MICRO-523: Optical Detectors

Week Five: Photodiodes (Solutions Ex5)

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Based on MICRO-523, P.-A. Besse, 2023

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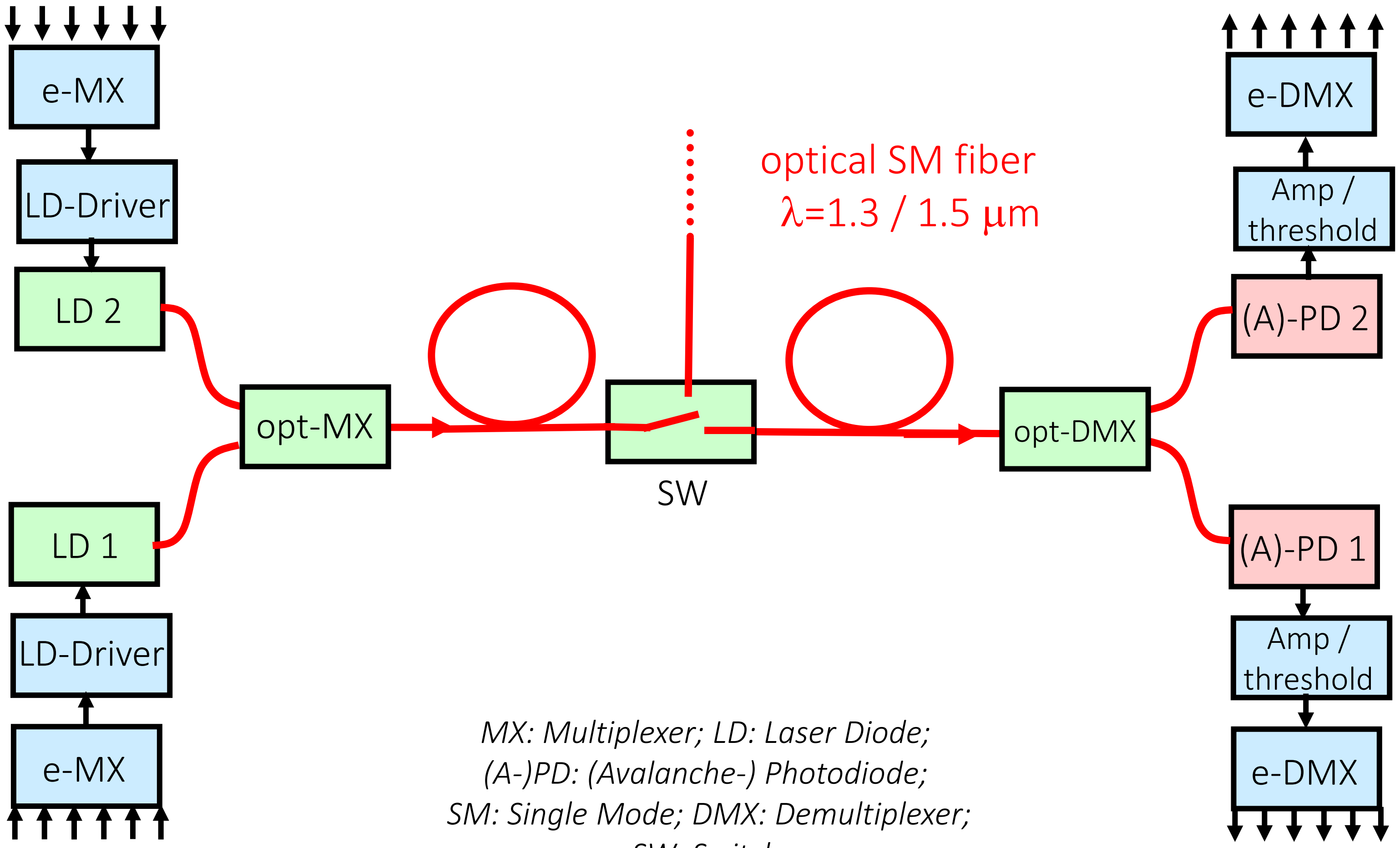
EPFL

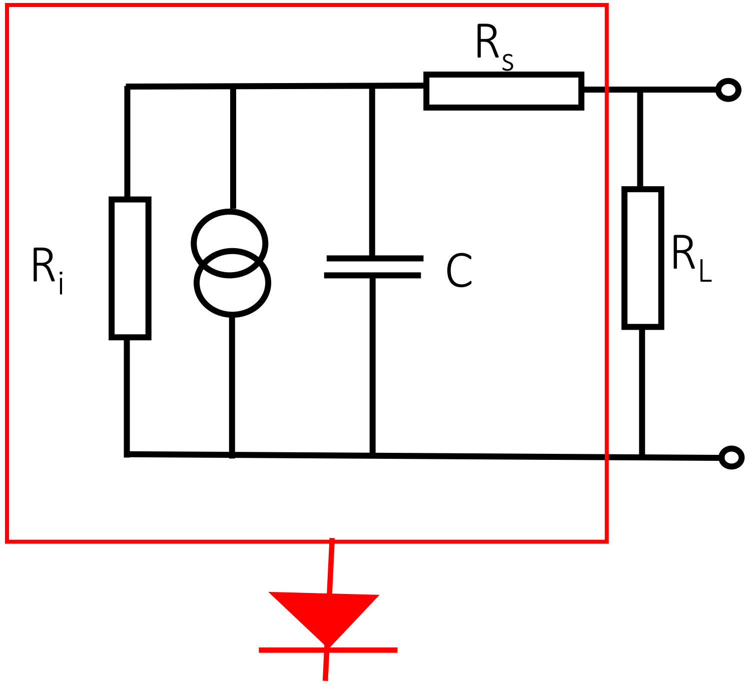
Outline

Exercise 5.1: Schematic Diagram of a Digital Optical Communication System



MX: Multiplexer; LD: Laser Diode;
(A-)PD: (Avalanche-) Photodiode;
SM: Single Mode; DMX: Demultiplexer;
SW: Switch

Exercise 5.1: Bandwidth Limits of PDs



1. RC-constant:

   $\tau_{RC}=2(R_s+R_L)C$

   ($R_i >> R_L$)

$$but\ C_j = S \cdot \frac{\varepsilon_0 \varepsilon}{W} = \pi \left(\frac{d}{2}\right)^2 \cdot \frac{\varepsilon_0 \varepsilon}{W}$$

2. Drift of carriers in the depletion layer:

   $\tau_{drift} = W/v_c$

   W*: width of depletion layer*

   v_c: carrier velocity (10^7cm/sec)

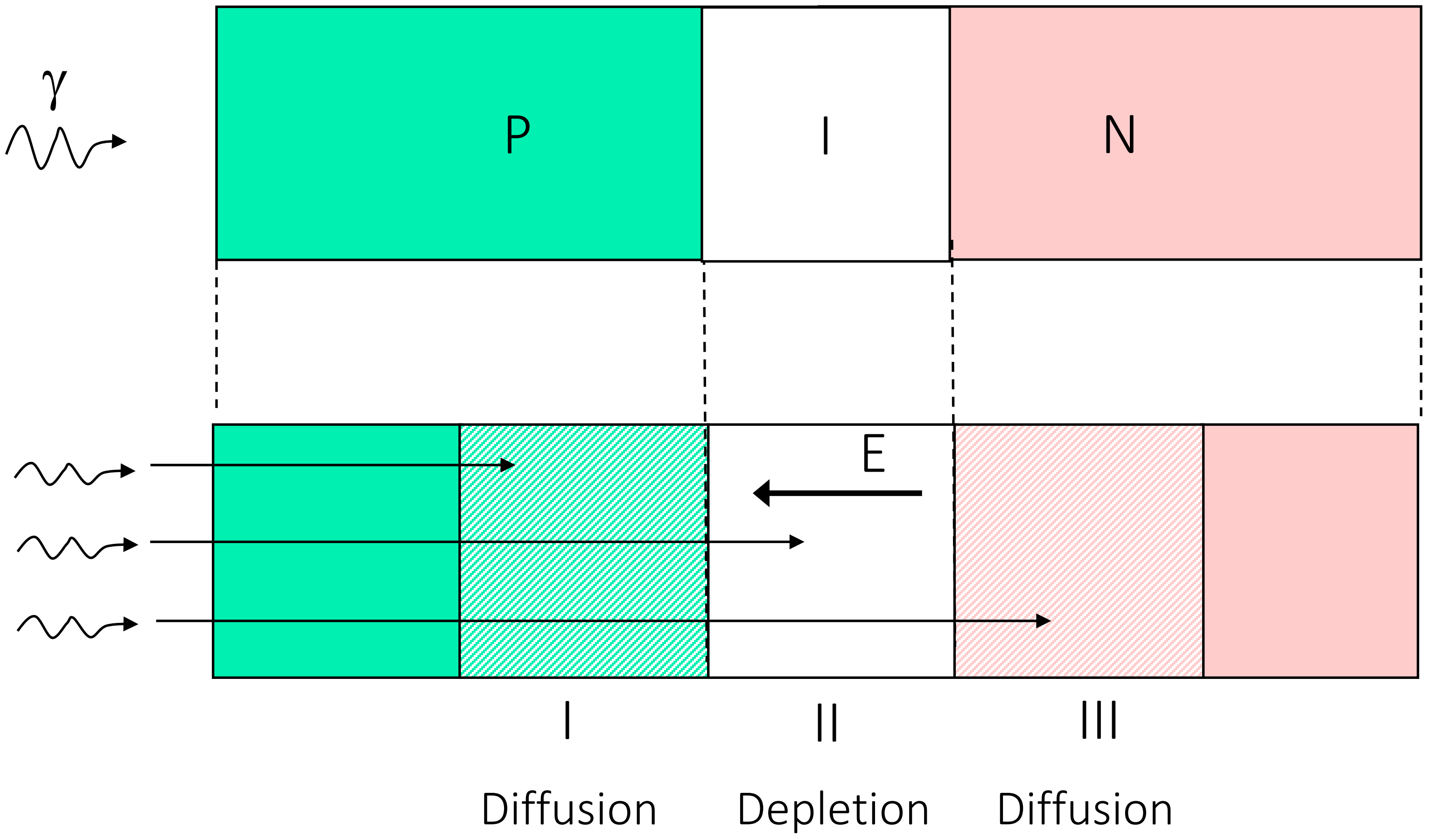
3. Diffusion of carriers to the p-n junction:

