MICRO-523: Optical Detectors

Week Five: Photodiodes

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

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Outline

5.1 p-n junctions (review)

5.2 p-n photodiodes

5.3 PIN photodiodes

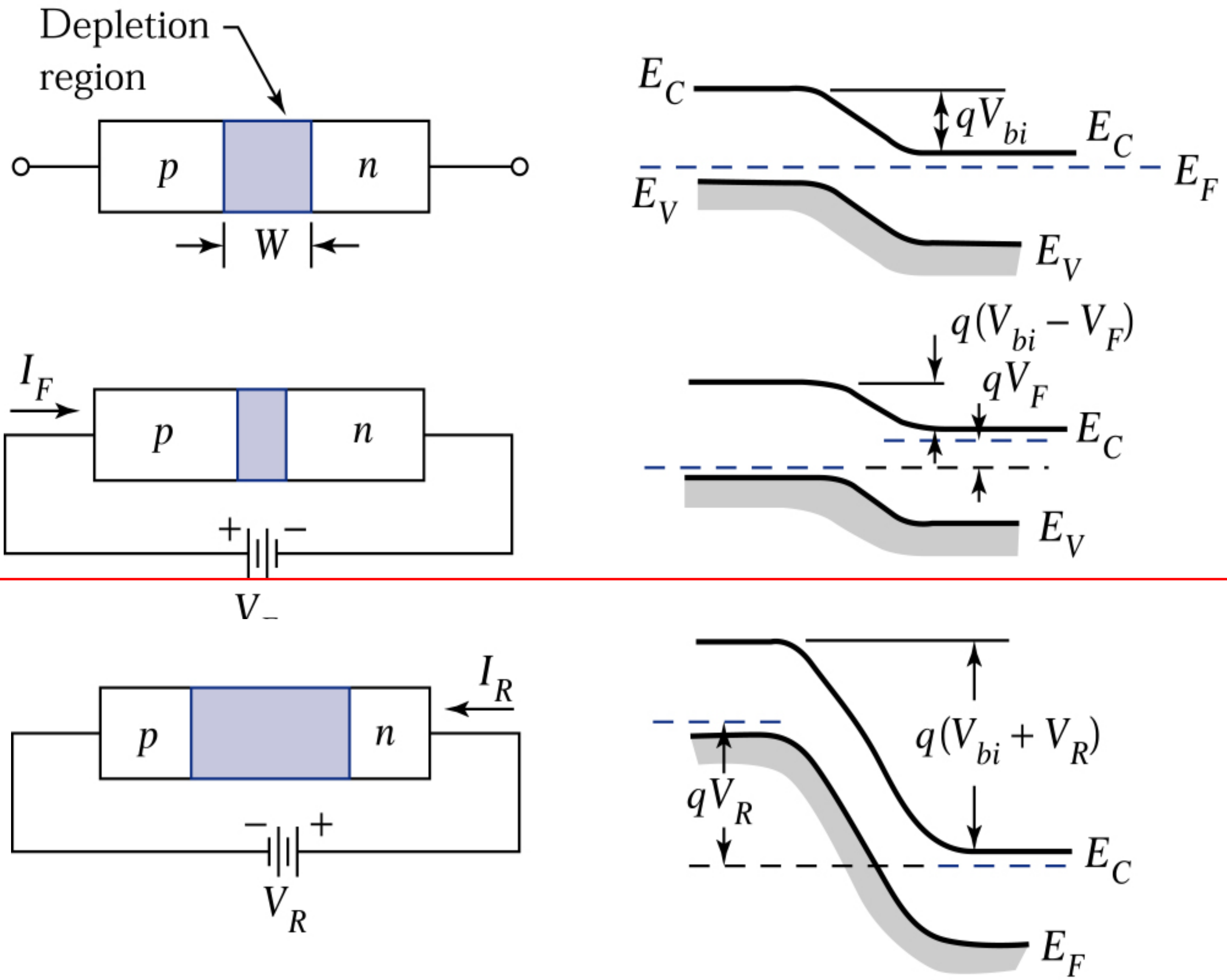
5.4 Case study: color sensors

5.5 Solar cells

5.6 Electronic circuits, cut-off frequencies, noise

5.7 Avalanche photodiodes

5.1 Non-Equilibrium p-n Junctions: Bands



Thermal equilibrium

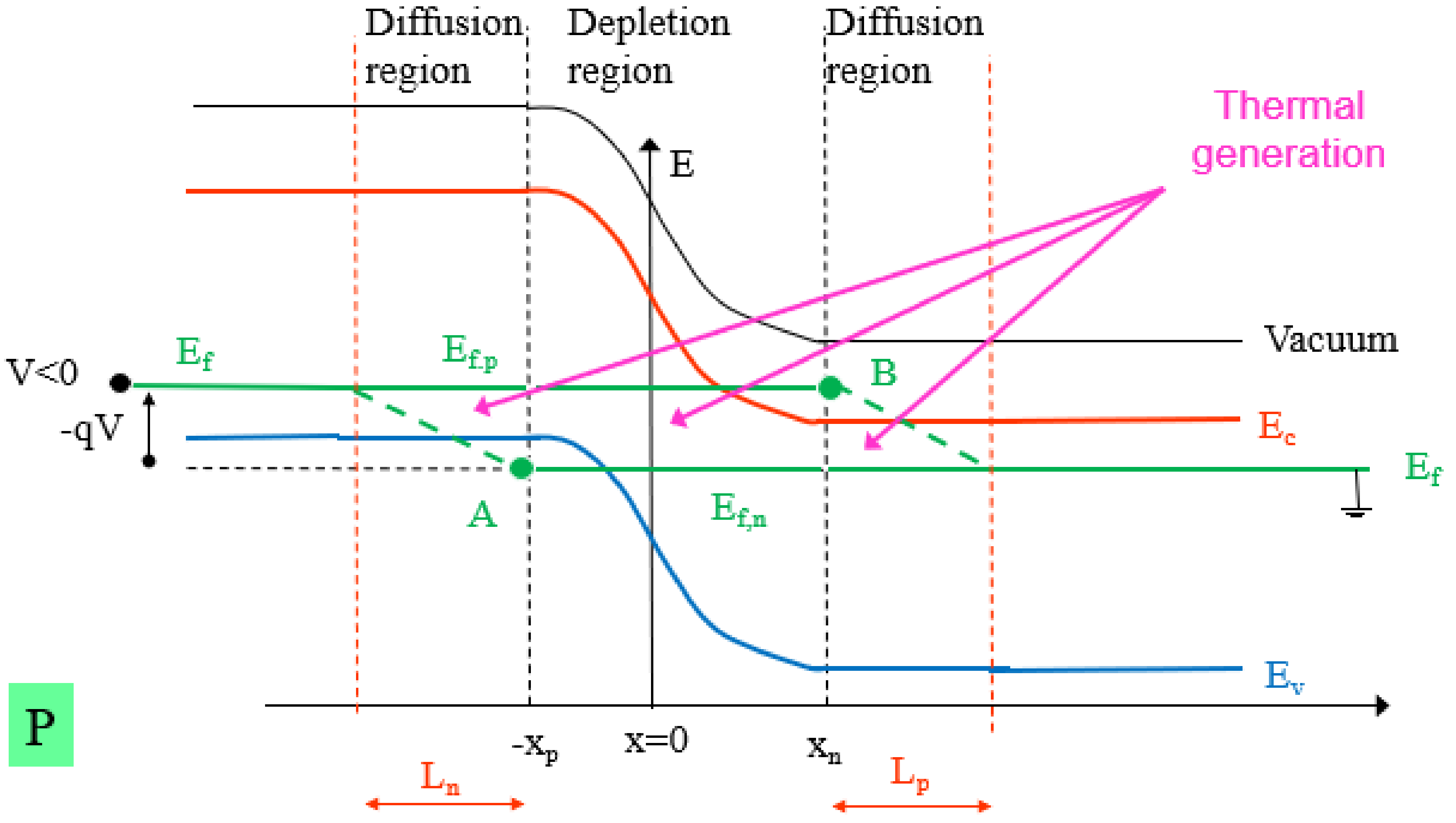
Forward-bias
(V>0)

Reverse-Bias
(V<0)

Related:
- Built-in potential
- Polarity
- I-V curve

S.M. Sze, « Semiconductor devices, physics and technology »

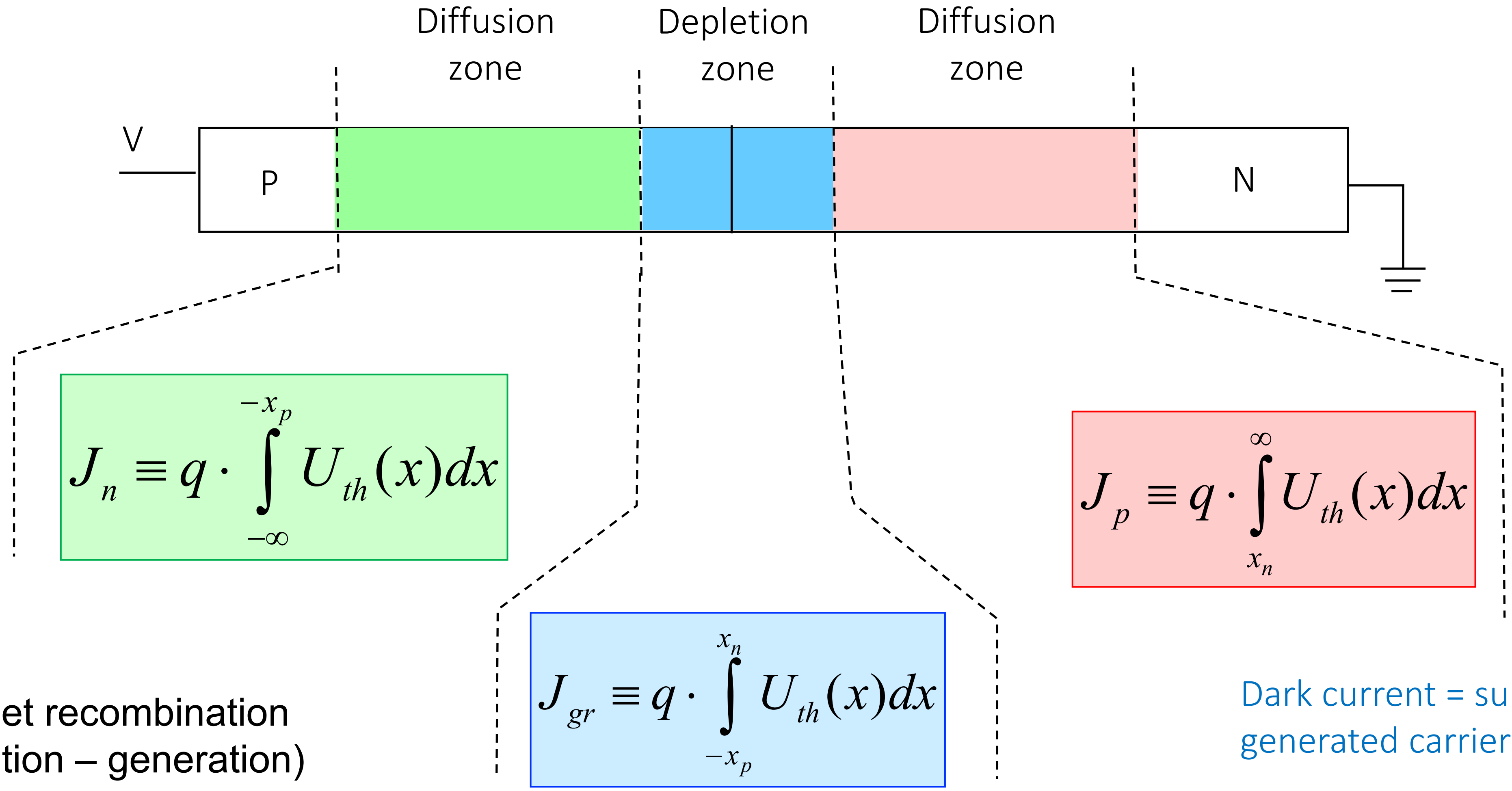
5.1 Quasi Fermi Levels: Reverse-Blocking Mode



