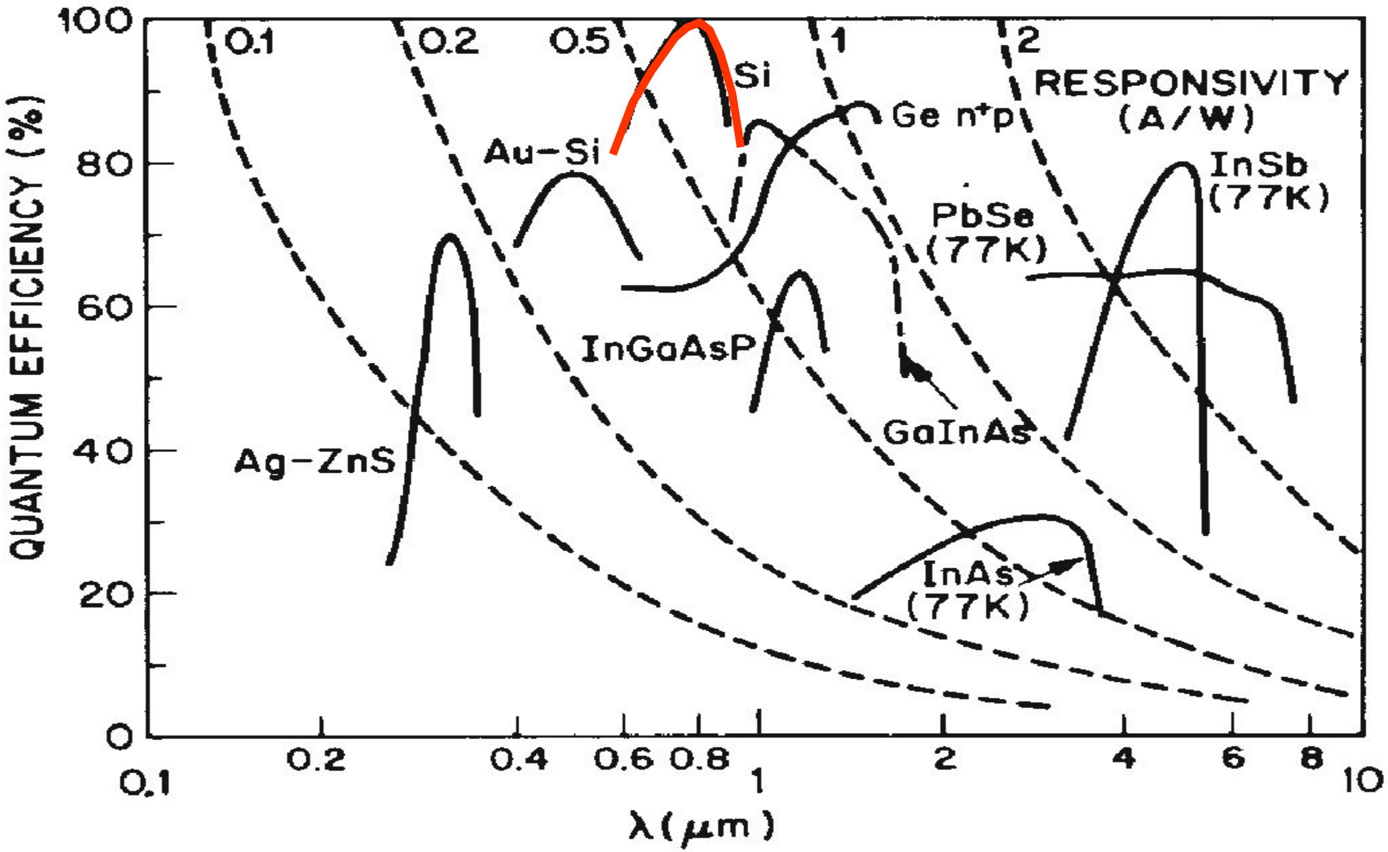
$$\eta = \frac{I_{ph}}{q} \cdot \frac{hc/\lambda}{P_{opt}}$$

I_{ph}: Photogenerated current

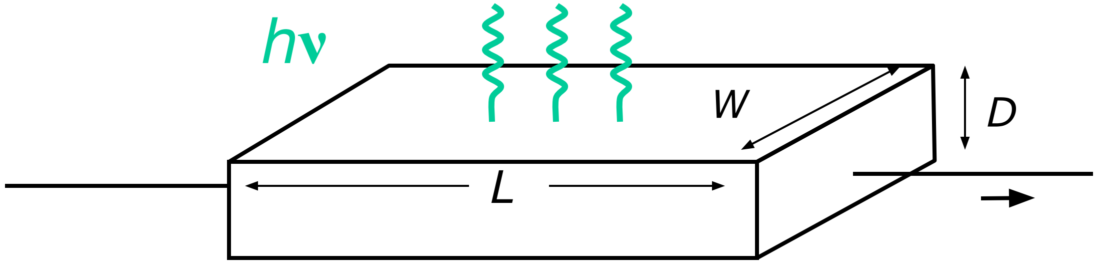
# of carriers in current

# of photons/s

Quantum Efficiency and Responsivity of Photosensors



Photoconductor (I)



No of photons arriving at surface per unit time is

$$\frac{P_{opt}}{E_{ph}} = \frac{P_{opt}}{h\nu}$$

Generation rate of carriers in semiconductor is

$$\eta \frac{P_{opt}}{h\nu}$$

where η is the quantum efficiency.

