VPI University Program

Photonics Curriculum Version 7.0

Lecture Series

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Introduction to Optical Receivers

Rx1

Module Prerequisites

- Introduction to Fiber-Optic Communications I & II
- Recommended – Transmitters I, Optical Amplifiers I

Module Objectives

- Introduction and basic requirements
- How a photodetector works
  - Basic structure: a PN junction photodetector
  - Optical Absorption Process
  - Reverse Bias, Dark Current, Quantum Efficiency, Responsivity
- PIN and APD photodetectors
- Noise sources

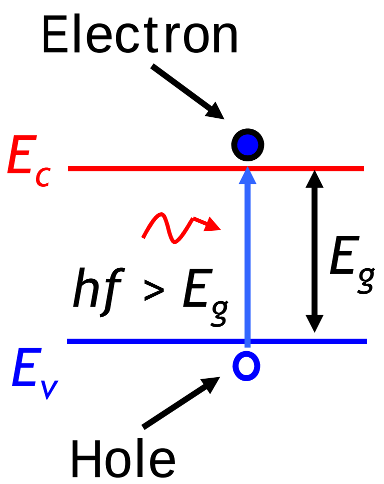
Photodetectors

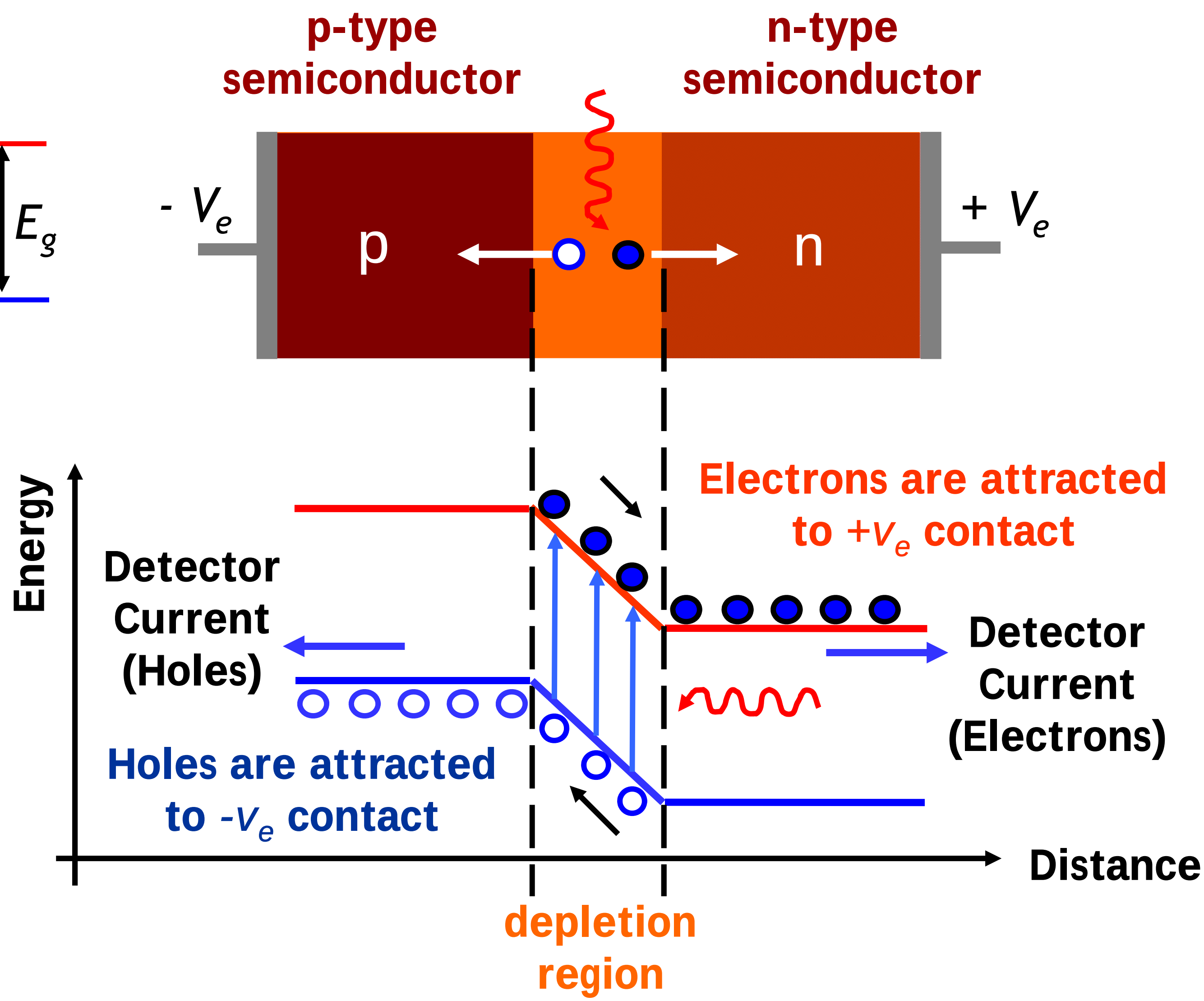
A photo detector (optical receiver) converts an optical signal into an electrical signal

