Sensors, Signals and Noise

COURSE OUTLINE

- Introduction
- Signals and Noise
- Filtering
- Sensors and electronics: PhotoDetectors PD1

TBD - Photon features and data

- Photon in the visible spectral range: features and data
- Photon statistics and noise
- Photon absorption in materials: absorption coefficient and penetration length
- Photon-Energy detectors: basic principle and main features
- Photon-Quanta detectors : basic principle and main features

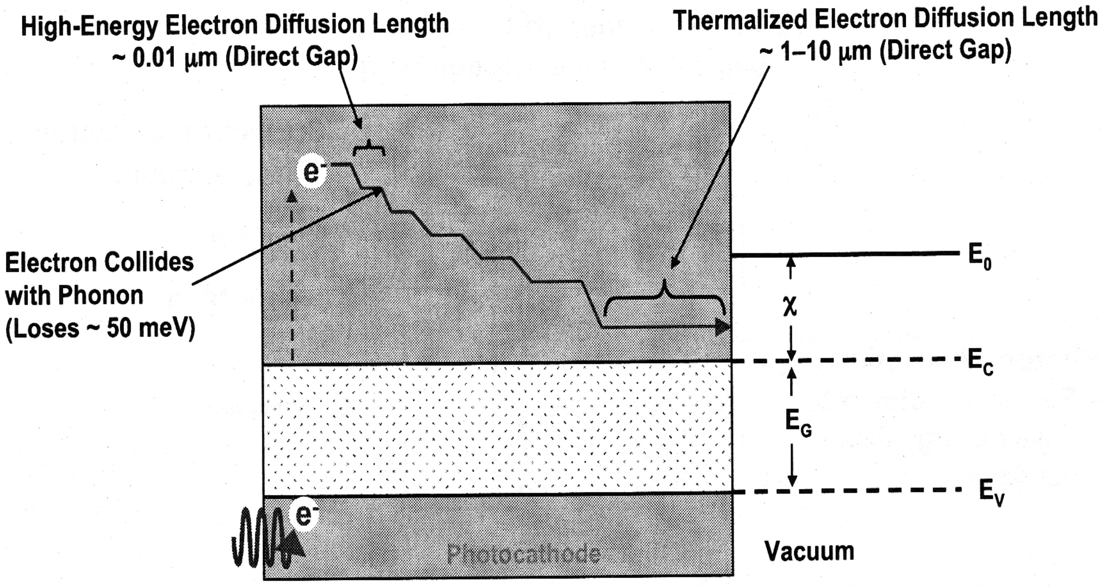
TBD – Photon-Energy Detectors

- Detector components and structure
- Steady state response
- Heating transients and dynamic response
- Radiant Sensitivity or Spectral Responsivity
- Bolometers and Thermopiles
- Outline of imaging detectors: focal plane arrays

TBD – Photon-Quanta Detectors

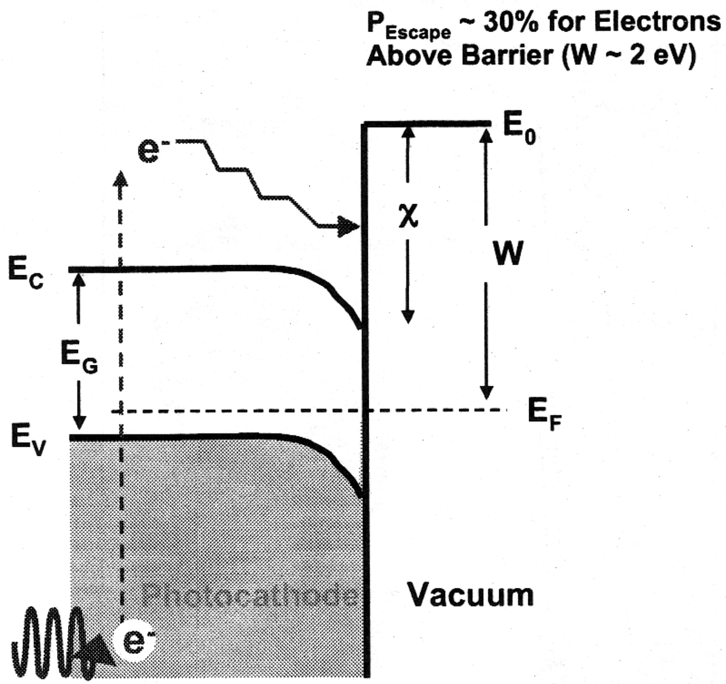
- External photoelectric effect: Photo-emission of electrons from material in vacuum
- Internal photoelectric effect: photo-generation of free carriers in semiconductors
- Physics of the photoelectric effect: outline, main features, inherent limitations
- Photon detection efficiency (Quantum detection efficiency)
- Relation between Quantum detection efficiency and Spectral Responsivity

Photocathode: photoelectron emission in vacuum

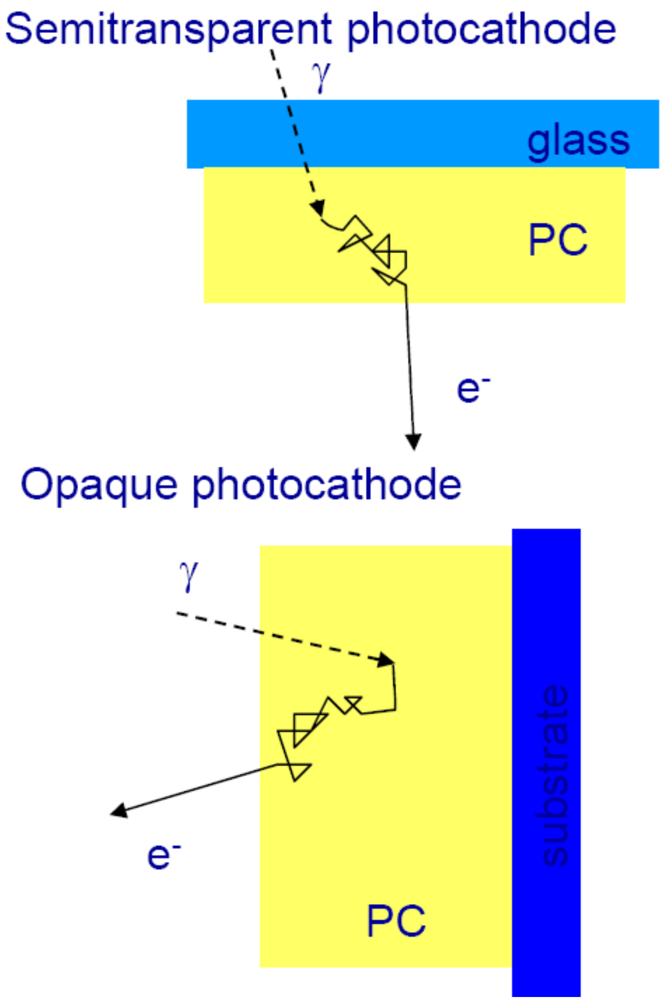


It's a 3-step process:

1. free electron generation
2. electron propagation through cathode
3. escape of electron into the vacuum



Photocathode: photoelectron emission in vacuum



It's a 3-step process:

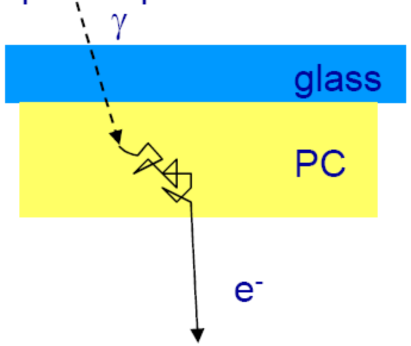
1. free electron generation
2. electron propagation through cathode
3. escape of electron into the vacuum