Recombination rate of carriers is

$$r = \frac{n}{\tau}$$

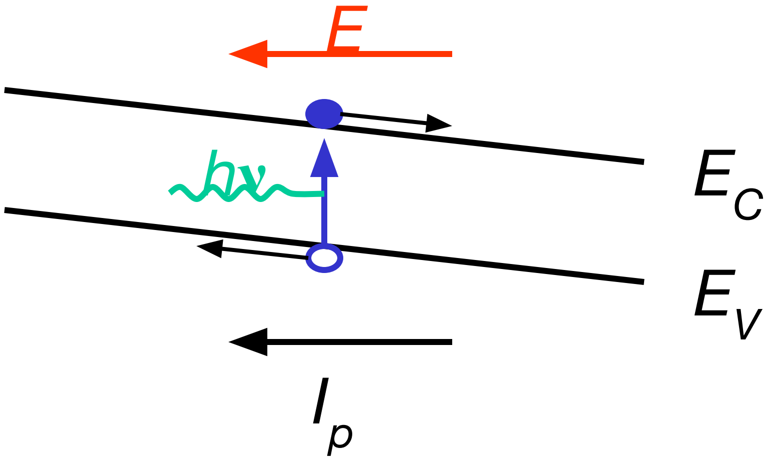
where τ is the carrier life time.

In steady state, recombination rate = generation rate:

$$\frac{n}{\tau} = \eta \frac{\left(P_{opt} / h\nu\right)}{WLD} \Rightarrow n = \tau\eta \frac{\left(P_{opt} / h\nu\right)}{WLD}$$

Photoconductor (II)

Charge transport by externally applied electric field *E*



$$I_p = (q\mu n|\vec{E}|)WD$$

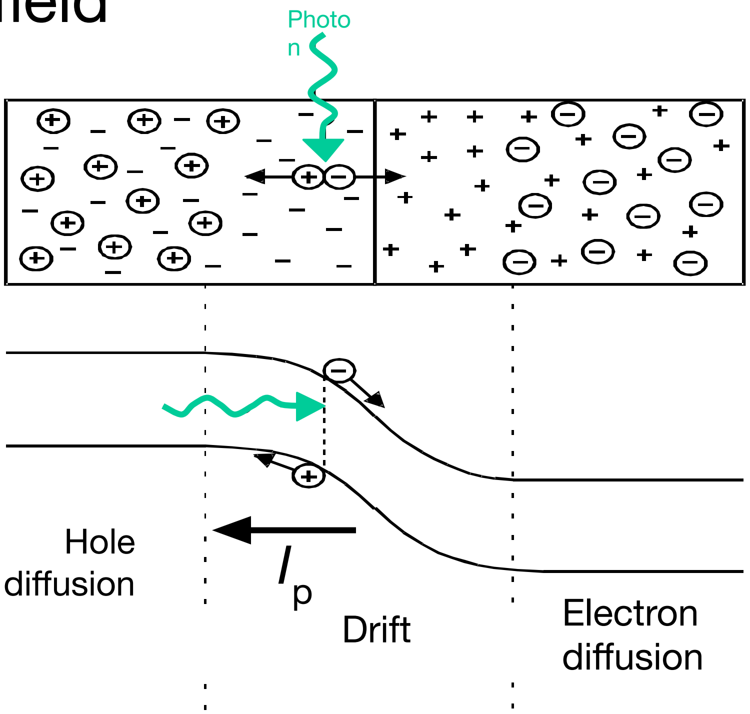
$$= q\left[\eta \frac{P_{opt}}{h\nu}\right] \cdot \left[\frac{\mu\tau|\vec{E}|}{L}\right]$$

