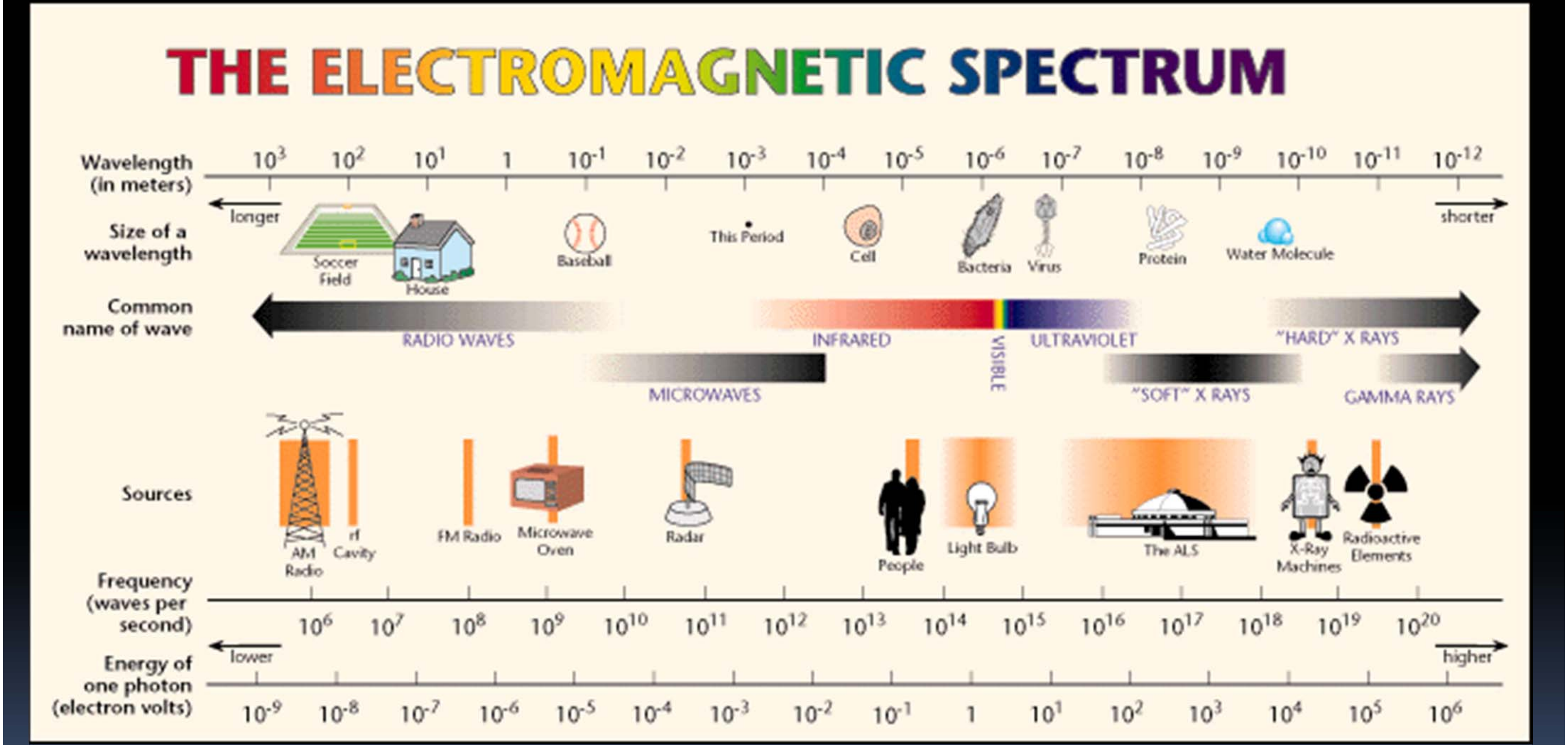
ECE 5358/6358

OPTICAL DETECTION AND DETECTORS

Outline

- (Part 1) Introduction
    - Concept
    - Detection mechanism and types of detectors
- Photoelectric detectors
    - Fundamental detection mechanism
    - Key common features
- Types of photodiodes
    - p-n and p-i-n
    - Advanced p-i-n structures
    - Others
- (Part 2) Optical detection - signal and noise


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6

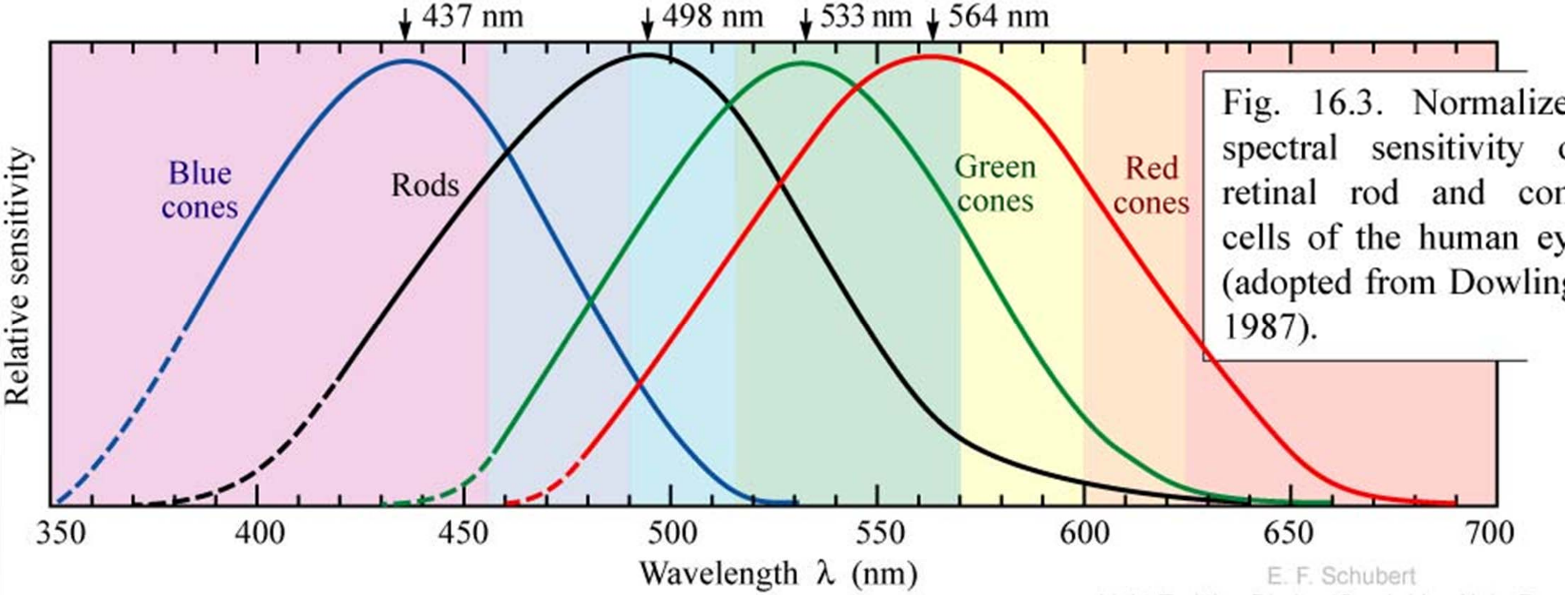


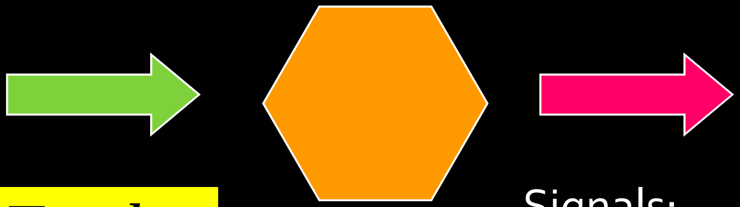
Fig. 16.3. Normalize spectral sensitivity retinal rod and cor cells of the human ey (adopted from Dowlin 1987).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Pres
www.LightEmittingDiodes.org

Detectors and transducers - concept

- Detector is "*a device that detects something*".. In science and engineering, that "*something*" at the most basic level is usually a physical stimulus: light, sound, heat, pressure, chemicals,…
- General concept: transducer is a device that converts a physical stimulus from one physical form to another in a different physical form
  - Physical form: electromagnetic (photons), chemical (a non-radiative form of electromagnetic energy, stored in atomic or molecular electronic energy level), and mechanical, kinetic energy of atoms or molecules
- Transducers are thus considered as energy converters (sometimes also called modifiers)
- Concept usually applied only for intrinsic and direct physical processes.
- Application of transducers are detectors. Light detectors are transducers of light

Photodetectors



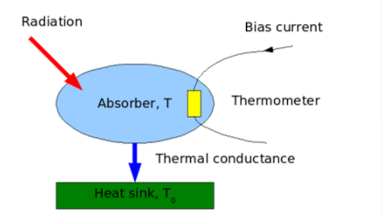
Photons

$E = h\nu$

Signals:
voltage or
currents

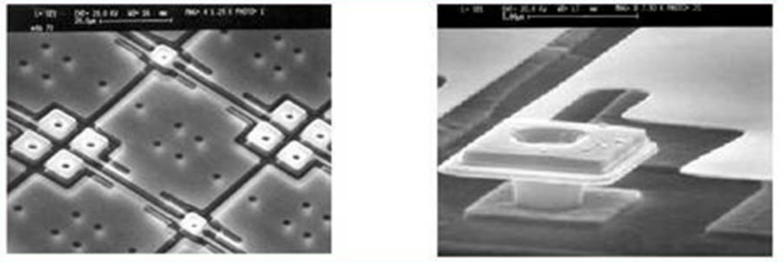
$V i \Delta t$

- Direct: direct conversion from photons to electronic changes, resulting in a voltage or a current signal.
- Indirect: photon energy is first converted into another form of energy, such as heat, pressure (including sounds), or chemical reaction,.. these responses are then converted into a convenient, measureable signals such as voltage and current



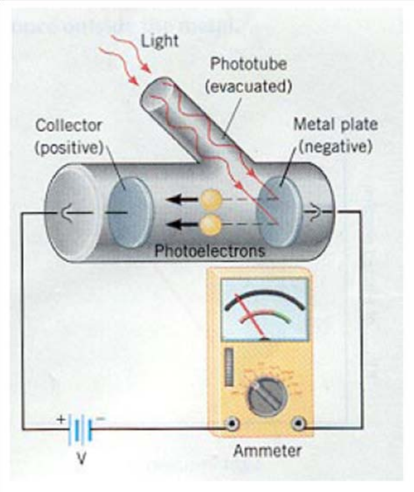
- Examples of indirect: bolometer, Golay cell, film…