Semi-transparent photocathode

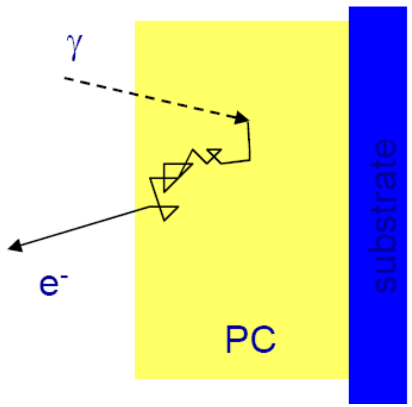
Semi-transparent photocathode

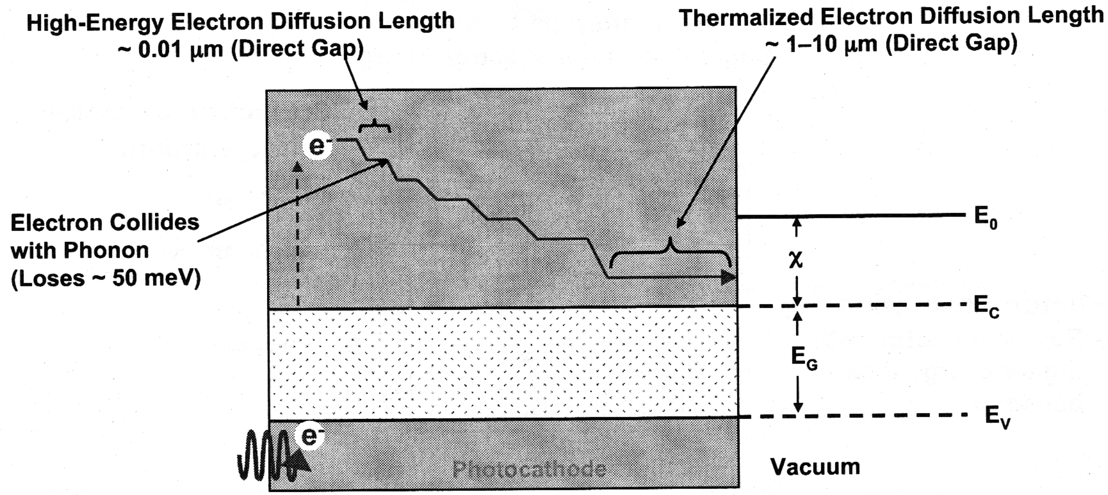
Photocathode: photoelectron emission in vacuum

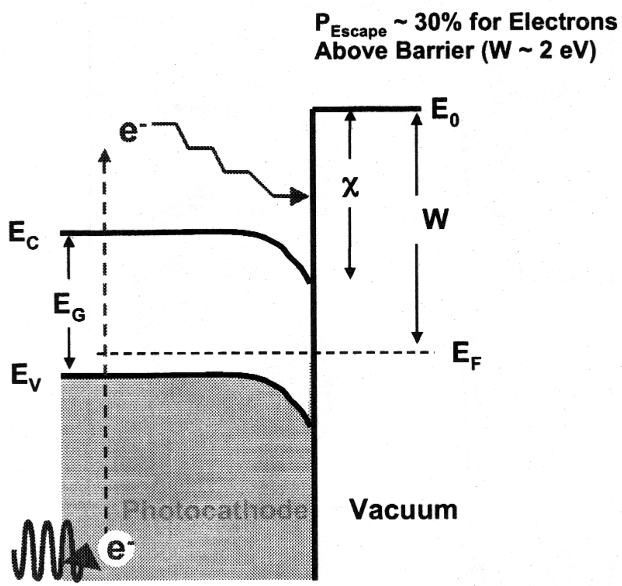
Semitransparent photocathode



Opaque photocathode

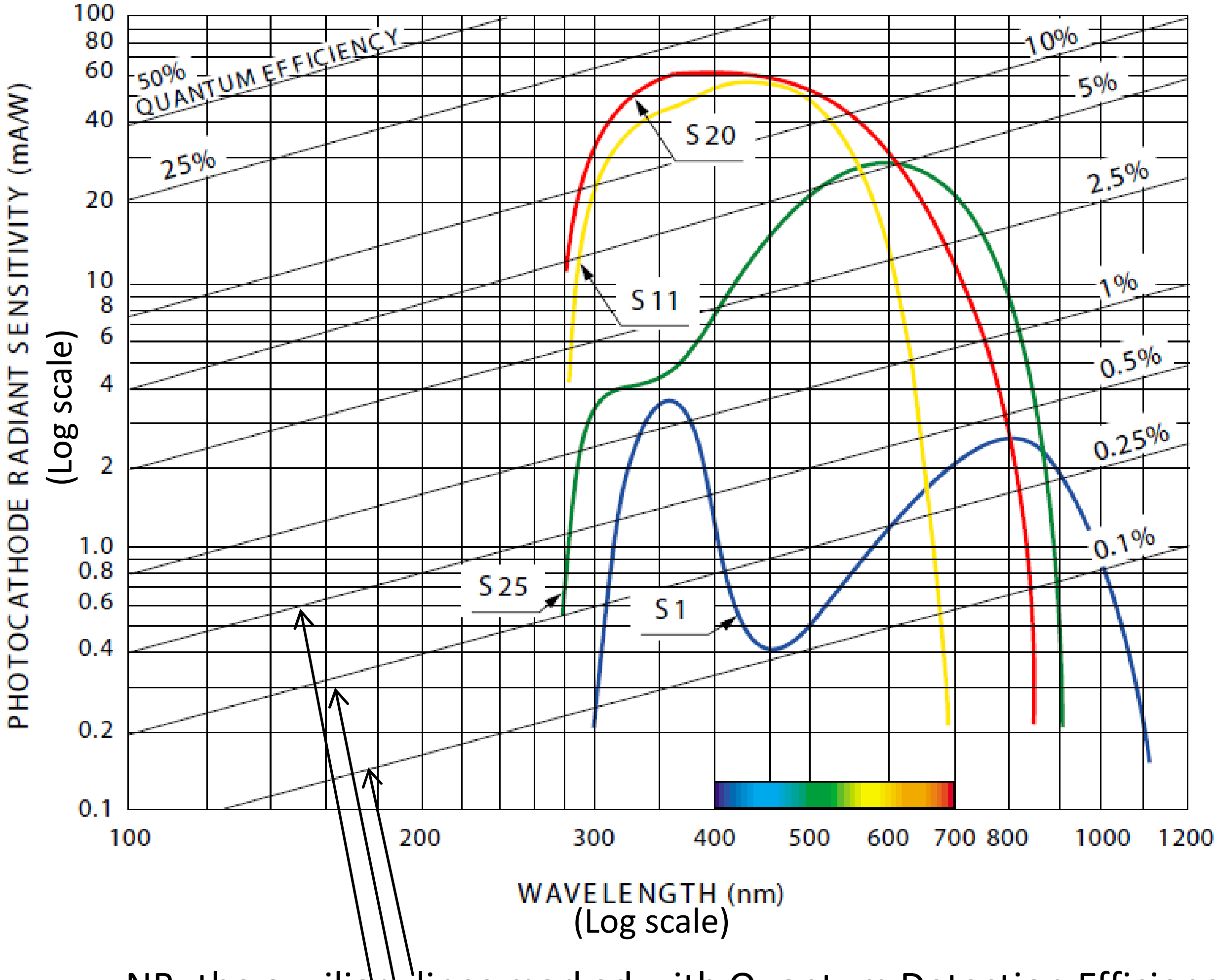






- **3-step process**
- **free electron generation**
- **electron propagation through cathode**
- **escape of electron into the vacuum**