   $\tau_{diff} = d^2/D$

   d: distance to depletion layer

   D: diffusion constant

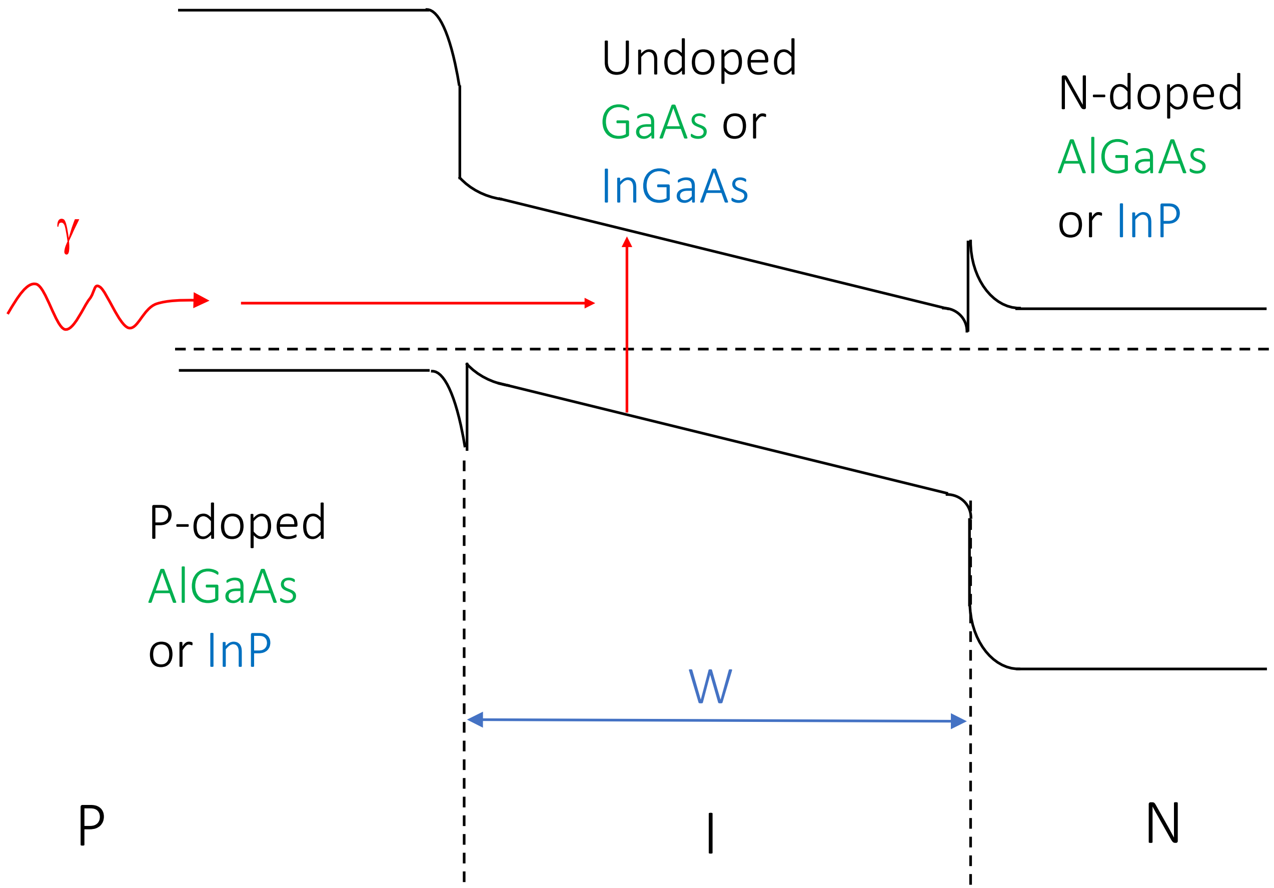
Exercise 5.1: PIN: Diagram of the Working Principle



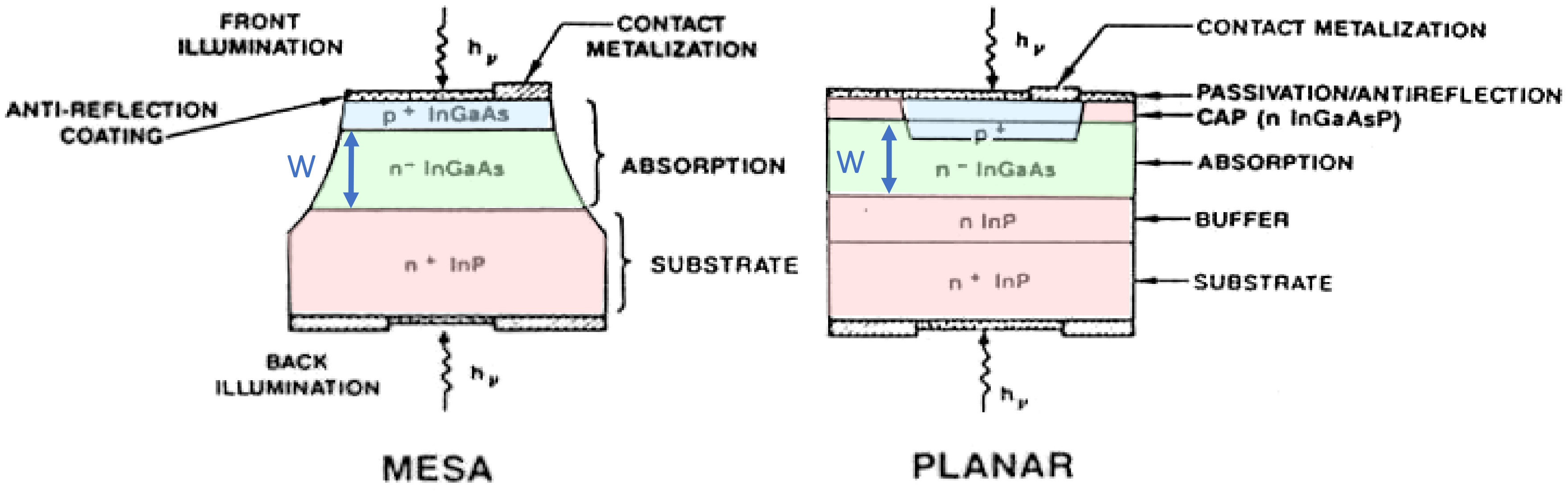
Exercise 5.1: PIN Heterojunction

$\tau_{drift} \approx W$

$\tau_{RC} \approx \frac{1}{W}$



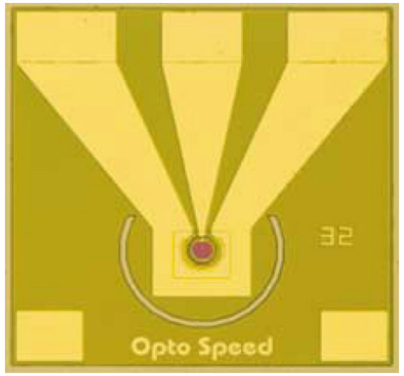
Exercise 5.1: InGaAs PIN Heterojunction Photodiode