Basic requirements

- Sensitivity at the required wavelength
- Efficient conversion of photons to electrons
- Small area for low capacitance and a fast response
- Low noise
- Sufficient area for efficient coupling to optical fiber
- High reliability
- Low cost

Basic Structure: PN Photodiode



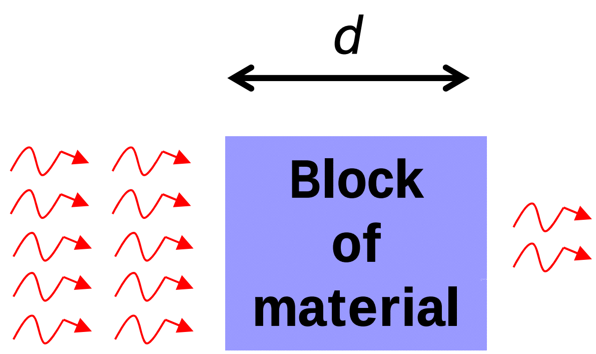


The Probability of Photon Absorption

Depends on

- Thickness of intrinsic region, *d*
- The material’s absorption coefficient, α
- The wavelength of the incident light, λ
- No. of photons lost on their way to the intrinsic region
- Surface reflection

Input photons/s
A



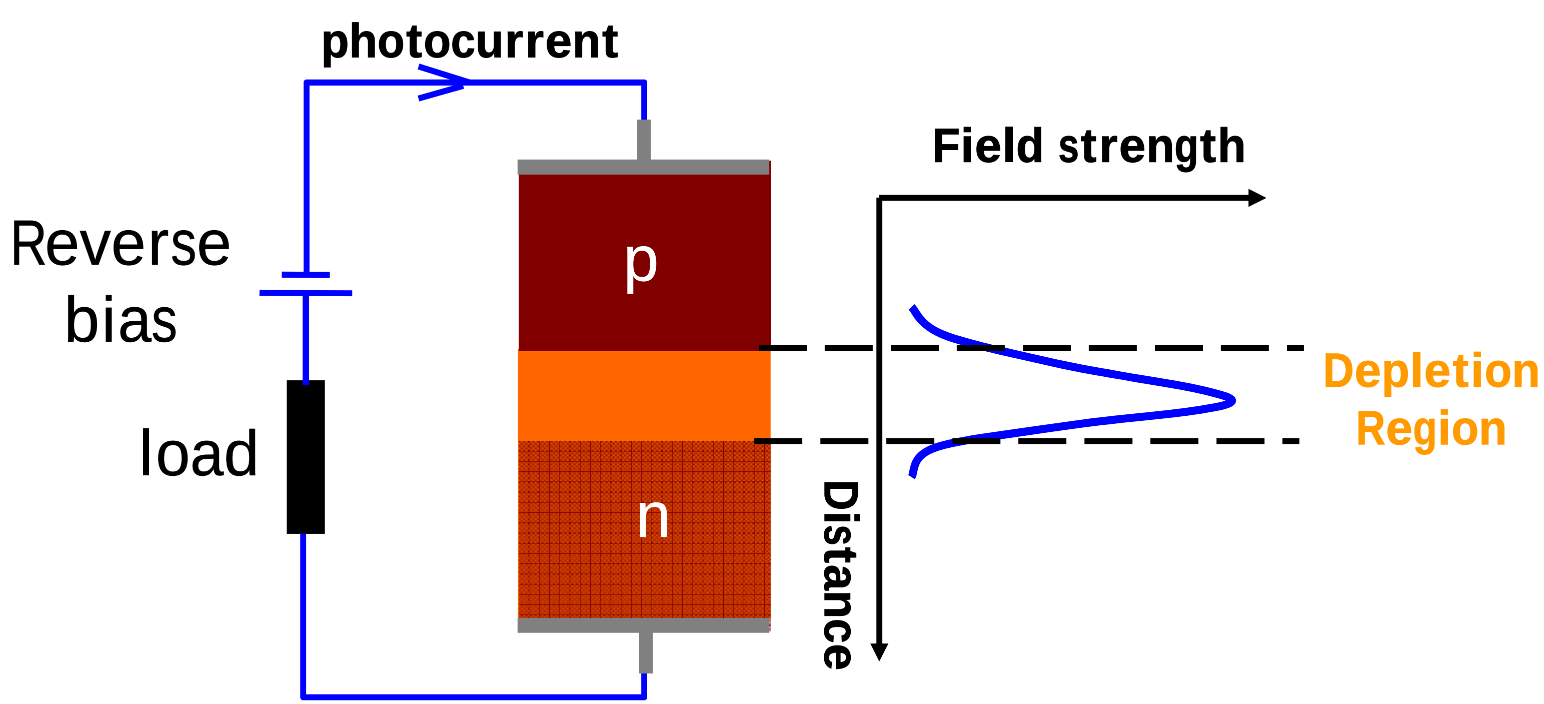
Output photons/s
$A\exp(-\alpha d)$

Absorbed photons/s
$A(1-\exp(-\alpha d))$

Reverse Bias and Photocurrent

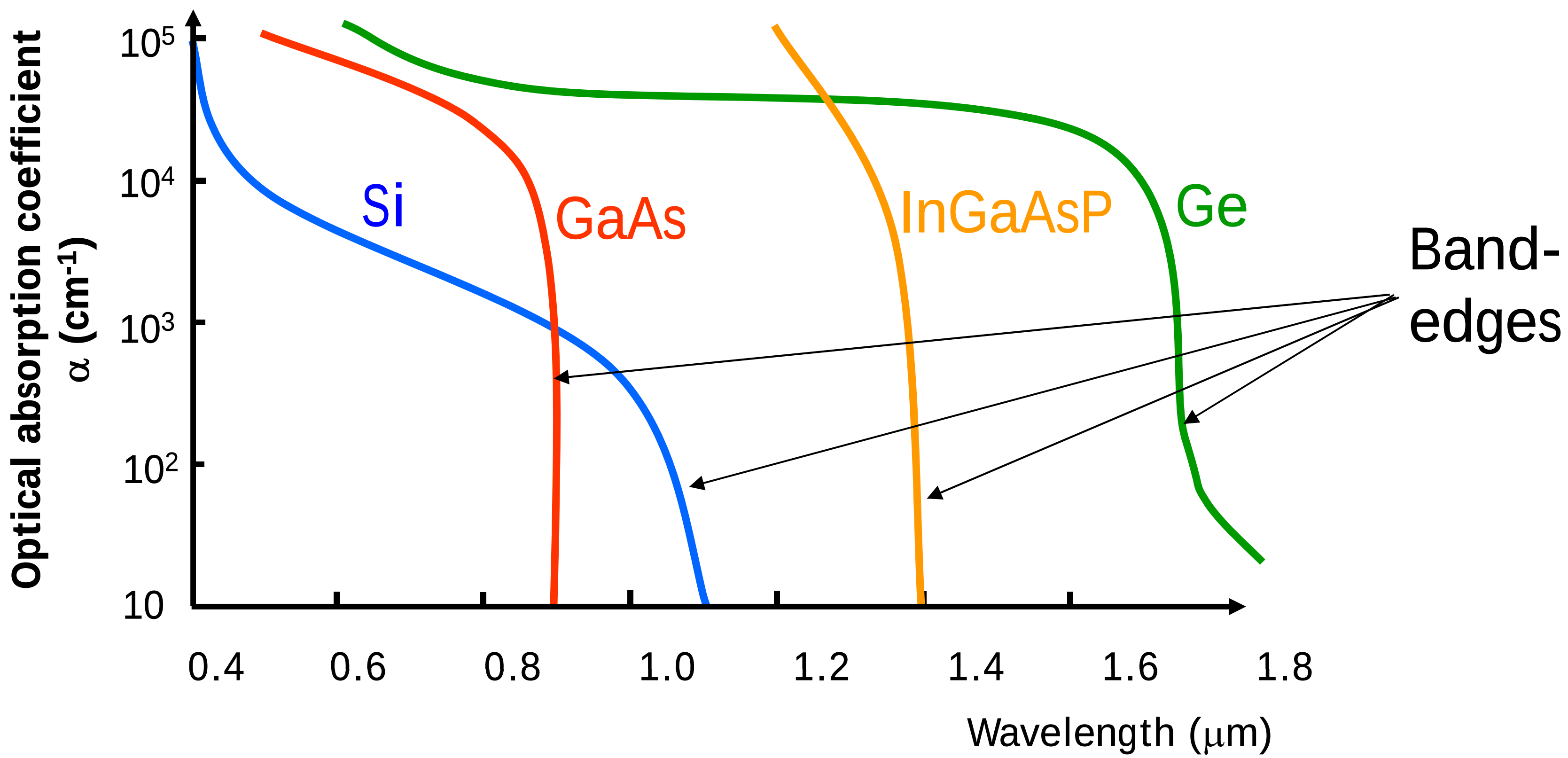
Reverse biasing the photodetector

- Increases the electric field in the depletion region
- Decreases its capacitance (increase speed)
- Increases its sensitivity and frequency response