Radiant Sensitivity or Spectral Responsivity

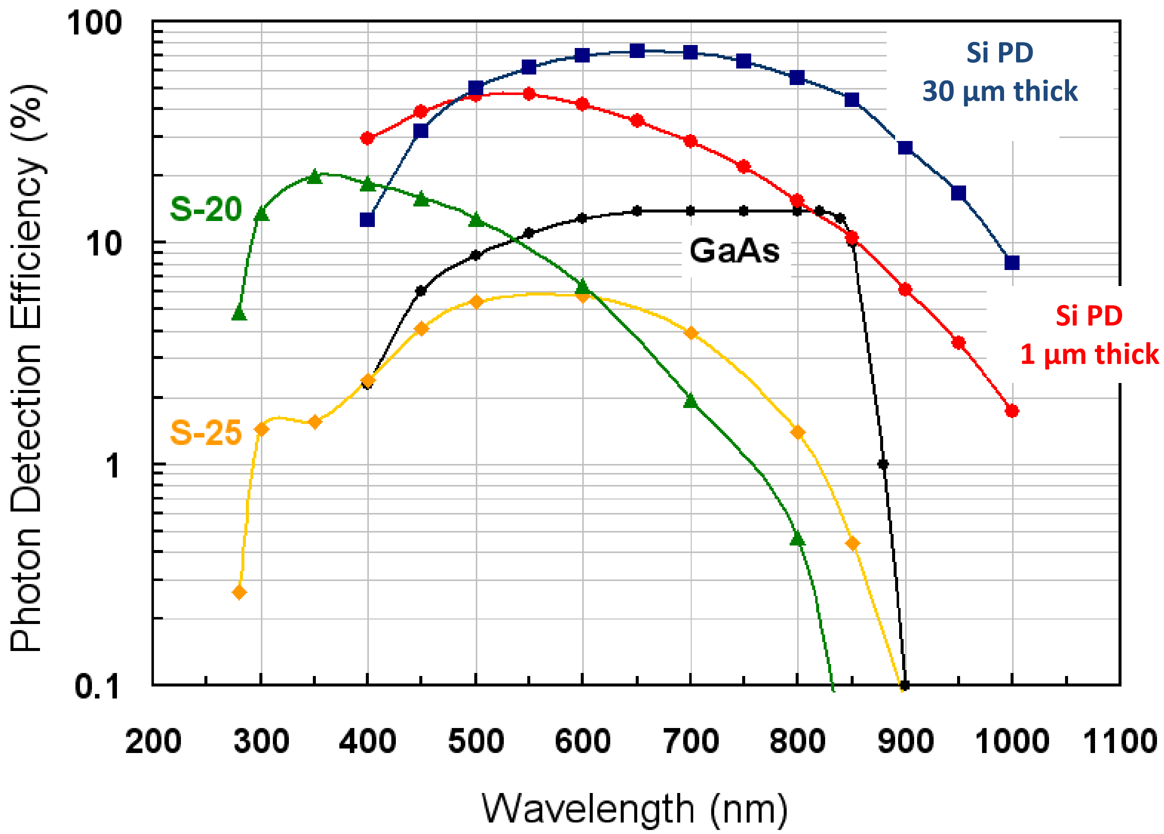


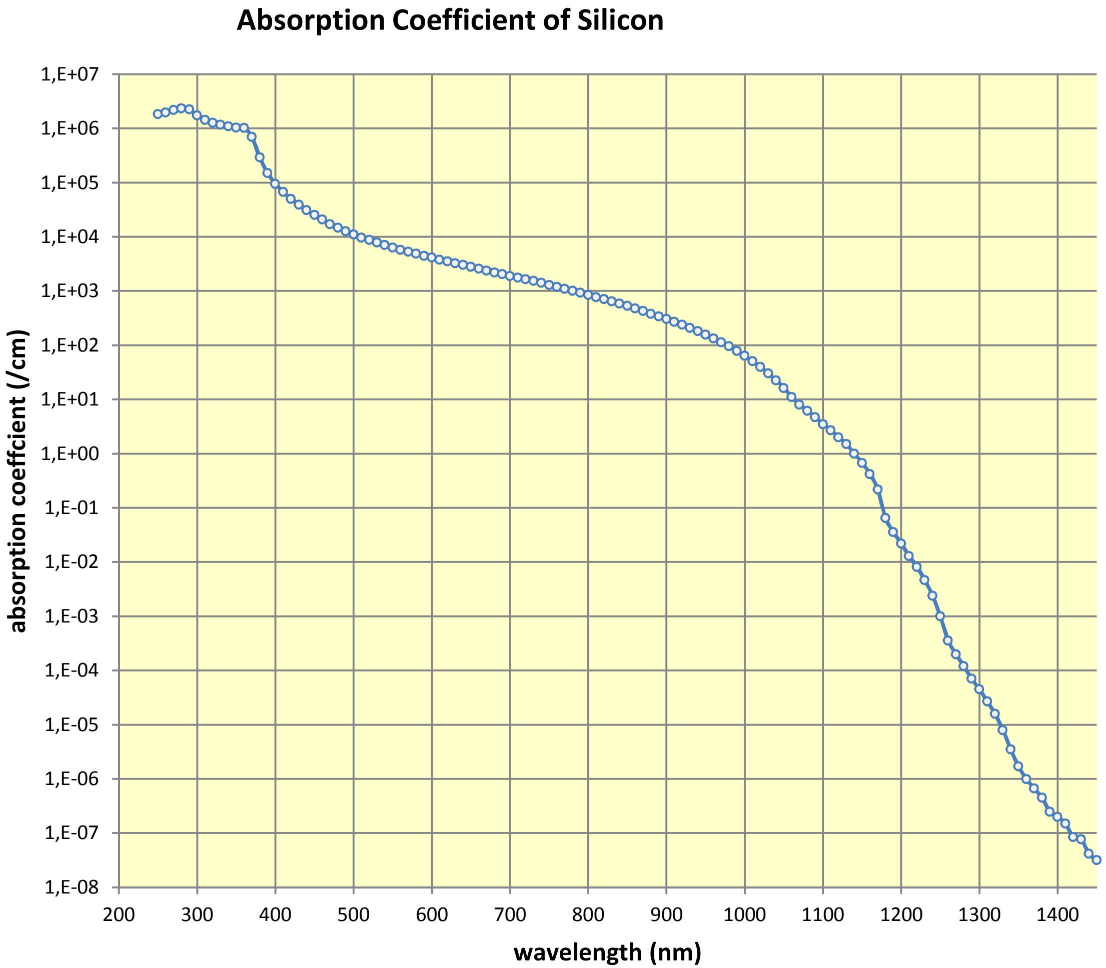
PHOTOCATHODE TYPES

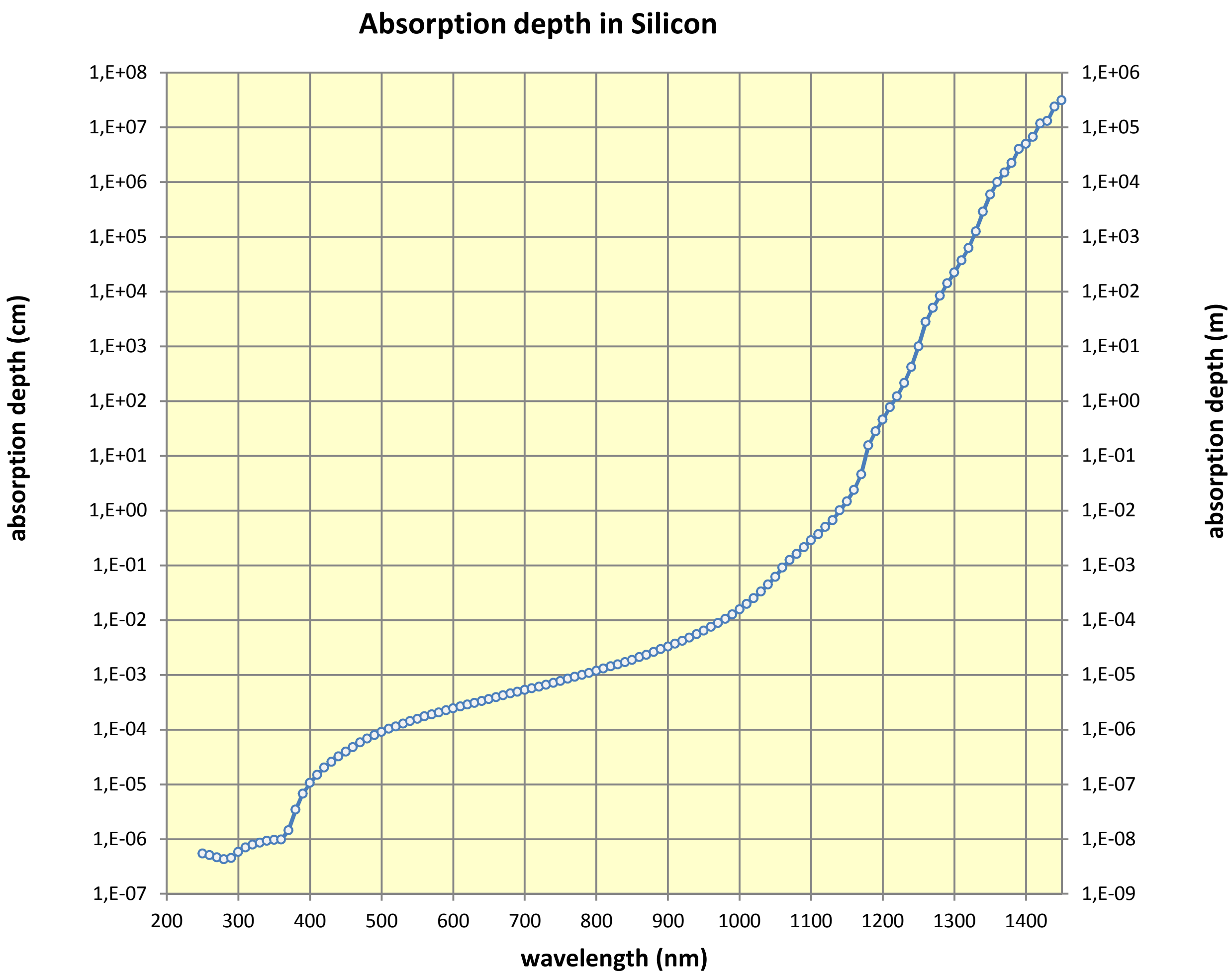
- S1 (Ag-O-Cs
  oldest type
  infrared-sensitive)
- S11 (Cs_3Sb
  alkali halide)
- S20 Na-K-Sb-Cs
  Multi-alkali halide
- S25 Multi alkali halide
  extended red sensitivity

NB: the auxiliary lines marked with Quantum Detection Efficiency (QDE) in %
make possible to read directly from the diagram also the QDE

