

ECE 6323

DETECTORS AND SIGNAL DETECTION

P.1

Detectors, Detection and Signals

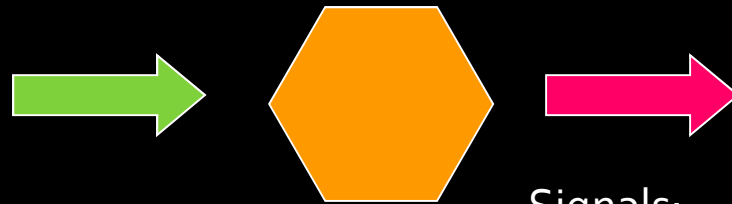
- Introduction
 - Concept
 - Detection mechanism and types of detectors
- Photoelectric detectors
 - Detection mechanism
 - Key common features
- (Part 2) Types of photodiodes
 - p-n and p-i-n
 - Advanced p-i-n structures
 - Phototransistors
 - Avalanche photodiodes
 - Others: MSM
- (Part 2) Signal and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

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

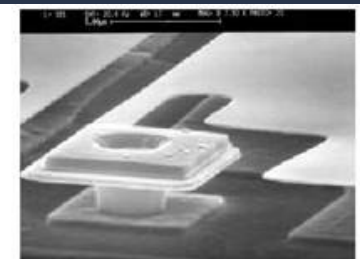
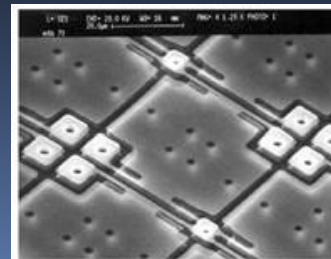
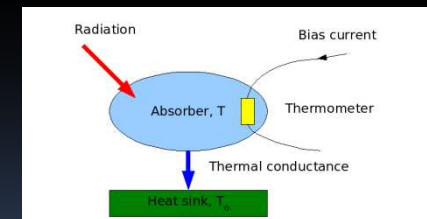
Photons



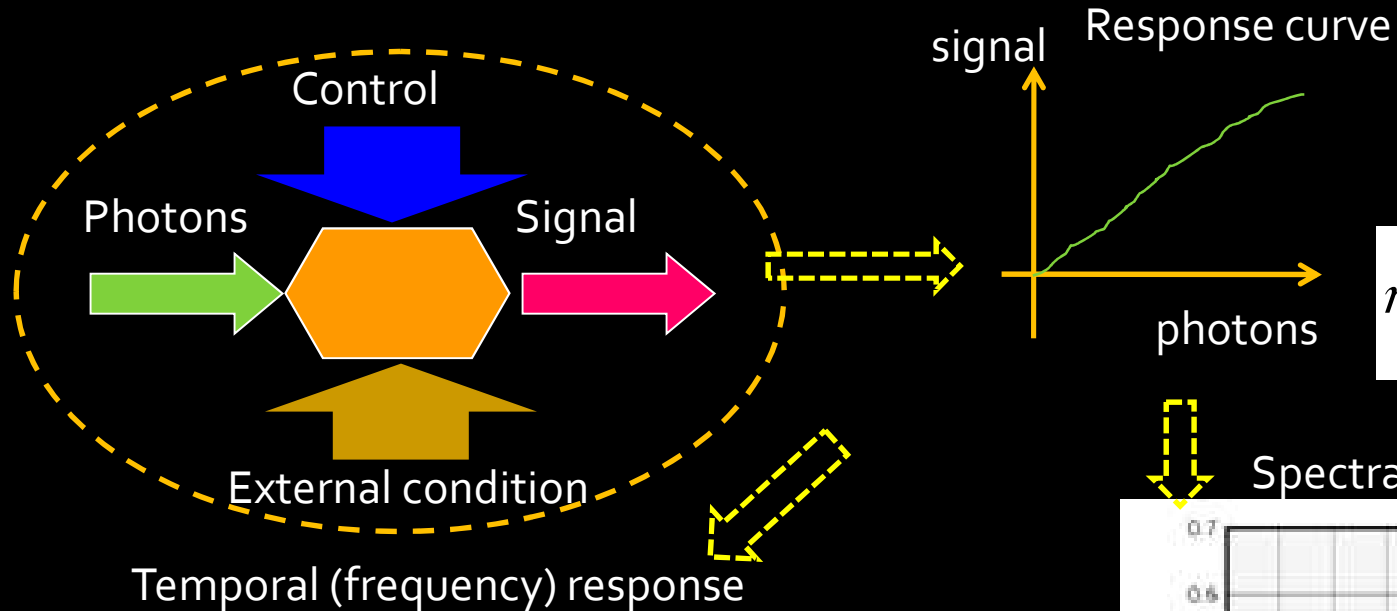
Signals:
voltage or
currents

- 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 optical communication applications, only direct photodetection is practical



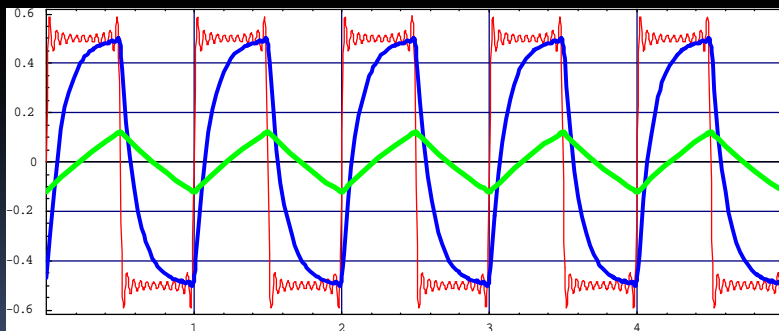
Basic Operational Concepts



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

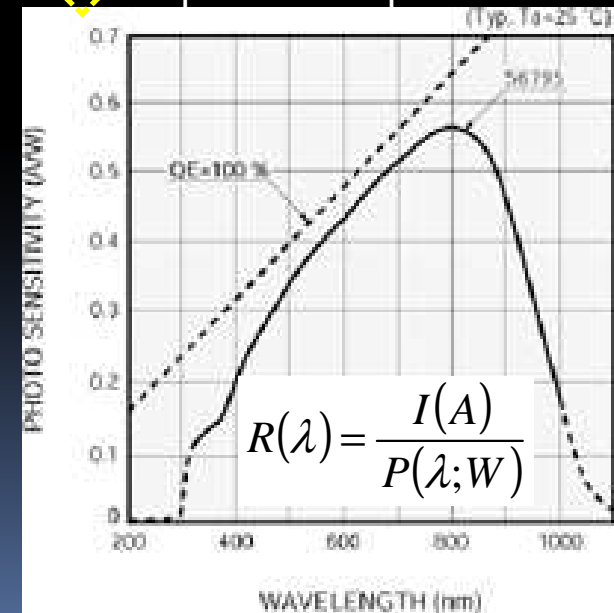
$$\eta_{QE} = \frac{\text{electron}}{\text{photon}}$$