Absorption

Absorption coefficient depends on wavelength, and the material (bandgaps again)



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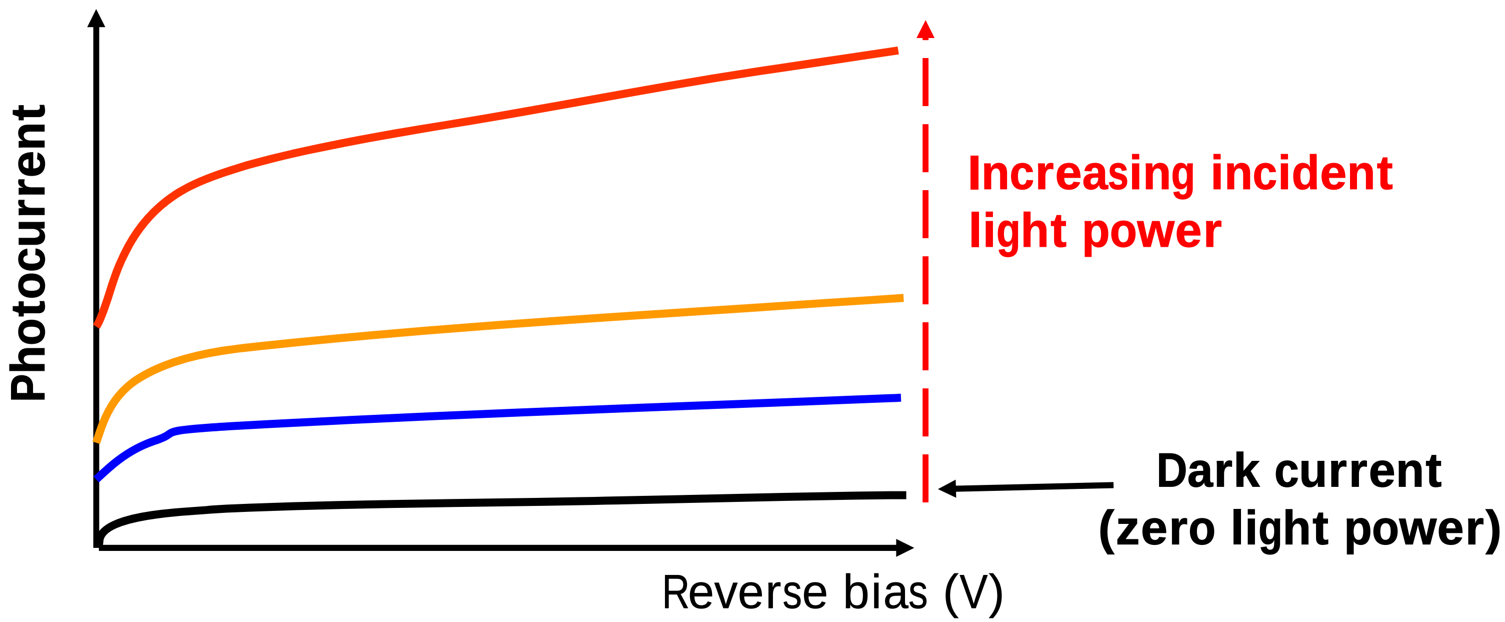
Dark Current

- Dark current (flows even when there is no light)
- As the incident light increases…
  the photocurrent increases linearly



Quantum Efficiency

The quantum efficiency (η) is the probability that an incident photon will produce an electron-hole pair

$$\eta = \text{electron flux / photon flux}$$

$$= \frac{\text{electrons per second}}{\text{photons per second}}$$

Responsivity

The responsivity, R_0 (A/W), is the photocurrent produced per unit of incident optical power

$$R_0 = I_p / P_i = q\eta / hf \qquad [A/W]$$

with I_p = (electron flux) • q [A]