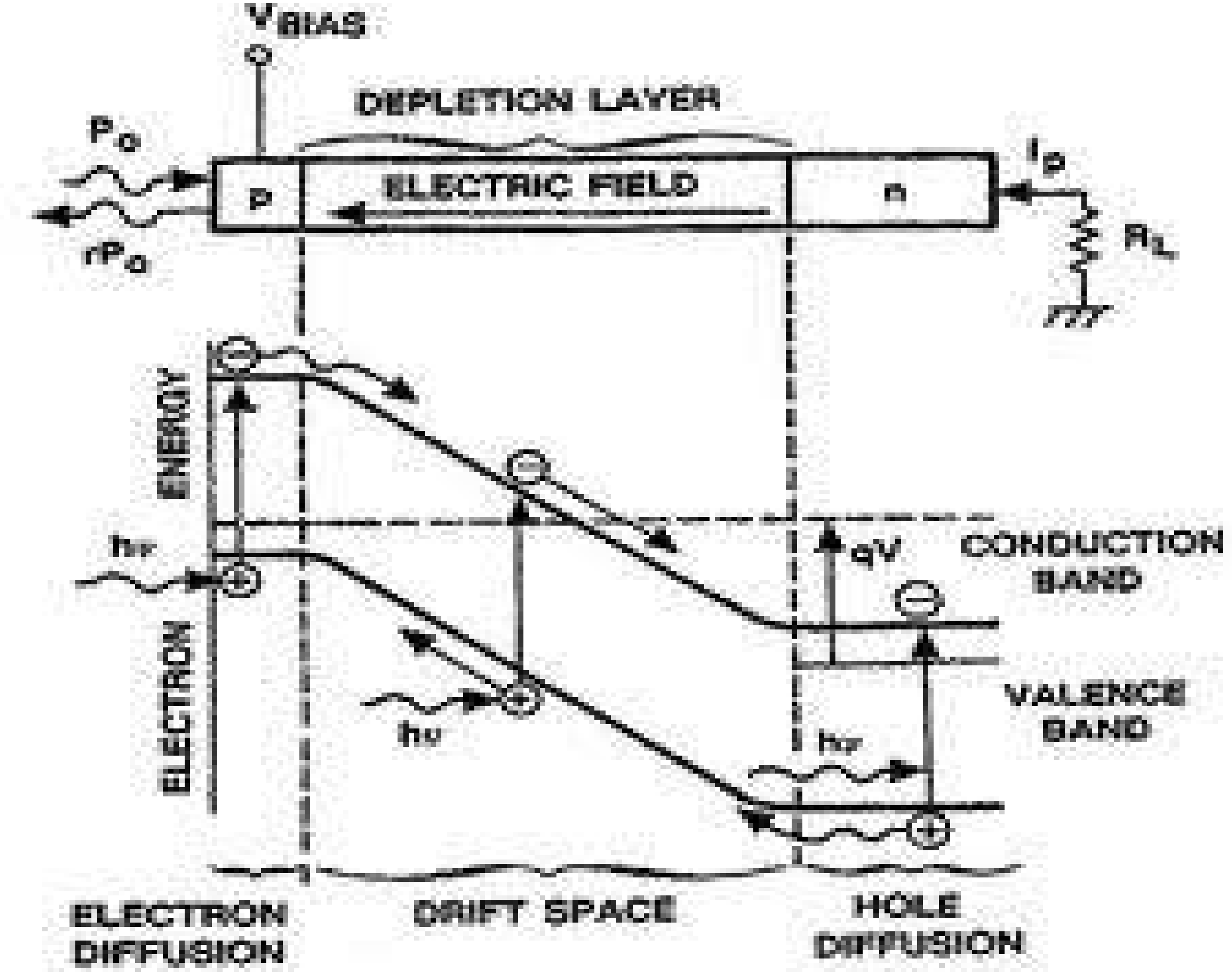
Quantum Detection Efficiency



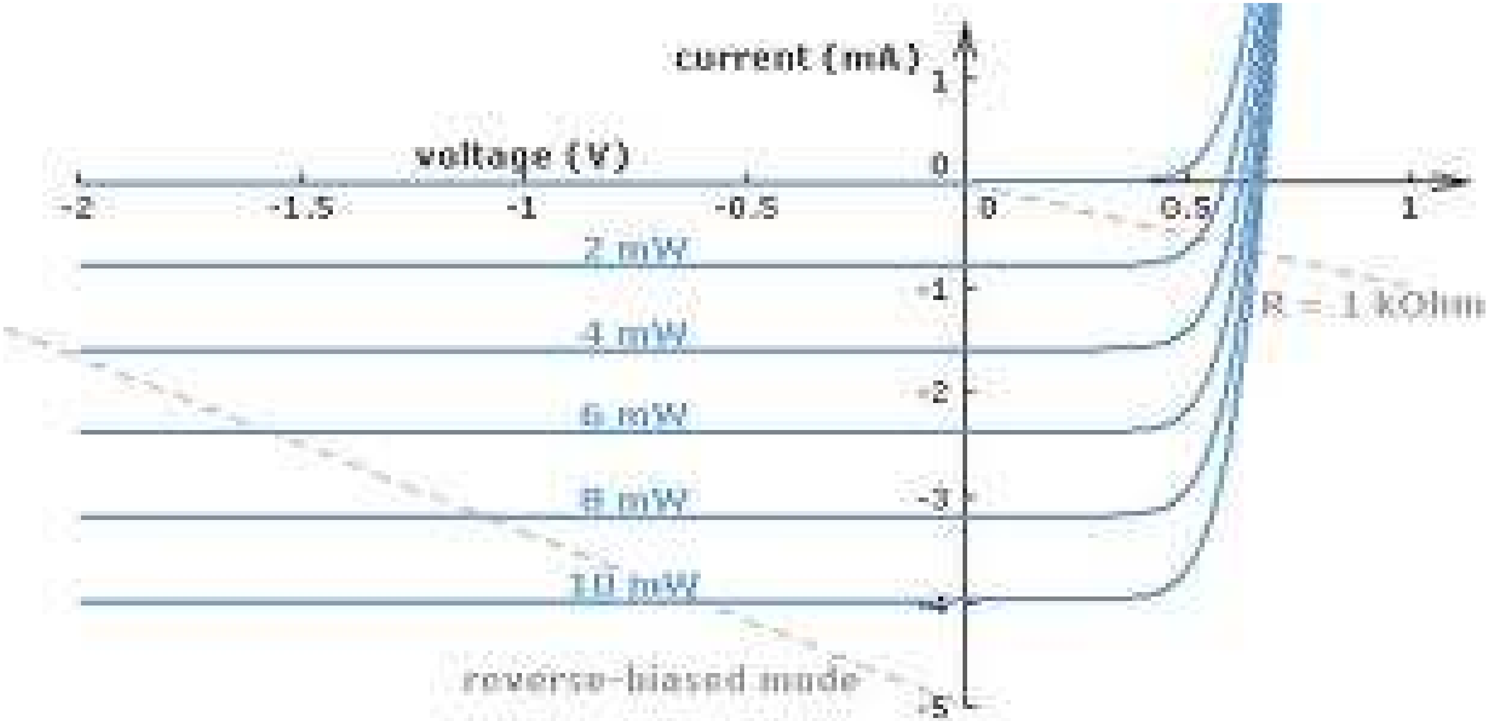

Absorption Coefficient of Silicon
1,E+07
1,E+06
1,E+05
1,E+04
1,E+03
1,E+02
1,E+01
1,E+00
1,E-01
1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
1,E-08
absorption coeffcient (/cm)
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
wavelength (nm)


Absorption depth in Silicon
absorption depth (cm)
1,E+08
1,E+07
1,E+06
1,E+05
1,E+04
1,E+03
1,E+02
1,E+01
1,E+00
1,E-01
1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
absorption depth (m)
1,E+06
1,E+05
1,E+04
1,E+03
1,E+02
1,E+01
1,E+00
1,E-01
1,E-02
1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
1,E-08
1,E-09
200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
wavelength (nm)

Silicon PhotoDiodes (Si-PD)