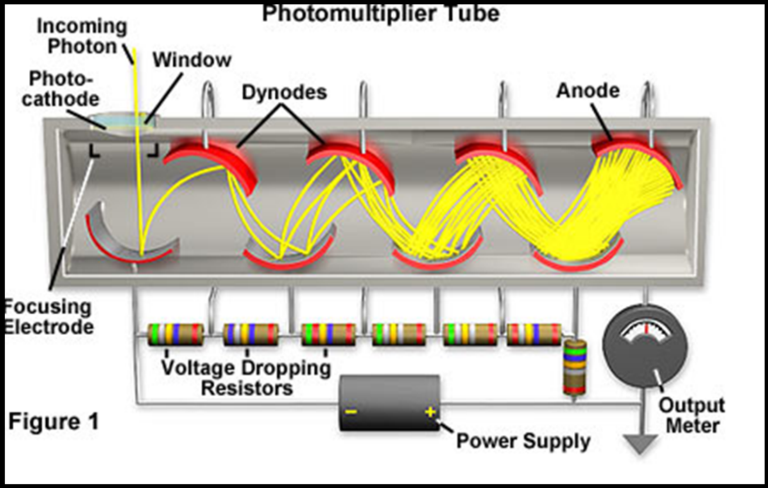
- For numerous (most) applications, only direct photodetection is practical