$\tau_{drift} \approx W$

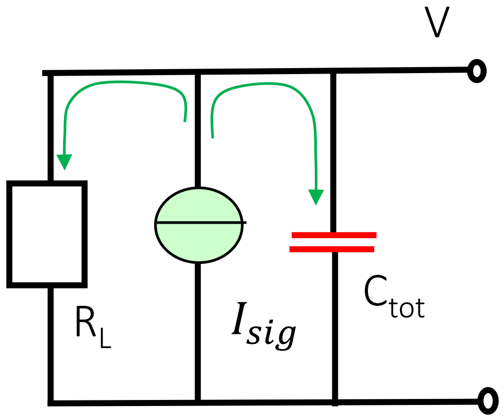
→ Decreased W

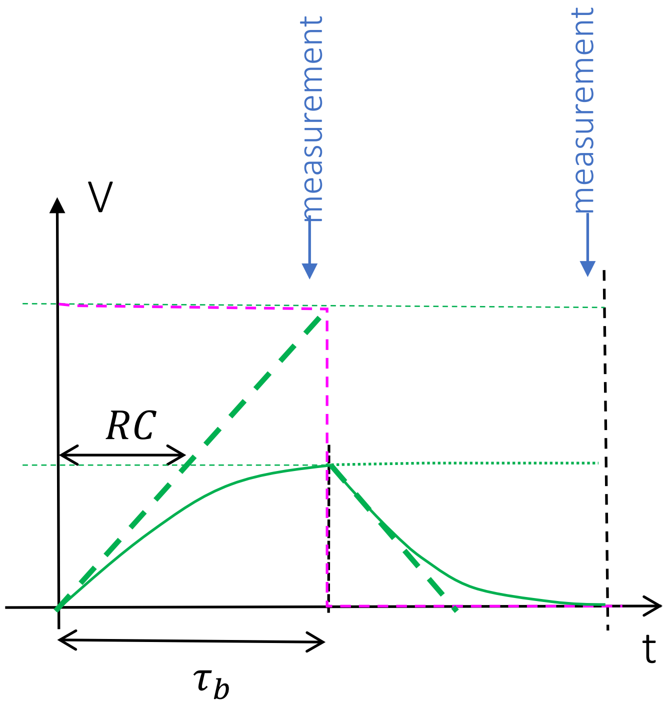
→ Decreased absorption



InGaAs/InP photodiode
Opto Speed

Exercise 5.1: Continuous Detection: High Speed Digital Transmission





1) At the beginning of the bit:

The current loads the capacitor

Number of electrons stored in the capacitor:

2) Once the capacitor is charged:

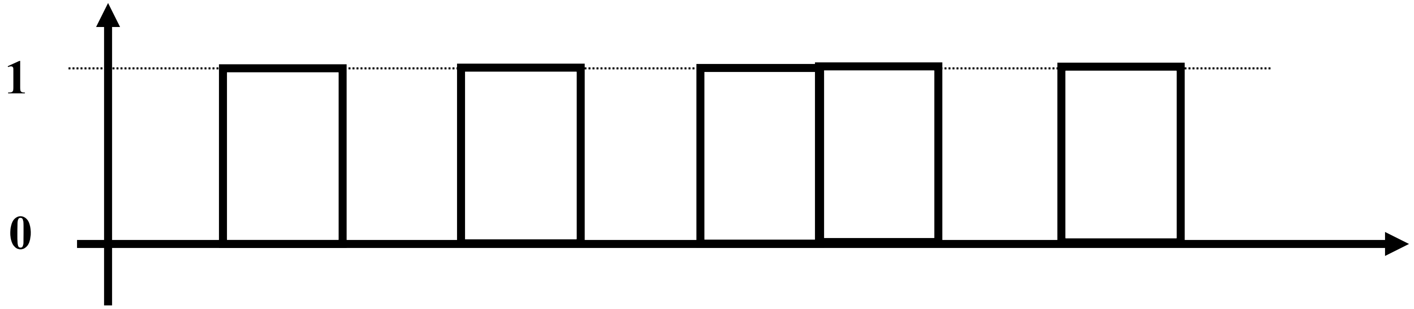
The current flows through the resistor

$$m_{c,sig} \cong \frac{RC}{\tau_b} mM \cong \frac{1}{2} mM$$

m: # of generated electrons per bit
M: amplification before the electronics (e.g. avalanche or optical amplification)

Exercise 5.1: Bit Error Rate (BER)

- On-off keying system: bits “0“ and “1“

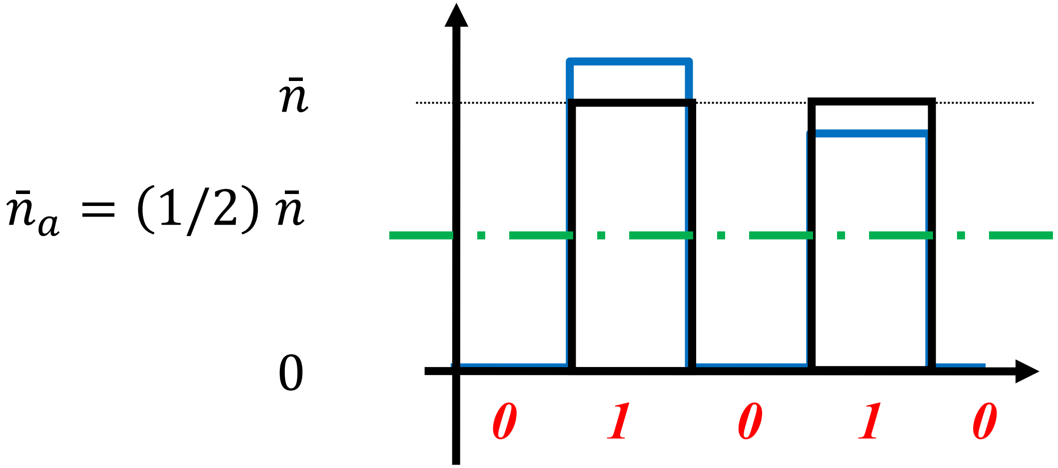


- BER: probability of error per bit
- If p_0 =probability of mistaking a “ 0“ for a “ 1“
  & p_1 =probability of mistaking a “1” for a “0”, then

$$BER = p_0 /2 + p_1/2$$ *(BER definition)*

Exercise 5.1: Ideal BER (1)

Ideal = limited by the optical signal shot noise



- If an average of $\bar{n}$ photons is transmitted by a laser diode, the probability of detecting *n* photons is given by:

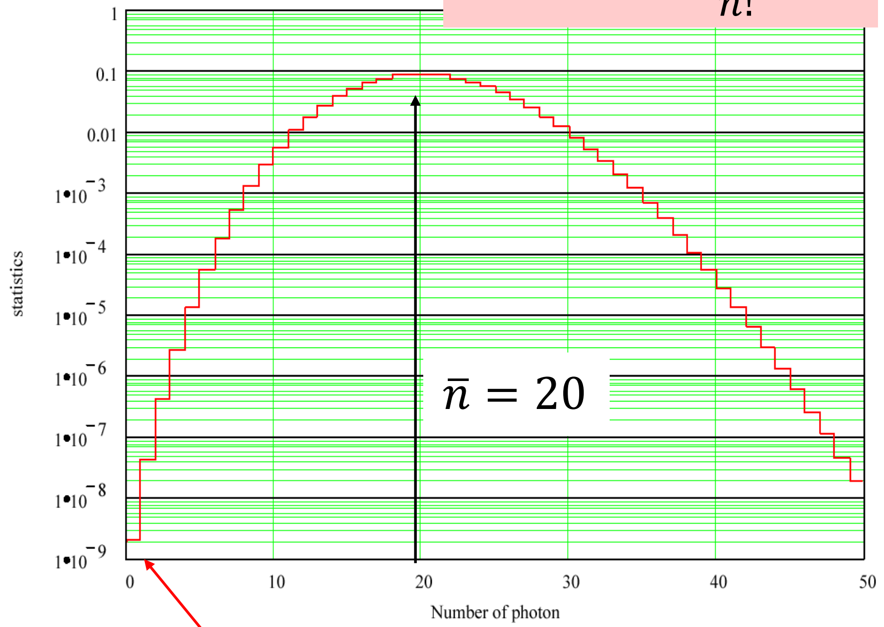
$$p(n) = \bar{n}^n \frac{\exp(-\bar{n})}{n!}$$

→ How many photons per "1" bit are needed to guarantee a BER of 10^{-9}?

Exercise 5.1: Ideal BER: Example

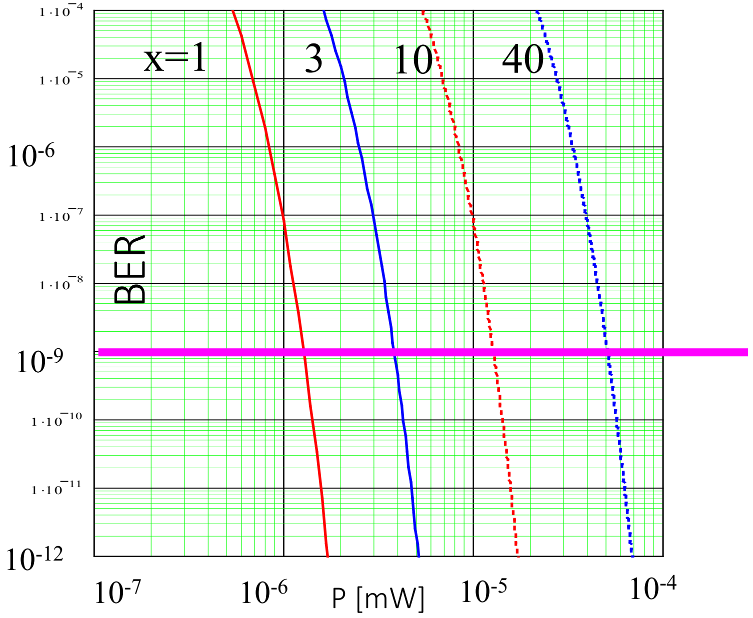
Because of the shot noise on each "1" bit, it takes 20 photons per "1" to guarantee a BER of 10^{-9}.