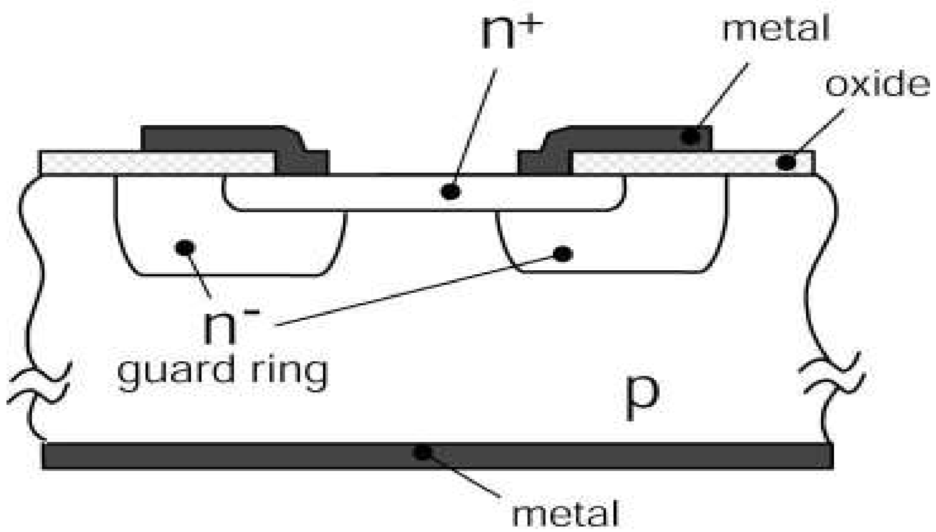


Silicon PhotoDiodes (Si-PD)



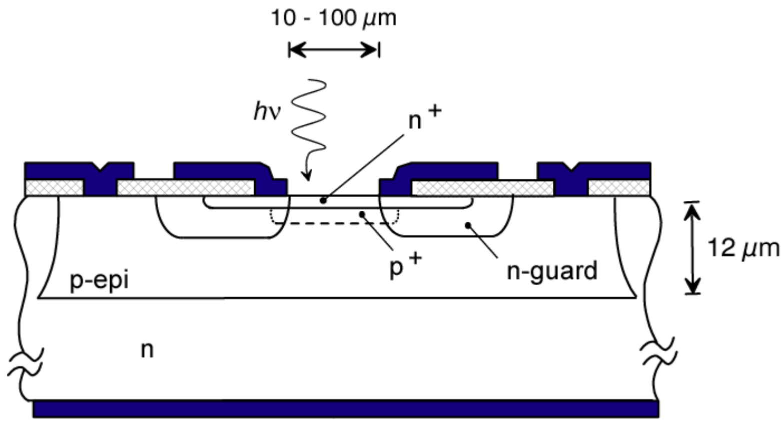
Silicon PhotoDiodes (Si-PD)

Simple planar device structure



Silicon PhotoDiodes (Si-PD)

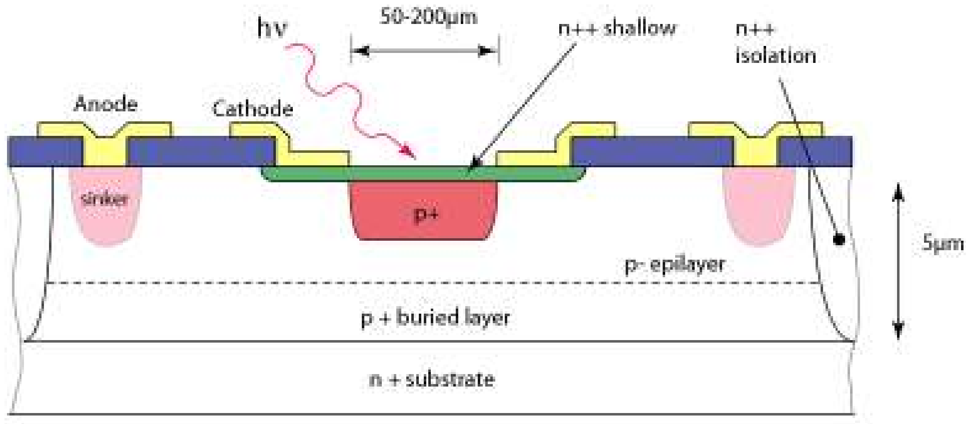
Epitaxial planar device structure



- Deep diffused guard ring
- V_{BD} control by p+ implantation
- fully isolated structure
- Short diffusion tail

Silicon PhotoDiodes (Si-PD)

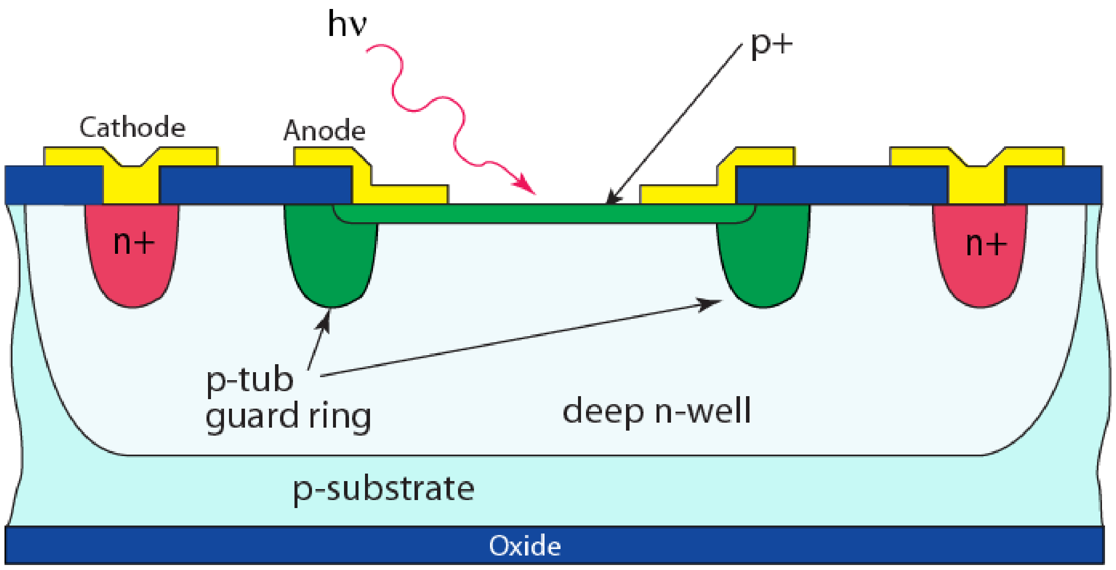
p-p$^+$-n Double-Epitaxial device



- No guard-ring
- Active area defined by p+ implantation
- Adjustable V_{BD} and E-field
- suitable for integration and array detector
- Short diffusion tail (simple exponential)

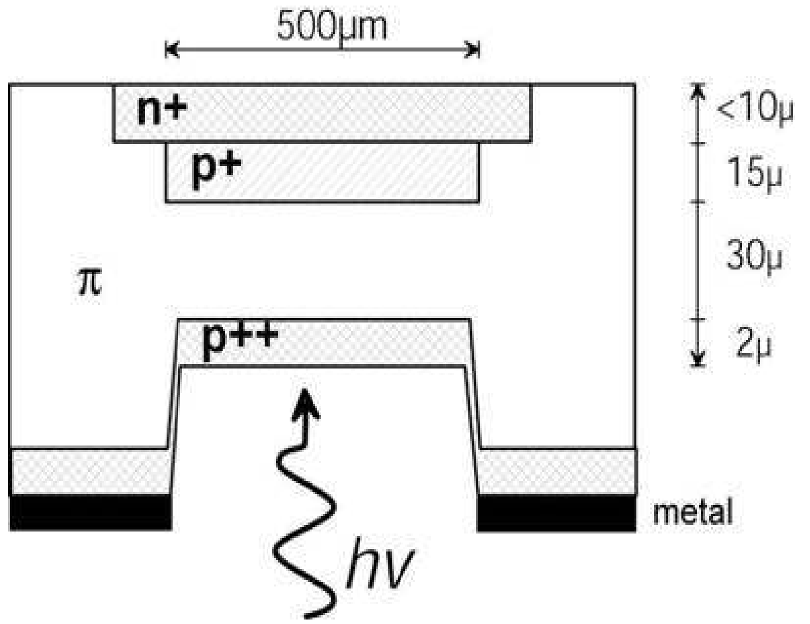
Silicon PhotoDiodes (Si-PD)