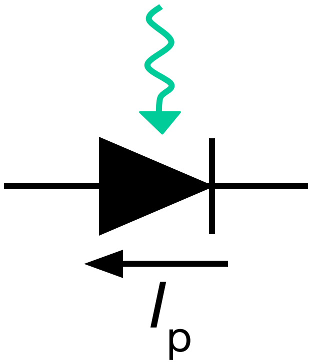
$$= I_{ph} \cdot \frac{\tau}{t_r}$$

μ: Mobility
L: Length
t_r: ($L/\mu E$) Carrier transit time

Photodiode

Charge transport by built-in electric field





Reverse current

$$I_p = I_{ph} = q\eta \frac{P_{opt}}{h\nu}$$

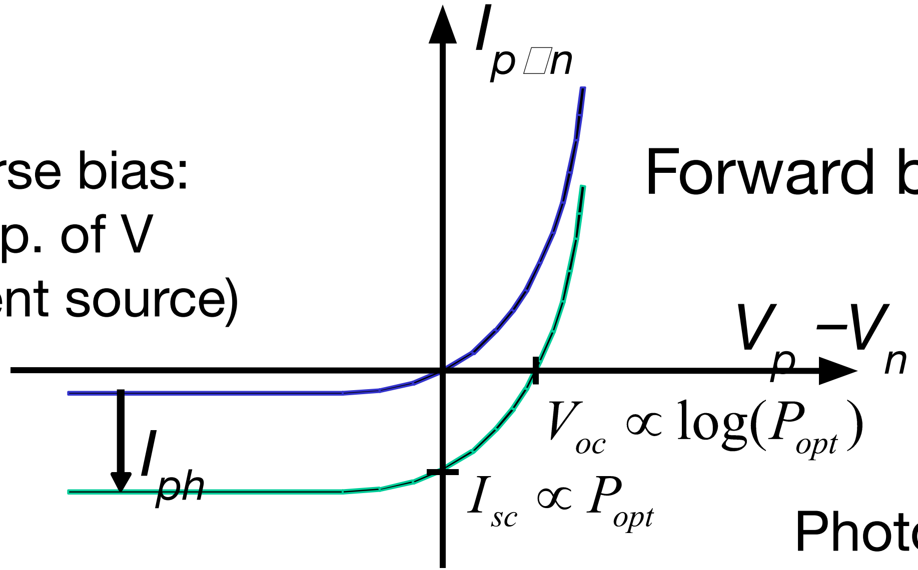
Responsivity

$$R = \frac{I_p}{P_{opt}} = \eta \cdot \frac{q\lambda}{hc} = \frac{\eta\lambda}{1.24\mu\mathrm{m}} \cdot \frac{\mathrm{A}}{\mathrm{W}}$$

Current-Voltage Characteristics of Photodiode

Reverse bias:
I indep. of V
(current source)

Forward bias

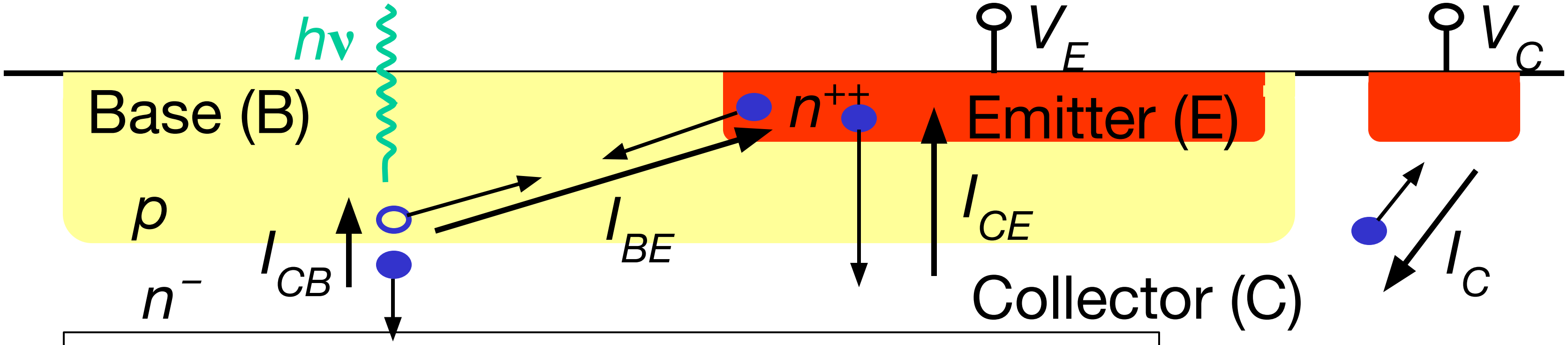


Photovoltaic
regime for
$I_{p□n} < 0$

V_{oc}: Open-loop voltage
I_{sc}: Short-circuit current

Phototransistor

Bipolar junction transistor with floating base

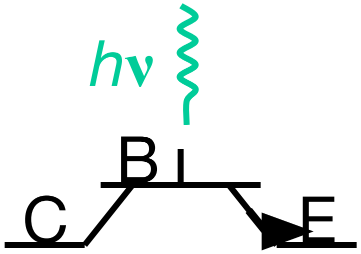


$I_{BE} = I_{ph}$ due to photogenerated holes

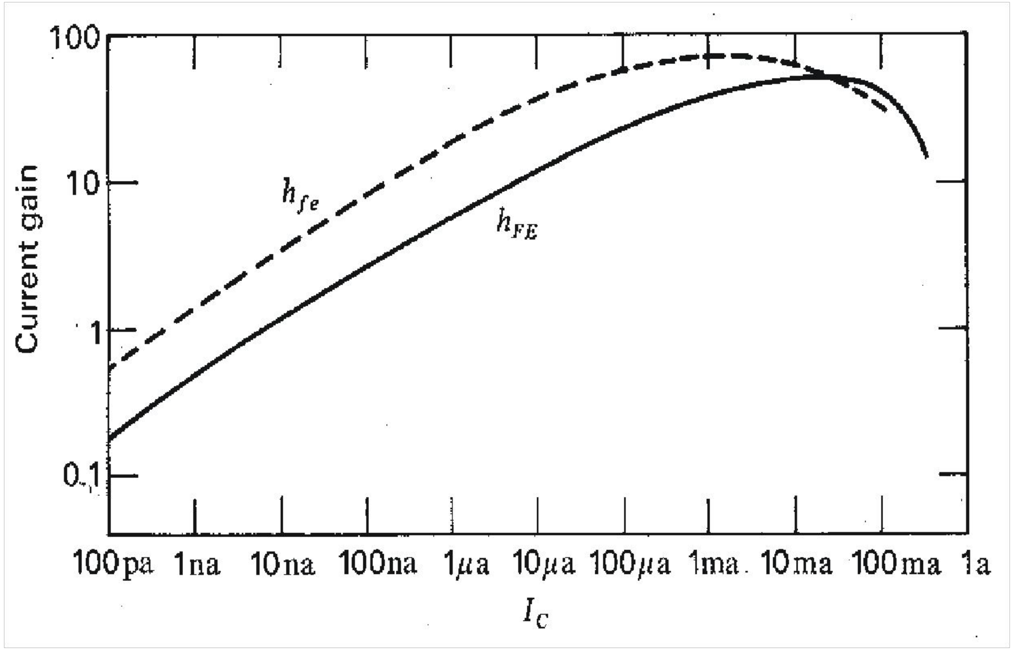
$I_{CB} = I_{ph}$ due to photogenerated electrons

$$I_C = I_{CB} + I_{CE} = I_{CB} + \frac{\partial I_{CE}}{\partial I_{BE}} \cdot I_{BE} = I_{ph} \cdot (1 + h_{FE})$$