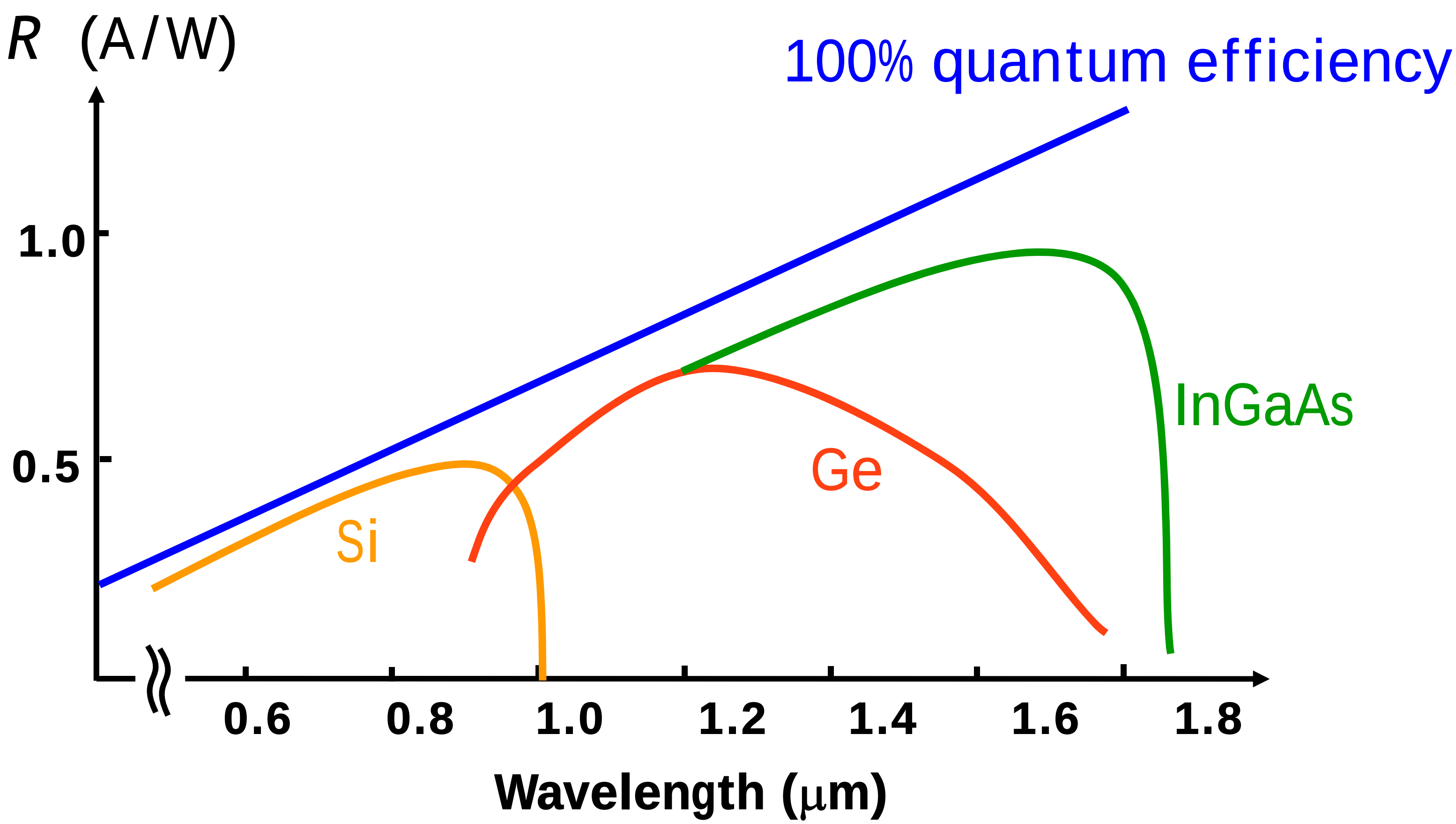
P_i = (photon flux) • hf [W]

The responsivity of a device relates to its design:

$$R = \underbrace{(1 - r)}_{\text{Facet factor}} \underbrace{\exp(-D\alpha_c)}_{\text{Contact absorption}} \underbrace{[1 - \exp(-d\alpha)]}_{\text{Intrinsic absorption}} \underbrace{(q\lambda / hc)}_{\text{Wavelength factor}}$$