Temporal (frequency) response

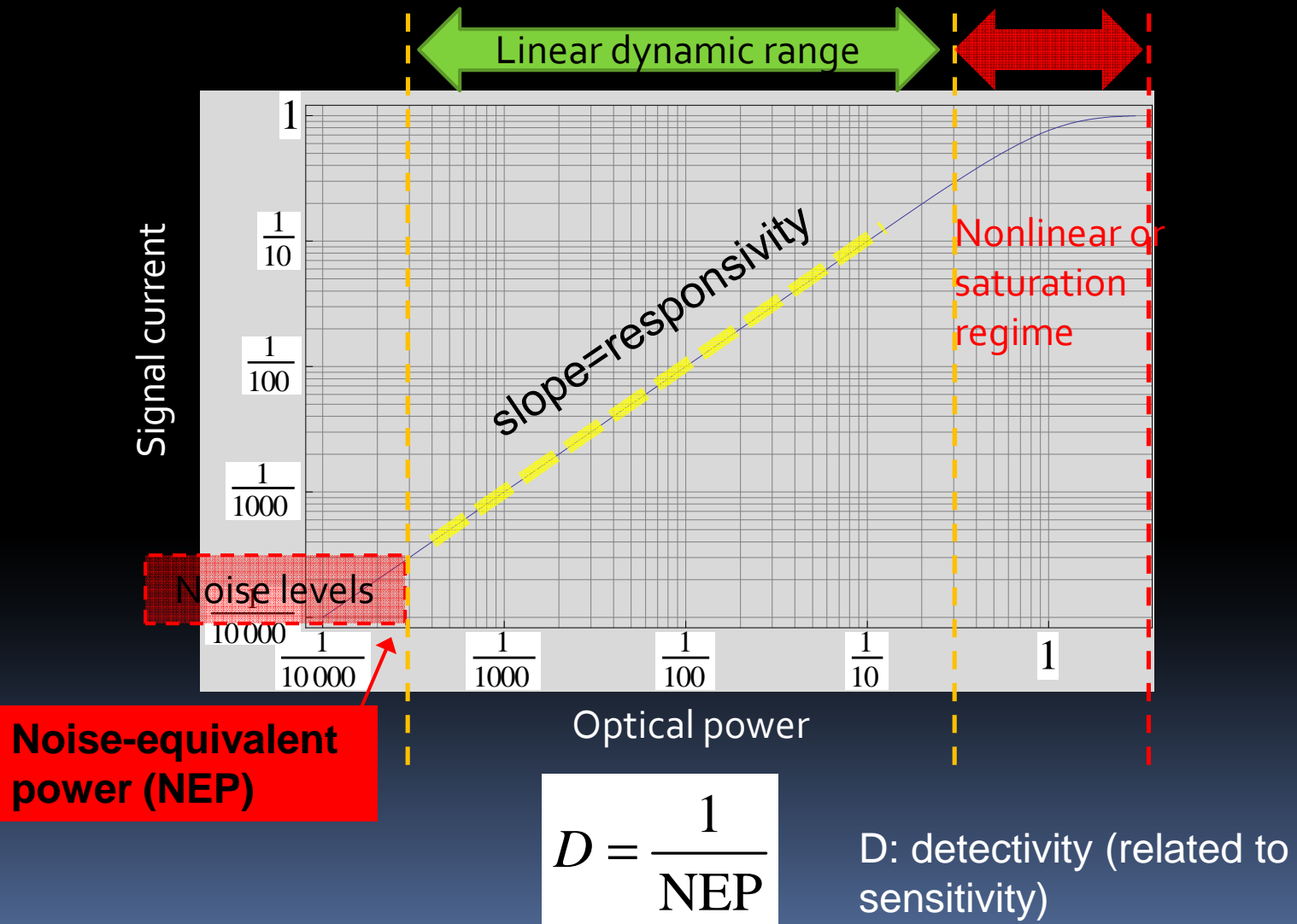


$$S(f) = H[f]P(f) \quad S(t) = \int h[t - \tau]P(\tau)d\tau$$

Spectral response



Basic Operational Concepts (*cont.*)



Basic Operational Concepts (*cont.*)

Others less technical aspects are also important:

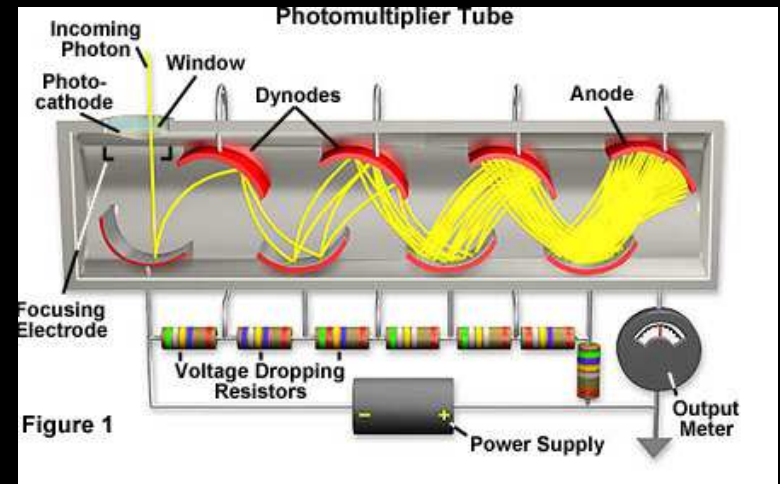
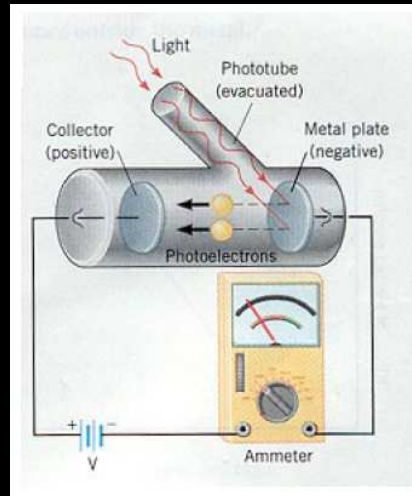
- Control: example: bias voltage: ease of control
- Stability: same performance (or within acceptable limits) over a range of external conditions: temperature, humidity, shock/vibration etc.
- Reliability: same performance over a long period of time and usage; cycled external conditions.
- Size, weight,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

Detectors, Detection and Signals

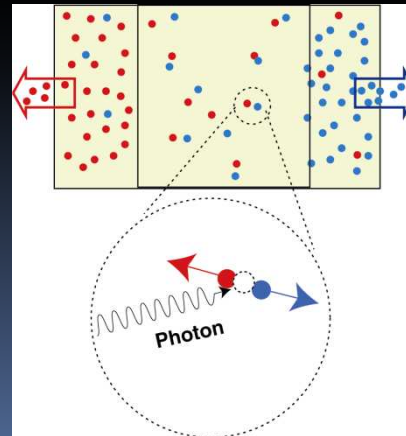
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Photoelectric detectors