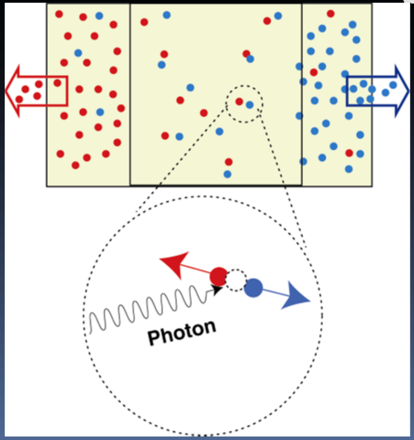
Photoelectric detectors

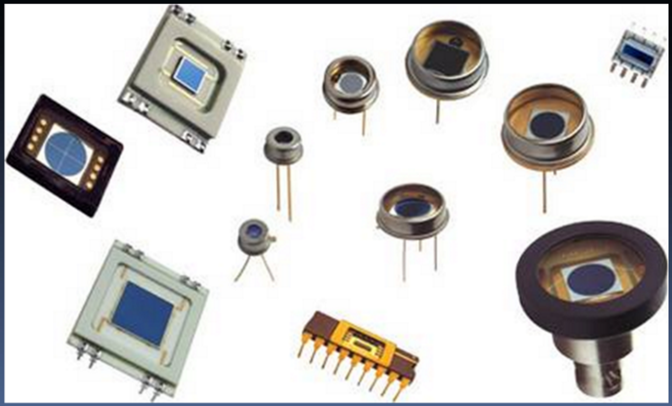
Photoelectrons generated in vacuum

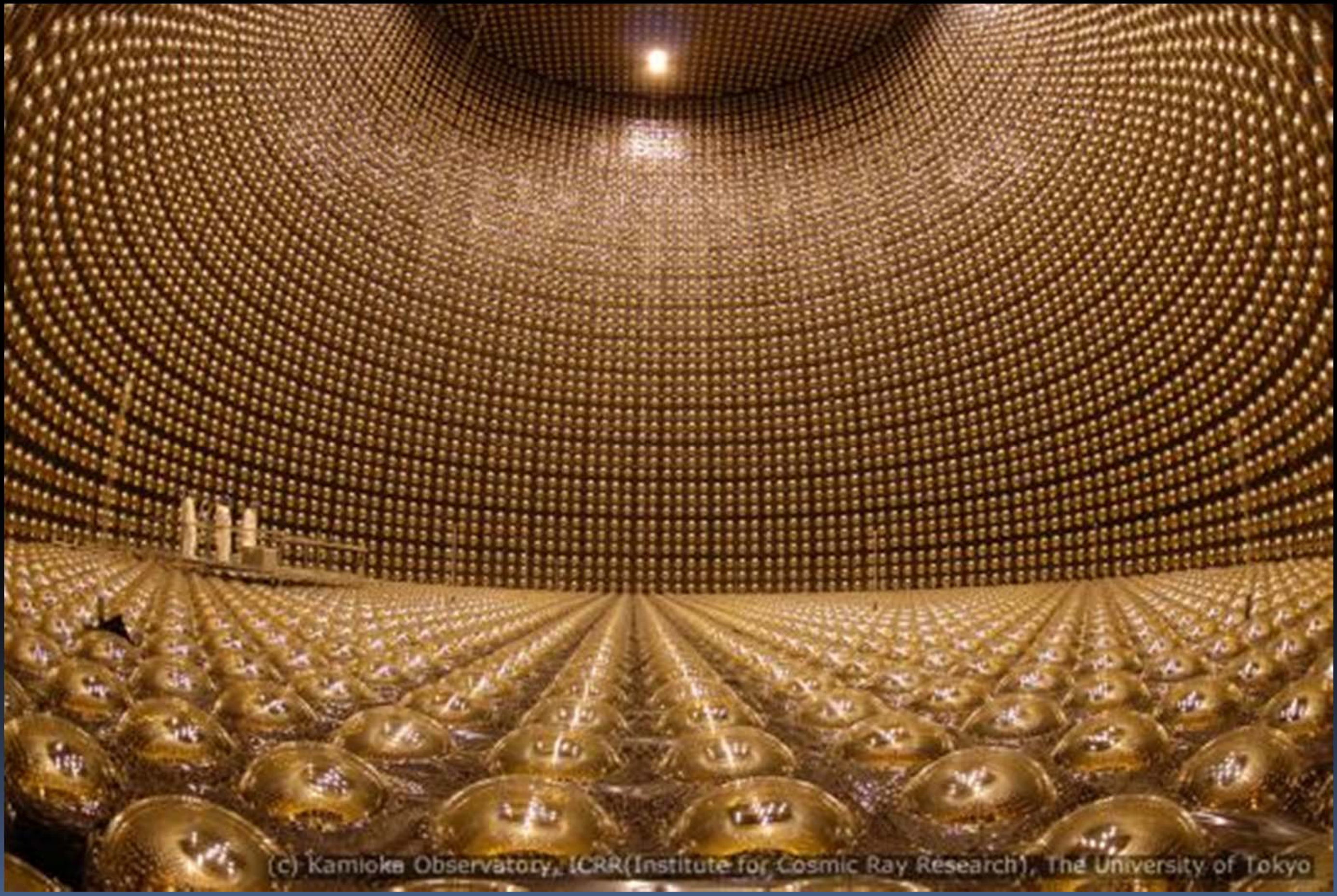




Photoelectrons generated in a solid



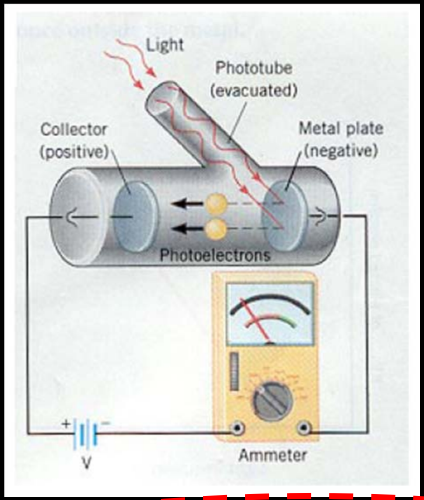


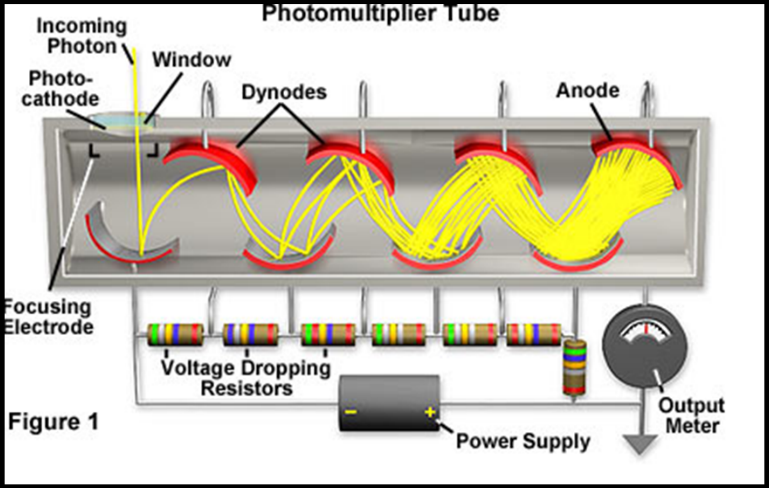


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

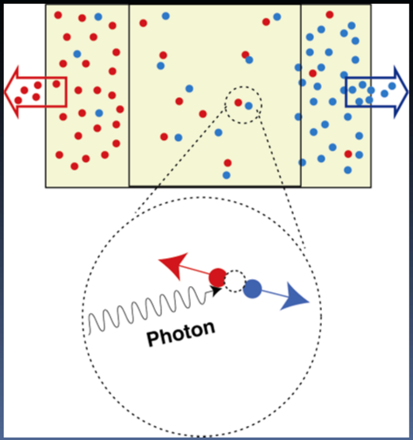
Photoelectric detectors

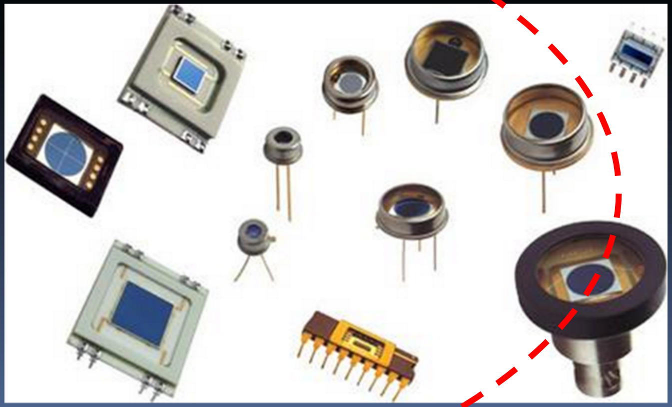
Photoelectrons generated in vacuum



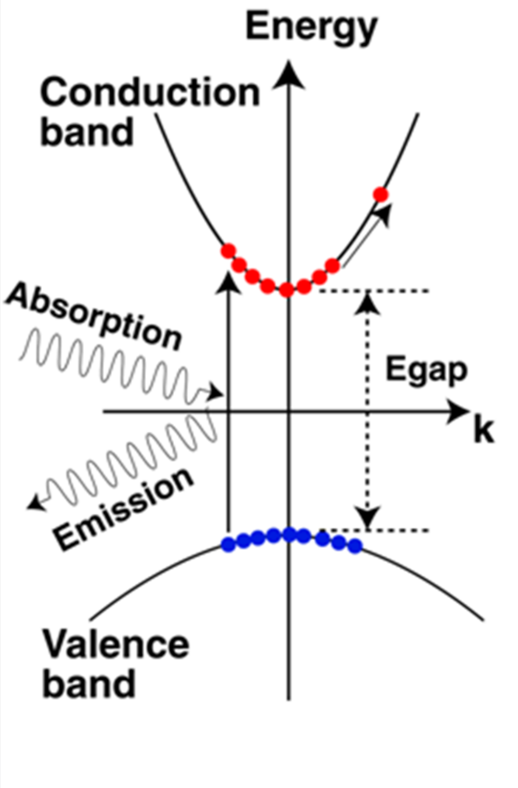


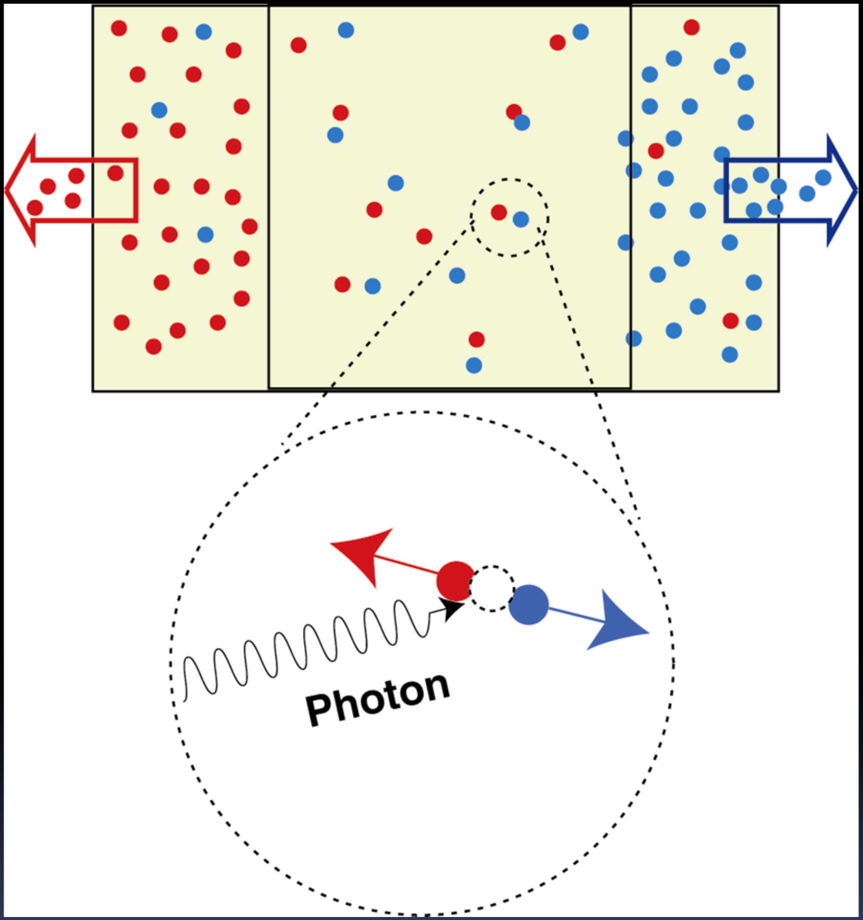
Photoelectrons generated in a solid



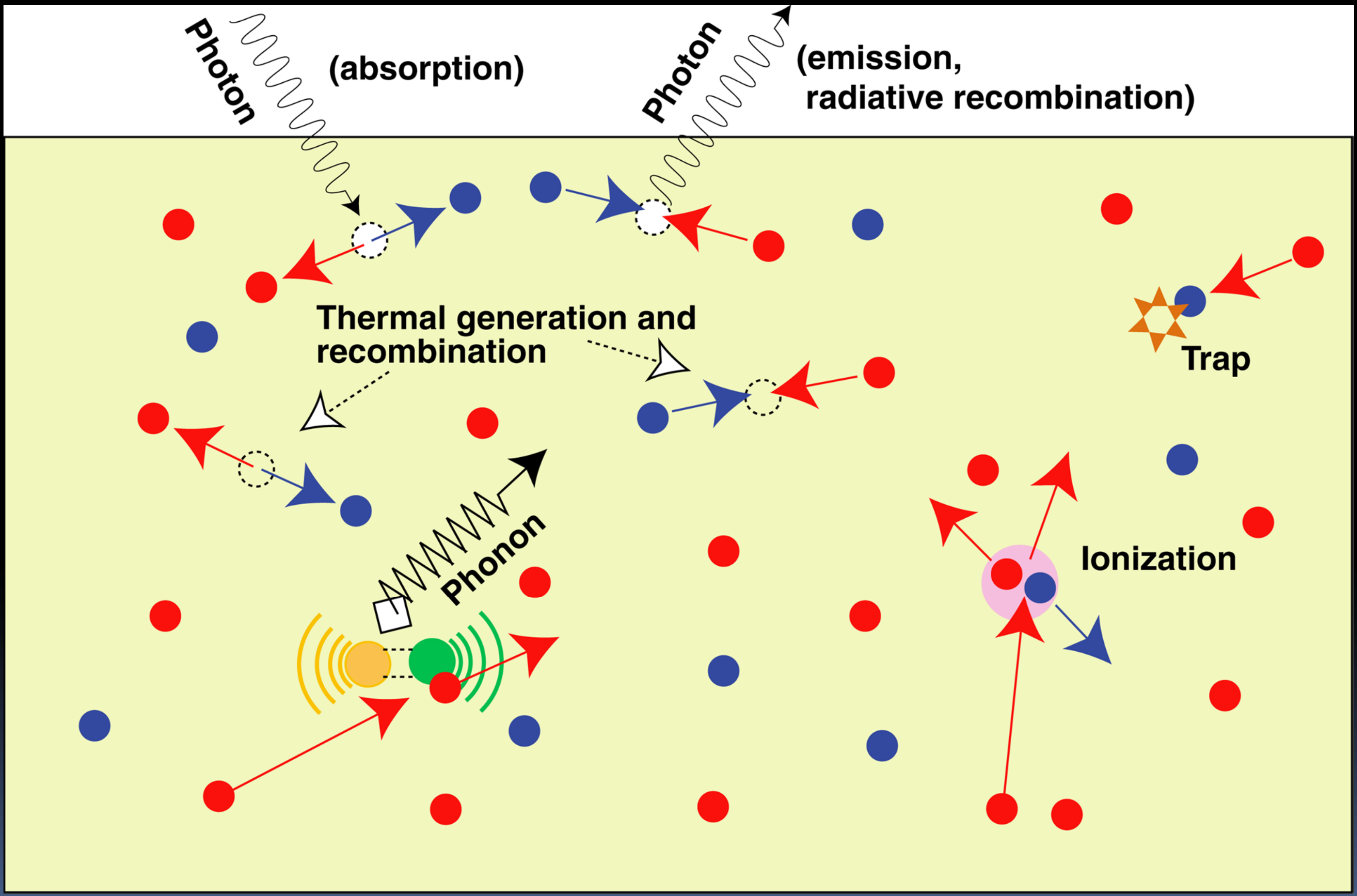


Photoelectric Effects in Semiconductors

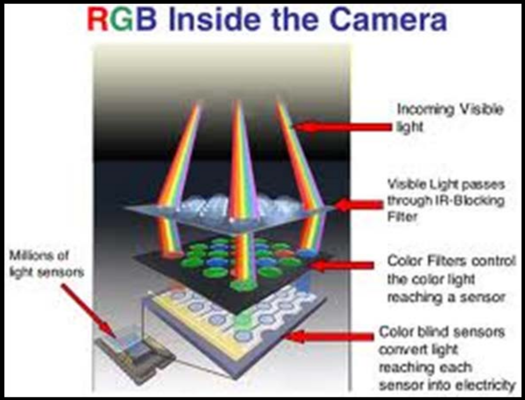


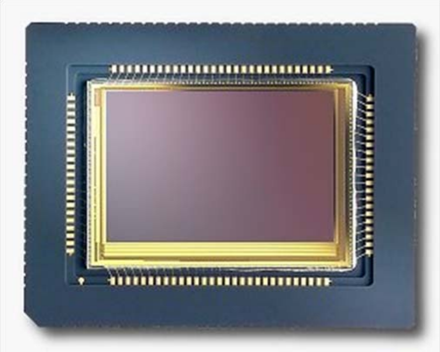


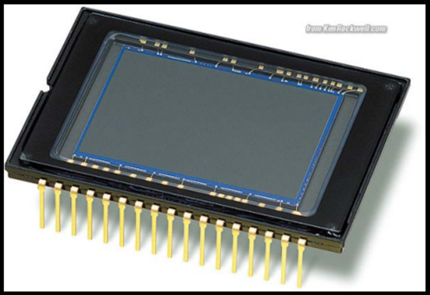
Excitation and Relaxation

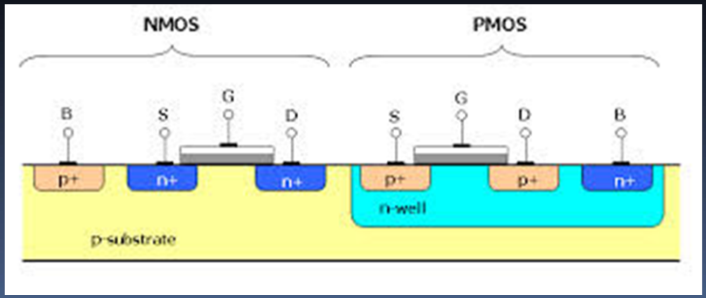



SONY
BIONZ
Sony Lens G
SONY
Cyber-shot
2.4-5.9/4.25-21.25
G


RGB Inside the Camera
Incoming Visible light
Visible Light passes through IR-Blocking Filter
Color Filters control the color light reaching a sensor
Color blind sensors convert light reaching each sensor into electricity
Millions of light sensors