$$p(n) = \bar{n}^n \frac{\exp(-\bar{n})}{n!}$$



$$p(0) = \exp(-\bar{n}) = 2 \cdot 10^{-9}$$

x = bit rate in Gbit/s



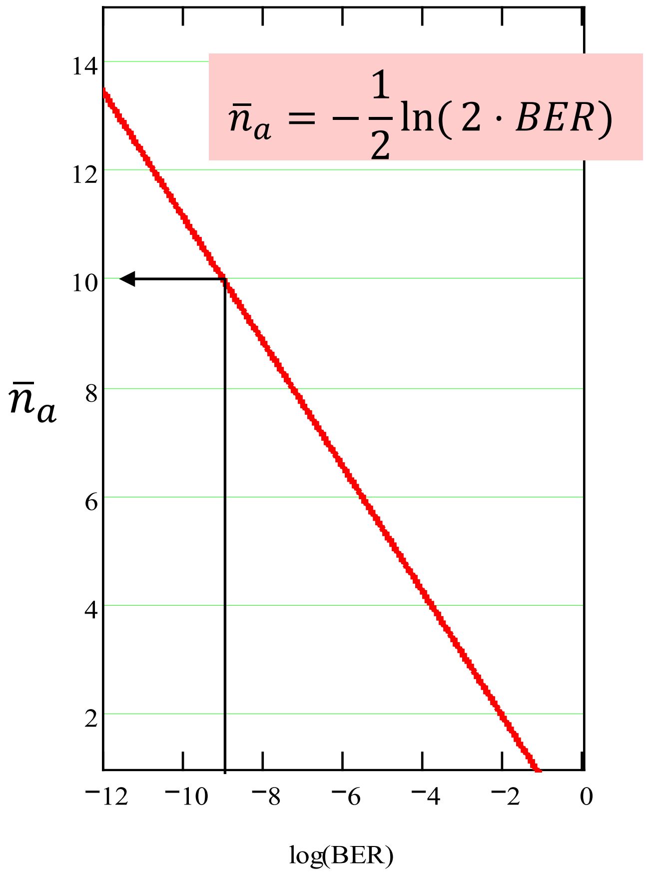
$$\bar{n}_a = \frac{P}{h\nu} T$$

$$BER = \frac{1}{2} e^{-2\left(\frac{P}{h\nu}\right)\cdot\left(\frac{1}{x \cdot 10^9}\right)}$$

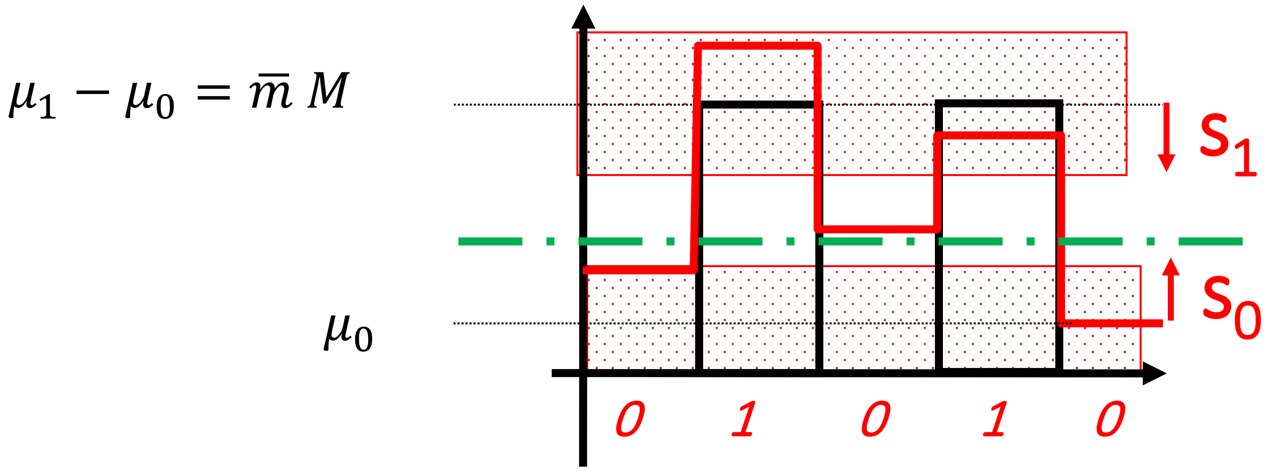
Exercise 5.1: Receiver Sensitivity of Ideal Digital Systems

- The receiver sensitivity of digital systems is defined as the average number of photons per bit required to achieve a certain BER (usually 10^{-9}).

- For an ideal receiver, 10 photons per bit are required to achieve a BER of 10^{-9}.
(20 photons for “1“ bits).



Exercise 5.1: Real Receiver: Sensitivity of a Receiver with Gaussian Noise

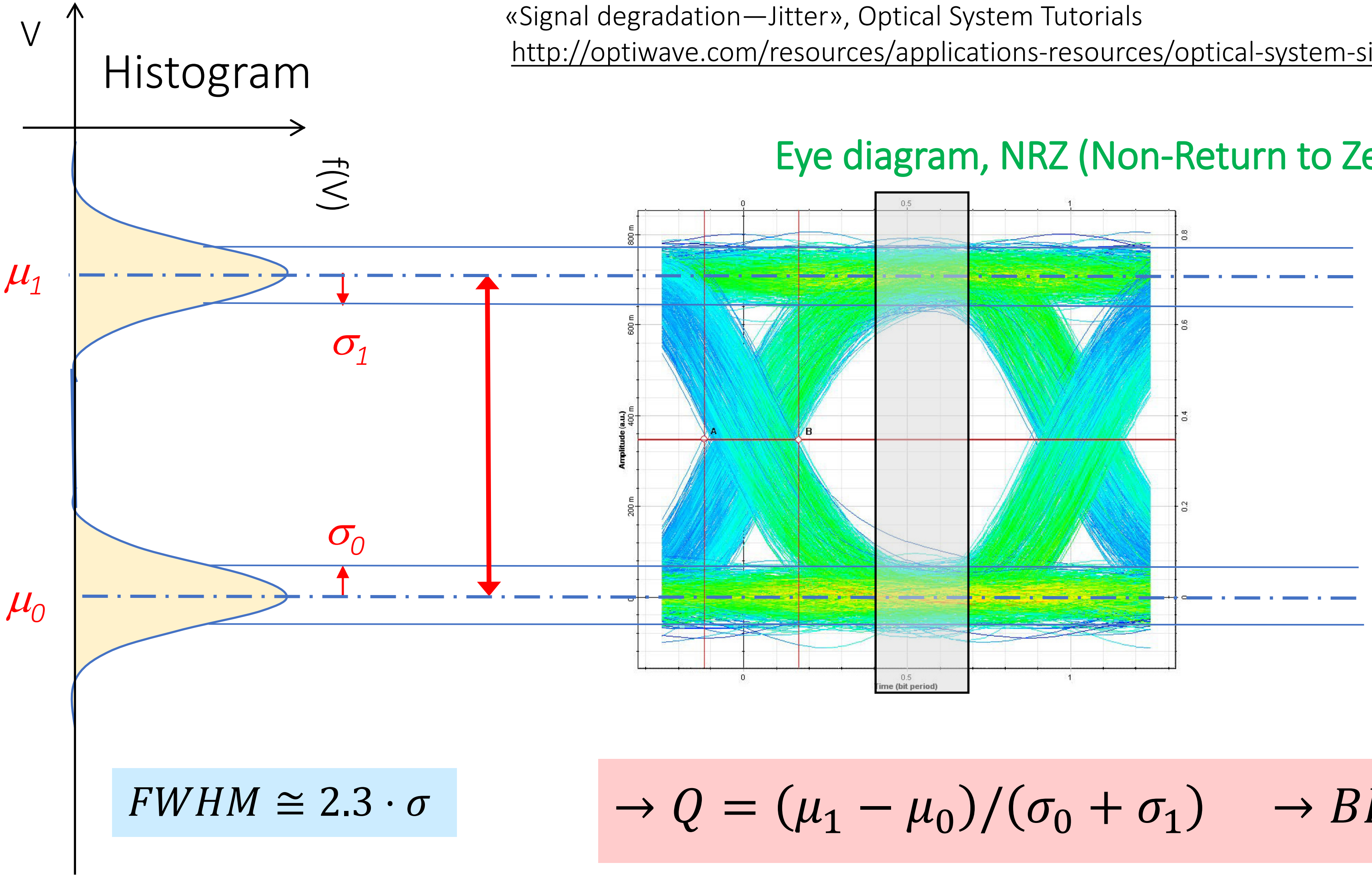


- Average number of photo-electrons: $\bar{m} = \eta_i\, \bar{n}$
  (*η_i: quantum efficiency)*

- Gaussian noise of a photo-detector circuit characterized by a zero mean and an rms value of $\boldsymbol{\sigma}_q$ (noise parameter) within a bandwith Δf.