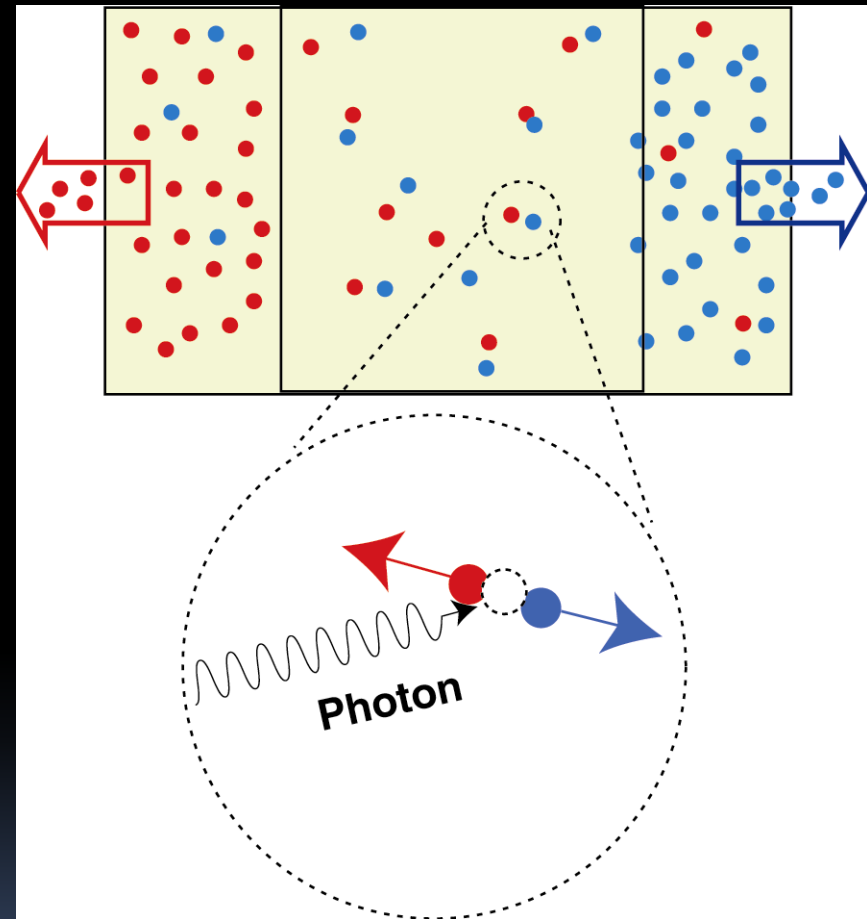
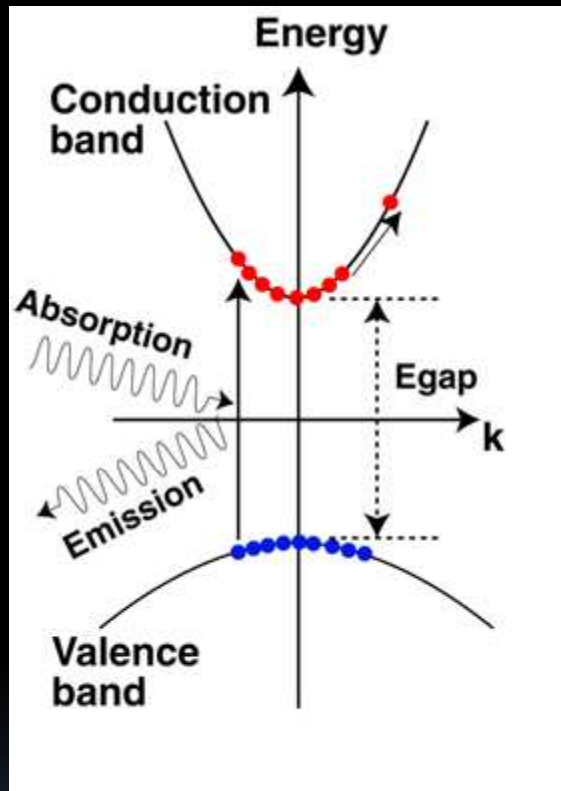
Photoelectrons generated in vacuum