$h_{FE} = \frac{\partial I_{CE}}{\partial I_{BE}}$: Common-emitter current gain



Common-Emitter Current Gain of Phototransistor



h_{fe}: Small-signal common-emitter current gain

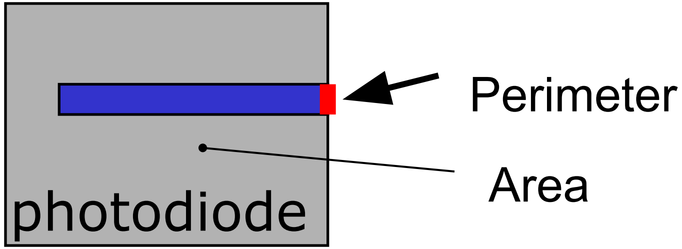
h_{FE}: Common-emitter current gain

Photodiode vs. Phototransistor

- $I_p = I_{ph} \propto P_{opt}$
- Linear
- No gain
- Fast response
- Small size
- Low noise

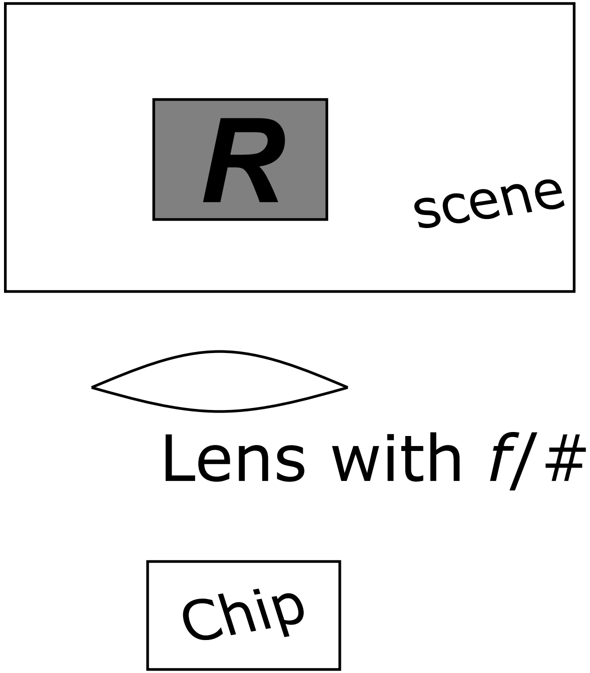
- $I_p = I_{ph}\,(1+h_{FE})$
- Nonlinear: $h_{FE}\,(I_{CE})$
- Gain: $h_{FE} \sim 10^2$
- Slower response
- Larger size
- Noise amplified

Dark current limits low-light performance



- Typical process leaks 1nA/cm^2 for large area junctions at 25°C
- Corresponds to about moonlight **scene** illumination
- Dominated by edges of junctions, where leakage is 10-100x higher: red edge leaks as much as blue area.
- Doubles every ~6-8°C; from 25°C to 60°C increases 30X
- e.g. vendors advertise 20-50x lower dark current, but these processes not available to usual multiproject services like MOSIS and Europractice

Estimating photocurrent



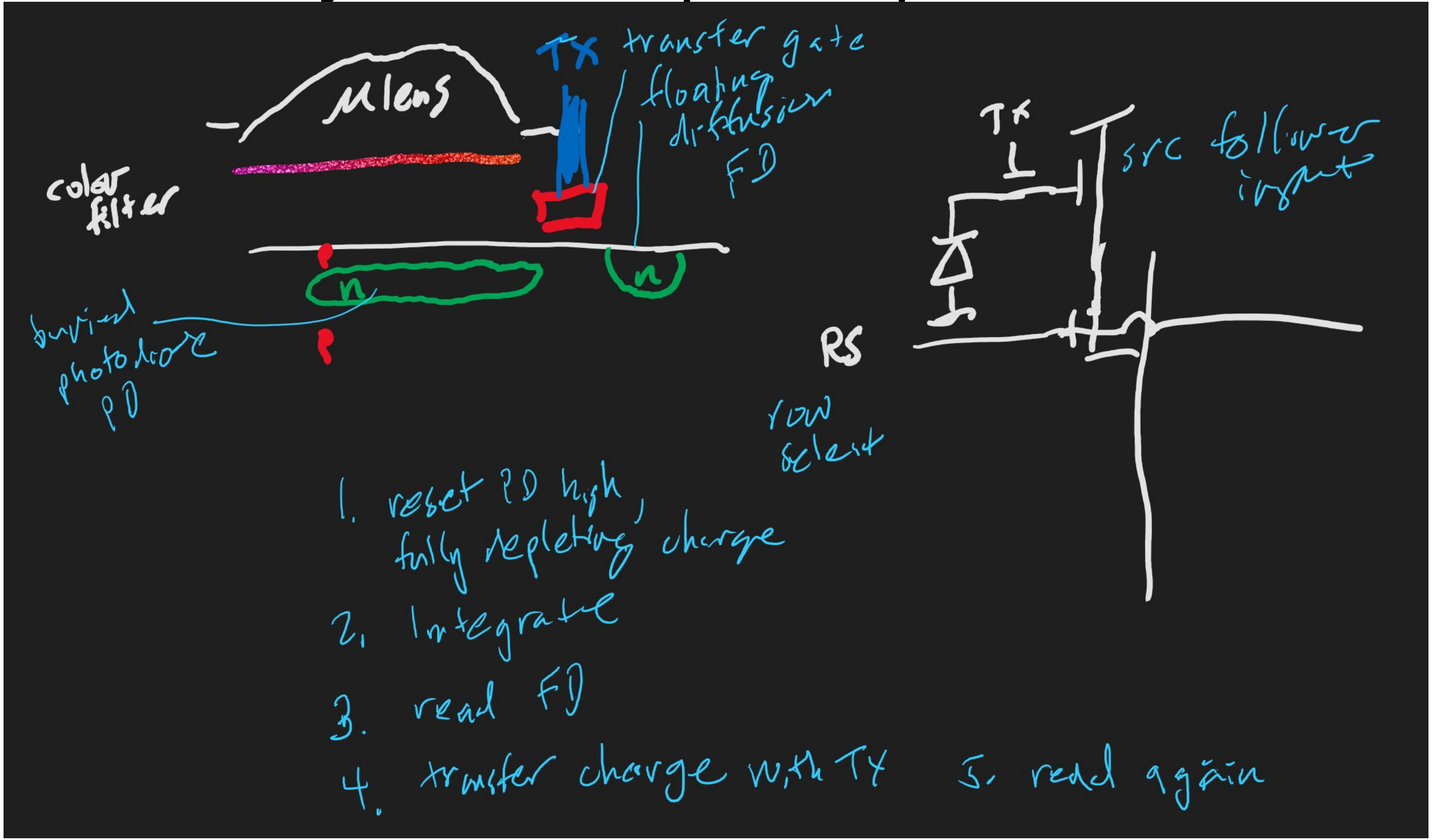
- Good rule of thumb:

  1 lux = 10^4 photons/um^2/s (Rose, 1973)
  - Moonlight 0.1 lux
  - Office light 500 lux
  - Sunlight 10^5 lux
- Average scene reflectance *R* is 18% (Kodak gray)
- Lux falling on chip is $1/4f^2$ imaged from white surface. *f* is focal-length/aperture, e.g. a fast lens will have *f*=1.4
- Quantum efficiency QE is about 0.5

$$I_{\text{chip}}[\text{lux}] = \frac{I_{\text{scene}}[\text{lux}] R \bullet QE}{4f^2}$$

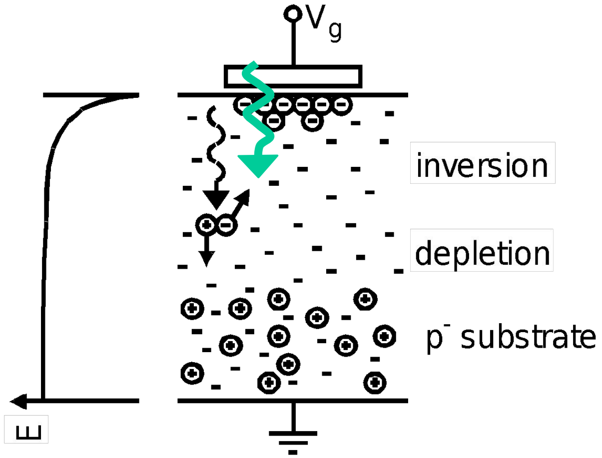
Notes on practical photometry (T. Delbruck) 1997, 2006, 2017

How your 3T cellphone pixel works

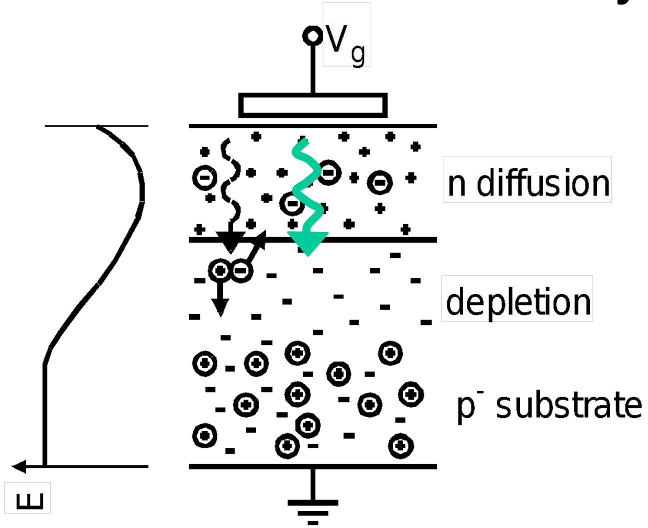


Photogate

A Metal-Insulator Semiconductor (MIS) structure where one type of photogenerated carriers is collected in a depletion region, underneath the gate, the other is collected by the substrate.