Device in standard CMOS technology



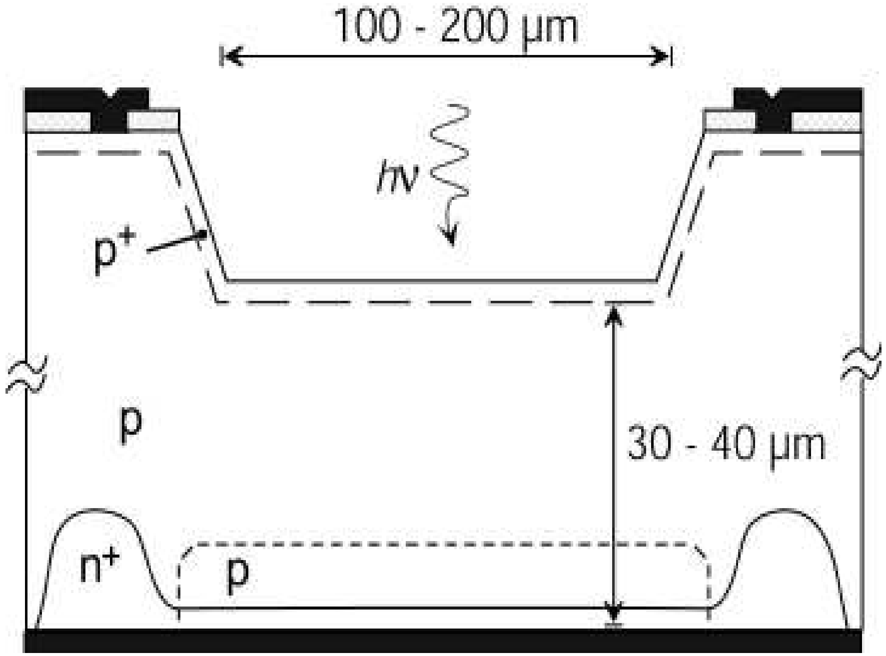
Silicon PhotoDiodes (Si-PD)

Etched device structure
for deep depletion layer (reach-through photodiode)



Silicon PhotoDiodes (Si-PD)

Improved reach-through device structure



Dark Current comparison: photocathode vs silicon PD

Data @ Room Temperature

Photocathode with diameter 1” (2,54 cm), current good devices:

- Primary Dark Current I_D < 1000 electrons / s
- i.e., current density j_D < 200 electrons / cm^2 s

$= 2 \times 10^{-6}$ elet / (μm)^2 **s**

Silicon Photodiode with active area diameter 200 μm, best available devices:

- Primary Dark Current I_D < 1000 electron / s
- i.e., current density $j_D < 4 \times 10^{+6}$ elet / cm^2 s =

$= 4 \times 10^{-2}$ el (μm)$^{-2}$ s

The Si-photodiode DC **density** j_D is higher by a factor > 20.000

Dark Current of Si junction reverse biased

In reverse-biased Silicon junctions thermal generation rate of carriers occurs over all the depleted volume with volume density n_G

$$n_G = \frac{n_i}{2\tau}$$

- n_i intrinsic carrier density
  @ Room Temperature is $n_i = 1{,}45 \text{ x } 10^{10} \text{ cm}^{-3}$
- τ minority carrier lifetime
  is strongly dependent on the technology,
  i.e on the fabrication process and on the starting material.
- Typical values

τ ~ µs	ordinary integrated circuits
τ ~ ms	high quality technology for detector devices
τ ~ s	best available etechnology for detector devices

Dark Current of Si junction reverse biased

In a photodiode with round active area A (diameter D) and depletion layer thickness w the total generation rate is

$$n_D = n_G\, A\, w$$

In order to limit it $n_D < n_{Dmax}$ we must limit the area $A = \pi D^2/4$

$$A < A_{max} = n_{Dmax} / n_G\, w$$

The corresponding limit for D can be expressed as a function of the thickness and of the miniority carrier lifetime (i.e of the actual device technology)

$$D \le D_{\max} = \sqrt{8 n_{D\max} \tau / \pi n_i w}$$

Example: with w = 1µm, for keeping $n_{Dmax} = 10^3$ el / s at room temperature

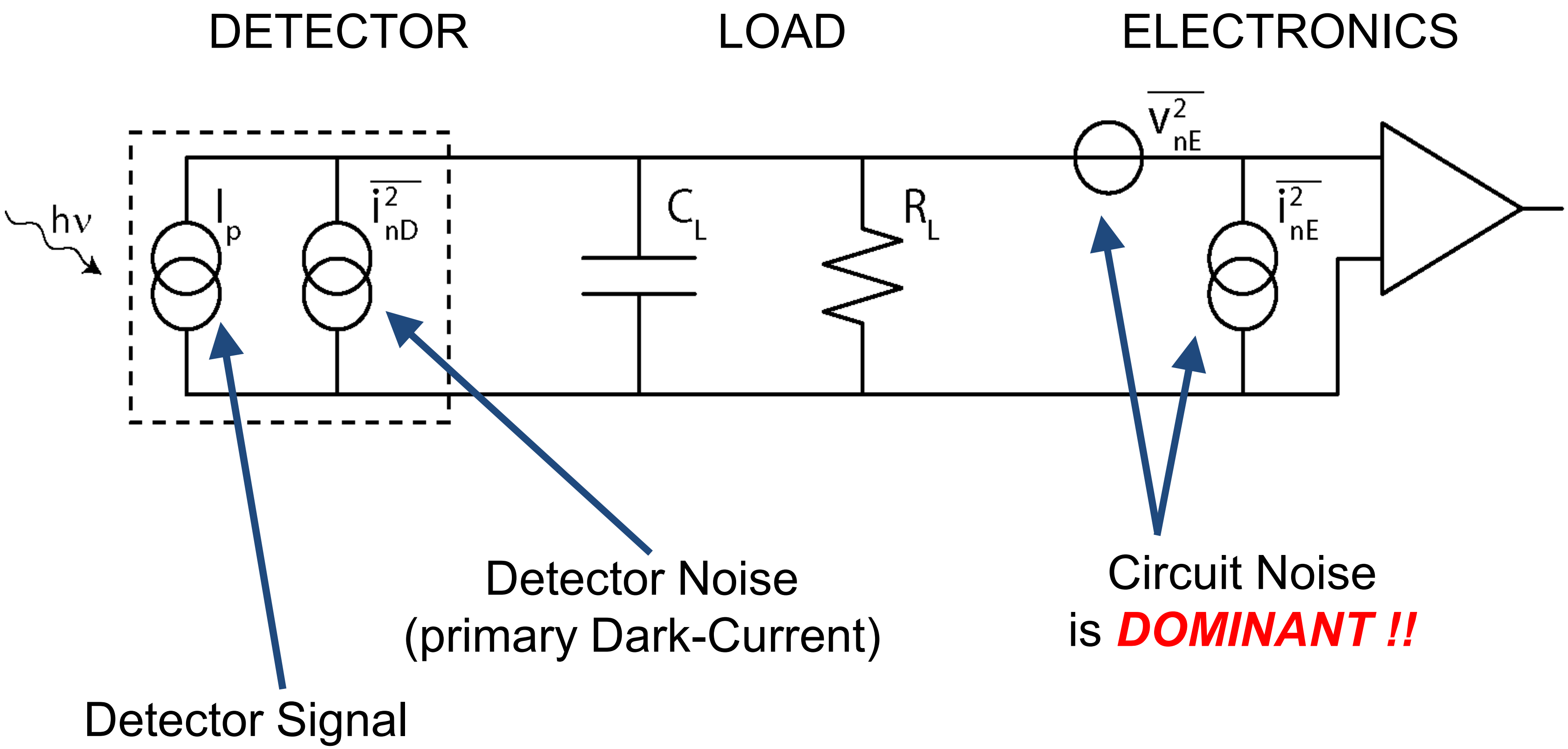
$$D < D_{max} = 420\, \tau^{1/2}$$ (D in µm if τ is in seconds)