Exercise 5.1: Eye Diagram

«Signal degradation—Jitter», Optical System Tutorials
http://optiwave.com/resources/applications-resources/optical-system-signal-degradation-jitter/

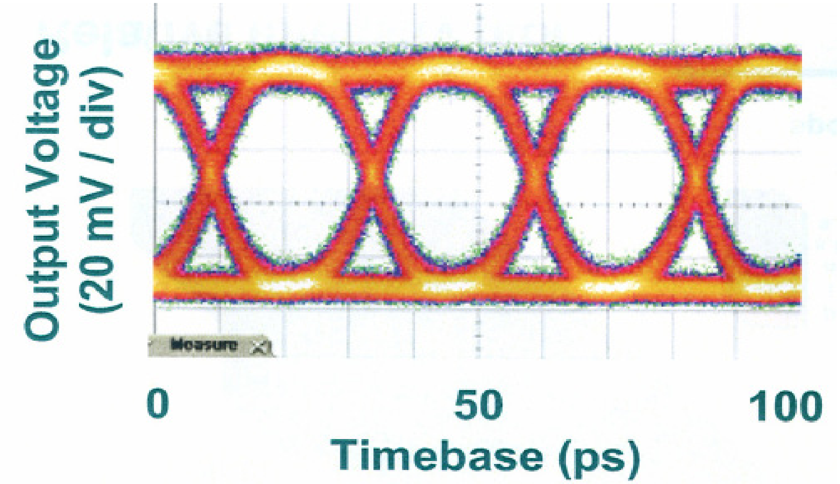


$FWHM \cong 2.3 \cdot \sigma$

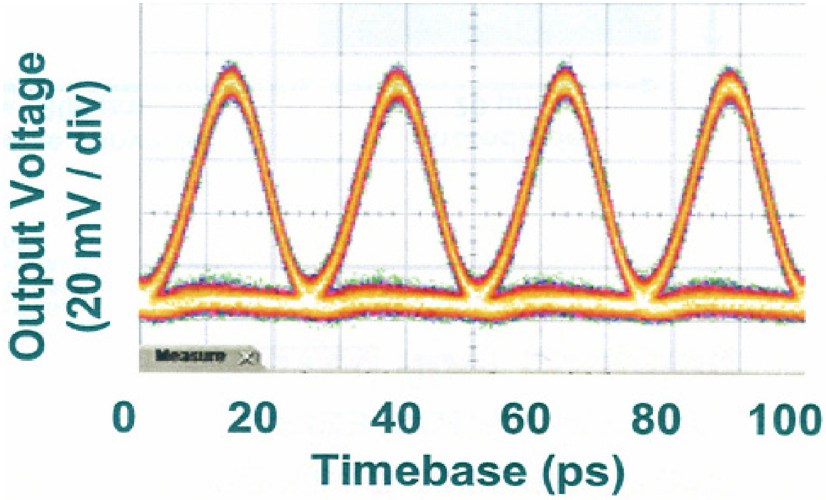
$\rightarrow Q = (\mu_1 - \mu_0)/(\sigma_0 + \sigma_1) \quad \rightarrow BER$

Exercise 5.1: High-Speed Detectors (1)

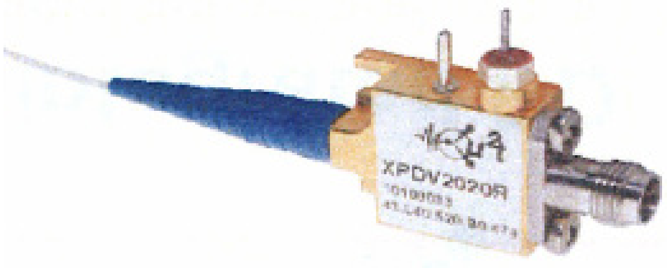
u²t: 40 GBits/s



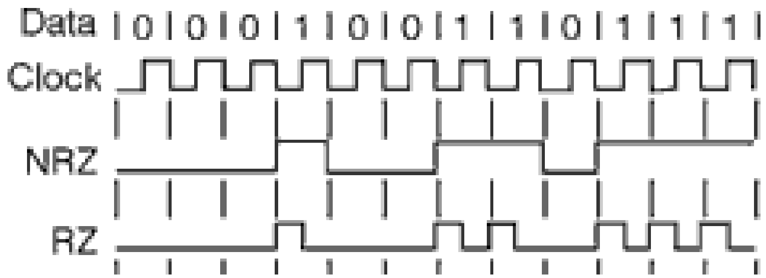
"NRZ: non-return to zero"



"RZ: return to zero"



Photoreceivers for DPSK, A.Umbach, May 2005. © u²t AG



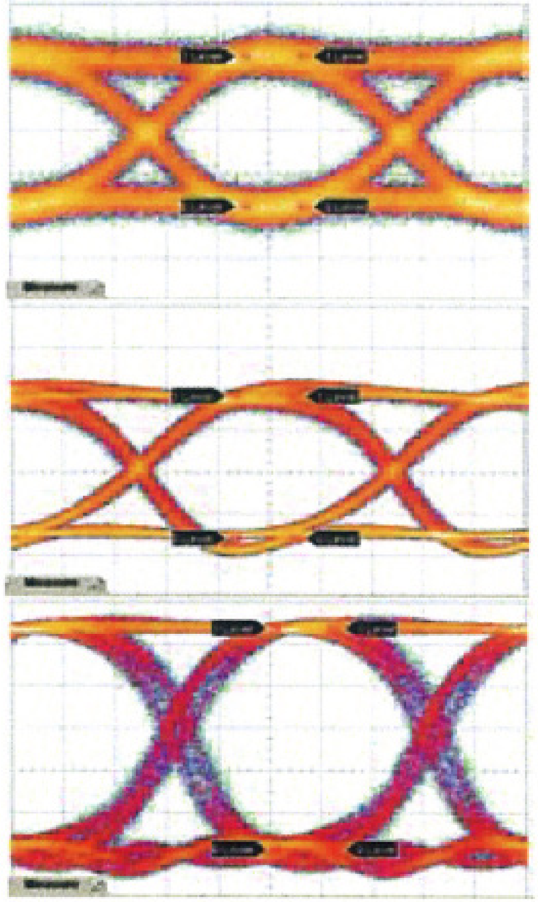
Exercise 5.1: High-Speed Detectors (2)

40 Gbit/s Eye Diagrams Photoreceivers for DPSK, A.Umbach, May 2005. © u²t AG

-10 dBm, 0.1mW
35 mV eye ampl.
SNR = 7, RMS
jitter = 1.1 ps

0 dBm, 1mW
340 mV eye ampl.
SNR = 10,
RMS jitter = 0.7 ps

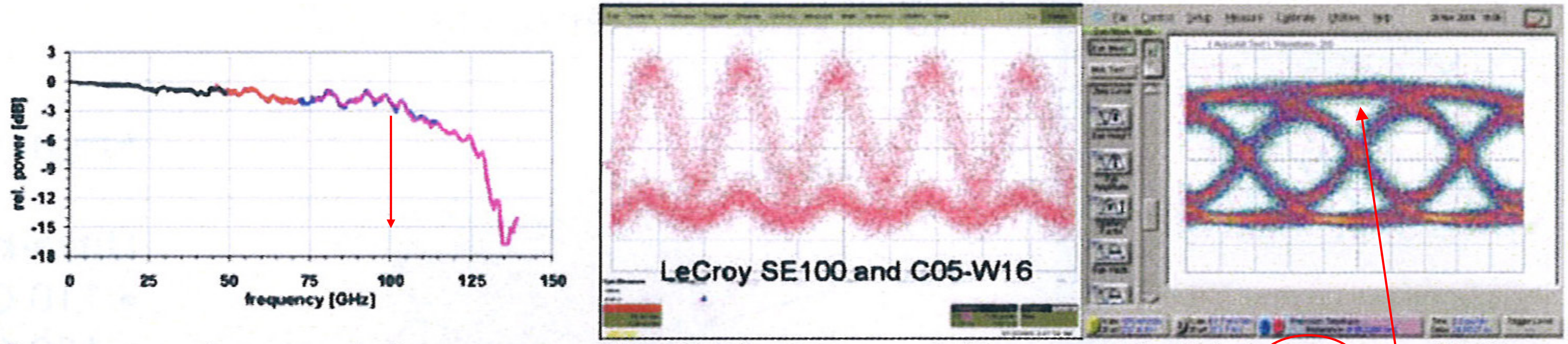
+5 dBm, 3mW
520 mV eye ampl.
SNR = 16,
RMS jitter = 1.1 ps



u^2t: 40 GBits/s

Increasing input power
→
Better SNR
"open eyes"

Exercise 5.1: High Speed PIN Detectors (3)



frequency characteristics ***100 Gbit/s RZ P_{opt}: +8dBm*** ***160 Gbit/s RZ P_{opt}: +12dBm***

NRZ

- DC responsivity: 0.73 A/W
- PDL: 0.41 dB at 1.55 µm
- pulse response (FWHM): 7.4 ps (@250 mV_p output voltage (internally 50 Ω)).