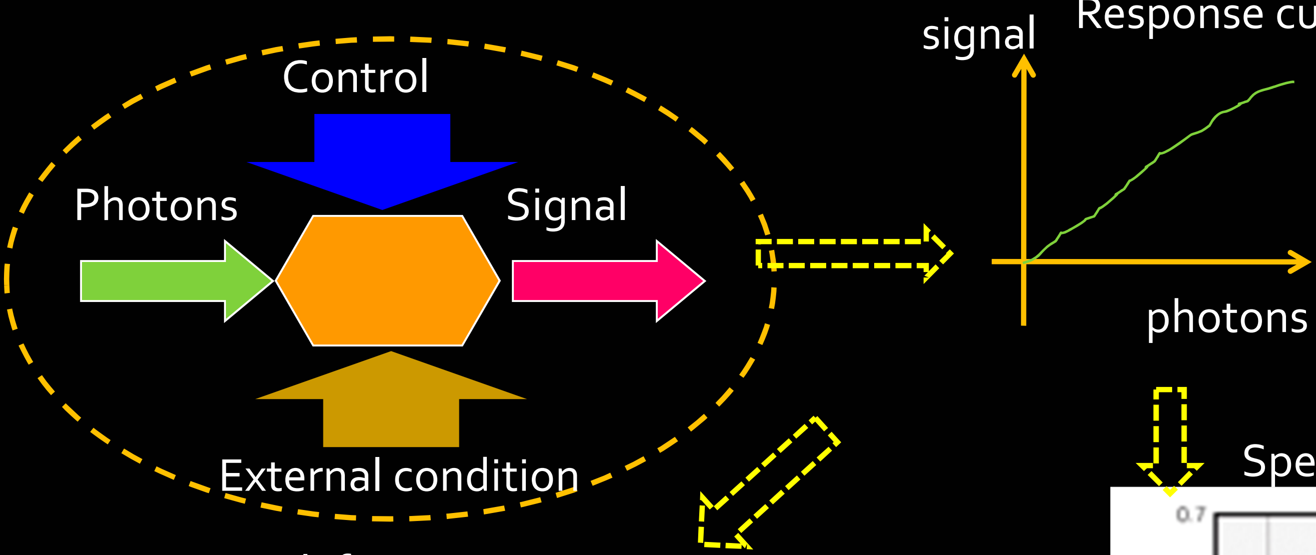



NMOS
PMOS
B
S
G
D
S
G
D
B
p+
n+
n+
p+
p+
n+
n-well
p-substrate

▶

Basic Operational Concepts

Responsivity

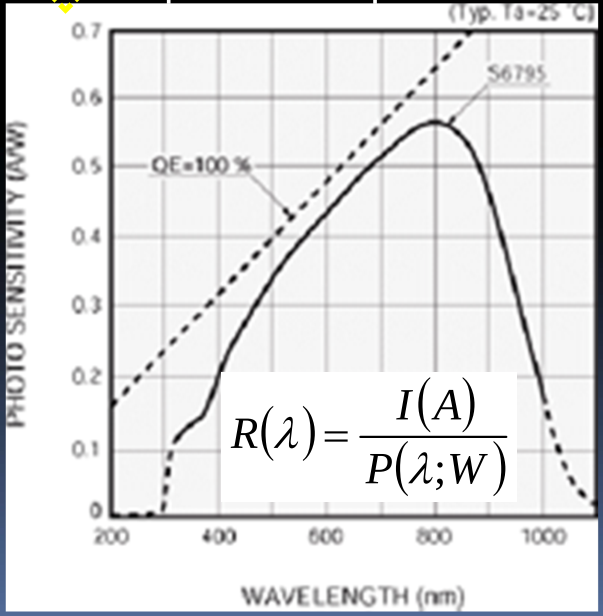


Response curve

$$R = \frac{I(A)}{P(W)}$$

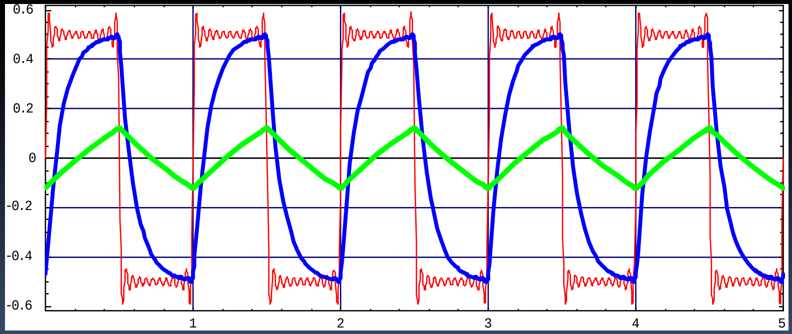
$$\eta_{\text{QE}} = \frac{\text{electron}}{\text{photon}}$$

Spectral response



$$R(\lambda) = \frac{I(A)}{P(\lambda;W)}$$

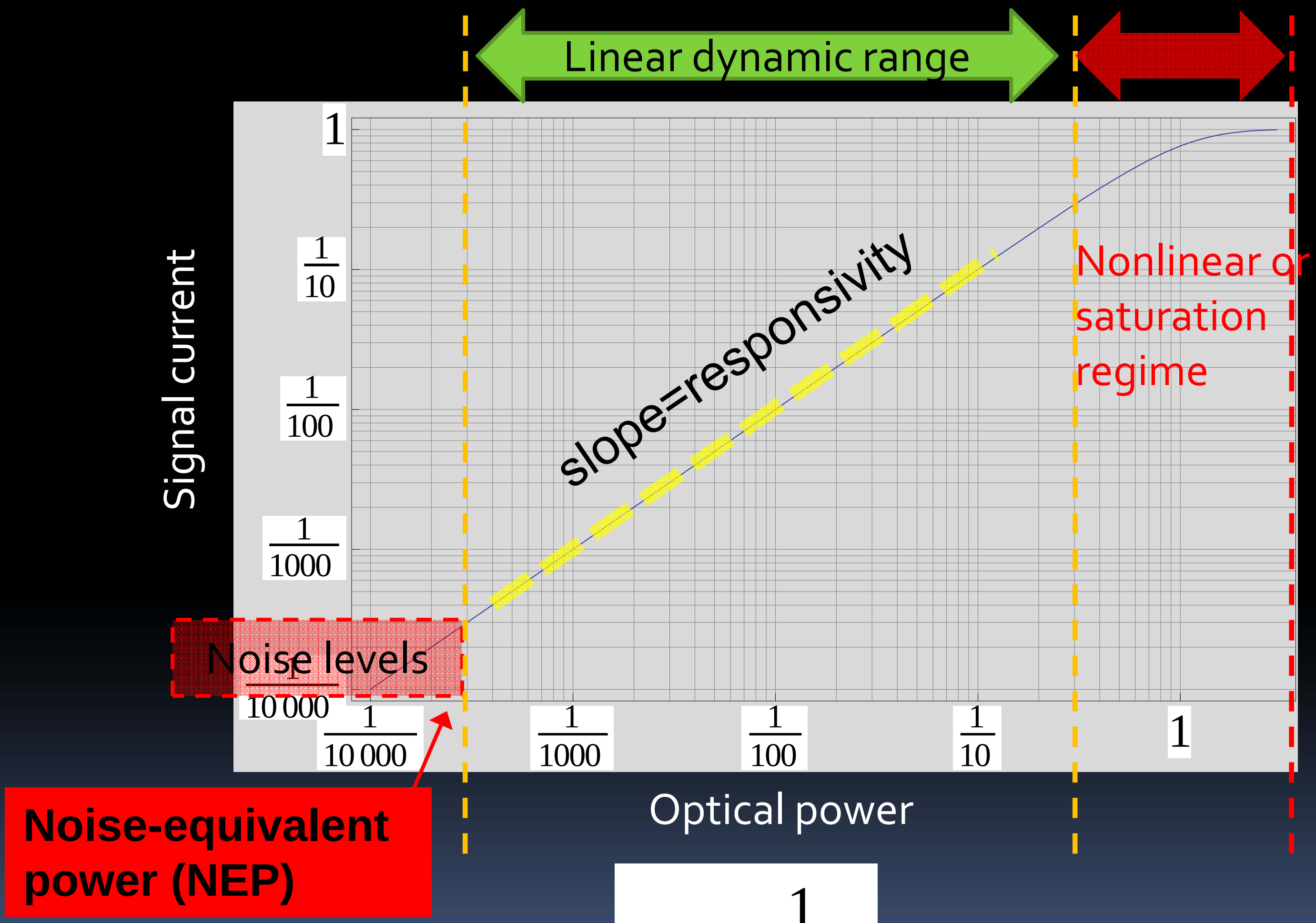
Temporal (frequency) response



$$S(f) = H[f]P(f)$$

$$S(t) = \int h[t-\tau]P(\tau)d\tau$$

Basic Operational Concepts (*cont.*)



Linear dynamic range

Nonlinear or saturation regime

Noise-equivalent power (NEP)

$$D = \frac{1}{\text{NEP}}$$

D: detectivity (related to sensitivity)

Basic Operational Concepts (*cont.*)

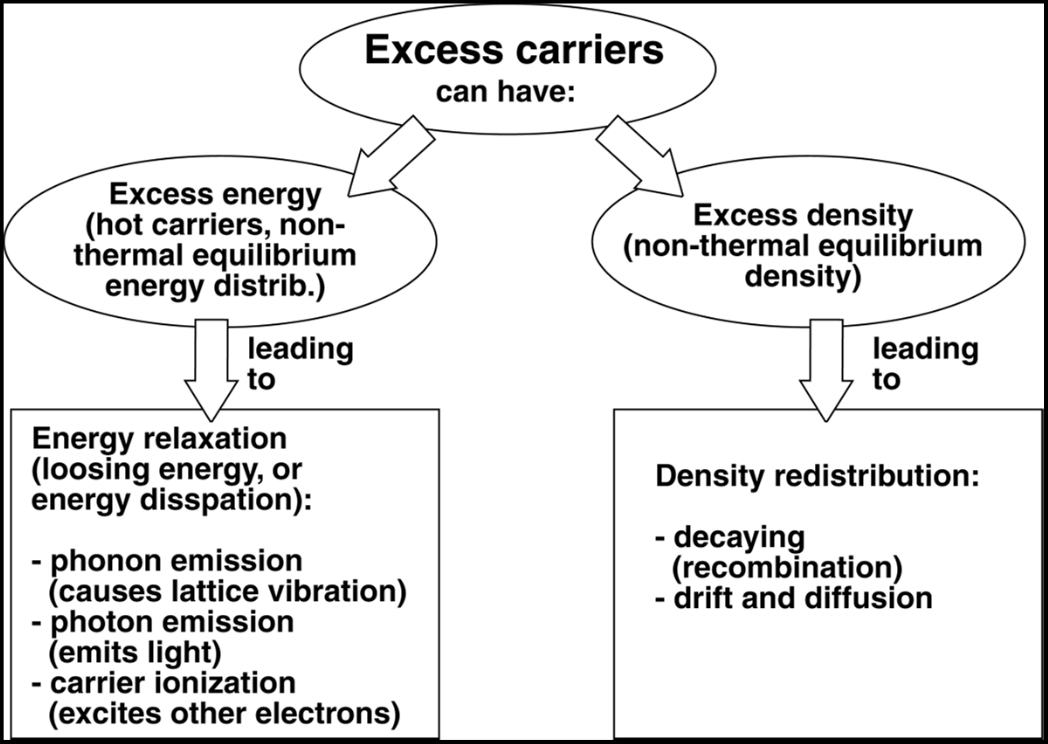
Others less technical aspects are also important:

- Control: example: bias voltage: ease of control
- Stability: same performance (or within acceptable limits) over a range of external conditions: temperature, humidity, shock/vibration etc.
- Reliability: same performance over a long period of time and usage; cycled external conditions.
- Size, weight, power consumption, ease of handling
- Cost

Detectors, Detection and Signals

- (Part 1) Introduction
  - Concept
  - Detection mechanism and types of detectors
- Photoelectric detectors
  - Fundamental detection mechanism
  - Key features
- (Part 2) Types of photodiodes
  - p-n and p-i-n
  - Advanced p-i-n structures
  - Phototransistors
  - Avalanche photodiodes
  - Others: MSM
- (Part 2) Signal and noise, detection theory

Non-equilibrium carrier behavior



Excess carriers
can have:

Excess energy
(hot carriers, non-thermal equilibrium energy distrib.)

Excess density
(non-thermal equilibrium density)

leading to

Energy relaxation (loosing energy, or energy disspation):

- phonon emission (causes lattice vibration)
- photon emission (emits light)
- carrier ionization (excites other electrons)

leading to

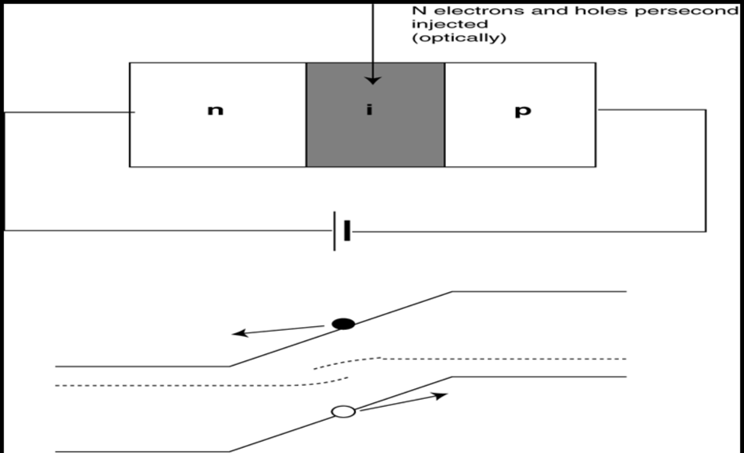
Density redistribution:

- decaying (recombination)
- drift and diffusion

- Photo-electron-hole pairs are collected as signal current → Normal operation
- Photo-electron-hole pairs can be lost before collected → Lower quantum efficiency
- Photo-electron-hole pairs can excite others → Gain (avalanche)

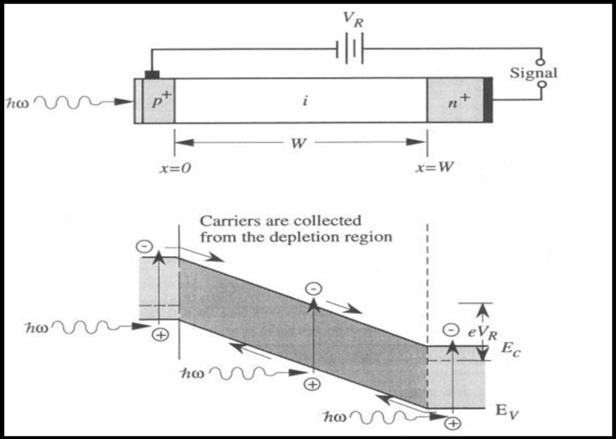
Photogenerated carriers collection

Photovoltaic



- Carriers are swept to collector regions with an internal field (p-n junction) + field from external bias: photodiode
- Easy to control high speed
- Very high linearity
- Application: signal detection (optical communication)

Photoconductive

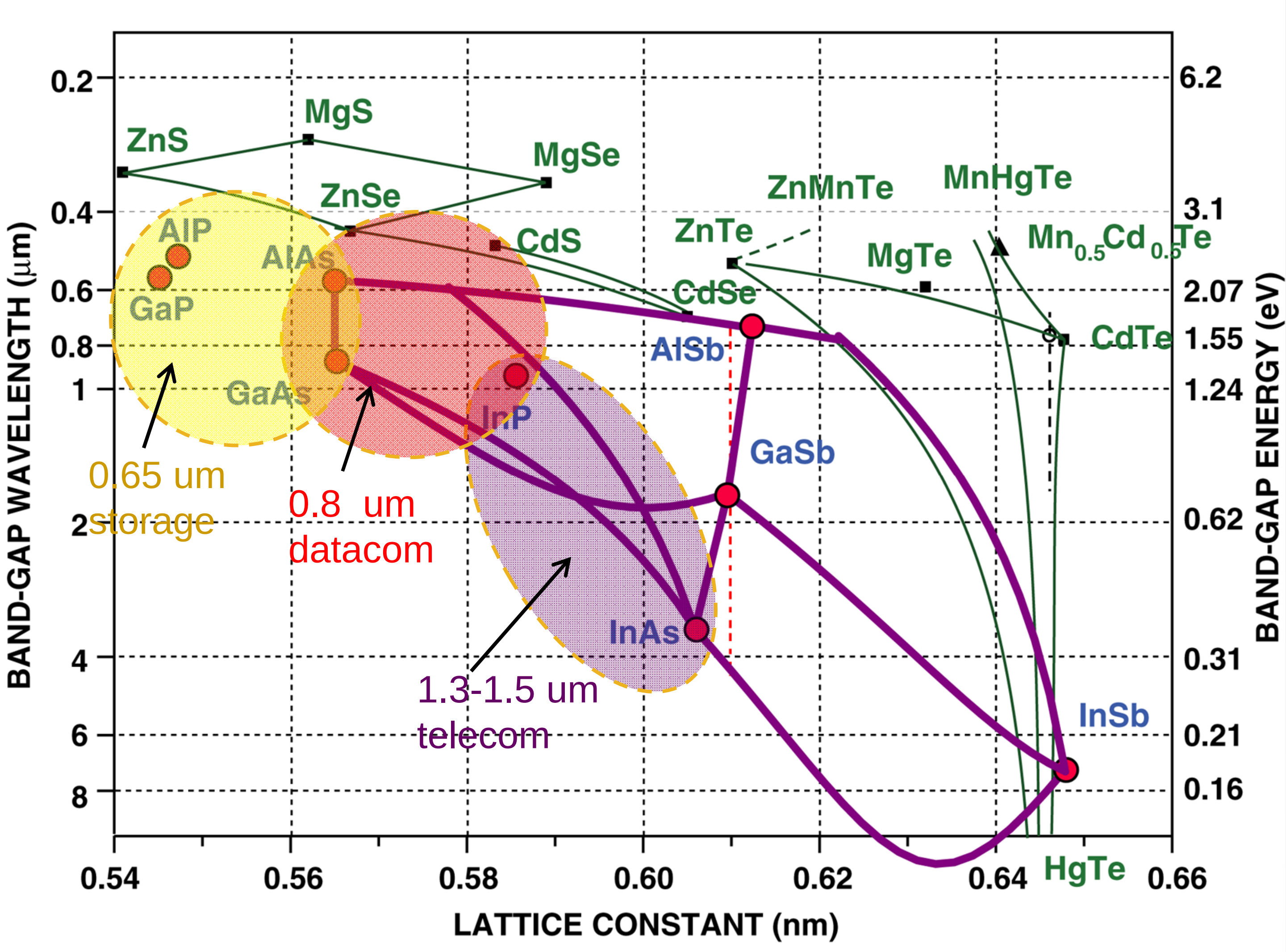


- Carriers are swept to collector regions with external bias field (a change of resistivity): photoconductive and metal-semiconductor-metal
- Speed depends on transit region, bias, carrier mobility
- Application: switch

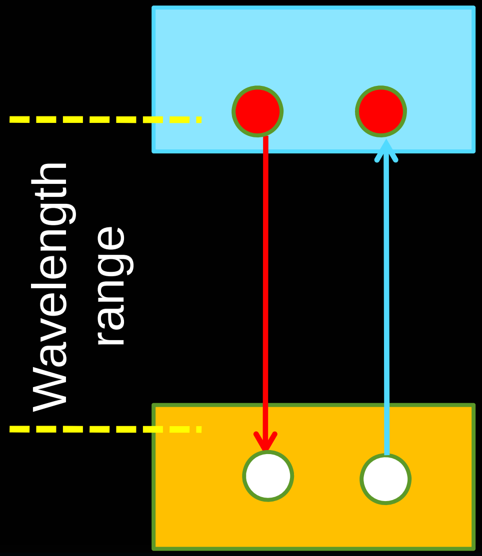
Key Aspects of Photodiode Engineering

Spectral response	Material bandgap engineering Absorption process and absorber design
Responsivity (quantum efficiency)	Collection process Diode structure design (reduce non-radiative recombination)
Speed (temporal or frequency response)	Collection process and circuit C-V characteristics (signal transmission) Carrier transit time
Gain	Avalanche region