Related:
- Dark current
- Recombination at edges
- Widths of regions
- p-i-n variant

$L_{n,p}$: diffusion lengths

5.1 Currents in p-n diodes



$$J_n \equiv q \cdot \int_{-\infty}^{-x_p} U_{th}(x)dx$$

$$J_{gr} \equiv q \cdot \int_{-x_p}^{x_n} U_{th}(x)dx$$

$$J_p \equiv q \cdot \int_{x_n}^{\infty} U_{th}(x)dx$$

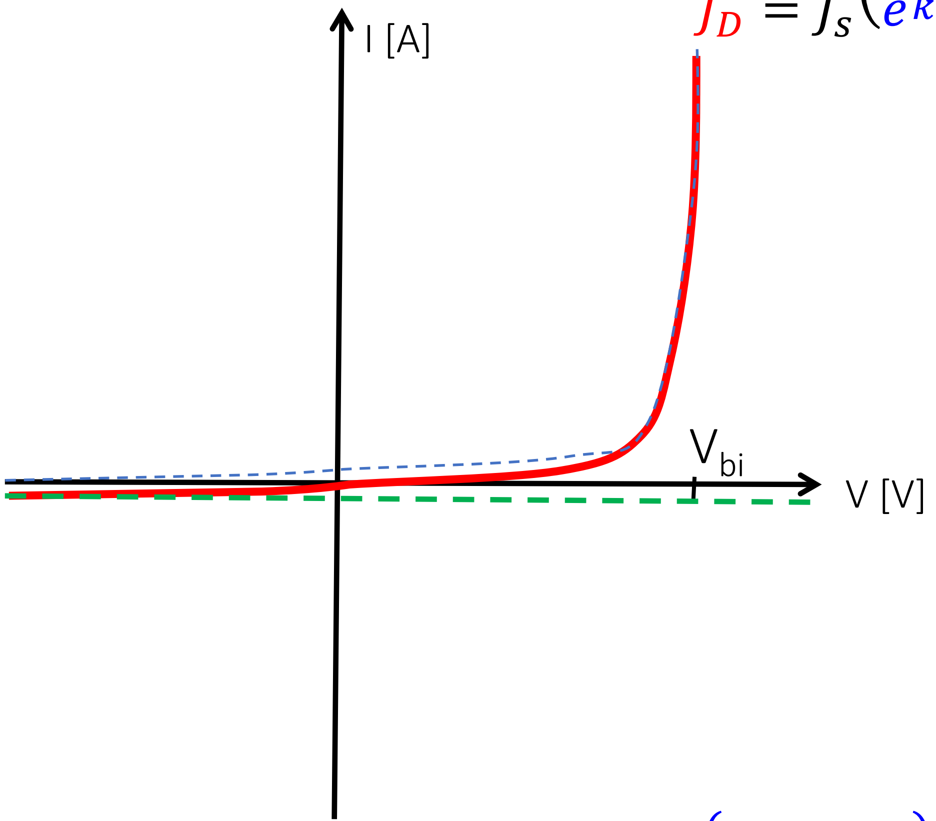
$U_{th} = R - G$ = net recombination rate (recombination – generation)

Dark current = sum of all generated carriers

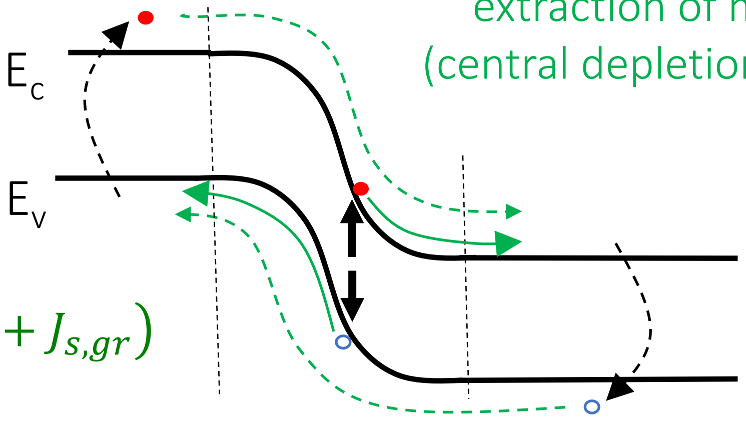
5.1 Currents in p-n diodes

Shockley equation
(ideal diode law)

$$J_D = J_s\left(e^{\frac{qV}{kT}} - 1\right)$$

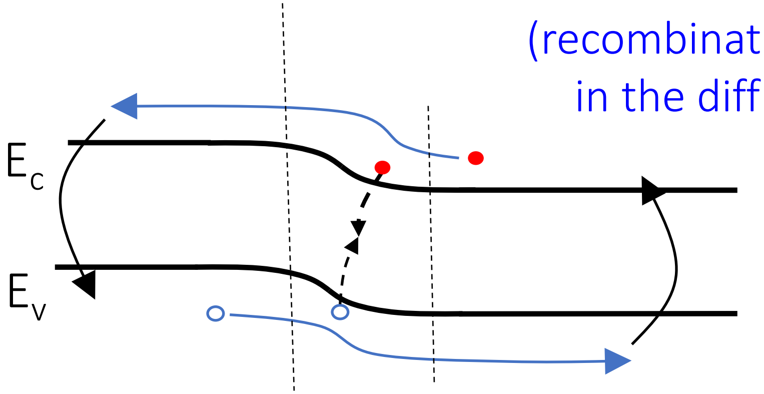


Generation and
extraction of minority carriers
(central depletion zone dominates)



$$-\left(\cancel{J_{s,n}} + \cancel{J_{s,p}} + J_{s,gr}\right)$$

Injection and recombination
of minority carriers
(recombination dominates
in the diffusion zones)



$$\left(J_{s,n} + J_{s,p}\right) \cdot e^{\frac{qV}{kT}} + \cancel{J_{s,gr} \cdot e^{\frac{1}{2}\cdot\frac{qV}{kT}}}$$

5.1 Initial Conclusions

1) The dark current in a p-n diode is the integral of thermal generation in:
   - I) the diffusion region of the electrons in P

     (typical length L_n: a few tens of micrometers)
   - II) the depletion region, with a strong electric field

     (typical length W: a few tenths of micrometers)
   - III) the diffusion region of the holes in N

     (typical length L_p: a few tens of micrometers)

2) The dark current of a silicon p-n diode at room temperature is dominated by generation in the depletion zone.
   It is not the current of an ideal diode!

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5.2 p-n photodiodes

5.3 PIN photodiodes

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5.5 Solar cells

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5.7 Avalanche photodiodes

5.2 Photodiode: PRINCIPLE

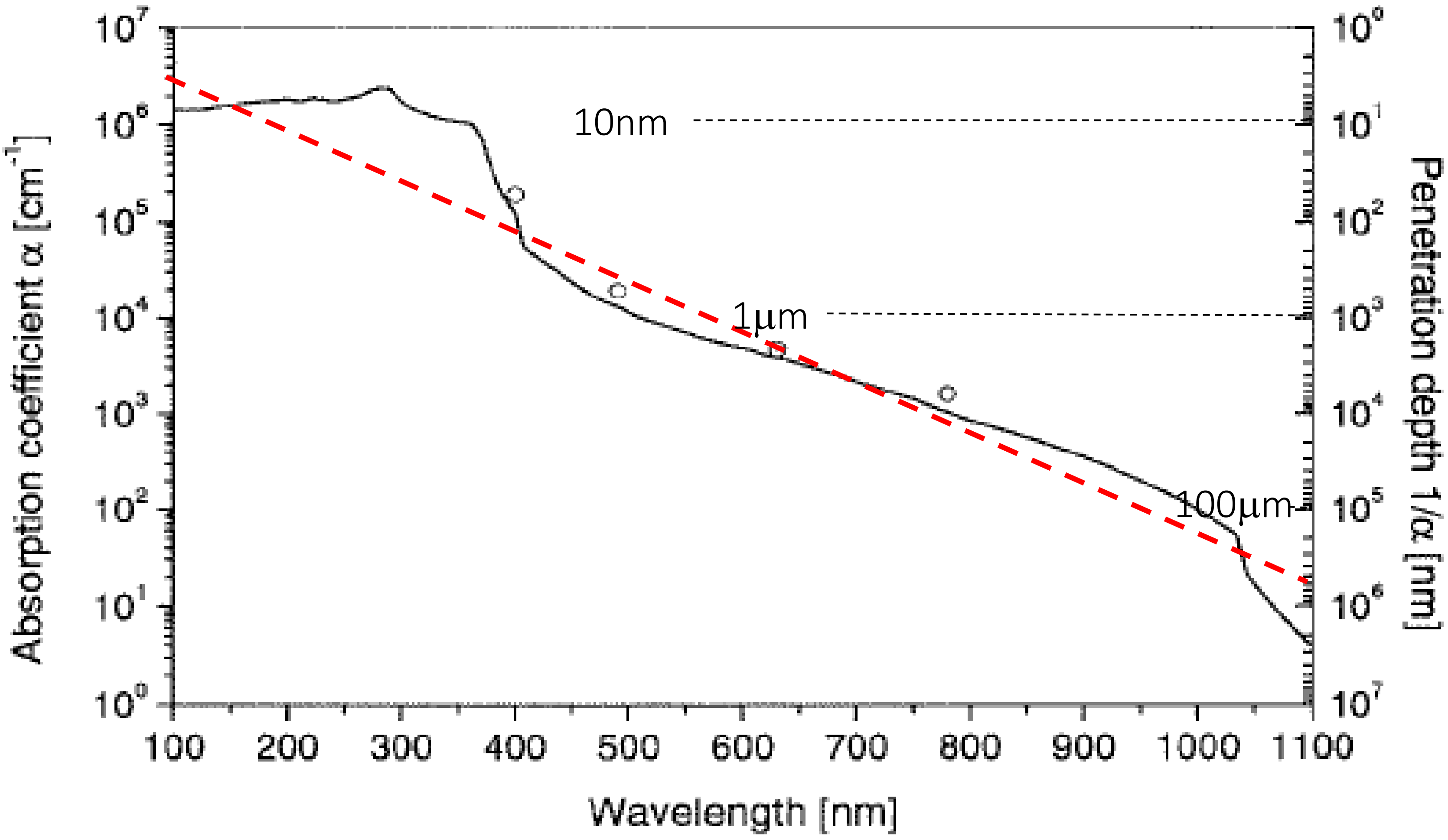
A two-step process to detect light:

1) Optical generation of electron-hole pairs
   = absorption of light by matter

2) Collection of charge carriers
   = extraction of carriers by the electrical field of the junction or by diffusion (main process in solar cells)

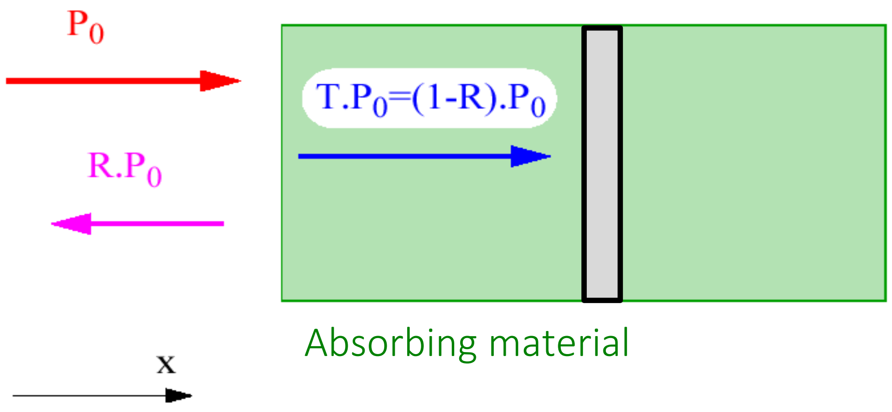
5.2 Absorption

For silicon



Approximation: $\alpha_{cm^{-1}}(\lambda_{\mu m}) \cong 10^{7.2-5.5\lambda}$

5.2 Absorption and Generation Rate



R= Reflection coefficient

T= Transmission coefficient

S= Surface of the detector

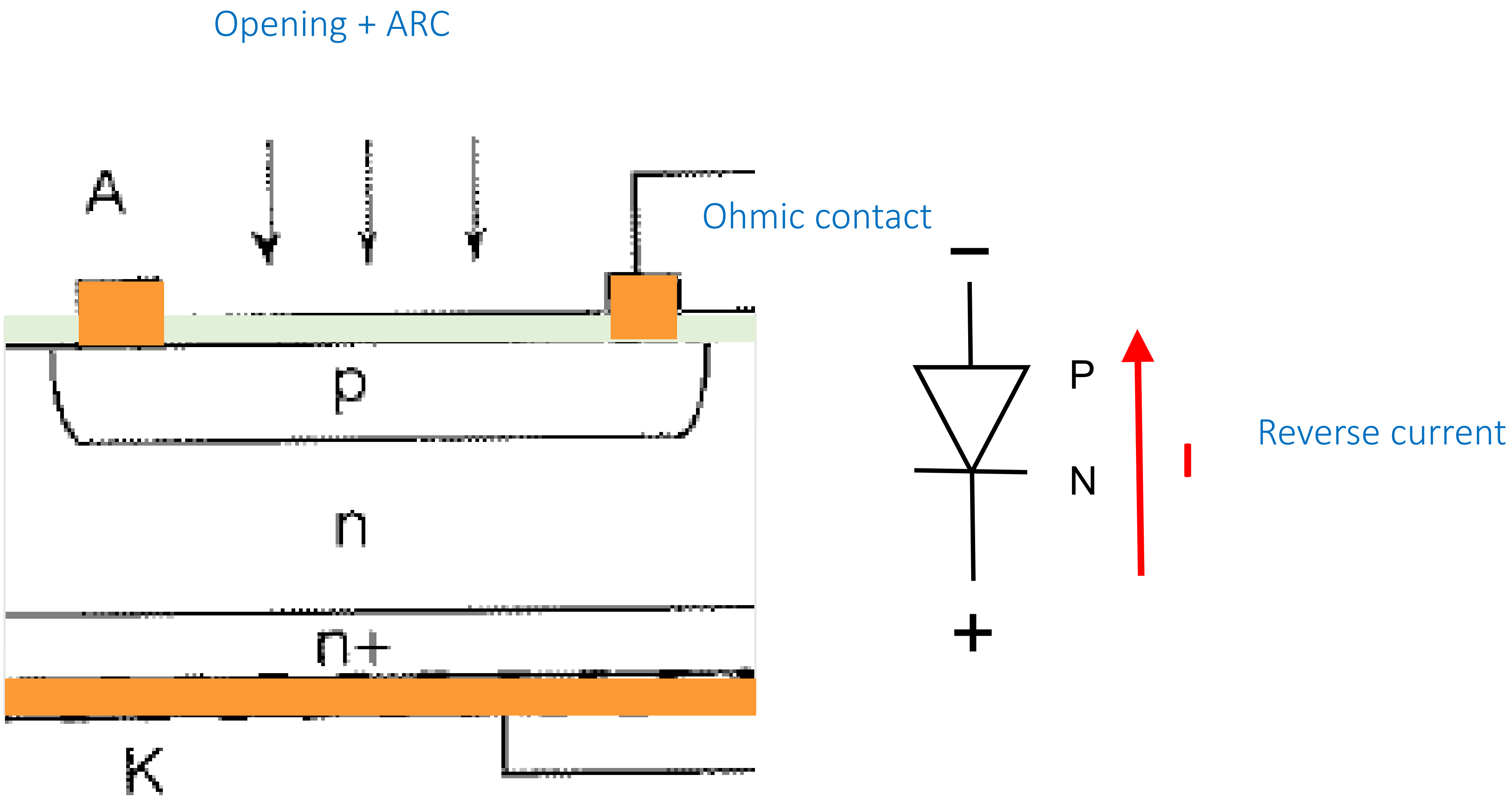
Same discussion as in 1.49 and Exercise 3.2

g(x)= generation rate of carriers

G_{opt}= generation rate per surface

$$G_{opt}(x) = \frac{P(x)/S}{h\,\nu}\cdot\alpha \quad = \quad \frac{P_0}{S}\frac{1}{h\,\nu}\cdot(1-R)\cdot e^{-\alpha\,x}\cdot\alpha \qquad \left[\frac{1}{cm^3\cdot s}\right]$$

5.2 Typical Structure of a p-n Photodiode

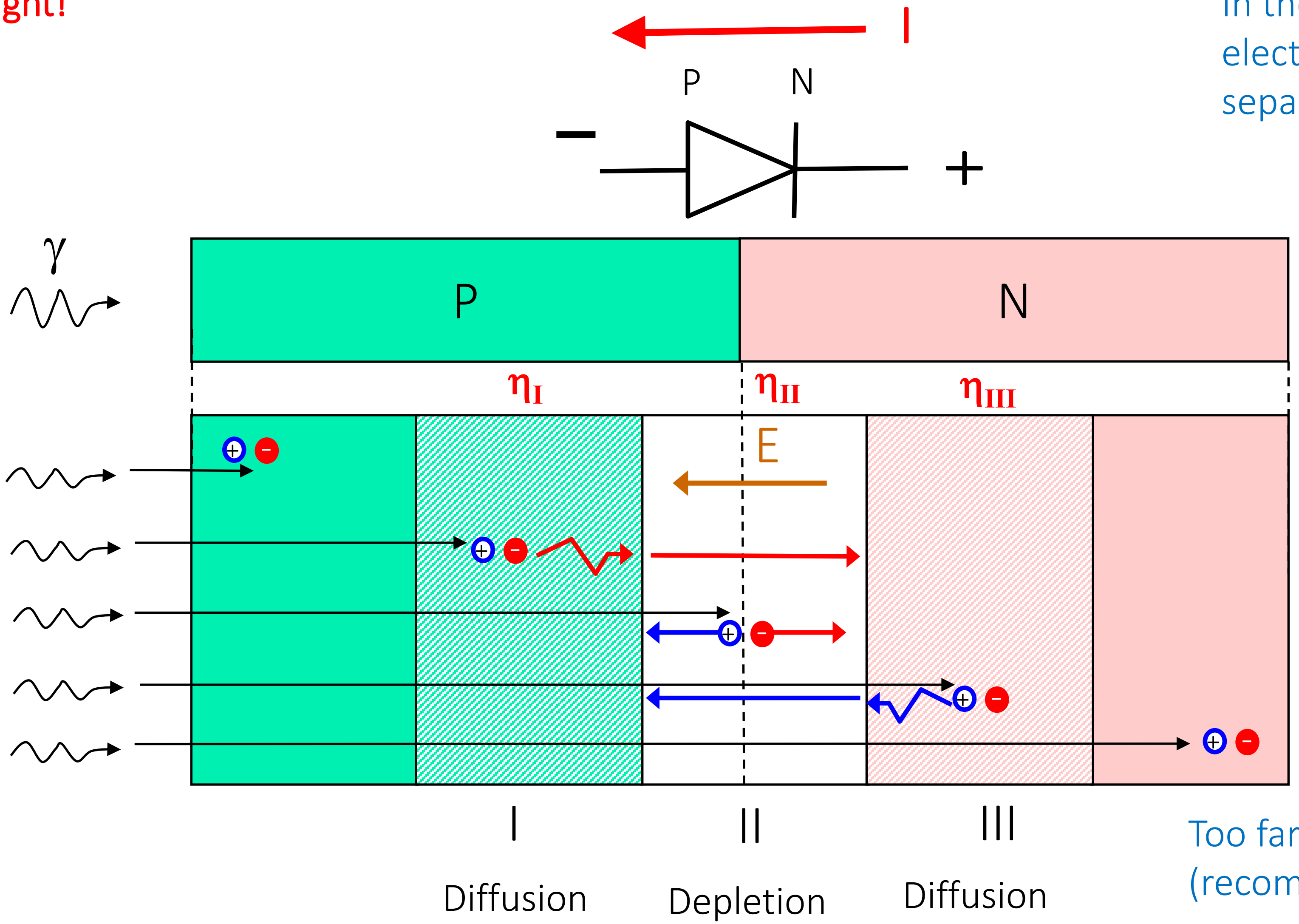


S. Donati, « Photodetectors, devices, circuits and applications »

5.2 Schematic Diagram of the Working Principle

Now subject to light!