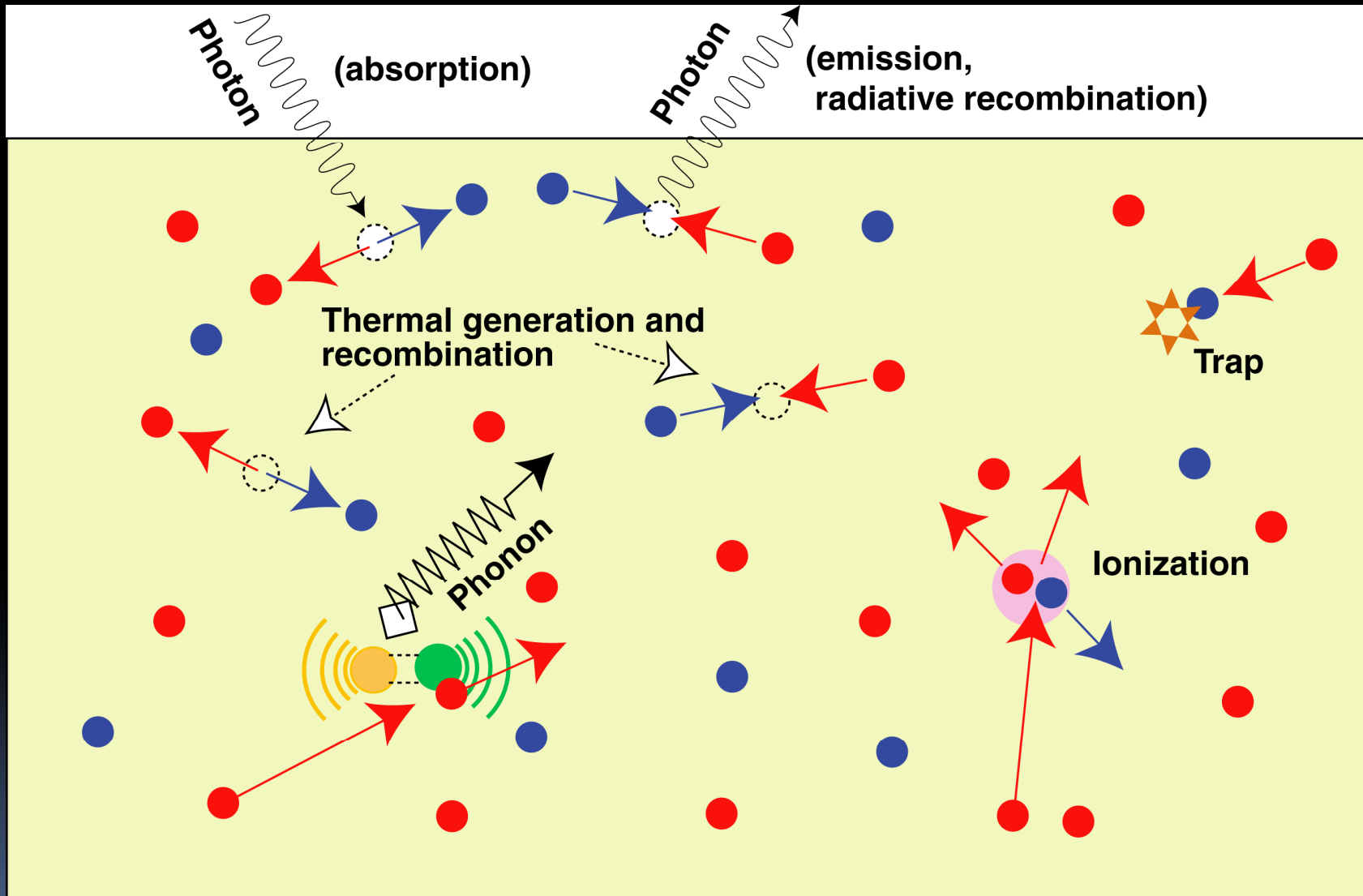
Photoelectrons generated in a solid



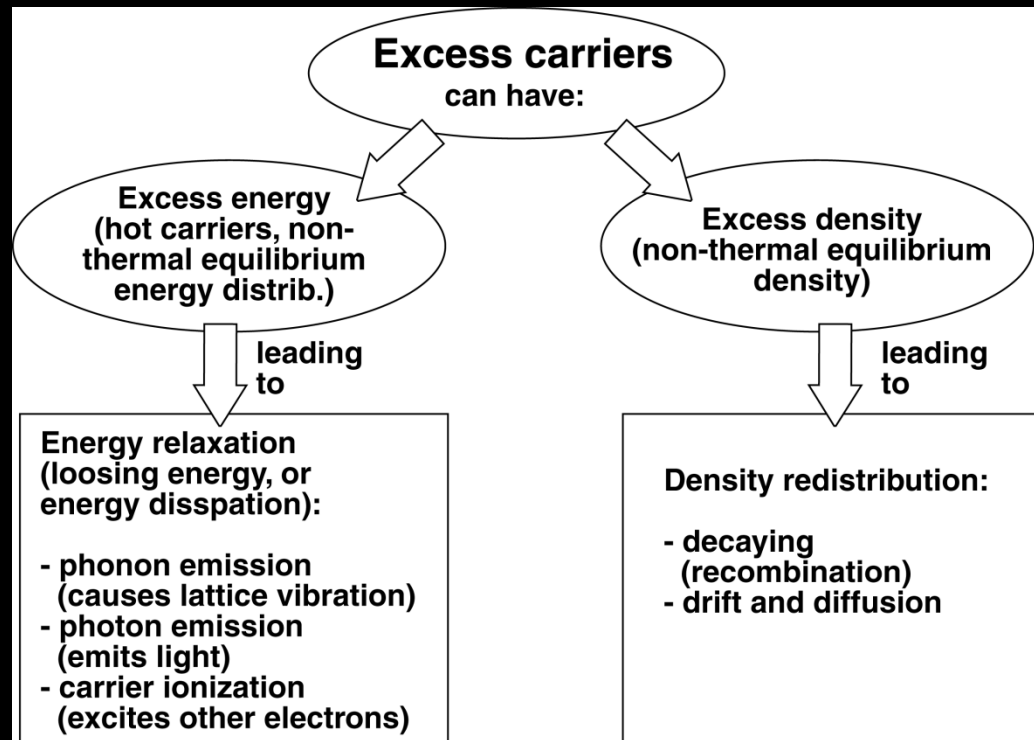
Photoelectric Effects in Semiconductors



Excitation and Relaxation



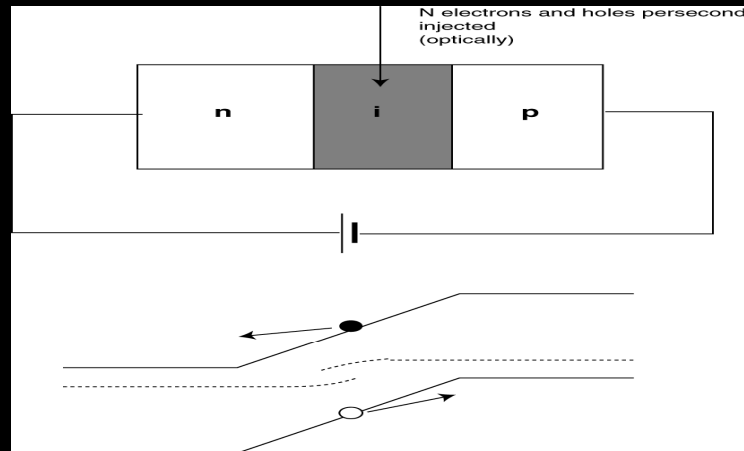
Non-equilibrium carrier behavior



- 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)

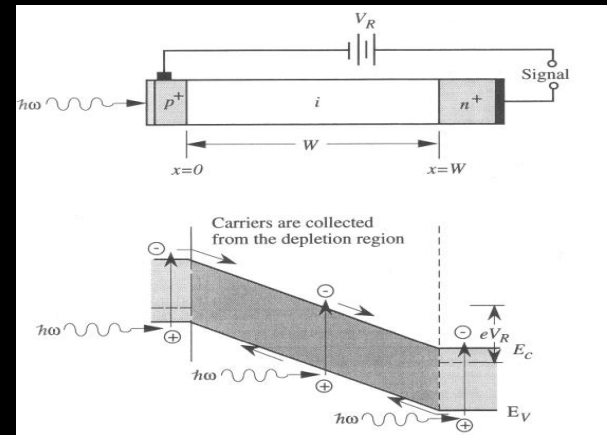
Photogenerated carriers collection

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

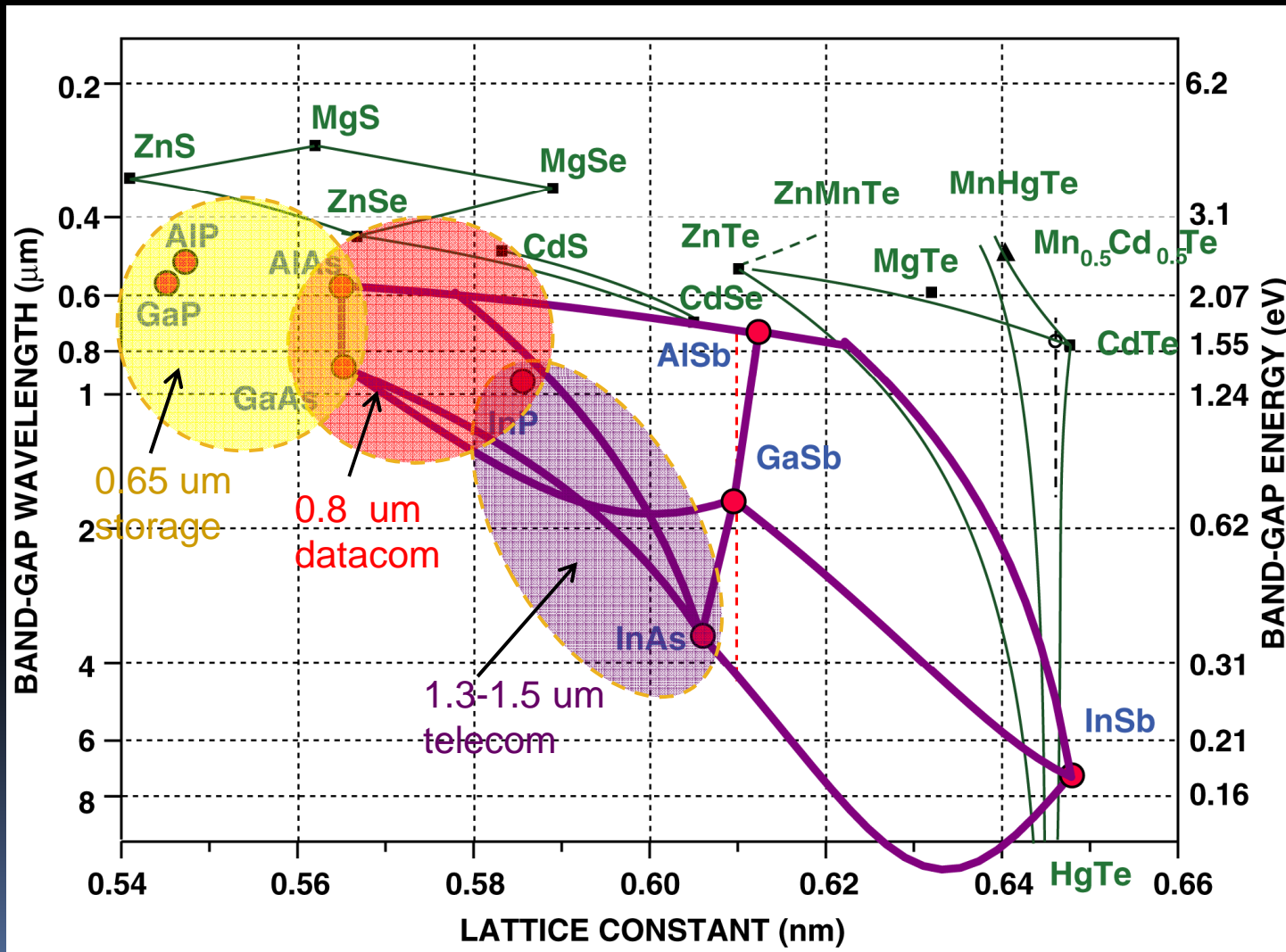


- Carriers are swept to collector regions with external bias field (a change of resistivity): **photoconductive and metal-semiconductor-metal**
- Speed depends on transit region, bias, carrier mobility
- Application: switch