Common semiconductor bandgap energy vs. lattice constant

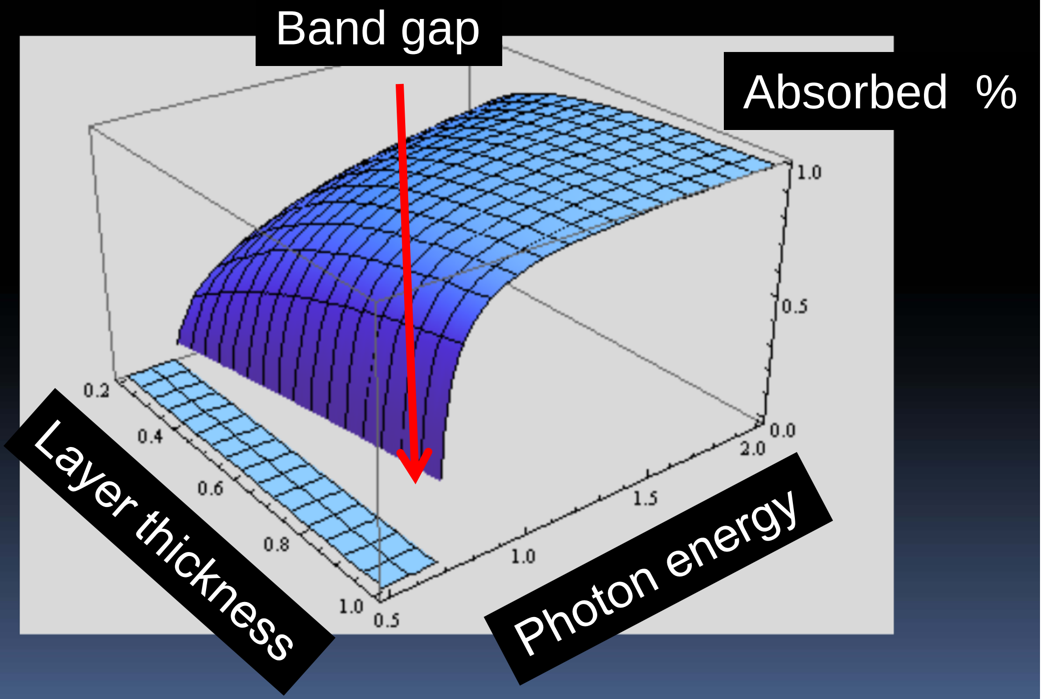


Absorption and Spectral Response



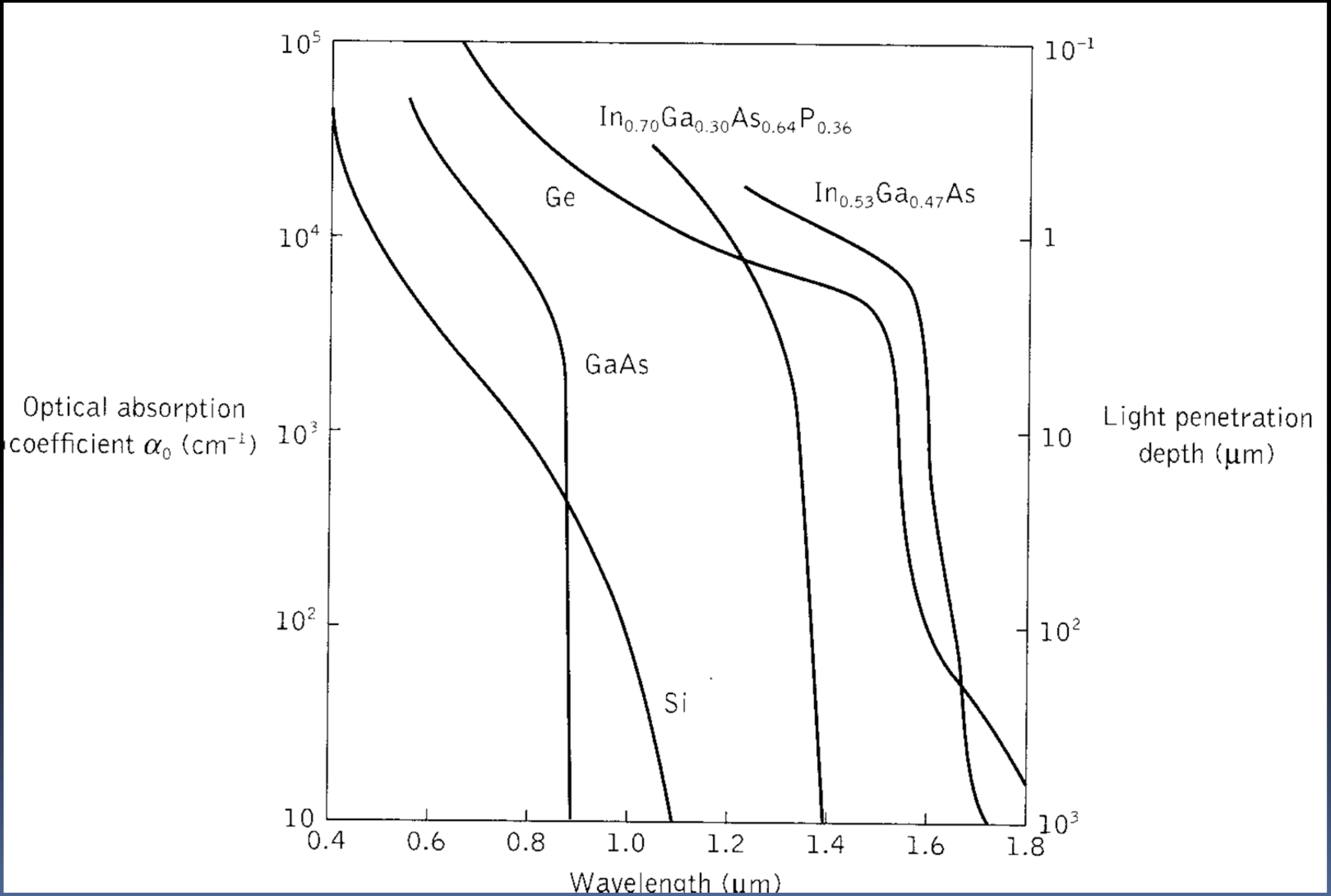
Absorption:

$$\alpha(E) = \alpha_{\mathrm{FS}} \frac{\lambda^2}{n_g} E \sum_{v} \frac{\left|\left\langle u_v^* \middle| \mathbf{p} \middle| u_c \right\rangle\right|^2}{m_o^2 c^2} \rho_{\mathrm{joint}} \left(E = E_{v,\mathbf{k}} + E_{c,\mathbf{k}}\right)\left(F\left(E_{c,\mathbf{k}}\right) - F\left(E_{v,\mathbf{k}}\right)\right)$$



- Very large absorption coefficient above Egap: ~ x10^4 -10^5 cm^{-1}
- Absorption > 90% easily with layer as thin as 0.5 um

Absorption Coefficients of Some Semiconductors



Spectral Response

$$R[\lambda] = \frac{i[\lambda]}{P_0}$$

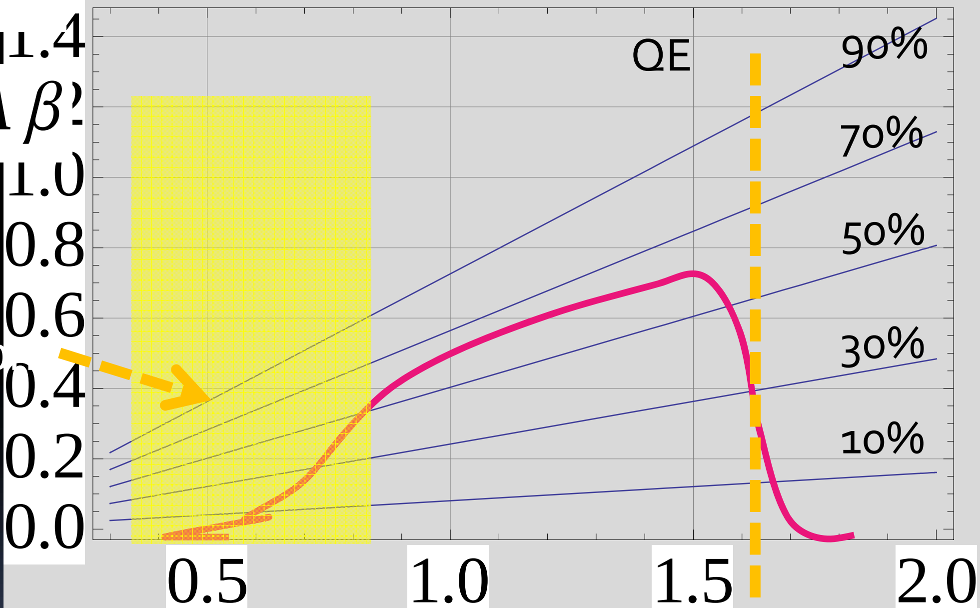
$$i[\lambda] = \eta_{int}[\lambda]\,\frac{P_{abs}[\lambda]}{h\nu}\,e$$

$$P_{abs}[\lambda] = P_0\,\beta\left(1 - e^{-\alpha[\lambda]\,d}\right)$$

$$R[\lambda] = \eta_{int}[\lambda]\,\frac{e}{h\nu}\,\beta\left(1 - e^{-\alpha[\lambda]\,d}\right)$$