In the depletion region: strong electric field → carriers quickly separated



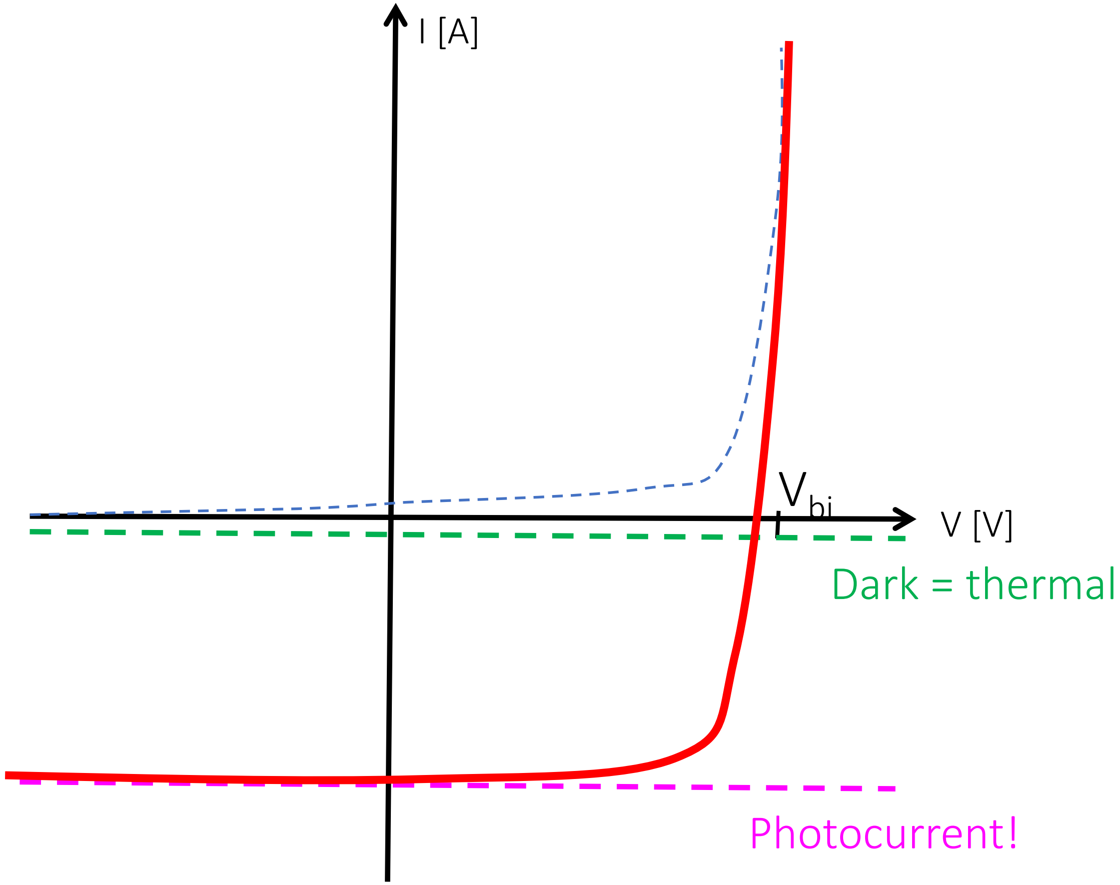
Diffusion = «slow» process (Brownian motion)

Too far from elecric field → «lost» (recombination)

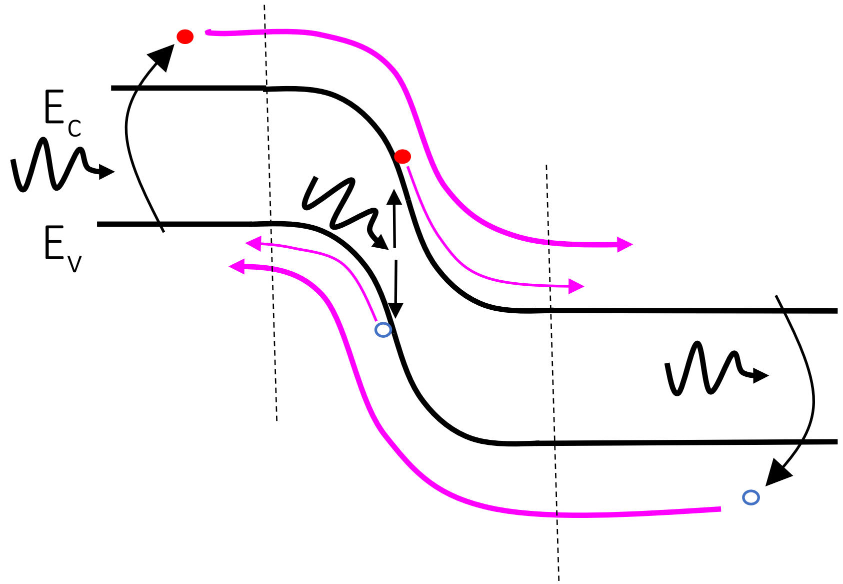
5.2 Current in photodiodes

Same as discussed in §5.1 but
now under illumination!

$$J = J_D - J_{ph}$$



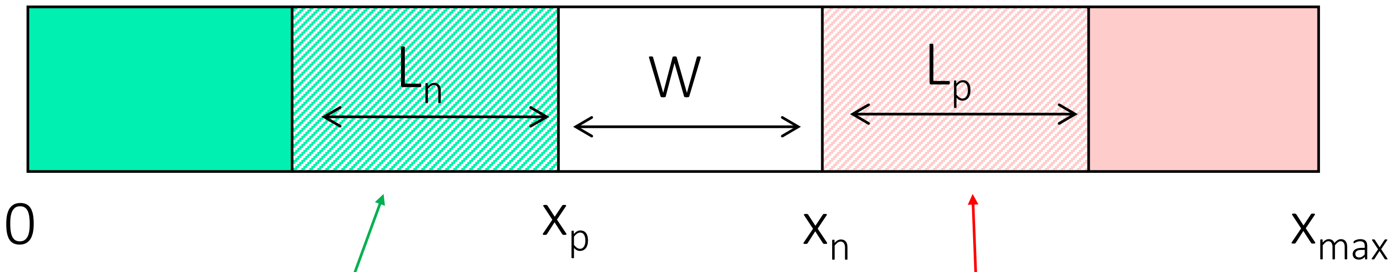
Generation and extraction
of photocarriers



$$-J_{ph} = -\left(\frac{q}{h\nu}\right)(\eta_I + \eta_{II} + \eta_{III}) \cdot P_{opt}$$

5.2 Continuity Equations of the Minority Carriers

$$I_{II} = -S \cdot q \cdot \int_{x_p}^{x_n} G_{opt}(x)dx$$



$x \le x_p$

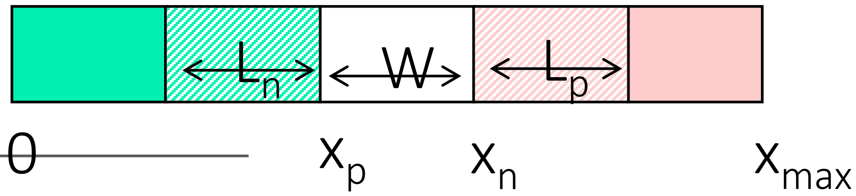
$$D_n \frac{\partial^2 n_p}{\partial x^2} - \frac{n_p - n_{p0}}{\tau_n} + G_{opt} = 0$$

$$D_p \frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{n0}}{\tau_p} + G_{opt} = 0$$

$x \ge x_n$

Diffusion equations

5.2 Solutions for the Photocurrent



General case:

$$\boxed{I = I_{th} + I_{ph} = -I_d - \frac{q}{h\nu}\left(\eta_I + \eta_{II} + \eta_{III}\right)\cdot\left(1-R\right)\cdot P_0}$$

Specific case: Shallow junction $x_p \ll L_n$ and Deep substrate $x_{max} - x_n \gg L_p$

See Exercise 2.2!

Main results:

$$\boxed{\eta_{II} = \left(e^{-\alpha x_p} - e^{-\alpha x_n}\right) = e^{-\alpha x_p}\cdot\left(1 - e^{-\alpha W}\right)}$$

$$\boxed{\eta_{III} = \frac{\alpha L_p}{1+\alpha L_p}\cdot e^{-\alpha x_n}}$$

What happens for very small L_p or large αL_p?