Surface charge storage



Bulk charge storage

Why a logarithmic response is useful

- If the photoreceptor has a log response, then scene illumination *I* appears as an additive term in the output, which is formed from the product of *I* and scene reflectance *R*:

$$\log(RI)=\log R+\log I$$

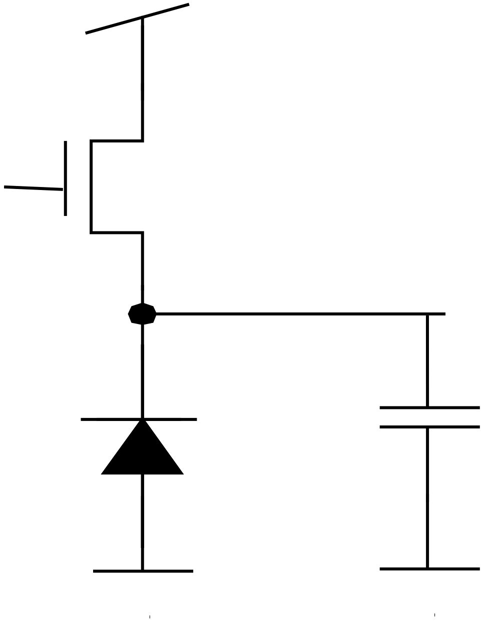
- Differences between receptors over space or time leave only the reflectance variations:

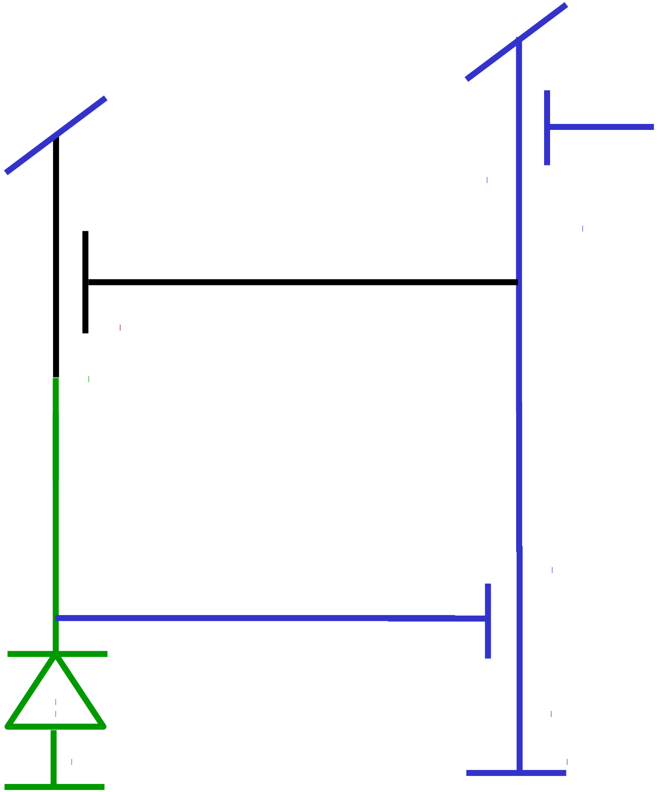
$$\Delta\log IR=\Delta\log R$$

- Reflectance variations are *object* properties, which are useful for vision.
- The log is also very compressive, allowing wide dynamic range within a power supply rail – as long as mismatch can be tolerated.

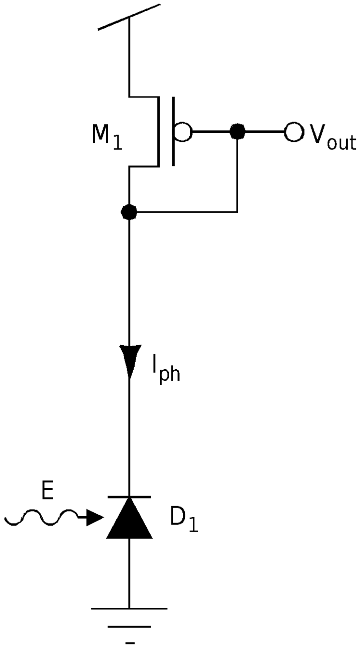
Exercise (in python Jupyter notebook)