Heinrich Hertz Institut (HHI): up to 160 GBit/s

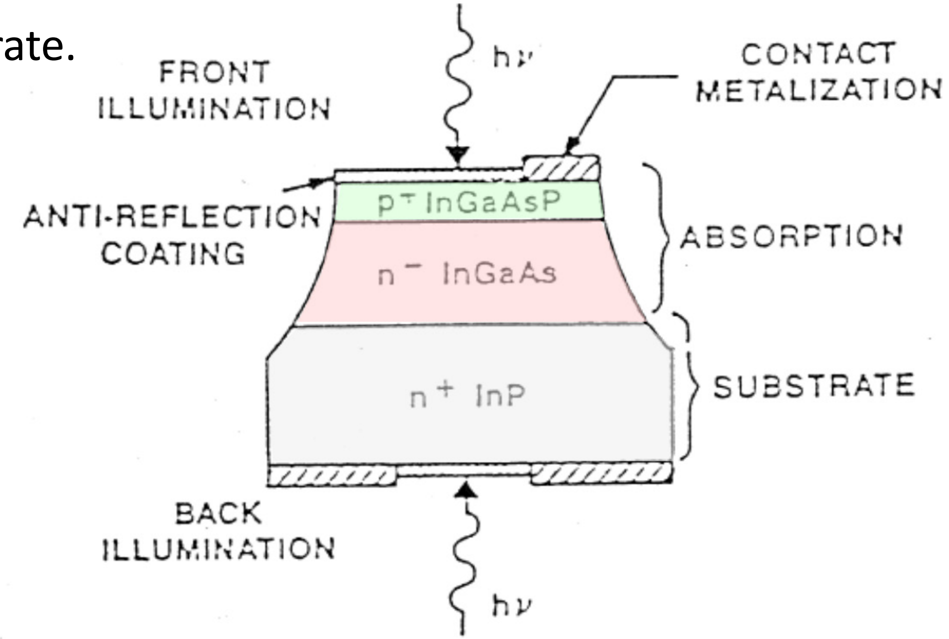
Outline

Exercise 5.2: PIN Heterostructure Photodiode

$In_{1-x}Ga_xAs_yP_{1-y}$ system on an InP substrate

a) To grow a monocrystal, we have to preserve the lattice of the InP substrate. This involves satisfying the following relationship:

$$x = \frac{0.4562 \cdot y}{1 - 0.031 \cdot y}$$



b) In this case ("lattice matched to InP") the gap can be changed according to:

$$E_g(y) = 1.35 - 0.72 \cdot y + 0.12 \cdot y^2 \quad [eV]$$

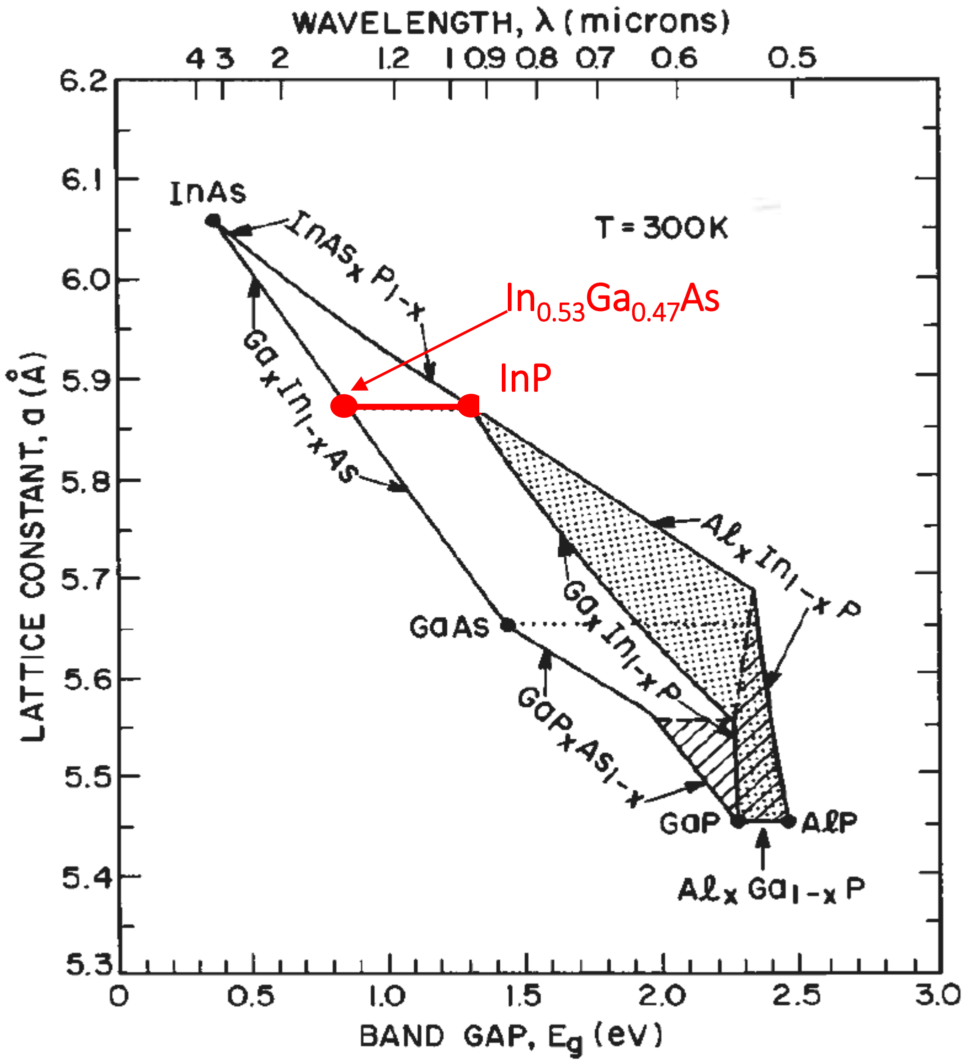
Exercise 5.2: PIN Heterostructure Photodiodes

This type of photodiode was designed for optical telecommunications and has to work at wavelengths between 1.50 μm and 1.60 μm. Its diameter is 10 μm, corresponding to that of a single mode fiber optic cable.

A) Considering a superficial layer with the following composition: $In_{1-x}Ga_xAs_yP_{1-y}$, with y=0.84.
   Sketch the quantum efficiency for front and back illumination. What is the main difference?

B) Estimate the width W of the intrinsic InGaAs region to optimize the bandwidth using a load resistance of $R_L = 50\ \Omega$.
   (use $\varepsilon = 12$ and $v_{sat} = 10^5$ m/s)
   Does the diode have to be polarized, and if so, why?

Exercise 5.2: Complement: $In_{1-x}Ga_xAs_yP_{1-y}$ Heterostructures



InGaAsP
matched to InP

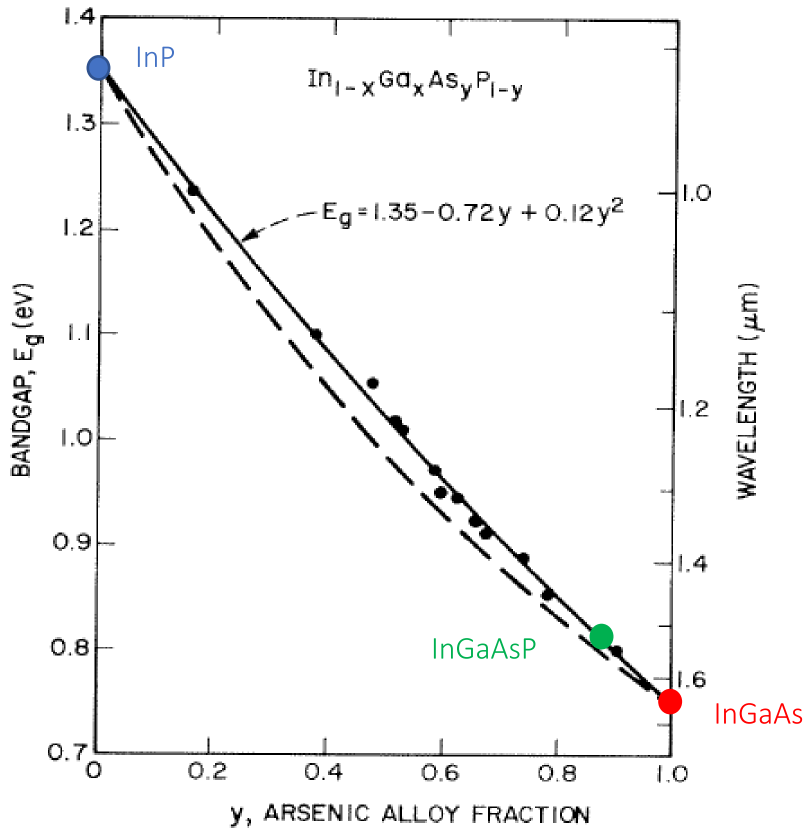
$$x = \frac{0.4562 \cdot y}{1 - 0.031 \cdot y} \cong 0.45 \cdot y$$