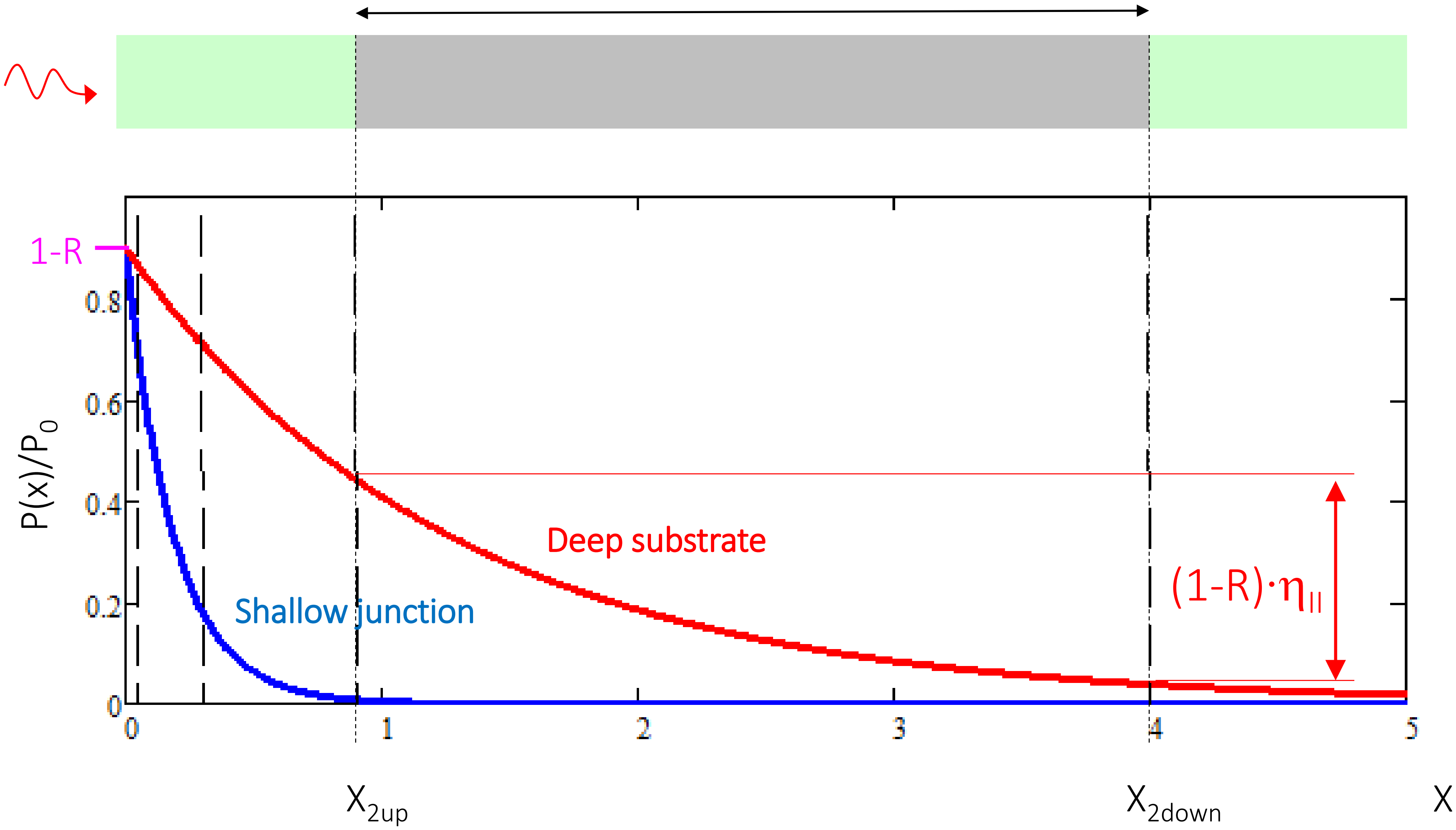
With recombination at the surface:

$$\boxed{\eta_I = \left(\frac{1-e^{-\alpha x_p}}{\alpha x_p}\right) - e^{-\alpha x_p}}$$

Without recombination at the surface:

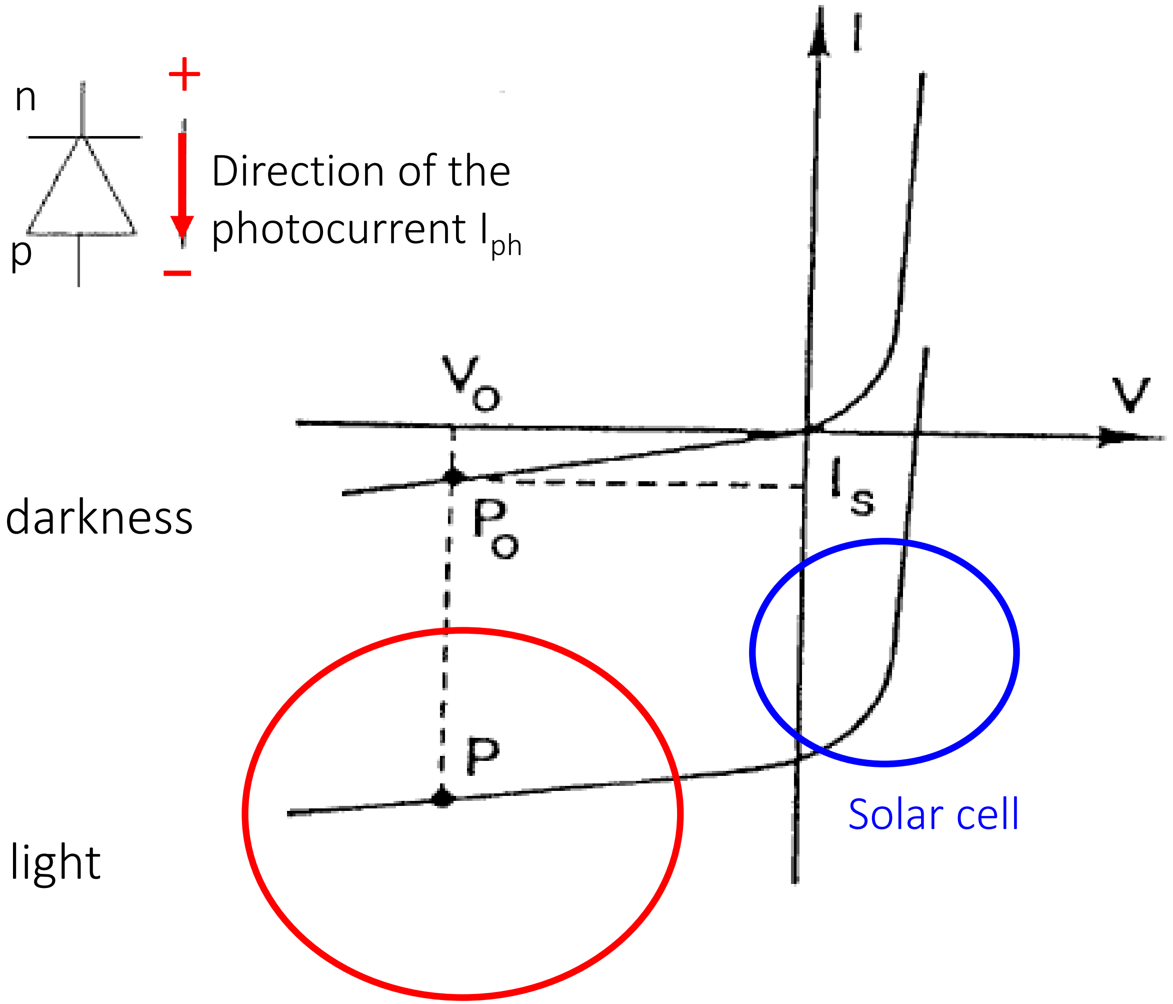
$$\boxed{\eta_I = 1 - e^{-\alpha x_p}}$$

5.2 Interpretation: Quantum Efficiency η_{II}



See Exercise 3.2

5.2 I(V) Plot



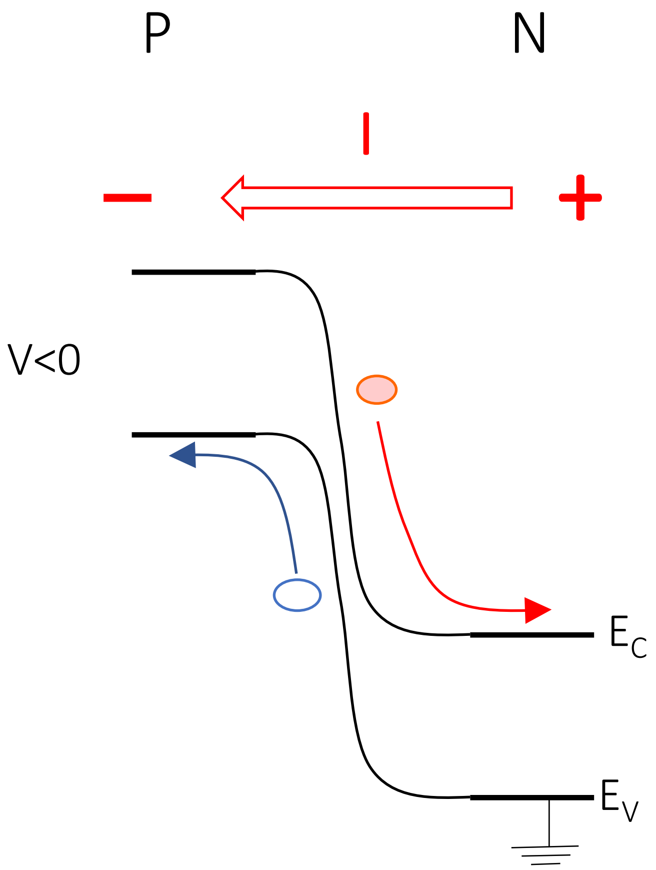
Direction of the photocurrent I_{ph}

darkness

light

Photodiode

Solar cell



Take-Home Messages/W5-1

5.1 p-n junction:

- Explain the working principle of a p-n junction – sketch the band diagram in equilibrium and non-equilibrium.
- How and why does it change in forward/reverse bias? In which regime does a photodiode typically work?

5.2 p-n Photodiodes:

- Explain the working principle and sketch/comment the typical (2D) structure of a p-n photodiode.
- Where should the light be absorbed to be correctly detected?
- Explain the main terms of the photocurrent.