passive ***source-follower*** and active ***transimpedance*** log photoreceptors

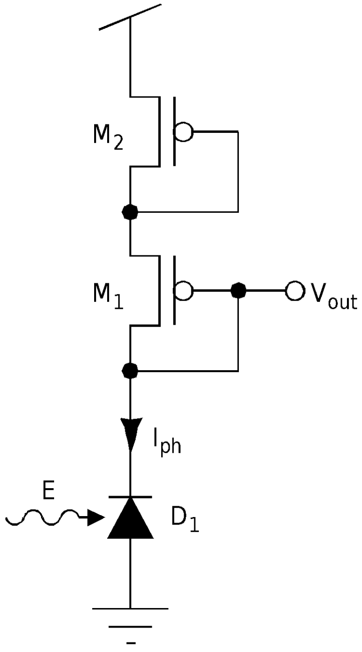




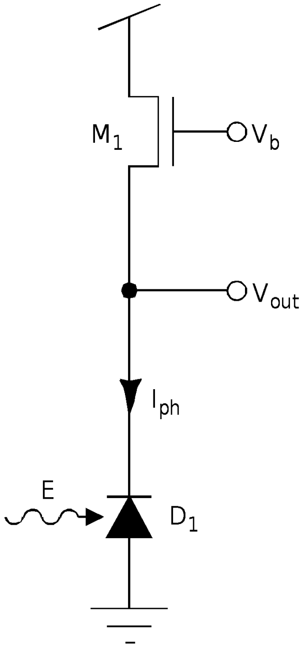
Simple Logarithmic Photosensors



Diode-connected MOSFET



Double diode-connected MOSFET



Source-follower MOSFET

Source follower photoreceptor DC response

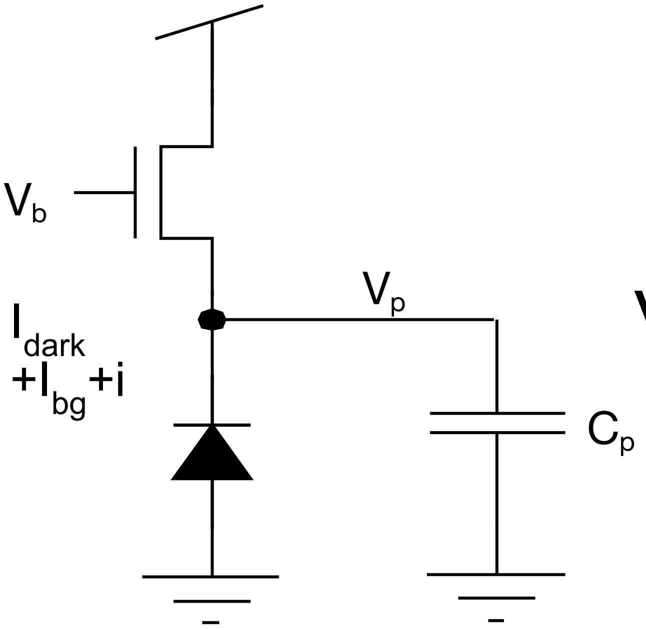
$$I_{\mathrm{dark}} + I_{\mathrm{bg}} + i = I_0 e^{\frac{\kappa V_{\mathrm{b}} - V_{\mathrm{out}}}{U_{\mathrm{T}}}}$$

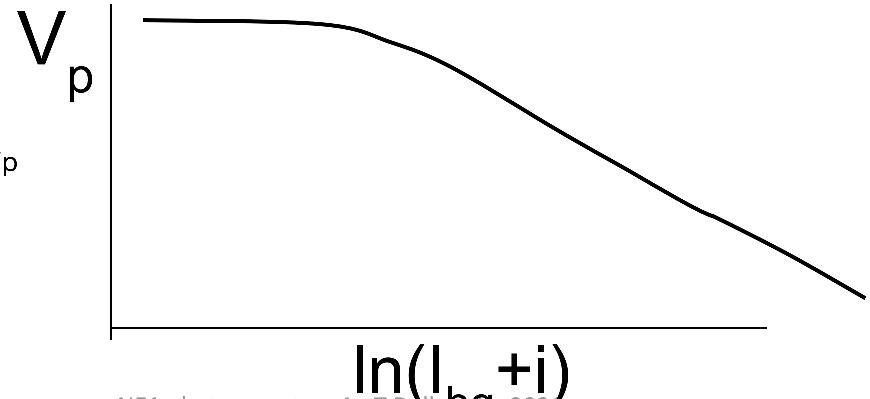
$$V_{\mathrm{p}} = \kappa V_{\mathrm{b}} - U_{\mathrm{T}} \ln\left(\frac{I_{\mathrm{dark}} + I_{\mathrm{bg}} + i}{I_0}\right)$$

$I_{\mathrm{dark}} =$ constant dark current

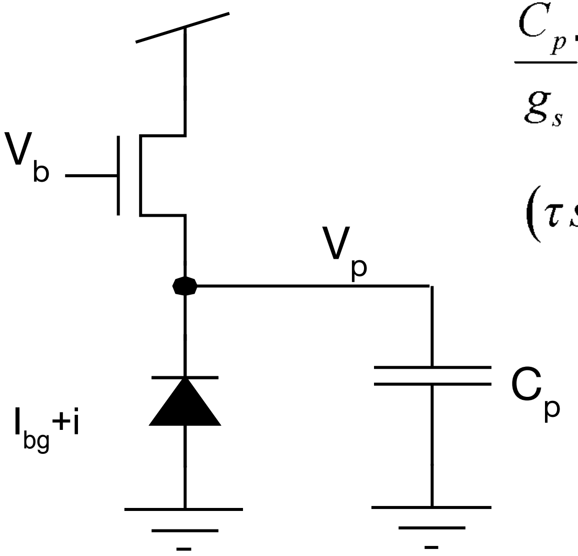
$I_{\mathrm{bg}} =$ static scene luminance

$i =$ signal luminance (varying part)