With good technology $\tau \sim 10ms$ → $D_{max} = 42$ µm

With excellent technology $\tau \sim 1s$ → $D_{max} = 420$ µm

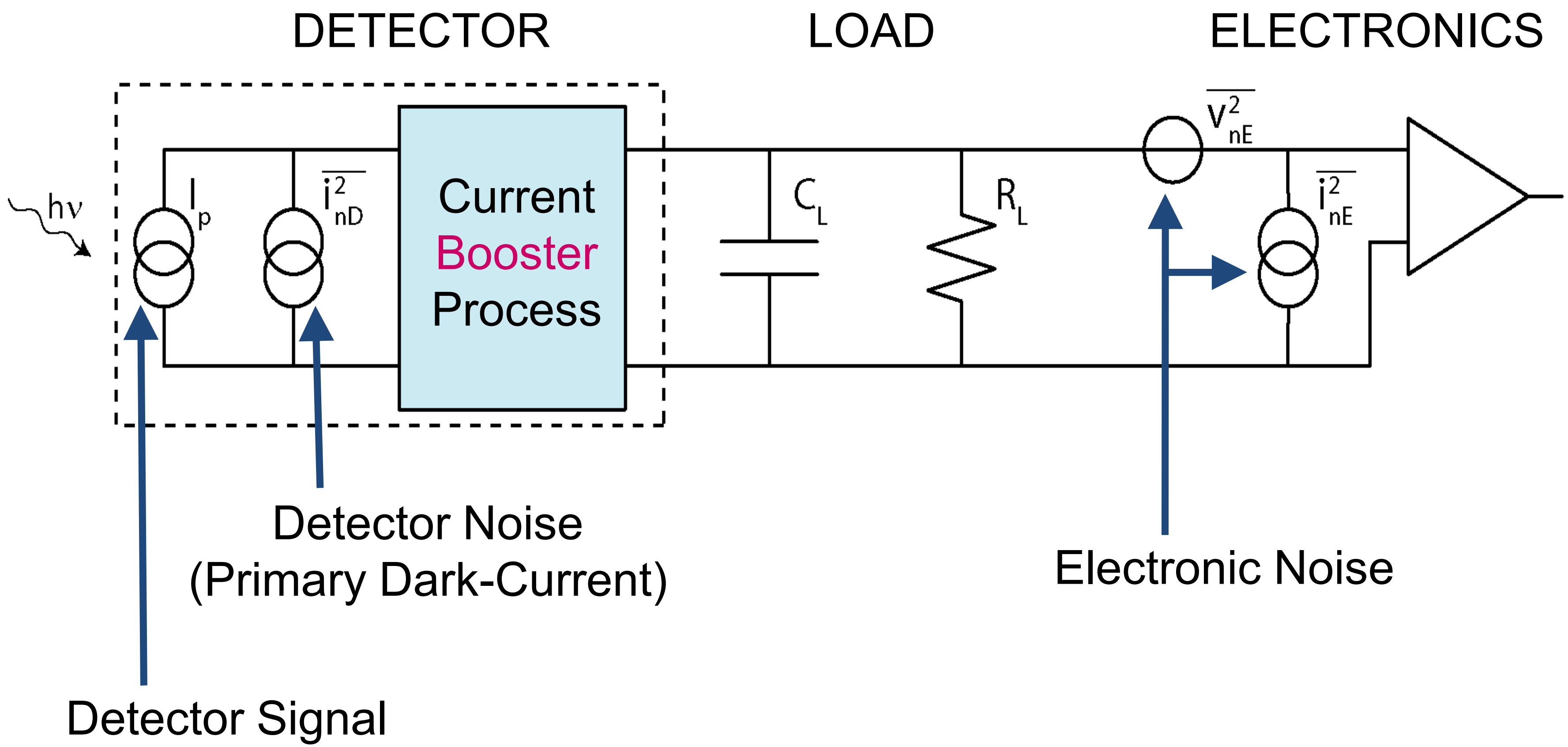
With exceptional technology $\tau \sim 10s$ → $D_{max} = 1.33$ mm

Circuit Noise impairs sensitivity of Analog Detectors



1 Photon $\xrightarrow{\text{PDE}}$ **1 Electron**

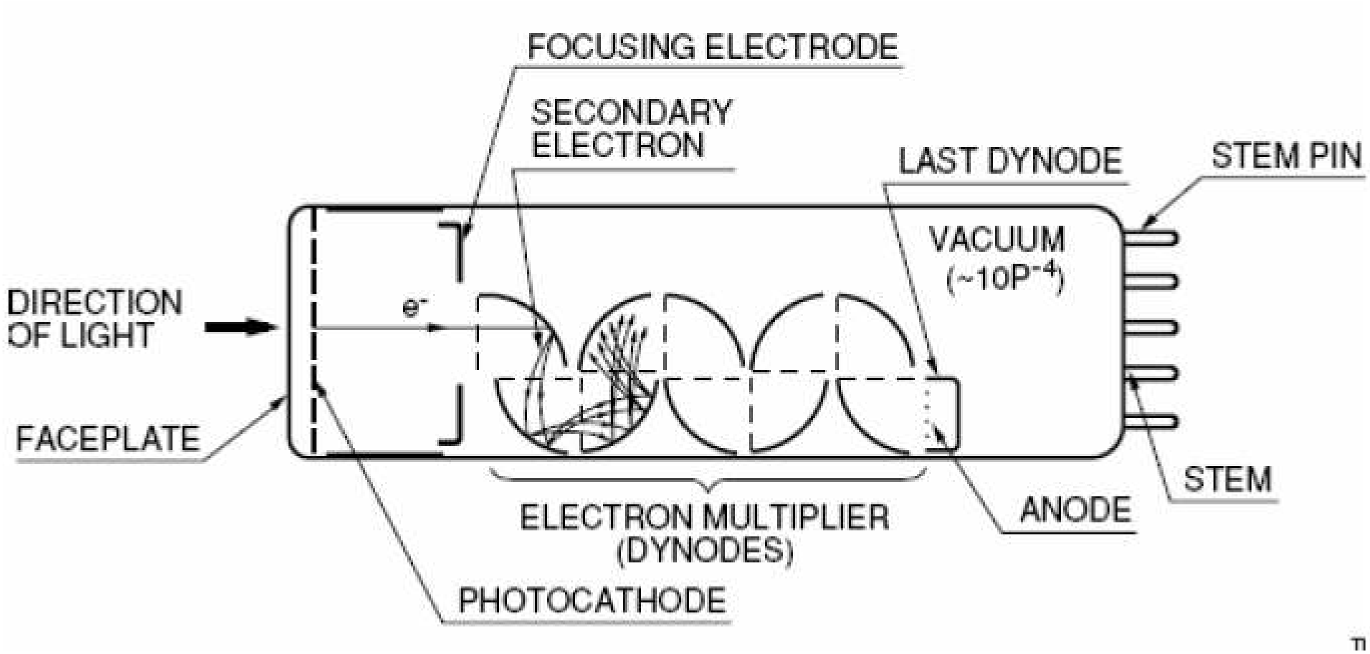
Single-Photon Detectors bypass the Electronic Noise Limit