$$\left(1 - e^{-\alpha[\lambda]\,d}\right) \sim \text{constant} = A$$

Define $\eta[\lambda] = \eta_{int}[\lambda]\,A\,\beta$



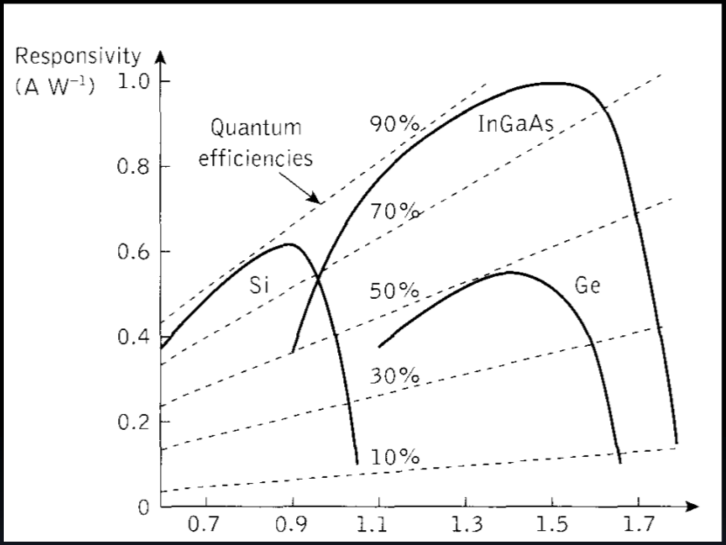
Band gap

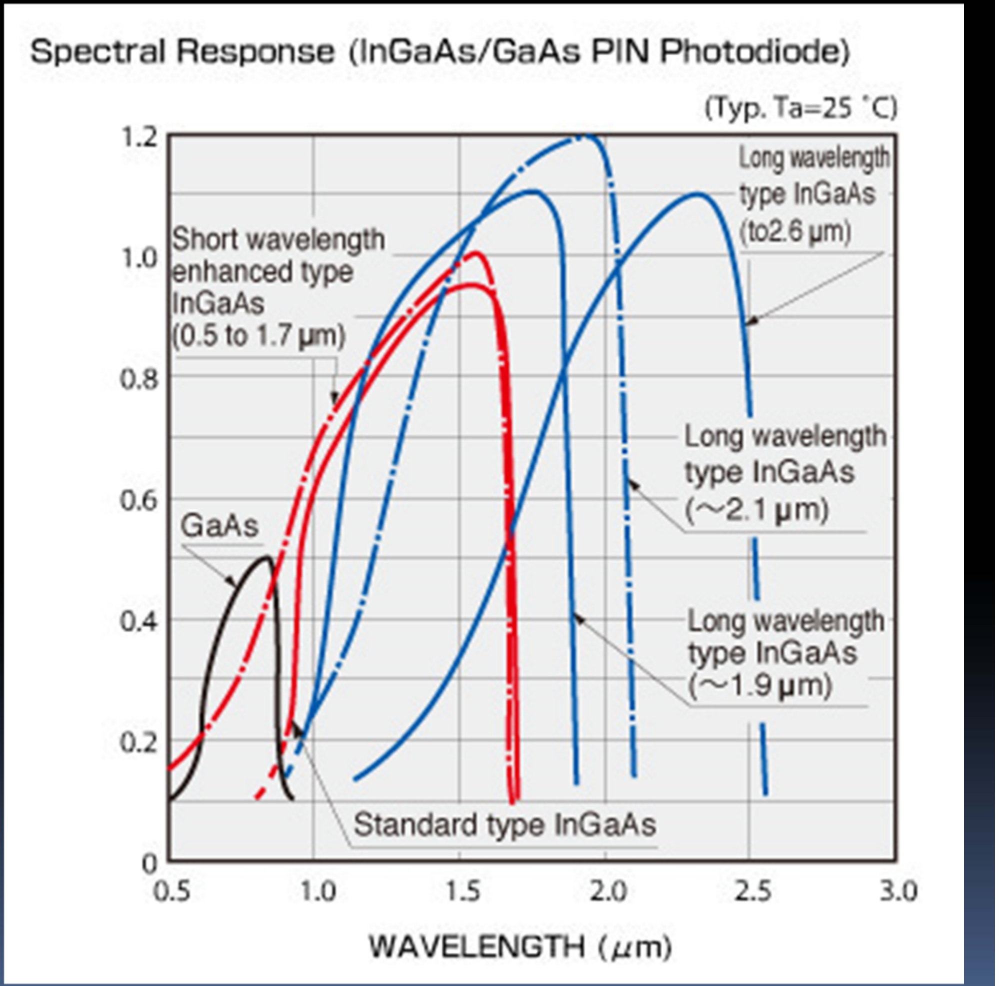
Loss of efficiency:

- surface recombinatio
- optical loss

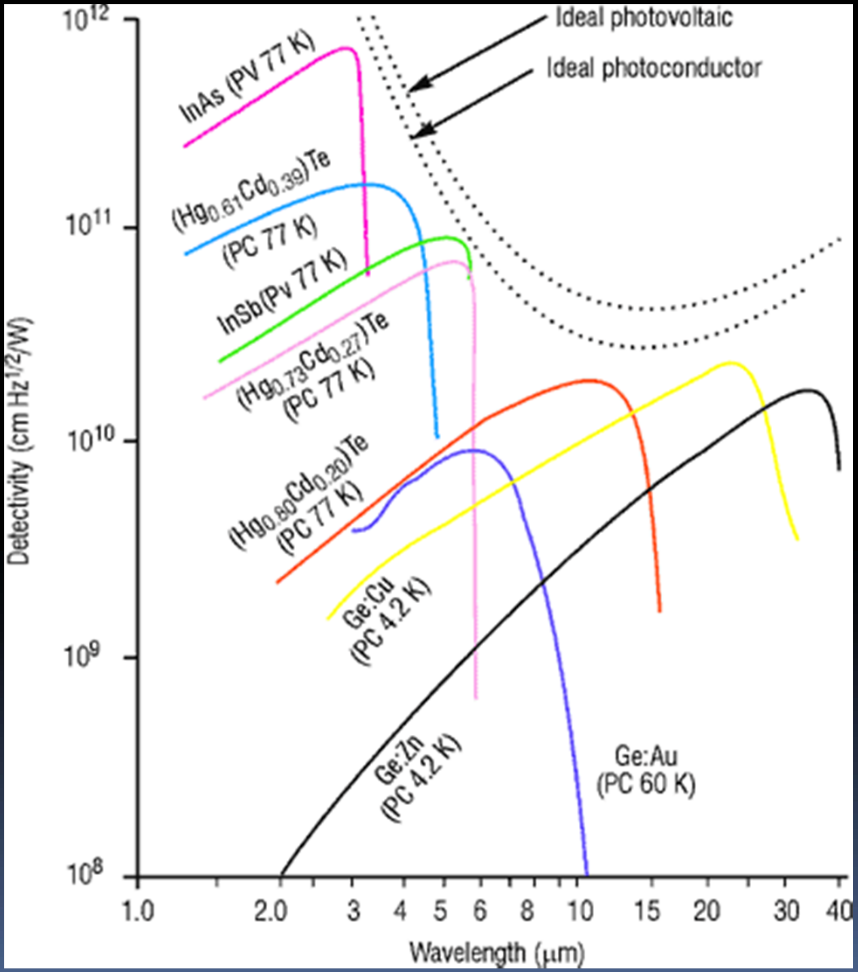
$$R[\lambda] \sim \eta[\lambda]\,\frac{e}{h\nu} = \eta\,\frac{e}{hc}\,\lambda = 2.41798946\,\eta\,\lambda[\mu\text{m}]\;A/W$$

Spectral response

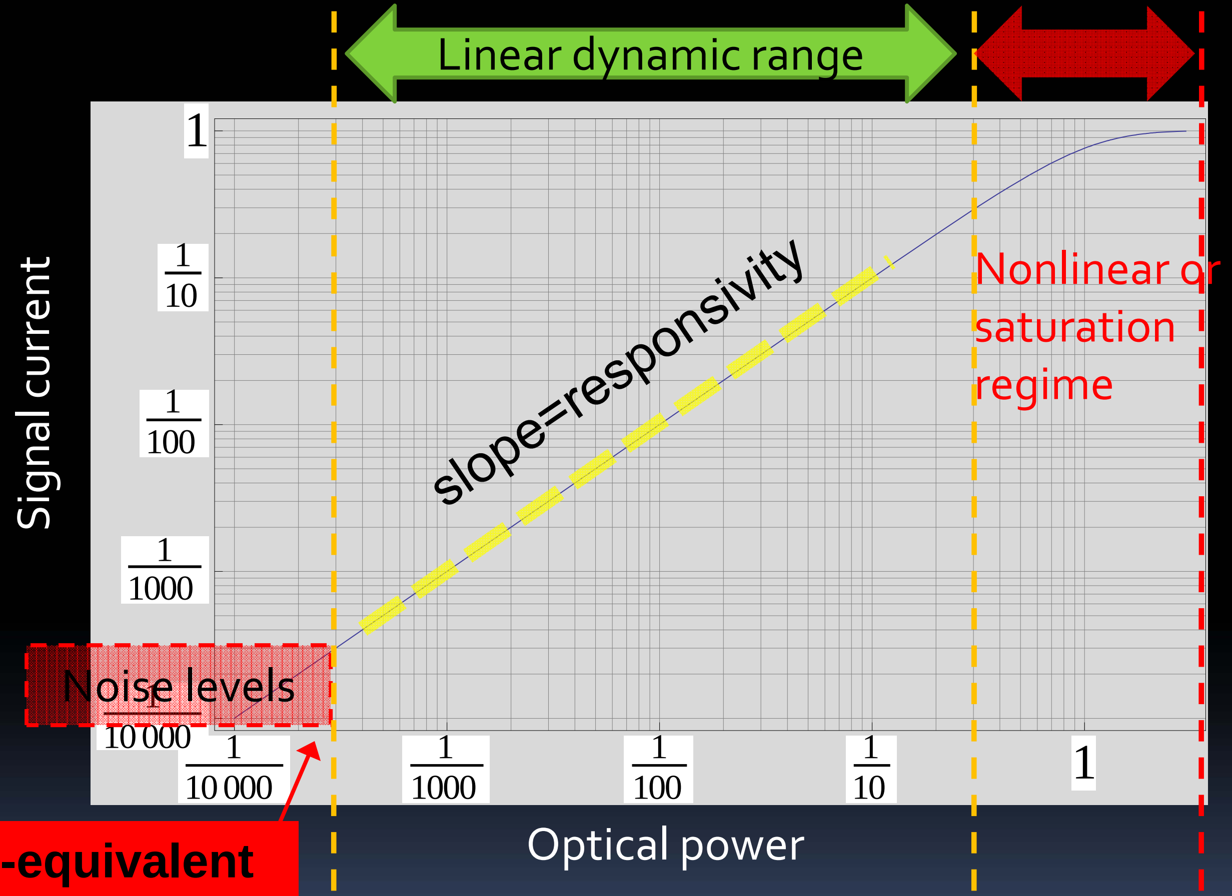




Spectral Response for the Mid- and Long-wave Infrared



Basic Operational Concepts



Noise-equivalent power (NEP)

$$D = \frac{1}{\mathrm{NEP}}$$

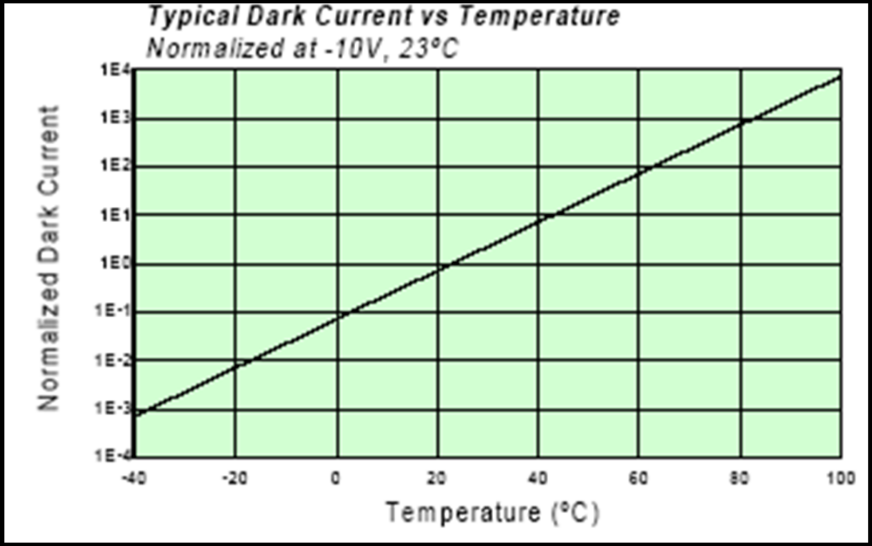
D: detectivity (related to sensitivity)