Agrawal, « Long-wavelength semiconductor lasers », VNR

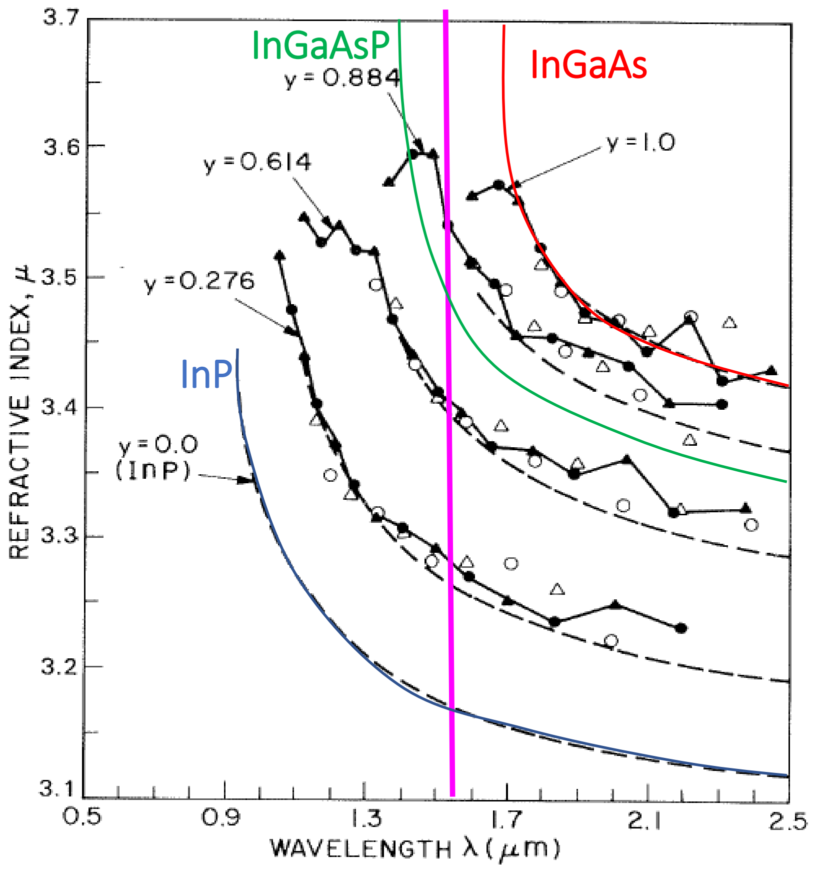
Exercise 5.2: $In_{1-x}Ga_xAs_yP_{1-y}$ Matched to InP

Bandgap

$$E_g(y) = 1.35 - 0.72 \cdot y + 0.12 \cdot y^2 \quad [eV]$$

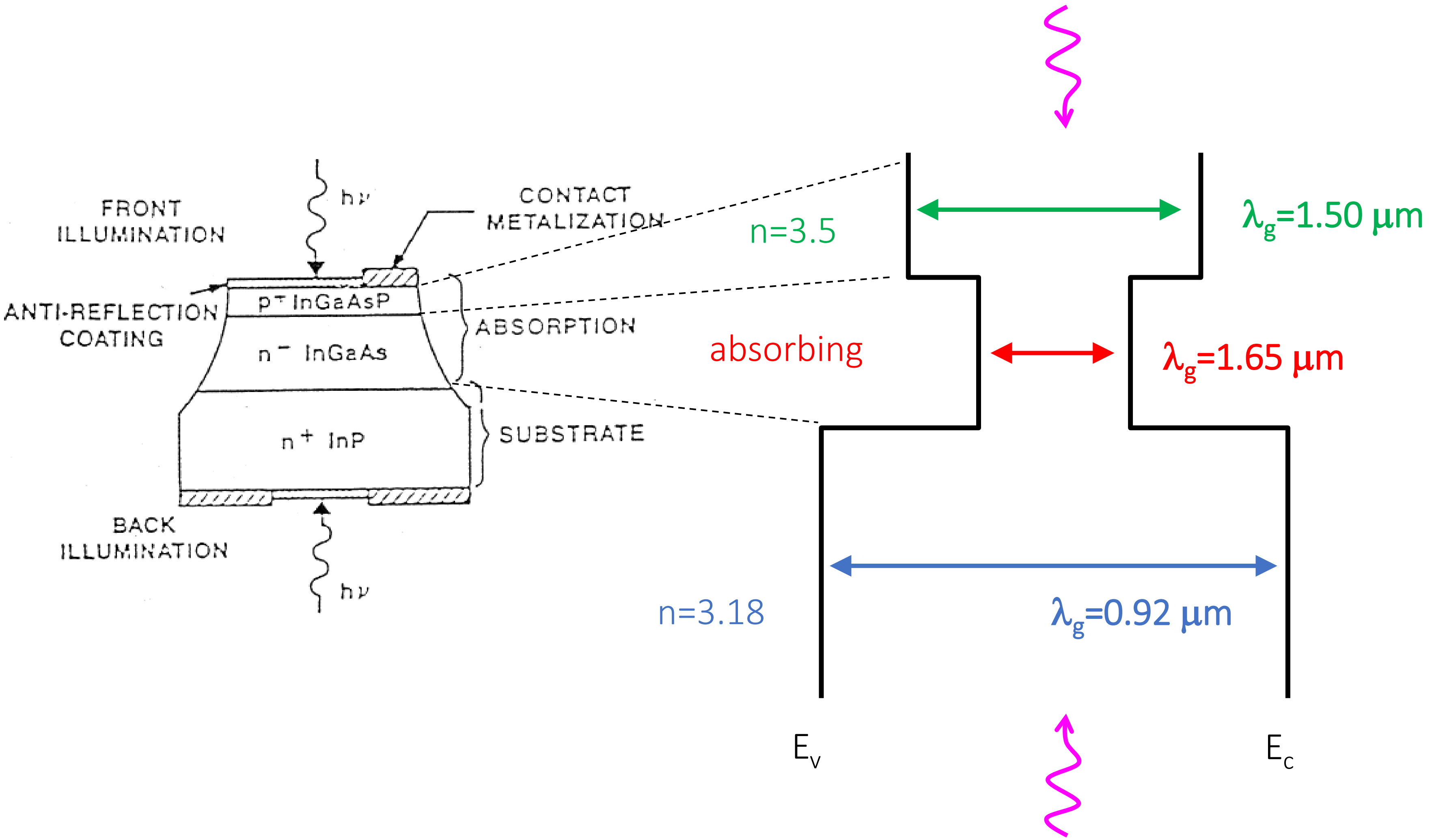


Refractive index



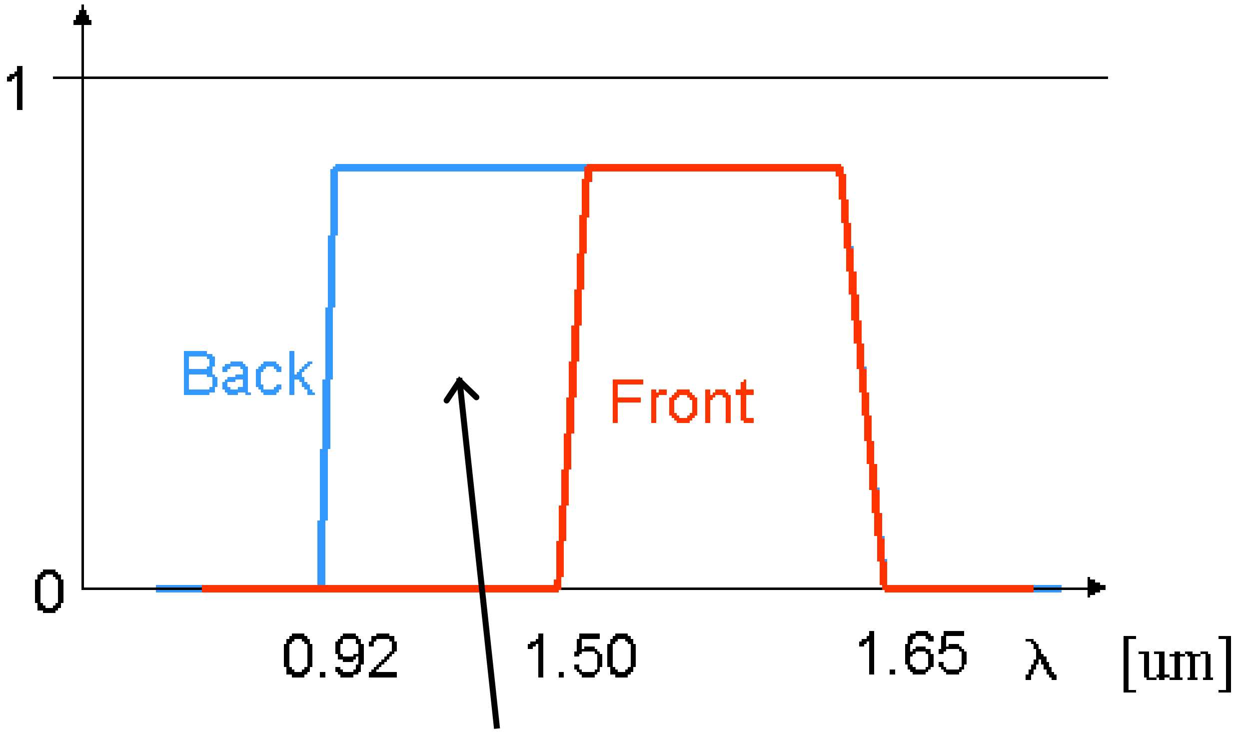
Agrawal, « Long-wavelength semiconductor lasers », VNR