Responsivity & Wavelength Dependence

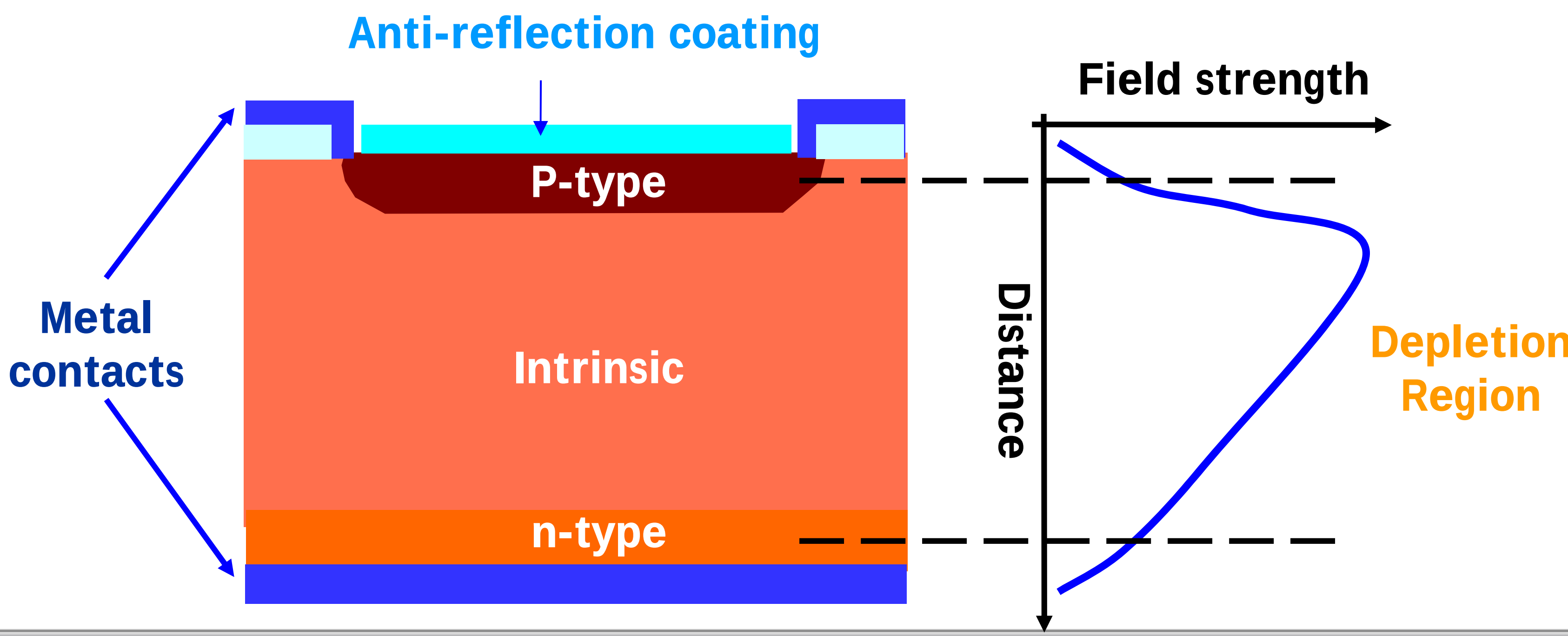
Different materials suit different wavelengths



PIN Photodetector

Adding an “intrinsic” region between P and N

- increases depletion region width
- increases absorption of incident light
- increases the quantum efficiency of the photo detector



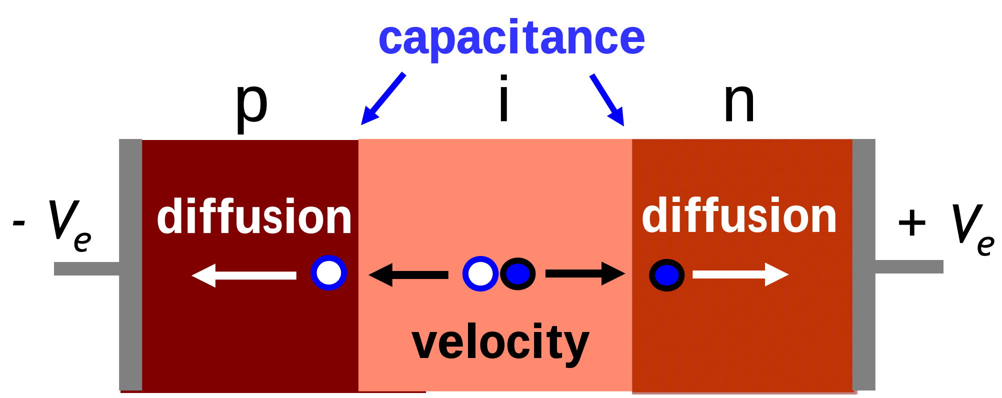
Speed of PIN Photodetector

Speed - maximum detectable modulation rate

- i.e. the electrical frequency response

Speed is limited by the:

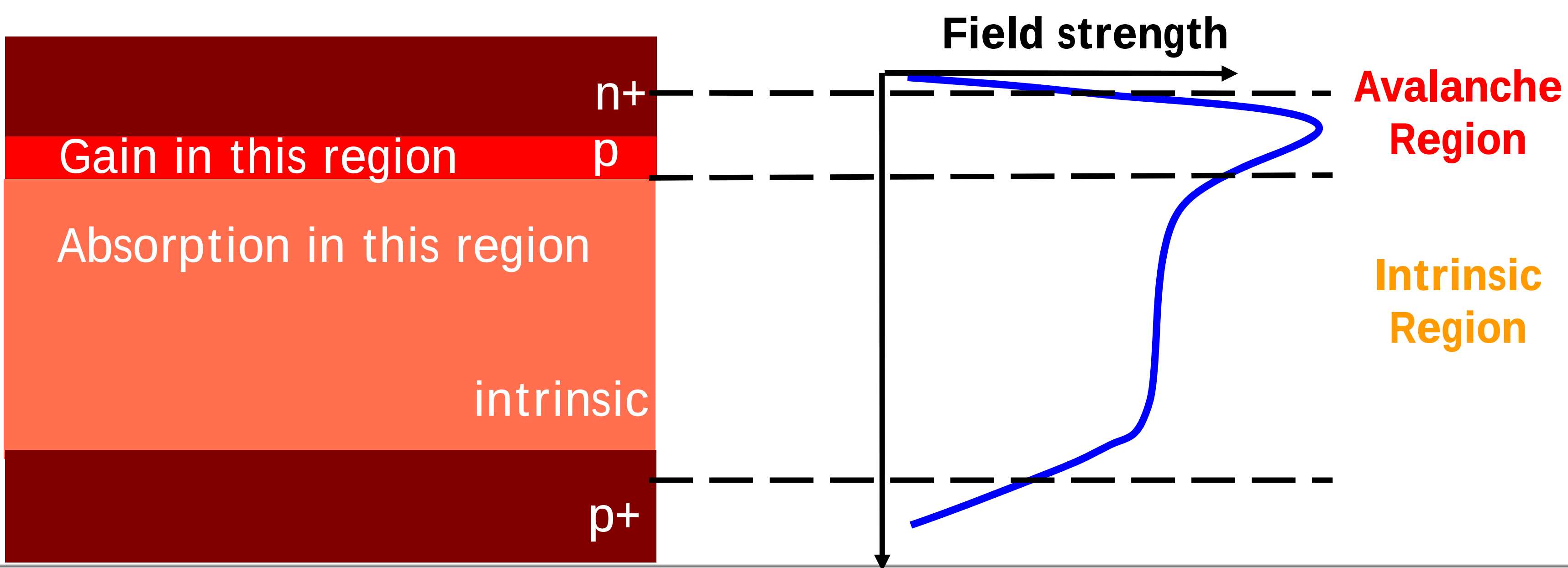
- Carrier velocity in depletion region
- Diffusion time of carriers outside the depletion region
- Time constant of the p-n junction capacitance
- Photodetector load resistance



Avalanche Photodetector (APD)

Avalanche region – higher internal electric field

- Accelerates carriers – more kinetic energy
- High energy collision frees bound electrons
- Freed electrons can collide - free more bound electrons
- Results in current gain (avalanche multiplication)



Comparison between APD & PIN

An APD:

- has gain, while a PIN does not
- can detect a weaker signal than a PIN
- requires a higher bias voltage than a PIN
- is noisier than a PIN
- is more sensitive to variations in temperature and bias voltage than a PIN
- is more expensive than a PIN

Noise Sources in Photodetectors

Electronic Shot Noise

- associated with the quantum nature of the light
- each incident photon produces an electron’s worth of current.

The total shot noise associated with a photocurrent current *I* flowing through a potential barrier is:

$$\langle i^2_{shot} \rangle = 2qIB$$

Electron charge

observation bandwidth

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Noise Sources in Photodetectors

Thermal Noise

- is the result of thermally induced random fluctuations in the charge carriers in a resistance
- occurs even when no voltage is applied across the resistance

Mean square thermal noise current is given by:

Boltzmann's constant

temperature

bandwidth

$$\langle i^2_{ther} \rangle = \frac{4kTB}{R}$$

resistance

Noise Sources in Photodetectors

Dark Current Noise I_d

- flows in the photo detector even in the absence of light.
- caused by current leakage paths in the photo detector
- and thermal excitation of carriers across the p-n junction

I_d gives rise to an additional shot noise current with a mean-square value of:

$$\langle i^2_{dark} \rangle = 2qI_dB$$

Noise Sources in Photodetectors

APD Excess Noise

- is present in avalanche photodiodes because the avalanche multiplication is essentially a random process

This causes the shot noise of the photodiode to be multiplied by:

$$\textit{Noise Multiplication factor} = M^{2+x}$$

$$(0.1 < x < 1.0)$$

where M is the avalanche gain

Noise Sources in Photodetectors

Optical Excess Noise

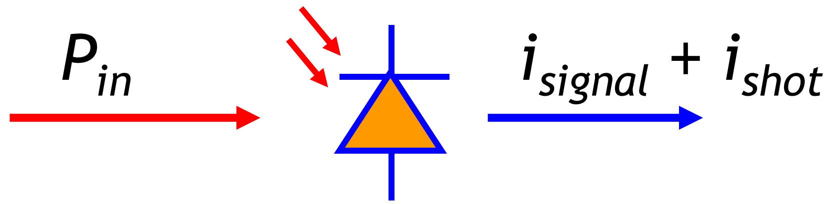
- can be broadly defined as any noise that appears along with the received signal, *other than* quantum shot-noise