Noise, NEP and Detectivity

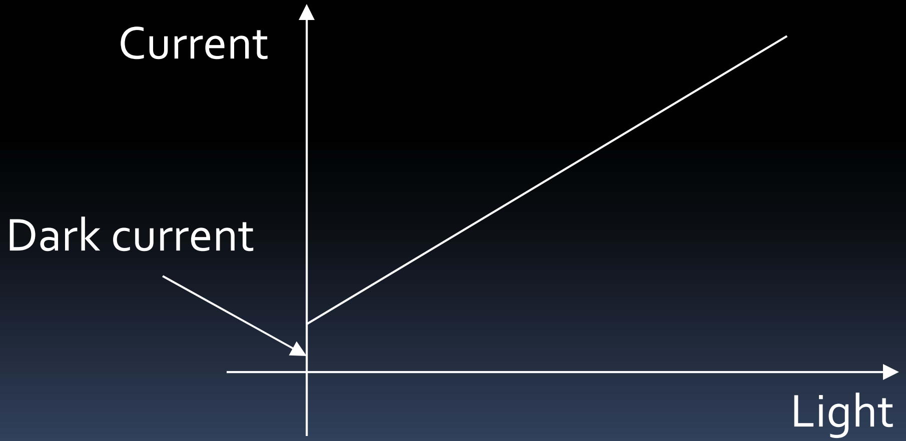
- There is random signal, called noise, intrinsically within the detector (to be distinguished from electronic circuit noise, such as from preamplifiers)
- Noise – more than responsivity- is what limits the capability of the detector to detect!
- Where does noise in a photodetector come from?

“Dark” Current

Photodetector

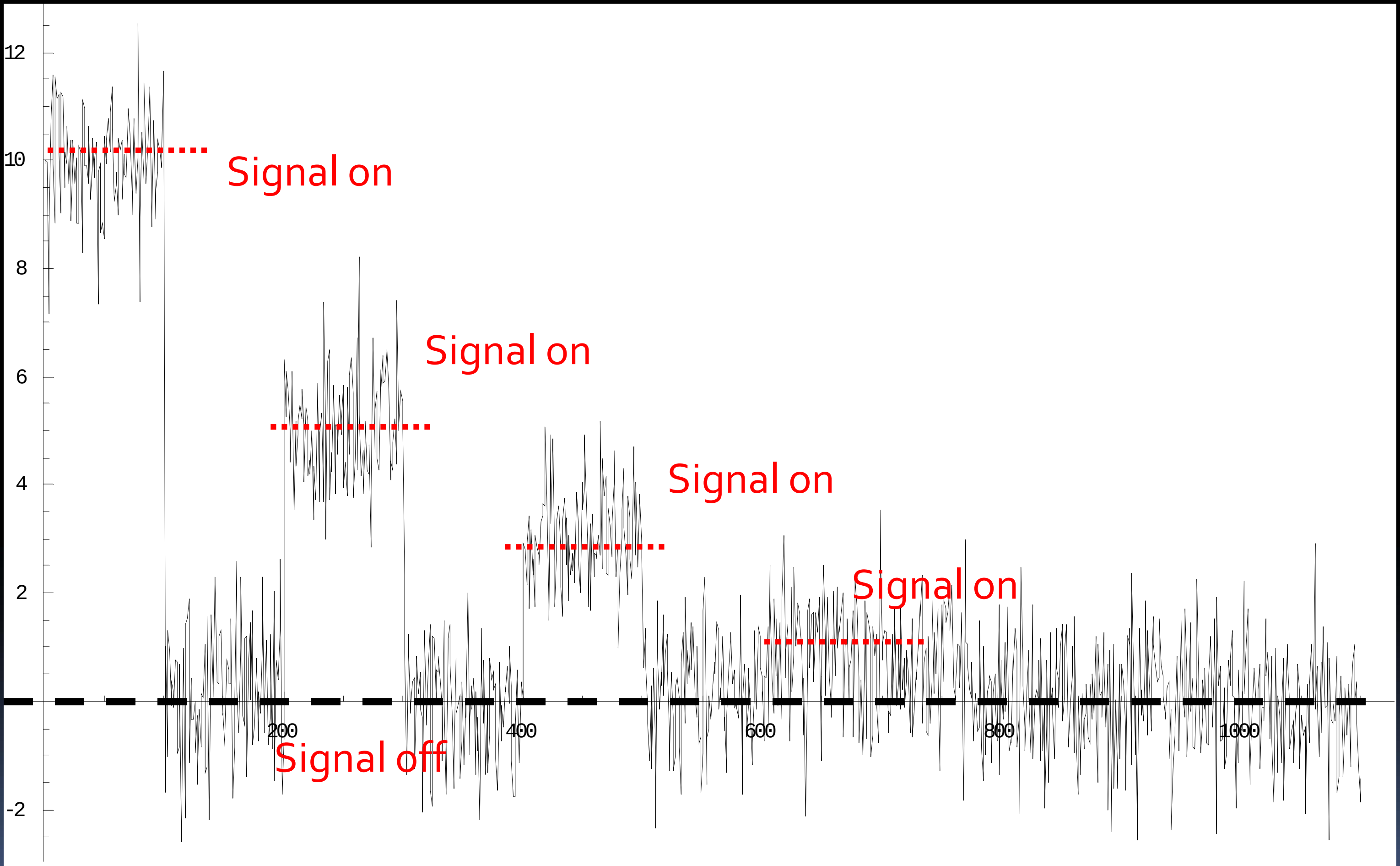


- A photodetector is an electrical device that conducts electricity even without light!
- Photodiode: it’s the reverse bias current
- Photoconductor: it’s the free carriers inside the material



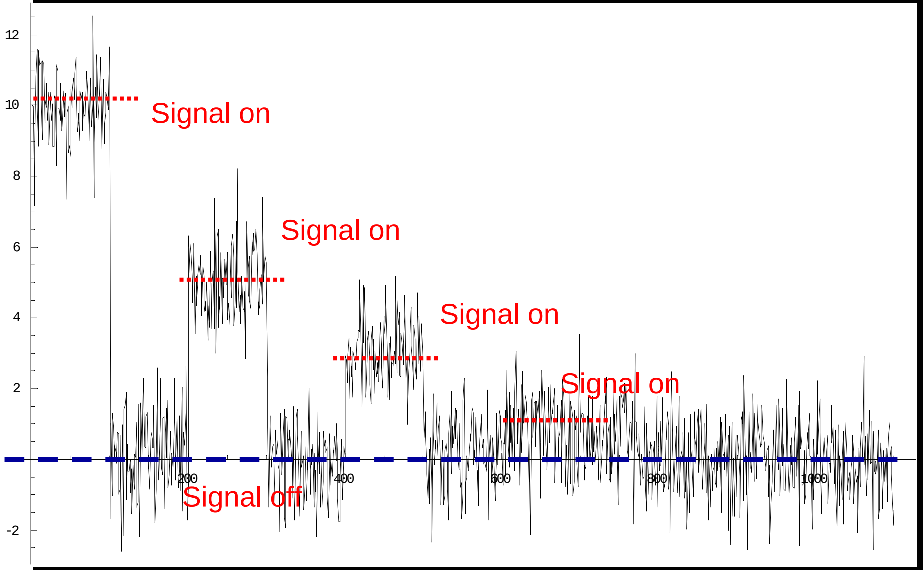
Noise: fluctuation of dark current because of the quantization of electron charge

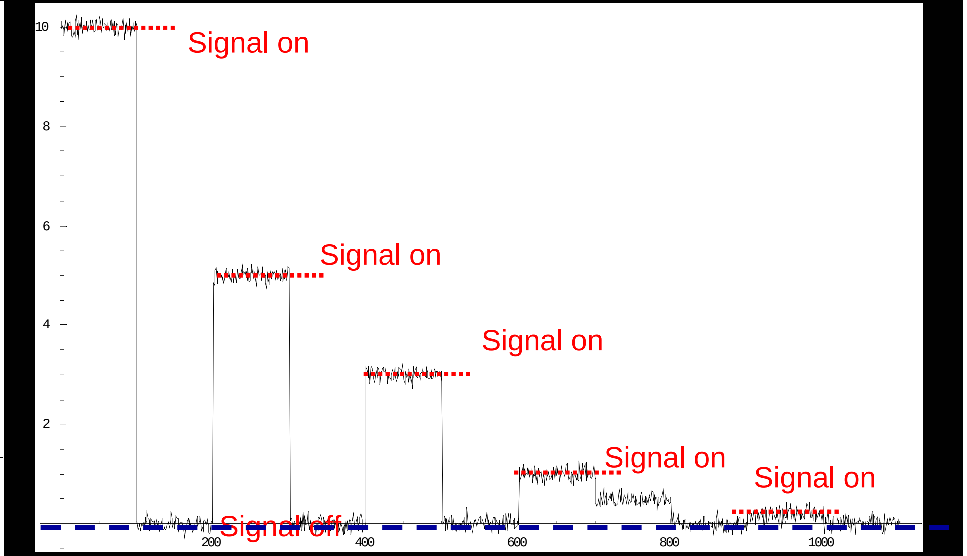
Noise Equivalent Signal?



When signal = Noise standard of deviation: signal is said to be **noise-equivalent**

Noise equivalent signal





- Which one is more capable of detecting weak signal? i. e. which one is more sensitive?

Definition:

$$\text{Sensitivity} = \text{Detectivity} = \frac{1}{\text{Noise} - \text{equivalent} - \text{signal}} = \frac{1}{\text{NES(P)}}$$

NEP= Noise equivalent power for sensor detecting power (e. g. optical)

Noise equivalent signal- SNR

$$\mathrm{NEP} = \frac{\mathrm{Noise}}{\mathrm{Responsivity}}$$

(linear range only)

$$\mathrm{NEP} \times \mathrm{Responsivity} = \text{The signal that is} = \text{noise}$$

Signal-to-noise ratio

$$\mathrm{SNR} = \frac{\text{Signal level}}{\text{Noise level}}(dB)$$

(*link to Mathematica file* Noise & Signal

▶

NOISE & SIGNAL