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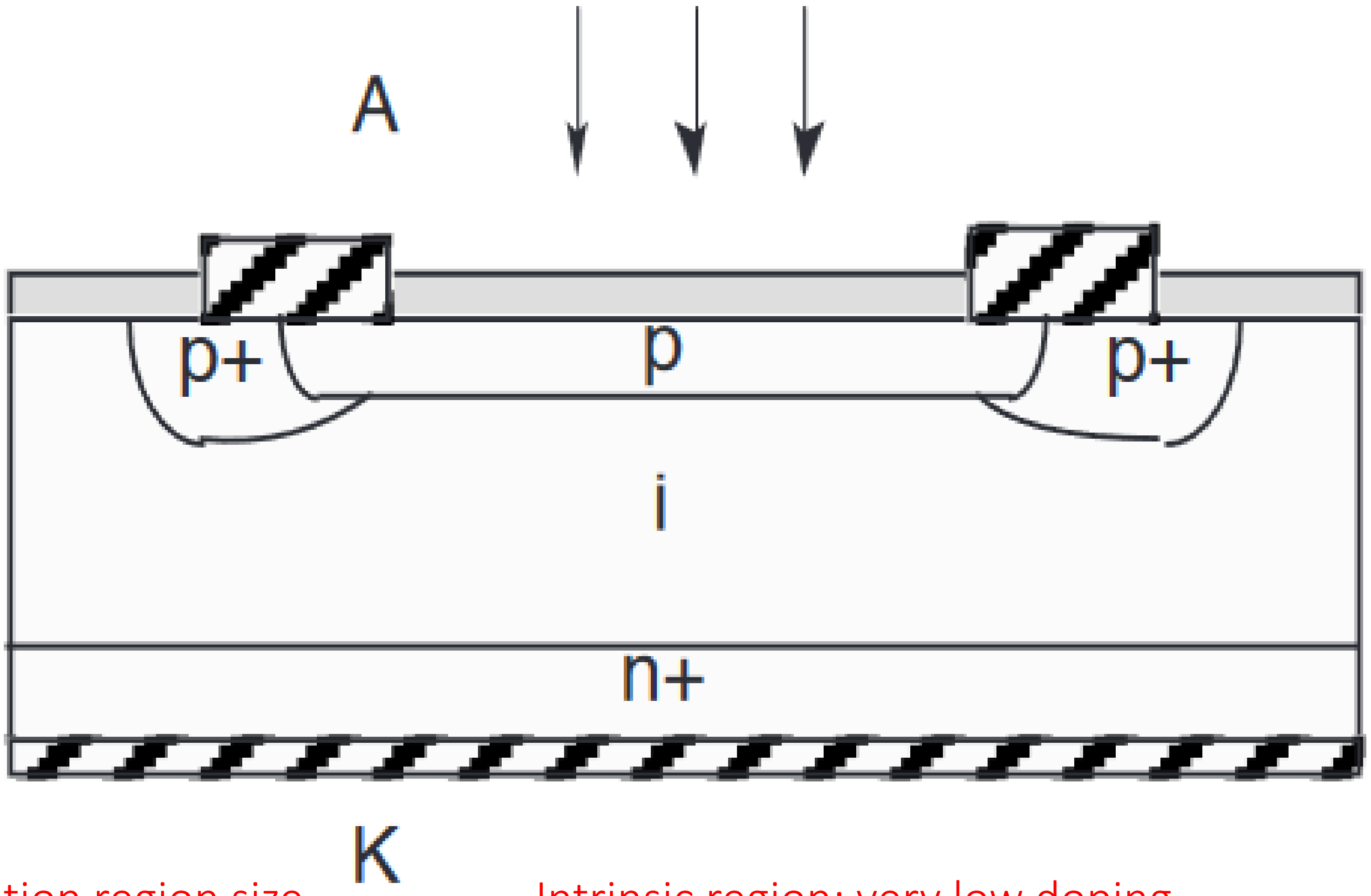
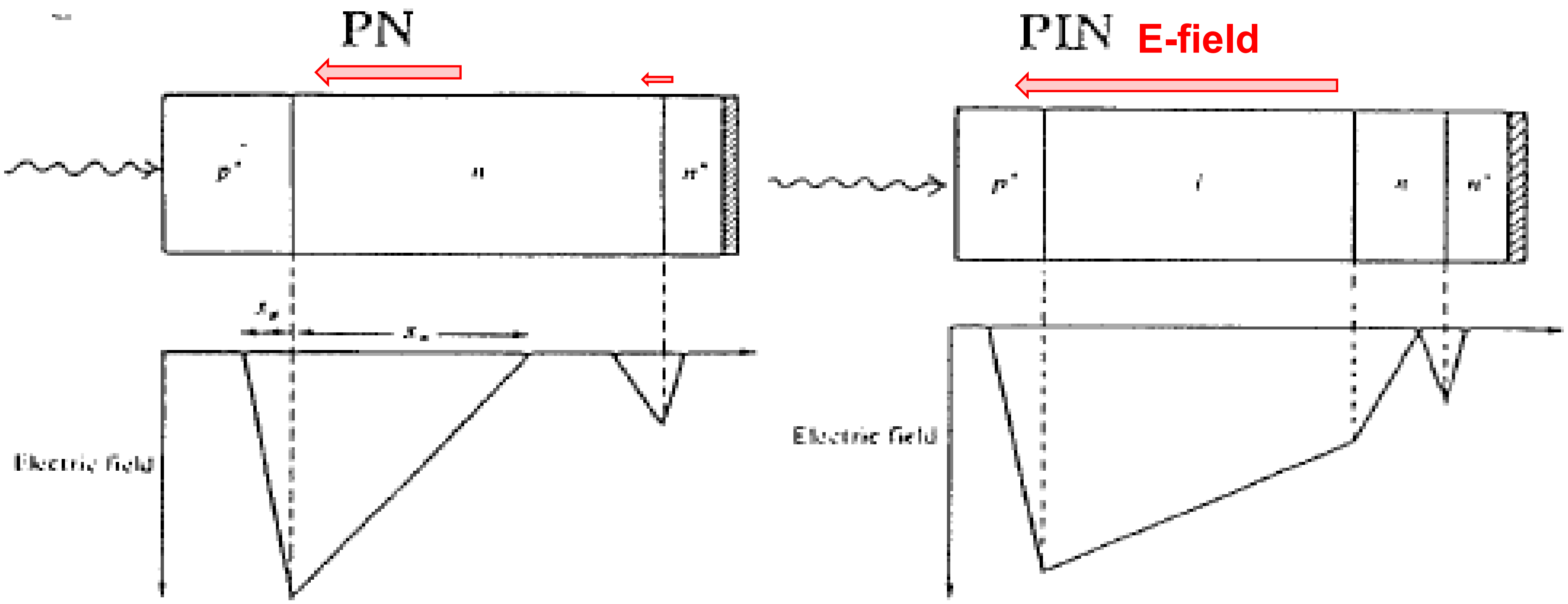
5.3 PIN Photodiode



Q: How can the depletion region size and η_{II} be increased?

Intrinsic region: very low doping

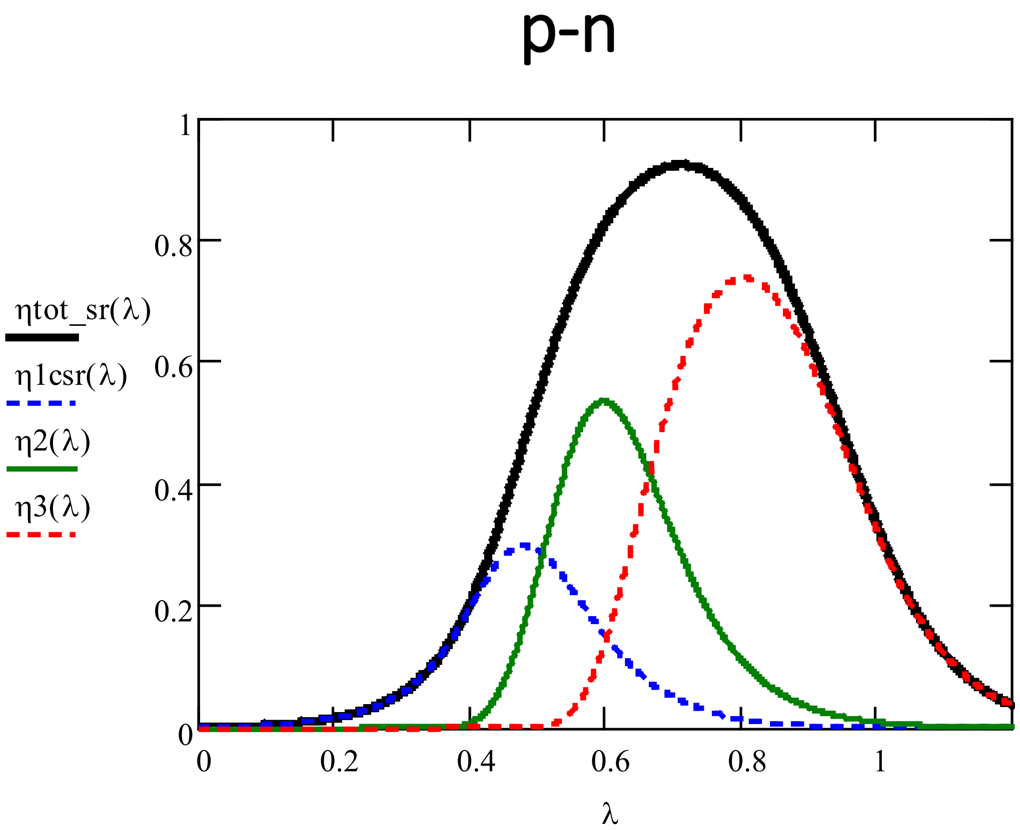
5.3 PIN: Broad and Homogeneous Electric Field



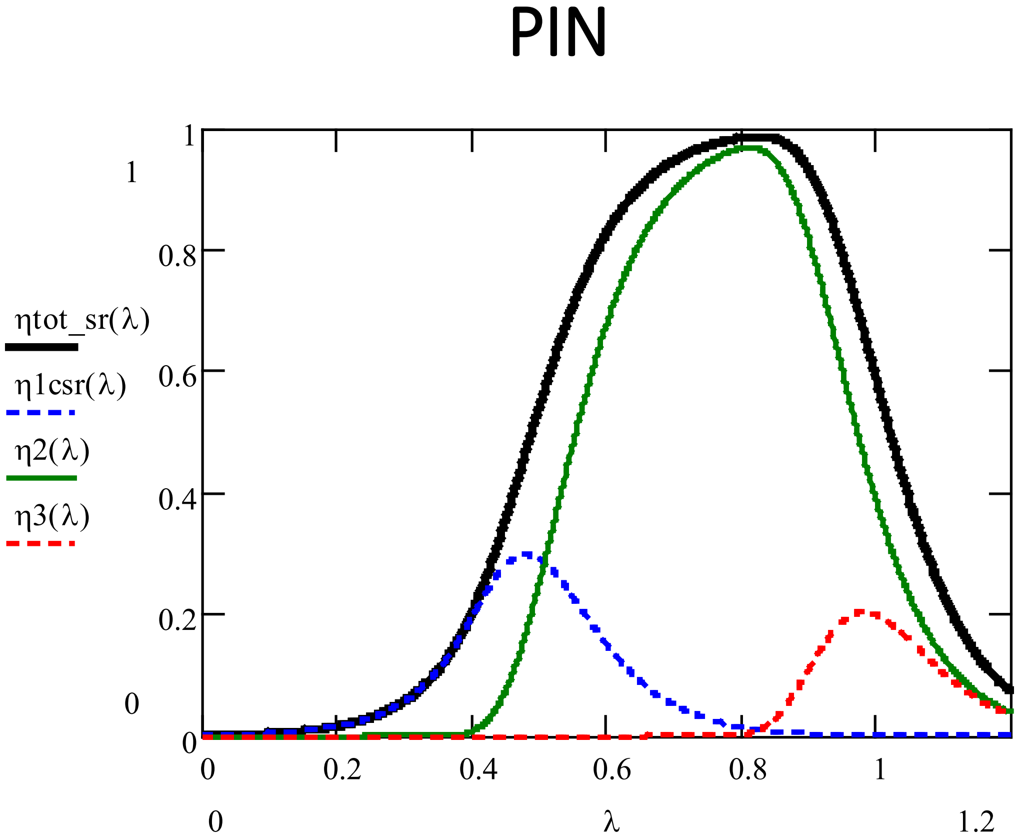
Quantum efficiency increased especially in the red and NIR