Key Aspects of Photodiode Engineering

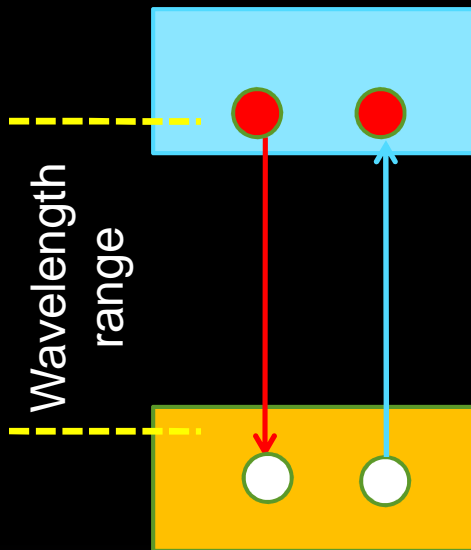
- Spectral response
- Responsivity (quantum efficiency)
- Speed (temporal or frequency response)
- Gain
- Material bandgap engineering
 - Absorption process and absorber design
- Collection process
 - Diode structure design (reduce non-radiative recombination)
- Collection process and circuit
 - C-V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

Common semiconductor bandgap energy vs. lattice constant



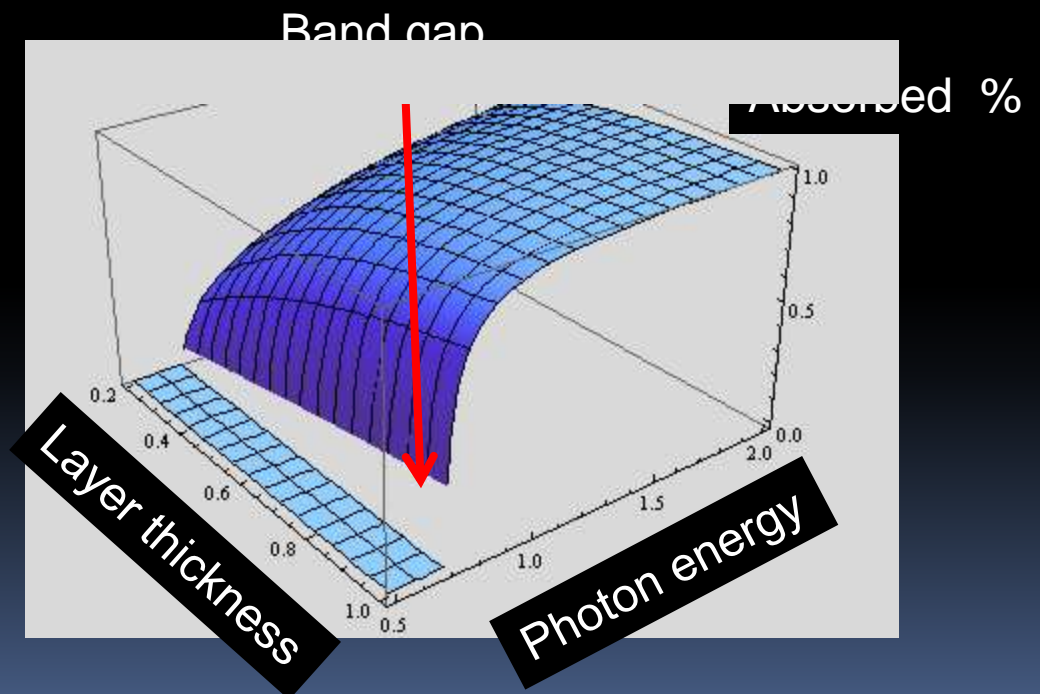
Absorption and Spectral Response

Absorption:

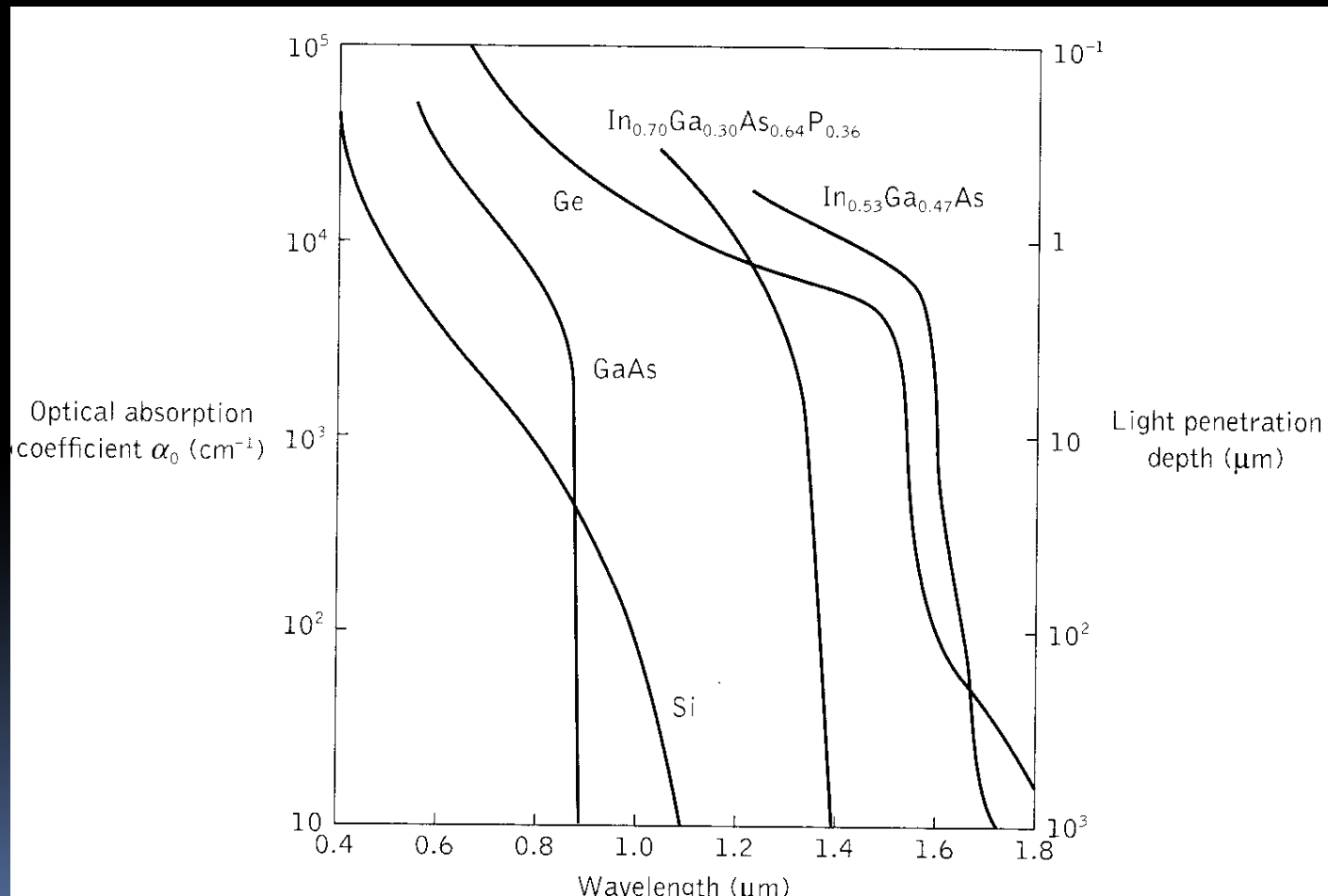


$$\alpha(E) = \alpha_{\text{FS}} \frac{\lambda^2}{n_g} E \sum_v \frac{|\langle u_v^* | \mathbf{p} | u_c \rangle|^2}{m_0^2 c^2} \rho_{\text{joint}}(E = E_{v,\mathbf{k}} + E_{c,\mathbf{k}}) (F(E_{c,\mathbf{k}}) - F(E_{v,\mathbf{k}}))$$

- Very large absorption coefficient above E_{gap} : $\sim 10^4 - 10^5 \text{ cm}^{-1}$
- Absorption $> 90\%$ easily with layer as thin as $0.5 \mu\text{m}$