1 Photon → 1 Electron

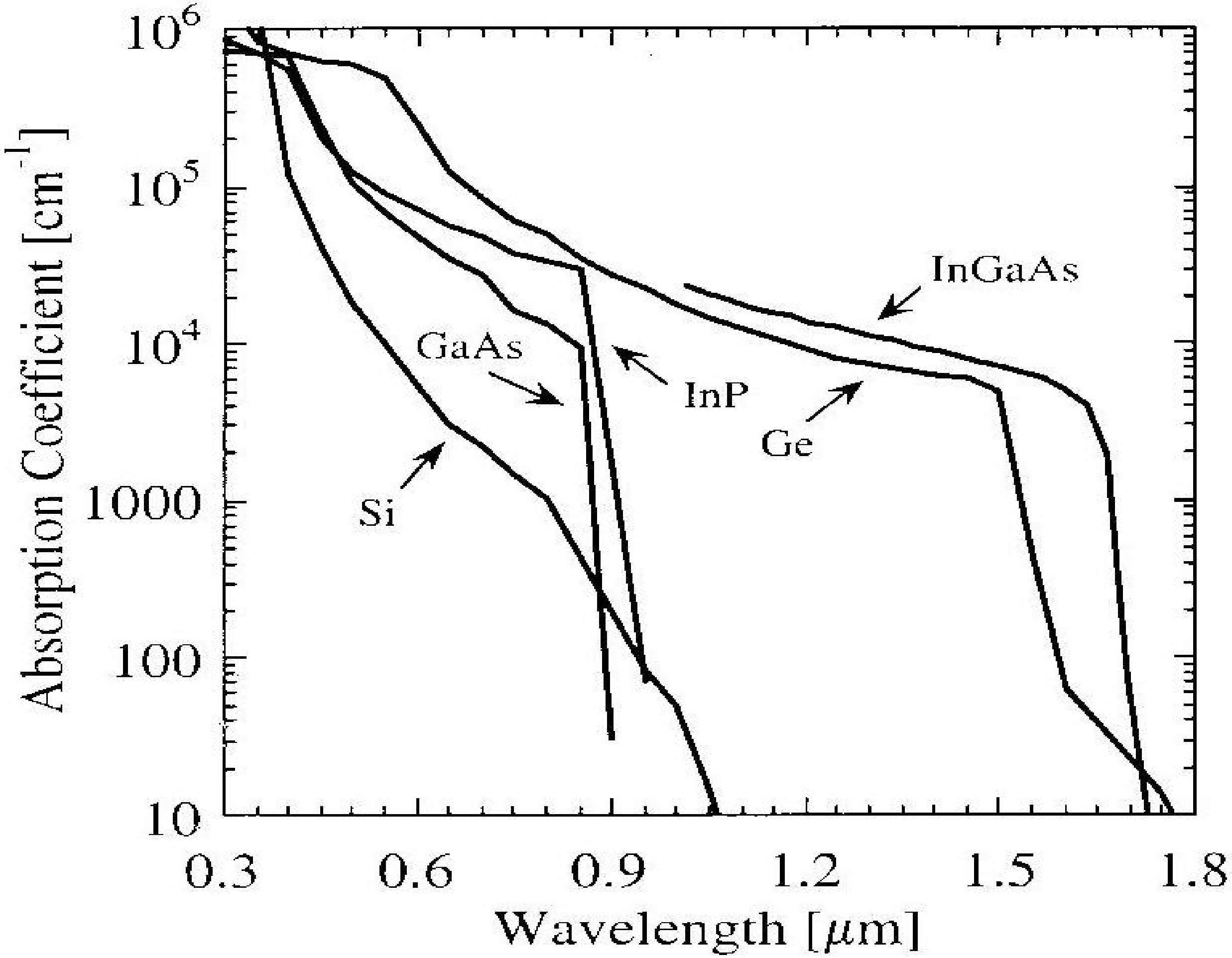
PDE

PhotoMultiplier Tube PMT



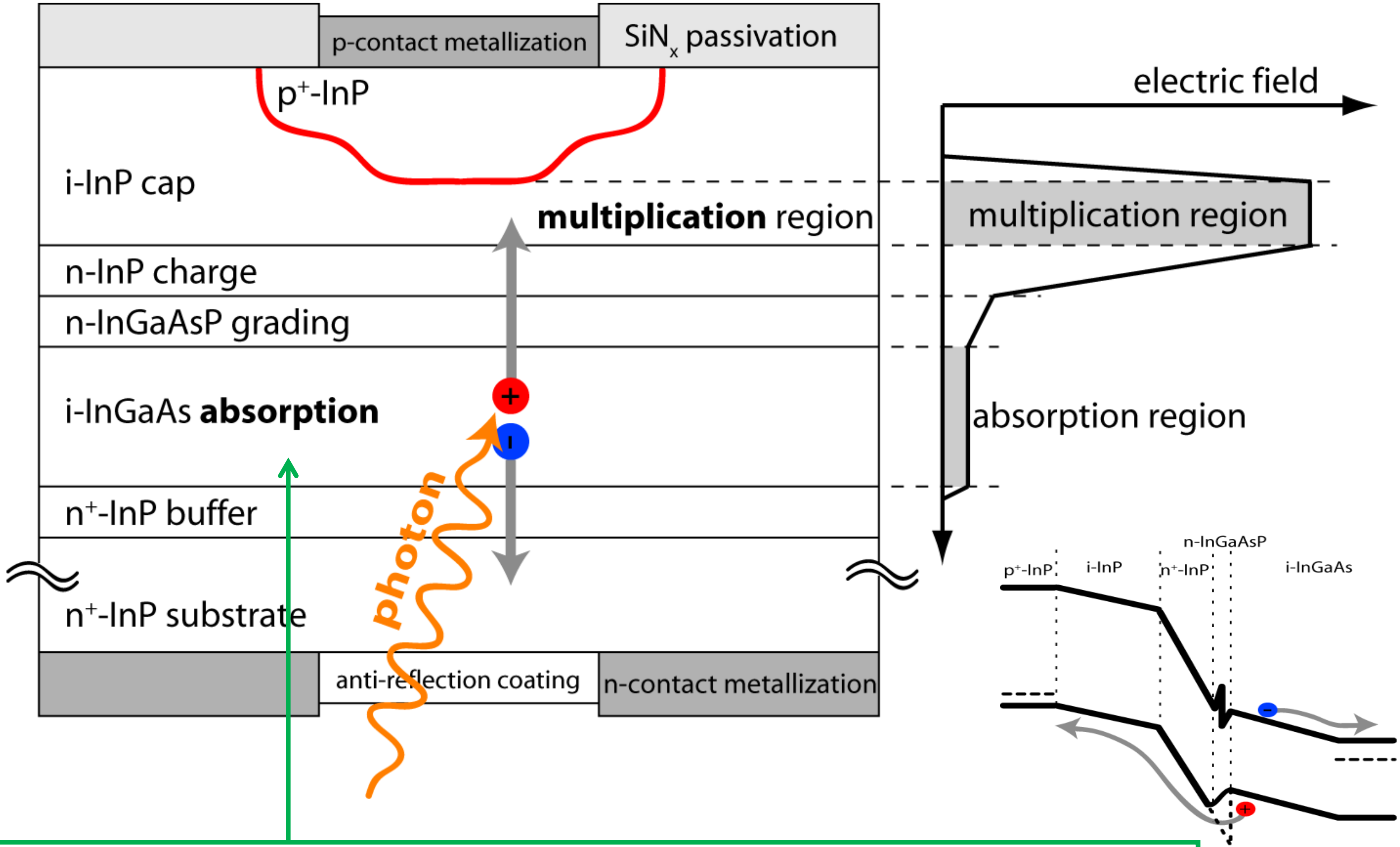
Semi-transparent photocathode

Optical Absorption of Semiconductors



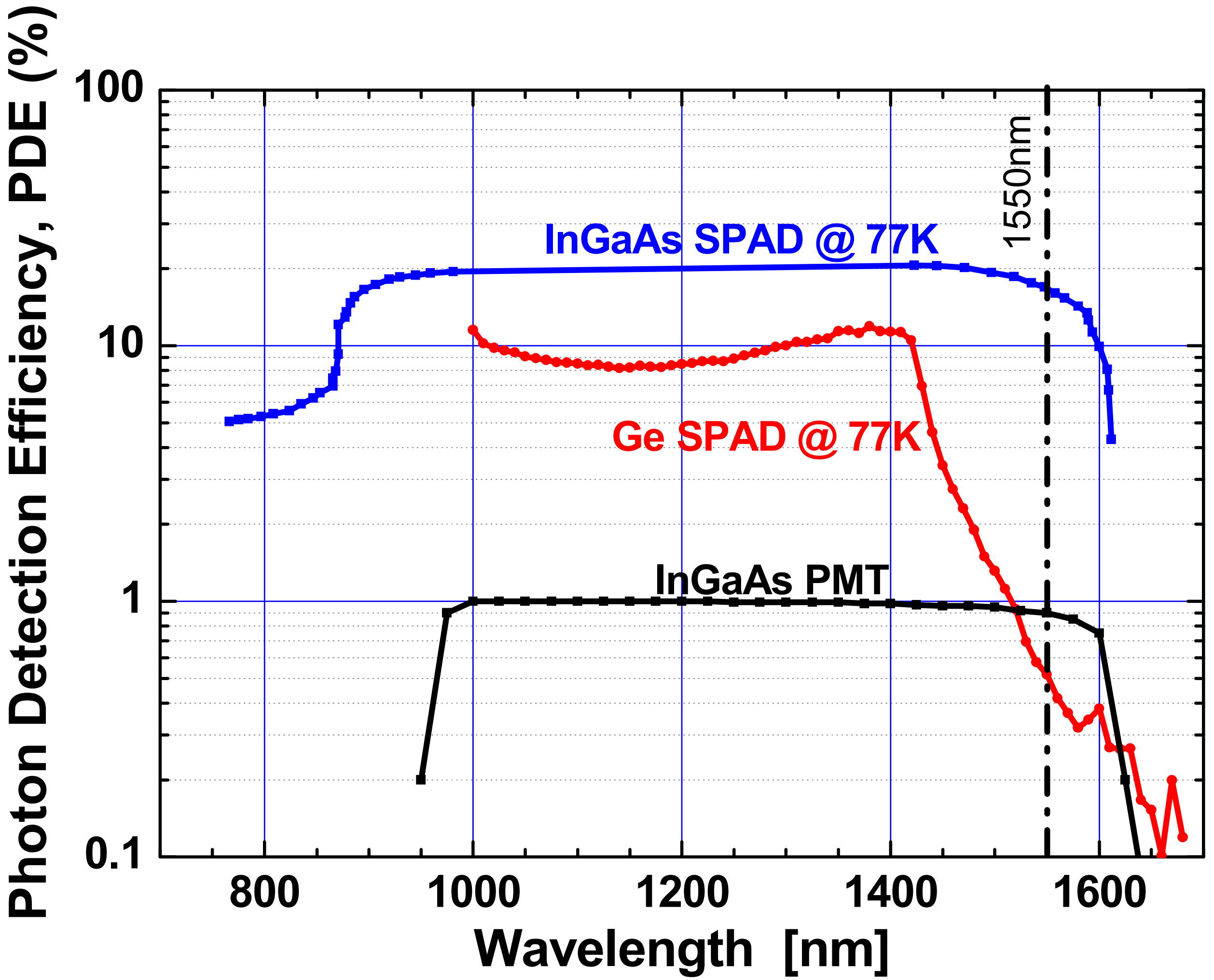
Handbook of Optical Constants of Solids, edited by Edward D. Palik, (1985), Academic Press NY.

Photon absorption and carrier collection



$In_{0.53}Ga_{0.47}As$ absorption layer → E_g ~ 0.75 eV → Cut-off 1.7μm

Photon Detection Efficiency: long λ detectors



Silicon Ionization Coefficients