Most common types:

- Laser Intensity Noise
- Modal Noise
- Mode Partition Noise
- Amplified Spontaneous Emission (ASE) Noise in optical amplifiers

Signal-to-Noise Ratio (SNR)

Electrical SNR (assuming shot noise dominates)



$$\langle i^2_{shot} \rangle = 2qIB \qquad = 2qR_0P_{in}B$$

$$i^2_{signal} = (R_oP_{in})^2$$

$$\mathrm{SNR} = \frac{(R_oP_{in})^2}{2qR_oP_{in}B} = \frac{P_{in}}{2hfB}$$

$R_o = \dfrac{q}{hf}$, *Responsivity of the photodetector*

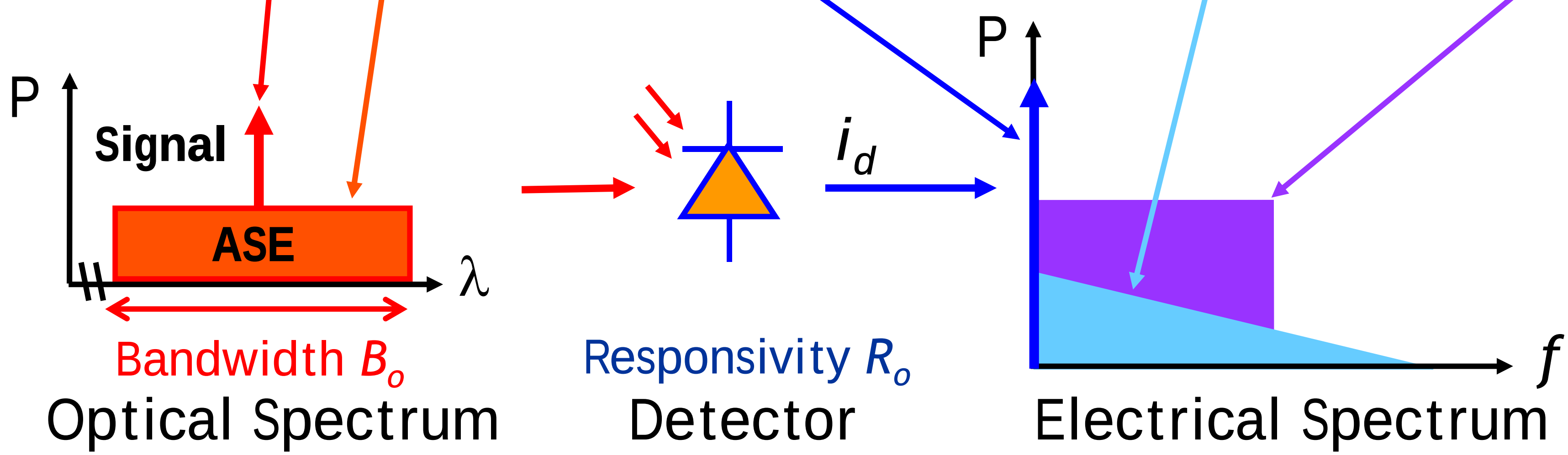
SNR in Optical Systems

Mixing products in the detected photocurrent:

$$i_d \propto R_o|E_s + E_{ASE}|^2 = R_o(\ |E_s|^2 + |E_{ASE}|^2 + 2Re[E_s E_{ASE}]\ )$$

$$= R_oP_s + R_oP_{ASE} + R_oP_{ASE\text{-}ASE} + R_oP_{s\text{-}ASE}$$

$$\Rightarrow i_d = i_s + i_{ASE} + i_{sp\text{-}sp} + i_{s\text{-}sp}$$



Total SNR of Optical Systems

The SNR at receiver with responsivity R_o, and electrical bandwidth B

$$SNR = \frac{i_s^2}{(i^2_{s\text{-}sp} + i^2_{sp\text{-}sp} + i^2_{shot} + i^2_{ther})B}$$

includes contributions from i_d, i_{ASE},
optical excess noise induced shot noise

Summary

- **How a basic PN junction photodetector works**
  - **Optical Absorption Process**
  - **Reverse Biasing , Photocurrent, Dark Current**
  - **Quantum Efficiency, Responsivity**
- **How PIN photodetectors and APDs work**
- **Overview of noise sources in photodetectors**
- **Signal to Noise Ratio**

Proceed with the *Interactive Learning Module*