Absorption Coefficients of Some Semiconductors



Spectral Response

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

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

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

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

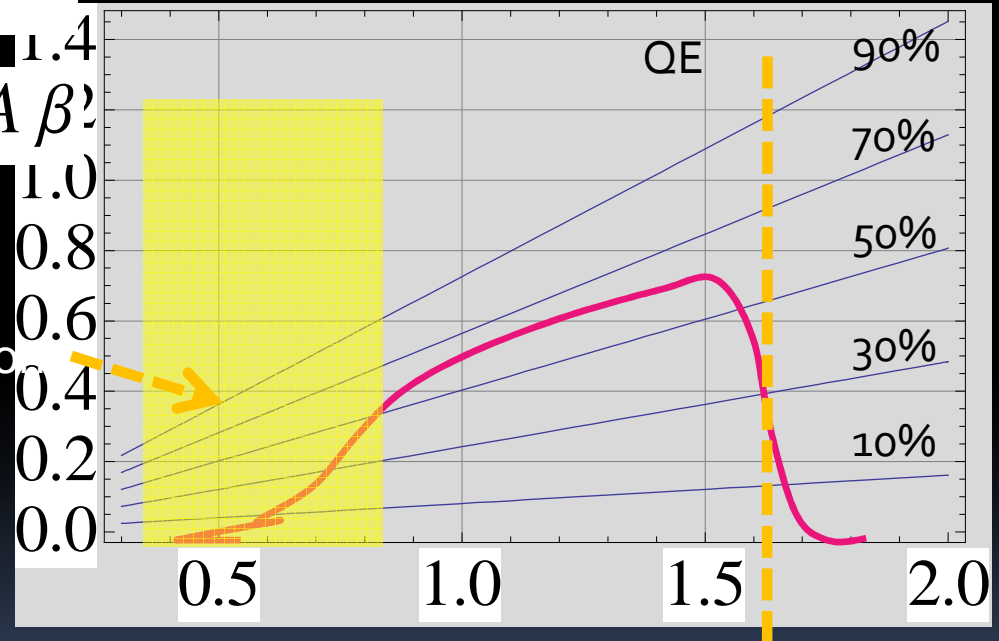
$$(1 - e^{-\alpha[\lambda] d}) \sim \text{constant} = A$$

Define

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

Loss of efficiency:

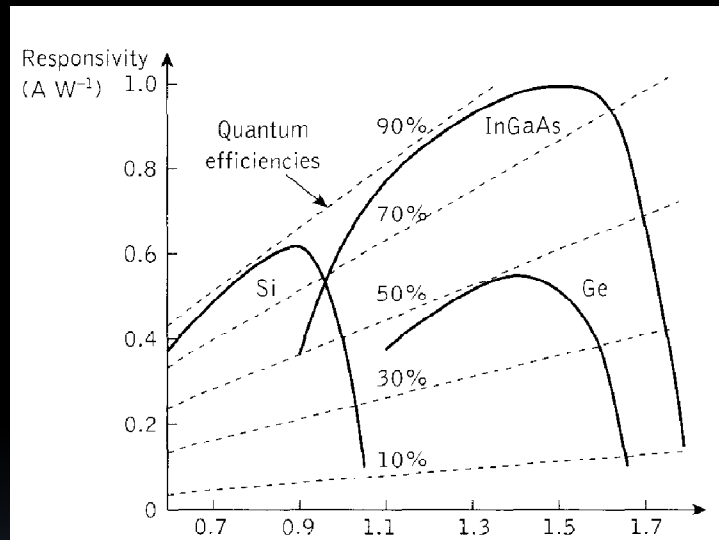
- surface recombination
- optical loss



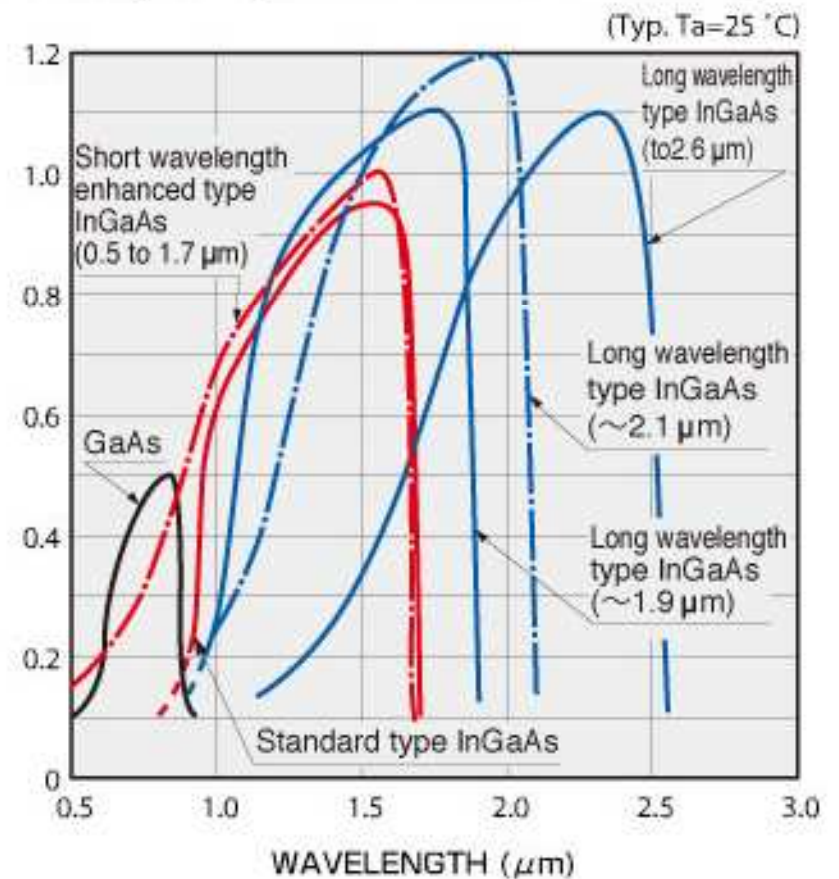
$$R[\lambda] \sim \eta[\lambda] \frac{e}{h\nu} = \eta \frac{e}{hc} \lambda = 2.41798946 \eta \lambda [\mu\text{m}] \text{ A/W}$$