J. Wilson, J.F.B. Hawkes, « Optoelectronics, an introduction »

5.3 Examples of Quantum Efficiency



x_p=0.5 μm
W=2 μm



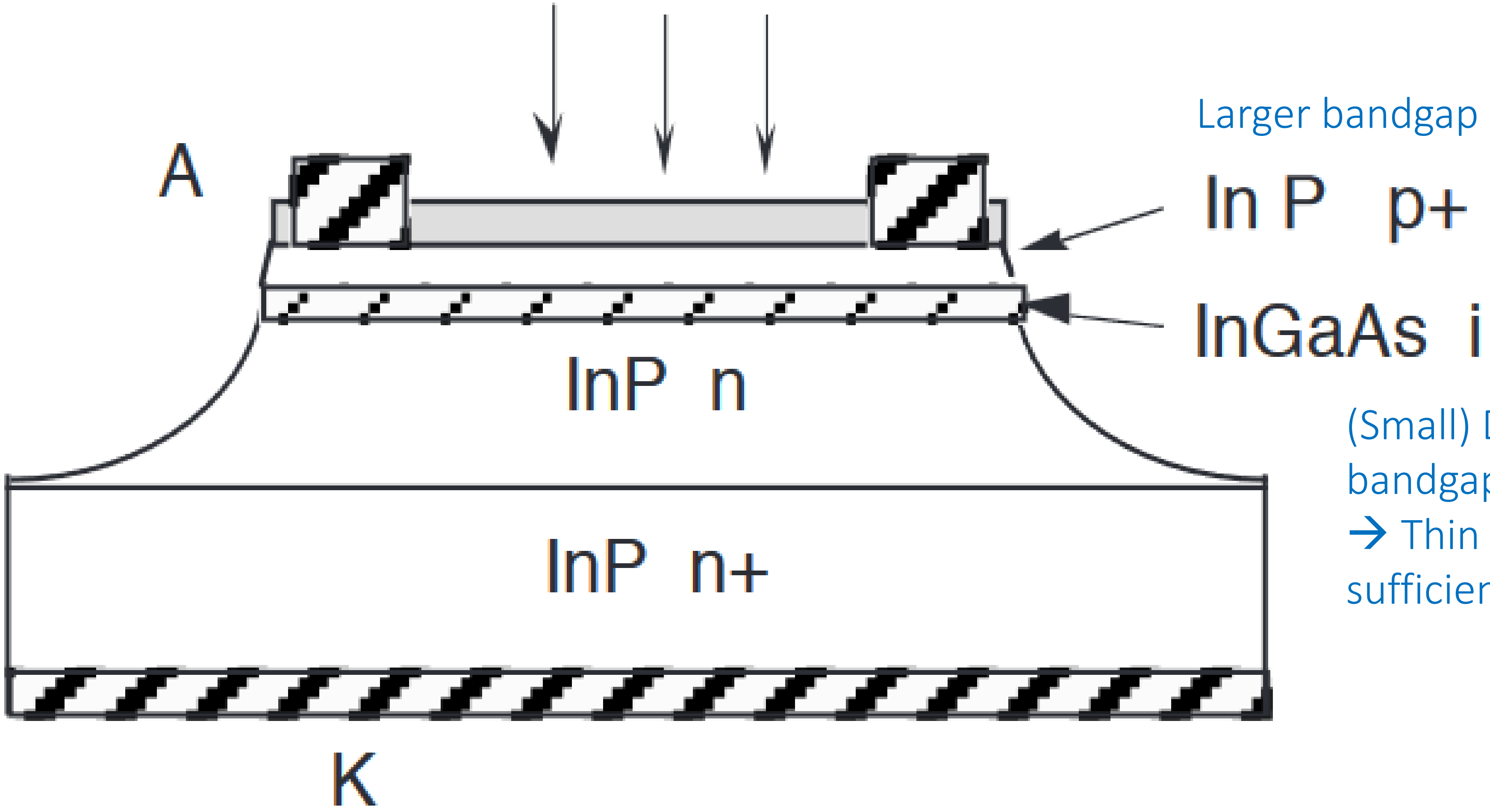
x_p=0.5 μm
W=100 μm

x_p: beginning of depletion region

Large QE increase in the intrinsic region

Drift dominates there → much faster response times/higher bandwidth

5.3 Heterojunctions for Photodiodes

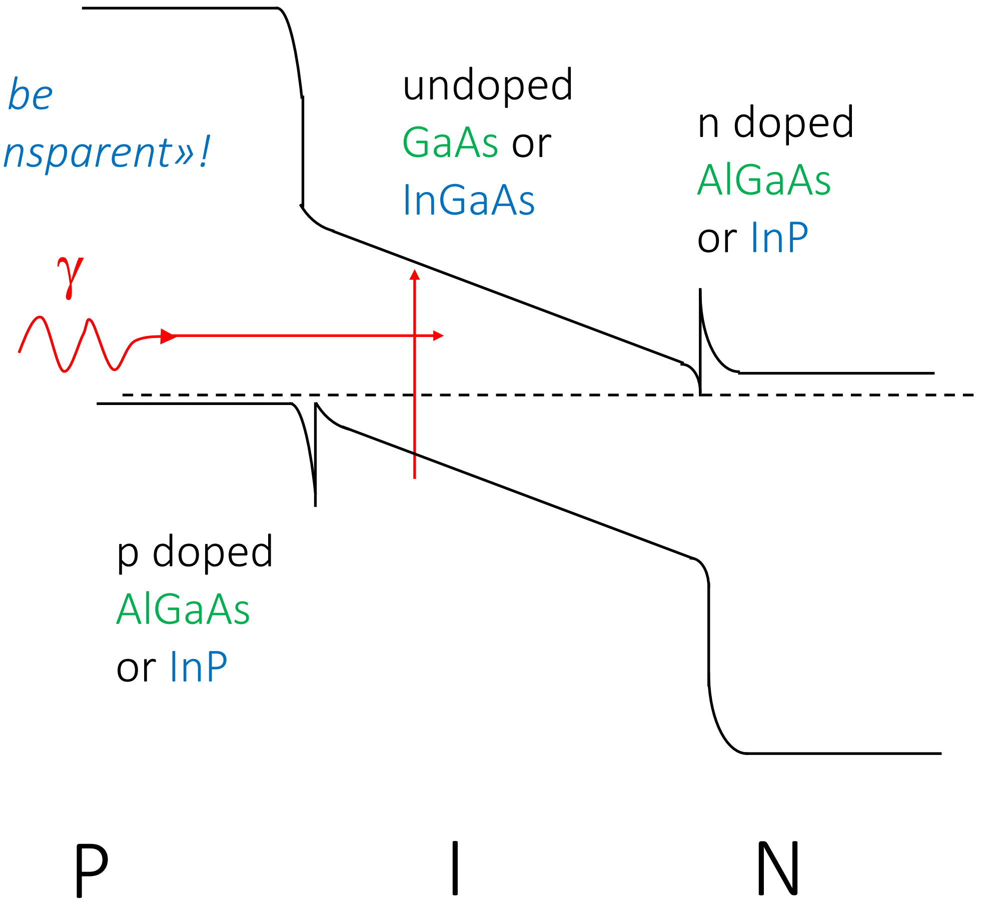


Larger bandgap

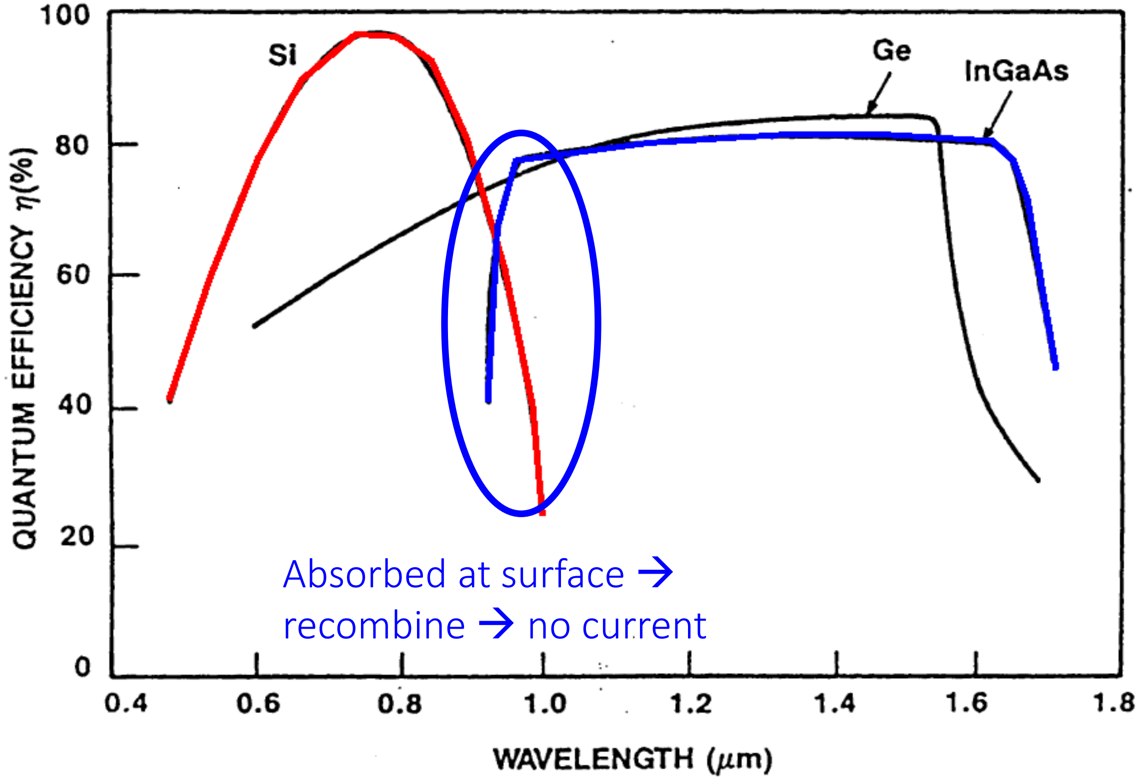
(Small) Direct bandgap material
→ Thin layer sufficient (1-5 μm)

S. Donati, « Photodetectors, devices, circuits and applications »

5.3 Heterojunctions for Photodiodes



Can be «transparent»!