Exercise 5.2: PIN Structure and Bands



Exercise 5.2: PIN Heterostructure Photodiodes

A) Quantum Efficiency



With front illumination, the diode is sensitive between 1.50 and 1.65 μm
With back illumination, the diode is sensitive over a wider region between 0.92 and 1.65 μm

Exercise 5.2: PIN Heterostructure Photodiodes

a) The capacity of the depletion zone:

$$C_j = S \cdot \frac{\varepsilon_0 \varepsilon}{W} = \pi \left(\frac{d}{2}\right)^2 \cdot \frac{\varepsilon_0 \varepsilon}{W}$$

b) The cutoff frequency due to RC time:

$$f_2 = \frac{1}{4R_L C_j} = \frac{W}{R_L \pi d^2 \varepsilon_0 \varepsilon}$$

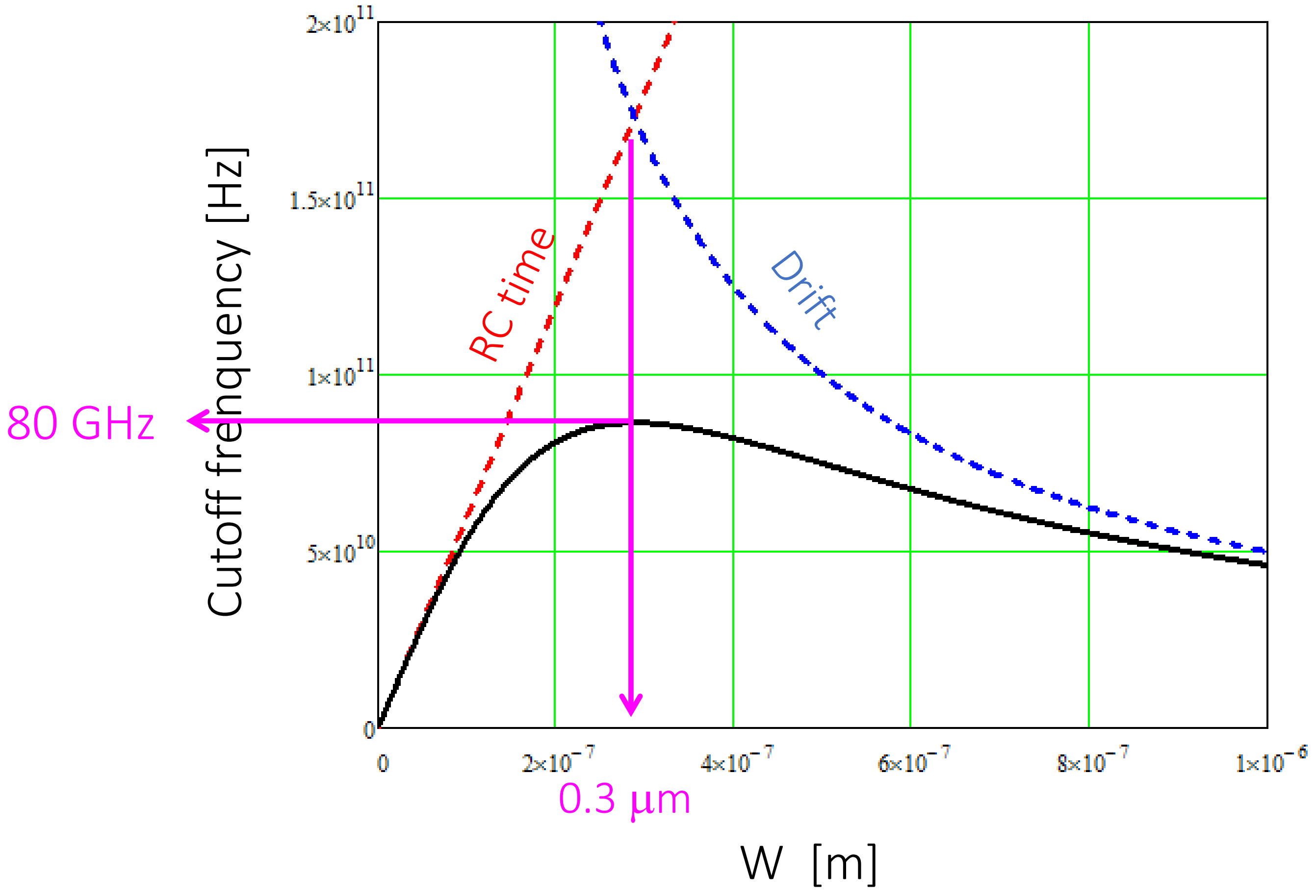
c) The cutoff frenquency due to the drift time in the intrinsic zone:

$$f_{2d} = \frac{1}{2\tau_{drift}} \approx \frac{v_{sat}}{2W}$$

Optimal:

$$f_2 = f_{2d} \quad \rightarrow \quad W_{opt} = d \cdot \sqrt{\frac{\pi}{2} v_{sat} R_L \varepsilon_0 \varepsilon} \cong \quad 0.3 \quad [\mu m]$$

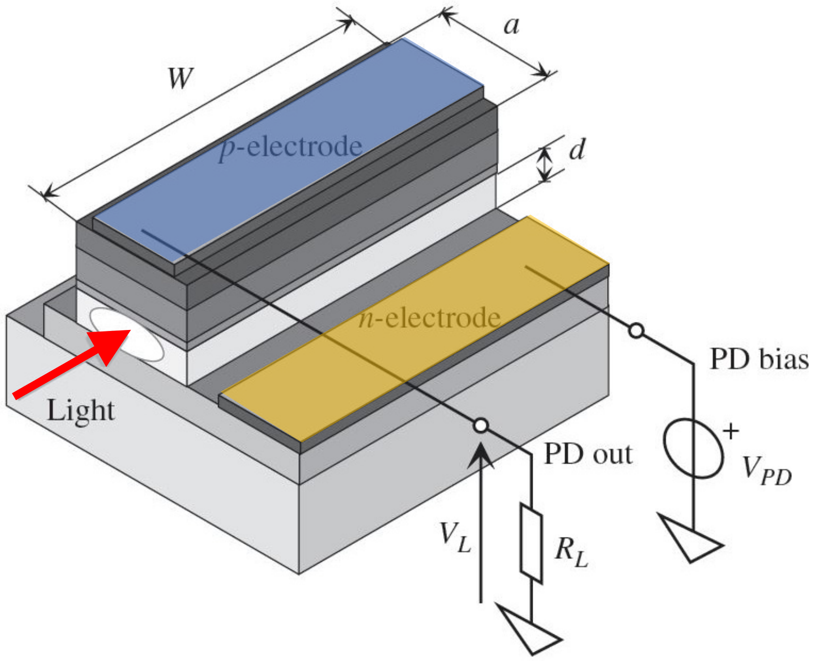
Exercise 5.2: Example

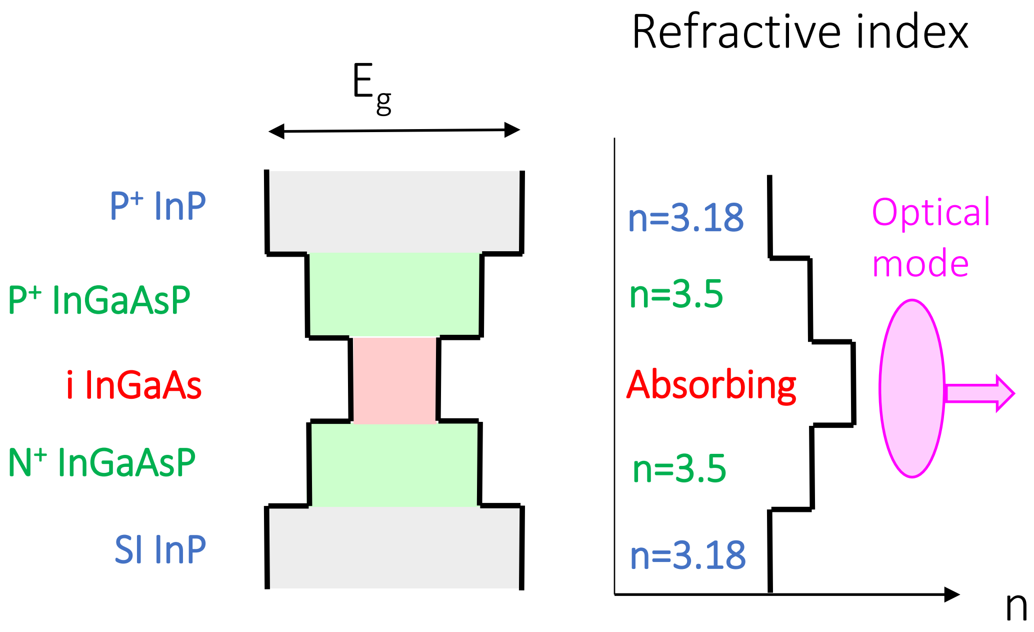


$$\frac{1}{f_{tot}} = \frac{1}{f_2} + \frac{1}{f_{2d}}$$

Thin absorbing layer !!

Exercise 5.2: Waveguide Photodiode (WG-PD)





G. Ghione, «Semiconductor devices for high-speed optoelectronics», Chap. 4, Cambridge

Large gap → lower refractive index → waveguide