Band gap

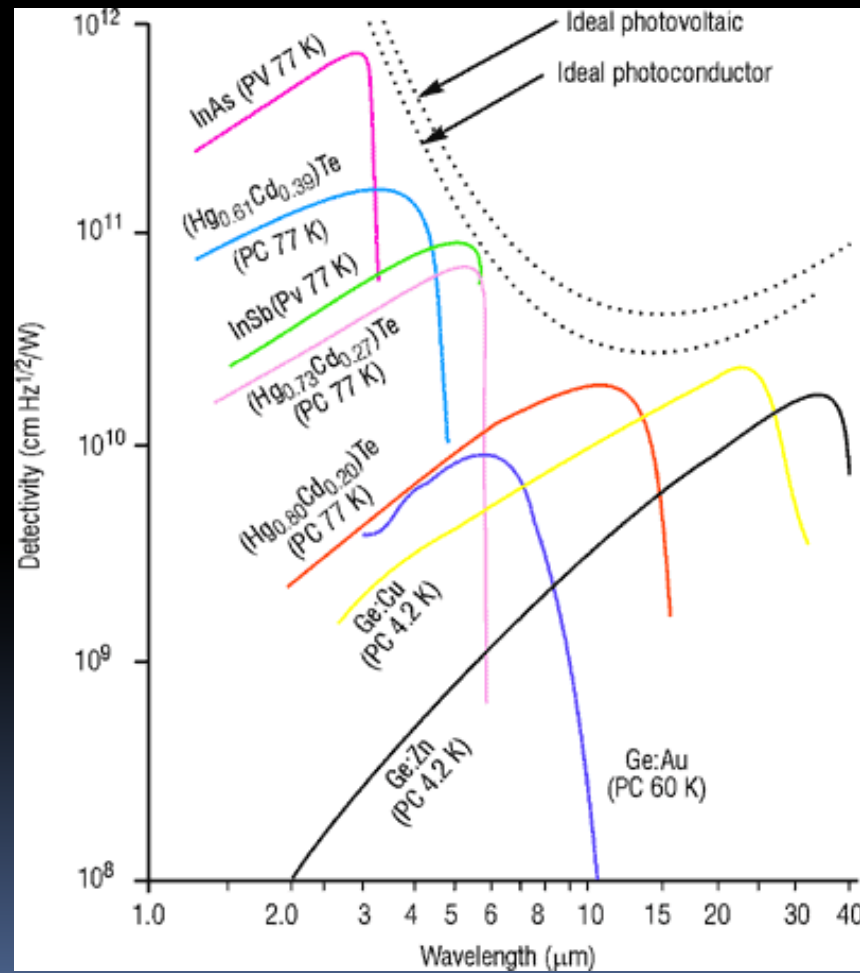
Spectral response



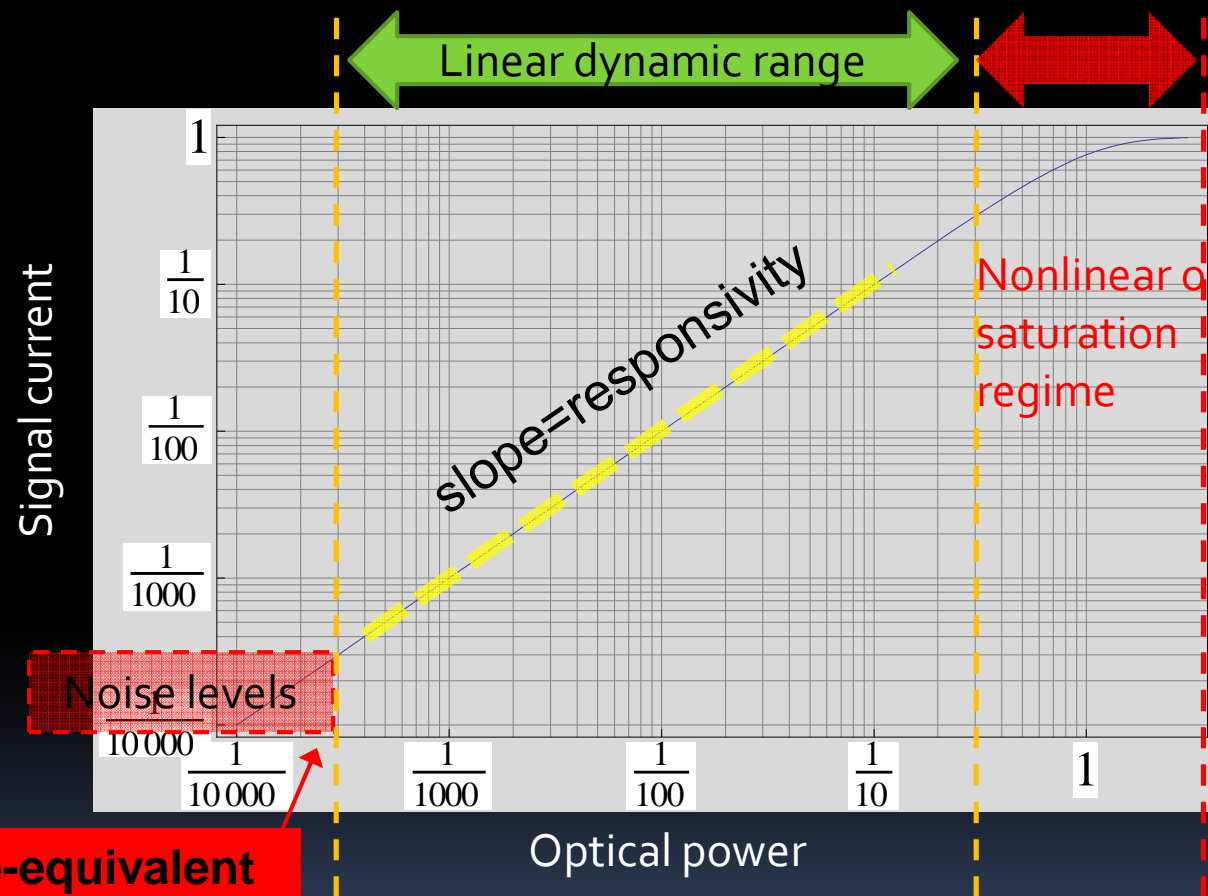
Spectral Response (InGaAs/GaAs PIN Photodiode)



Spectral Response for the Mid- and Long-wave Infrared



Basic Operational Concepts



Noise-equivalent power (NEP)

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

D: detectivity (related to sensitivity)

Noise, NEP and Detectivity

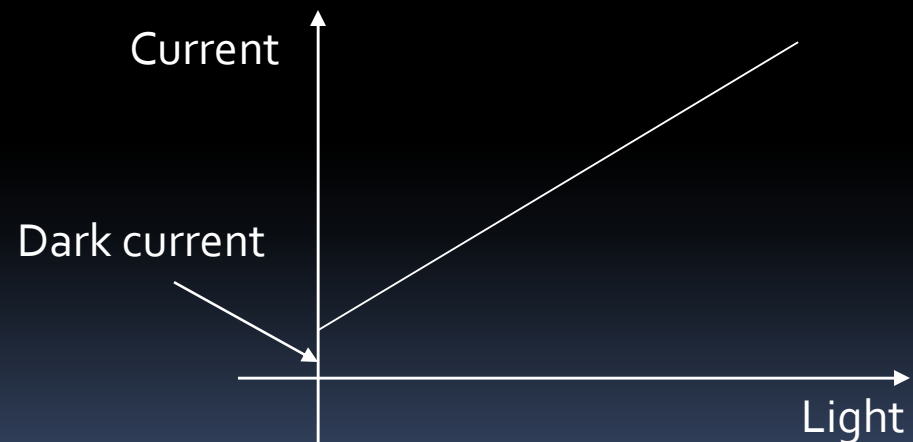
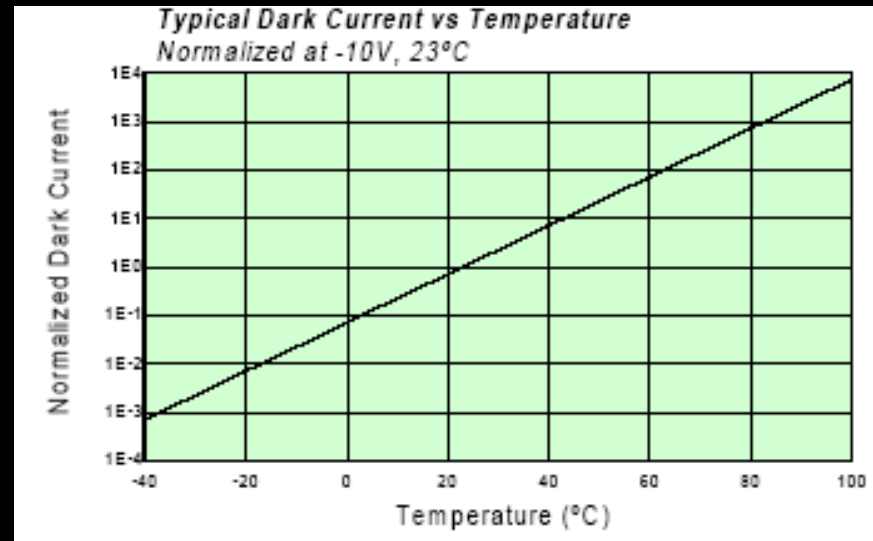
- There is random signal, called noise, intrinsically within the detector (to be distinguished from electronic circuit noise, such as from preamplifiers)
- Noise – more than responsivity- is what limits the capability of the detector to detect!
- Where does noise in a photodetector come from?