Source follower photoreceptor AC response



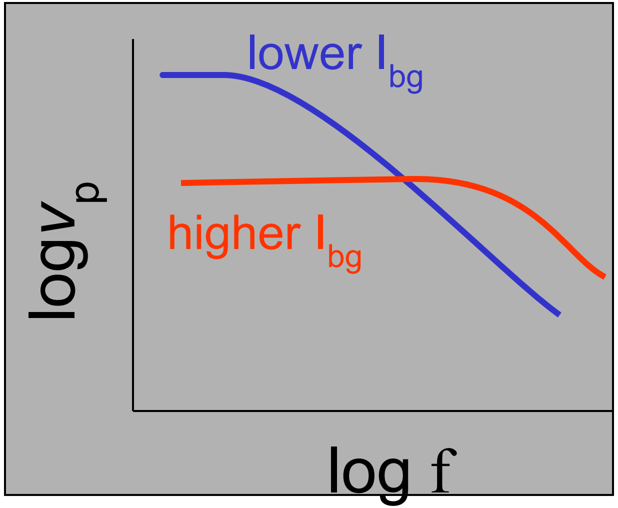
$$C_p \dot{v}_p = -i - g_s v_p$$

$$g_s = \frac{I_{bg}}{U_T}$$

$$\frac{C_p}{g_s}\dot{v}_p + v_p = \frac{-i}{g_s} = -U_T \frac{i}{I_{bg}}$$

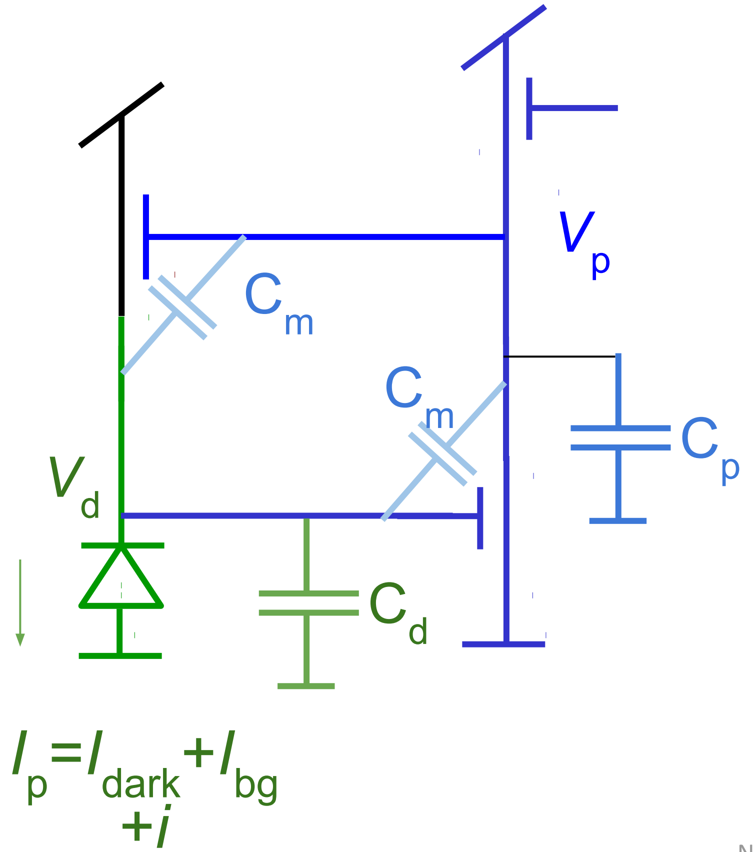
$$(\tau s + 1) v_p = -U_T \frac{i}{I_{bg}}$$

$$v_p = \frac{-U_T \frac{i}{I_{bg}}}{\tau s + 1}, \quad \tau = \frac{C_p U_T}{I_{bg}}$$



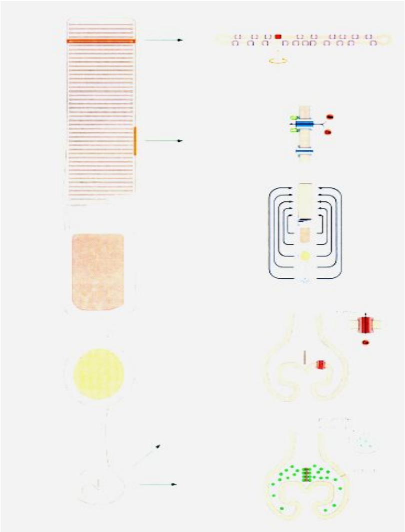
V

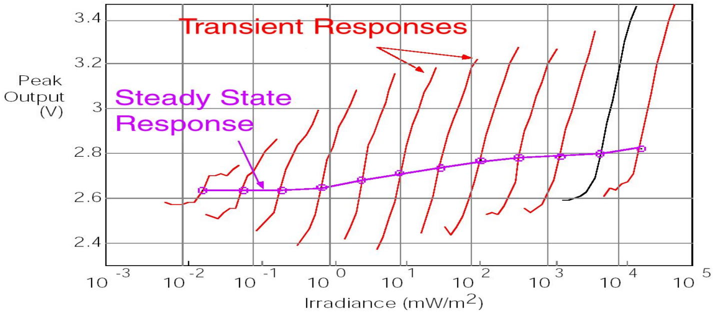
Active transimpedance log photoreceptor

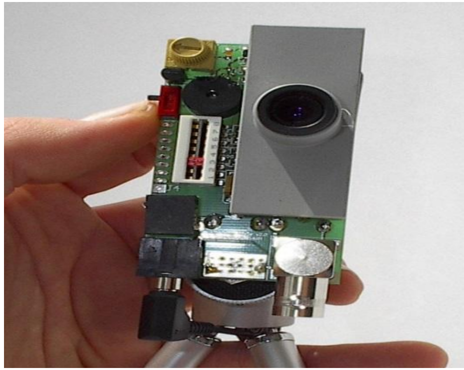


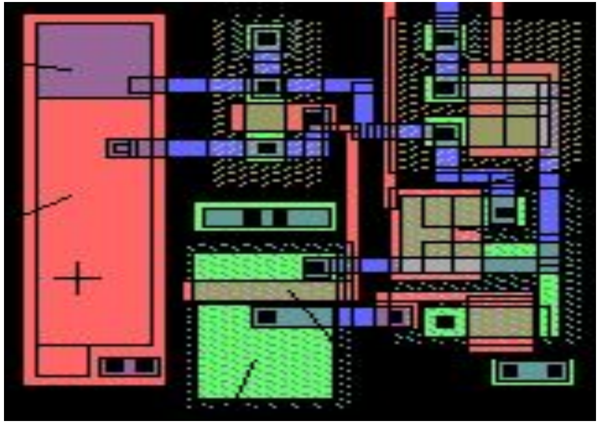
See Photoreceptor 2 slides for small signal analysis

Next week: Photoreceptors II









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