“Dark” Current



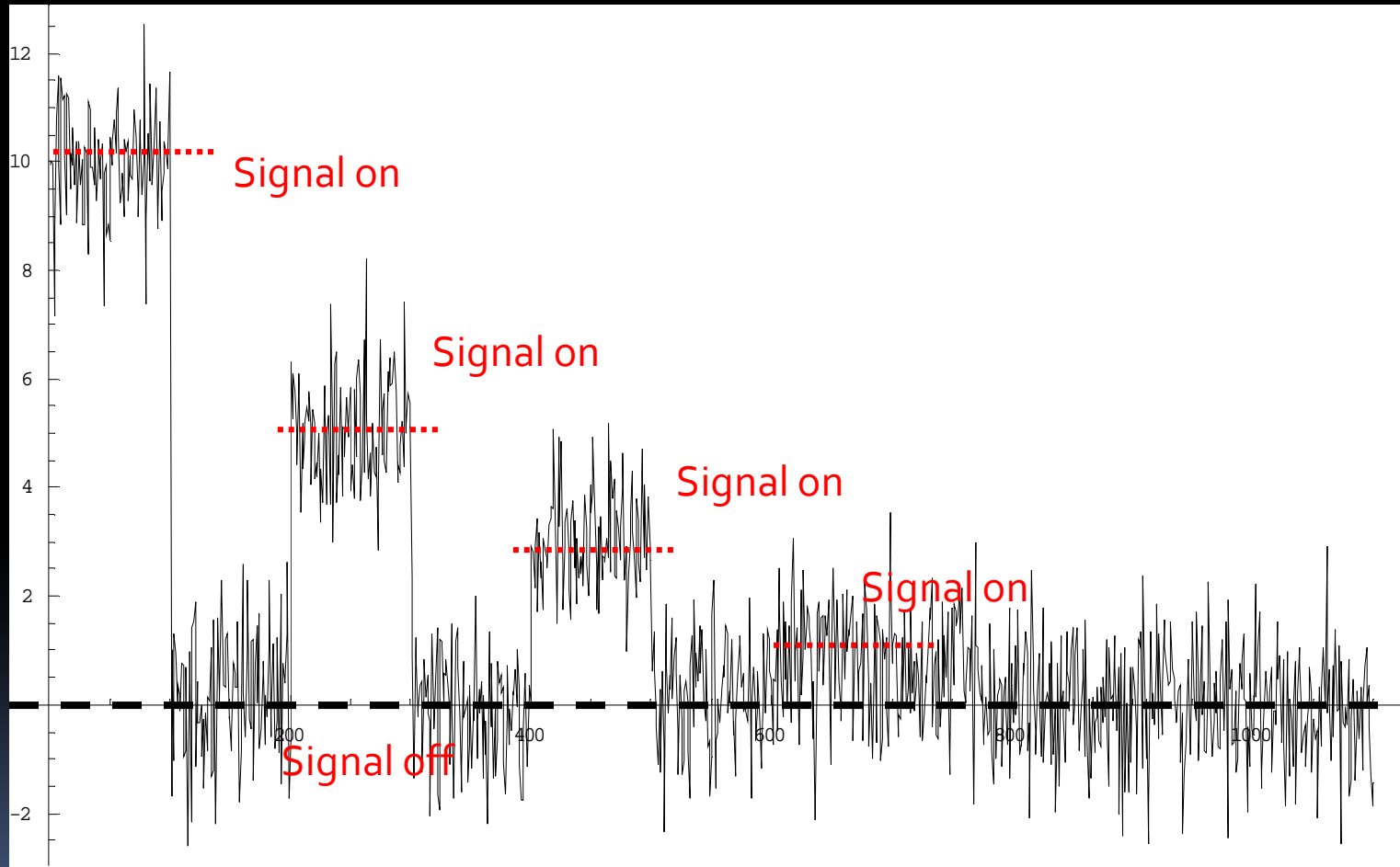
Photodetector

- 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



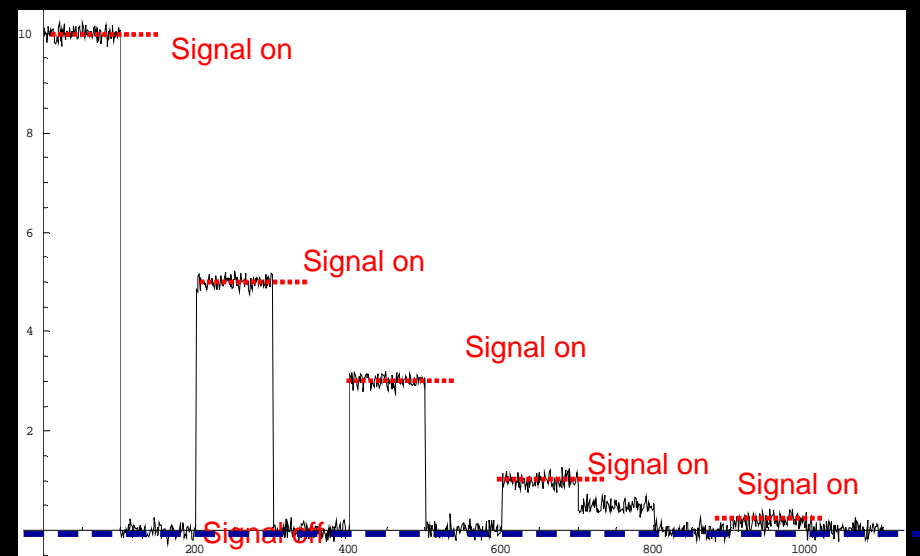
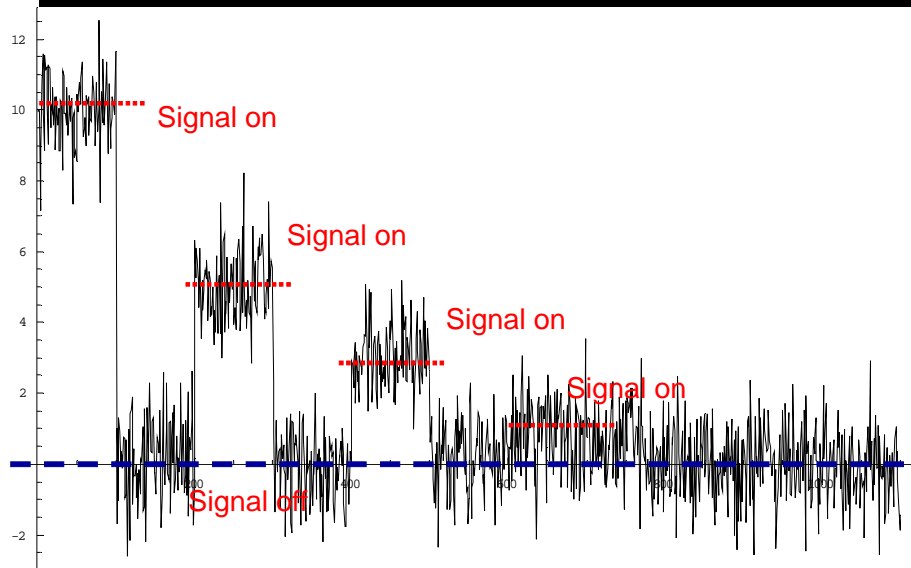
Noise: fluctuation of dark current because of the quantization of electron charge

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

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

Noise equivalent signal- SNR

$$\text{NEP} = \frac{\text{Noise}}{\text{Responsivity}} \quad (\text{linear range only})$$

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

Signal-to-noise ratio

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

(link to Mathematica file Noise

NOISE