Absorbed at surface → recombine → no current

«Small» vs large bandgap (see also §1.5 Bandgaps: InP: bandgap 1.35 eV, cut-off 0.92 μm)

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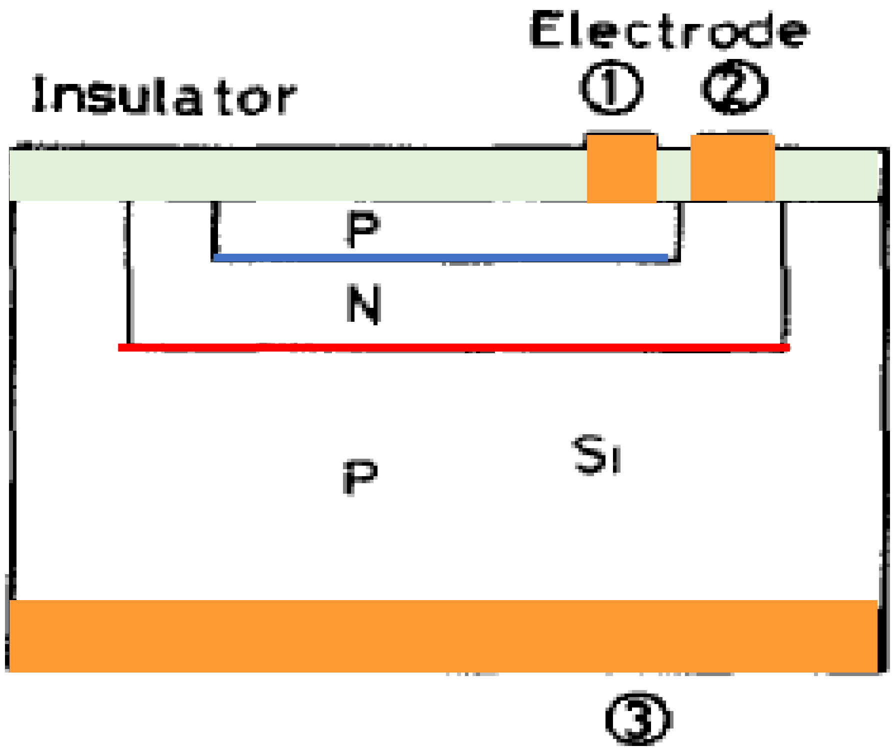
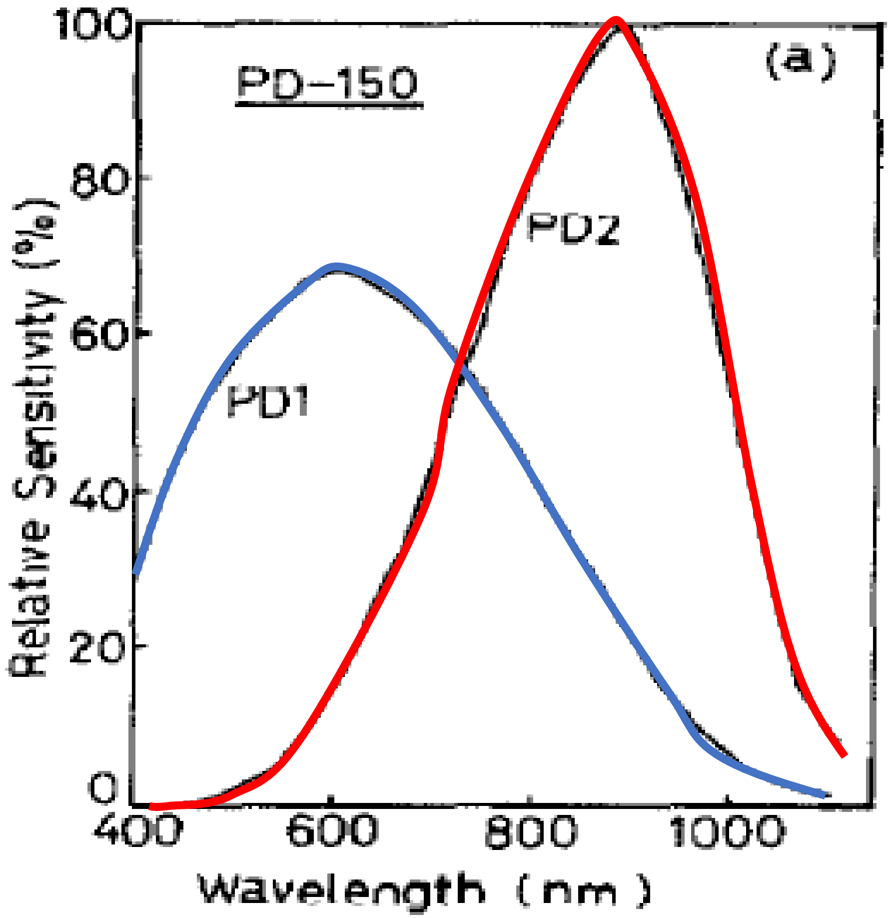
5.4 Case Study: Color Sensors

Double photodiode



N KAKO, *Sensors and Actuators, 4 (1983) 655 - 660*

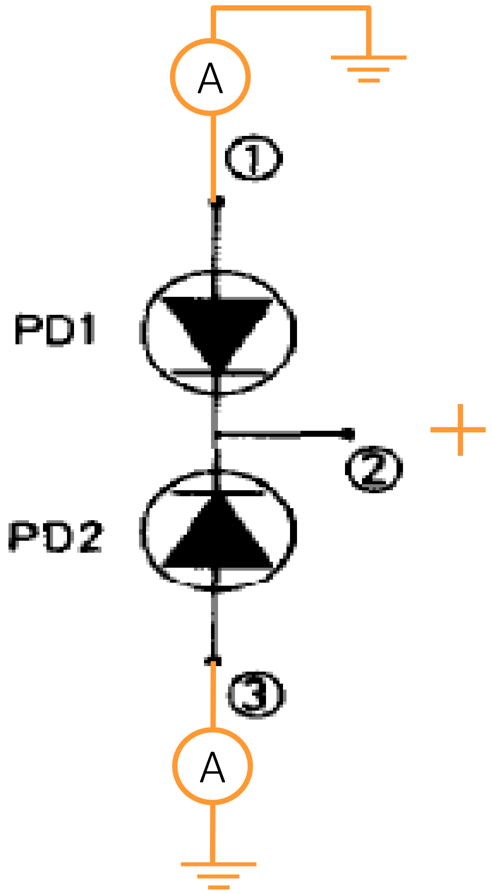


PNP transistor, two junctions in reverse one on top of the other → 1st diode: blue (surface), 2nd diode: red (depth)

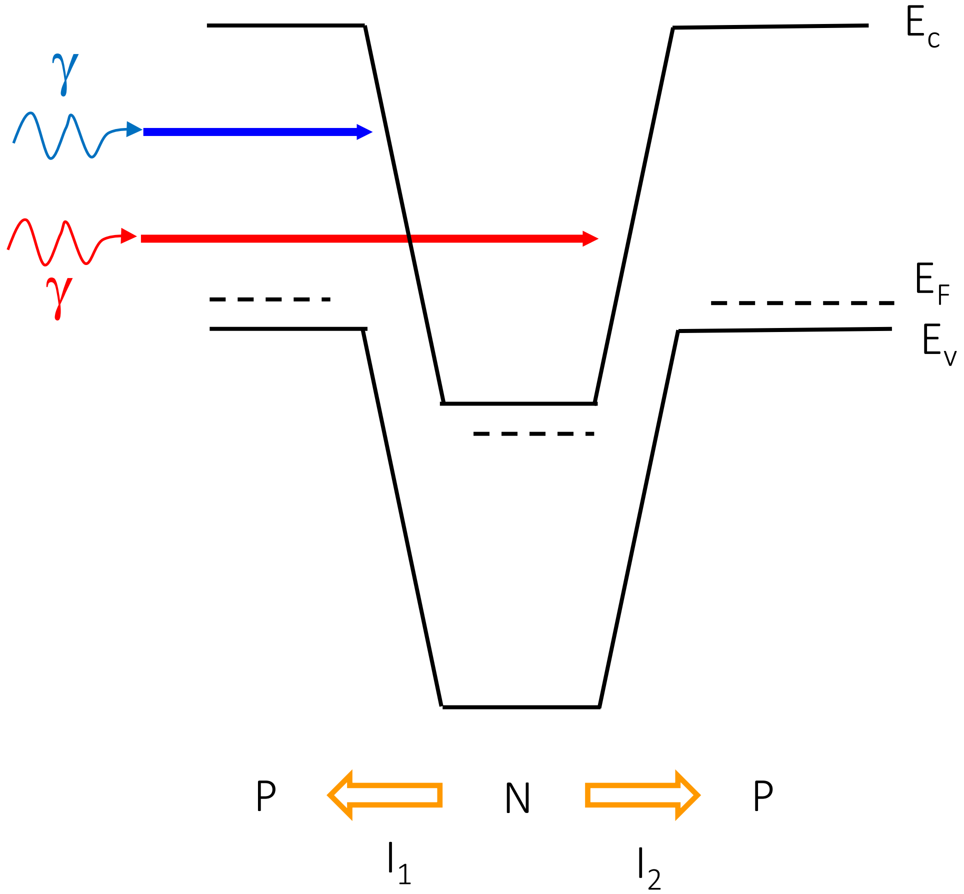
Example of application: flame colour detection (blue = ok; yellow = too little oxygen)

5.4 Color Sensors

Both junctions in reverse

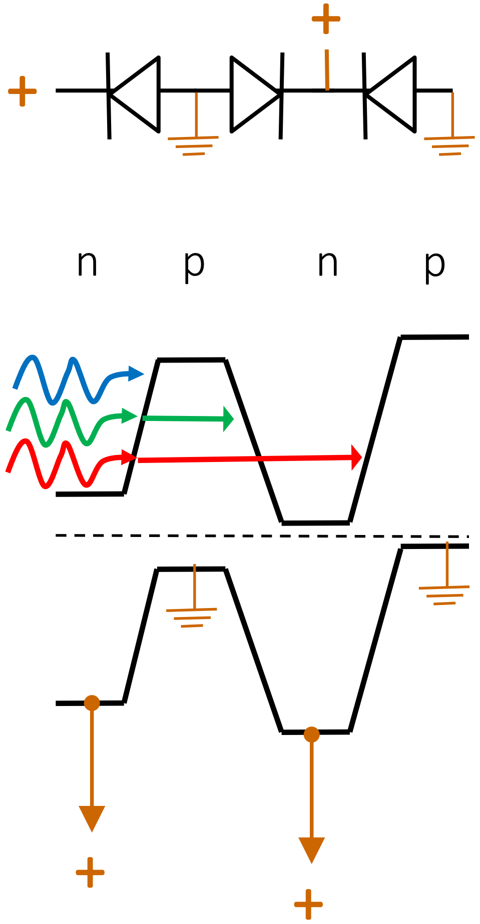


Bipolar PNP structure in reverse-bias
(transistor in «cut-off mode»)

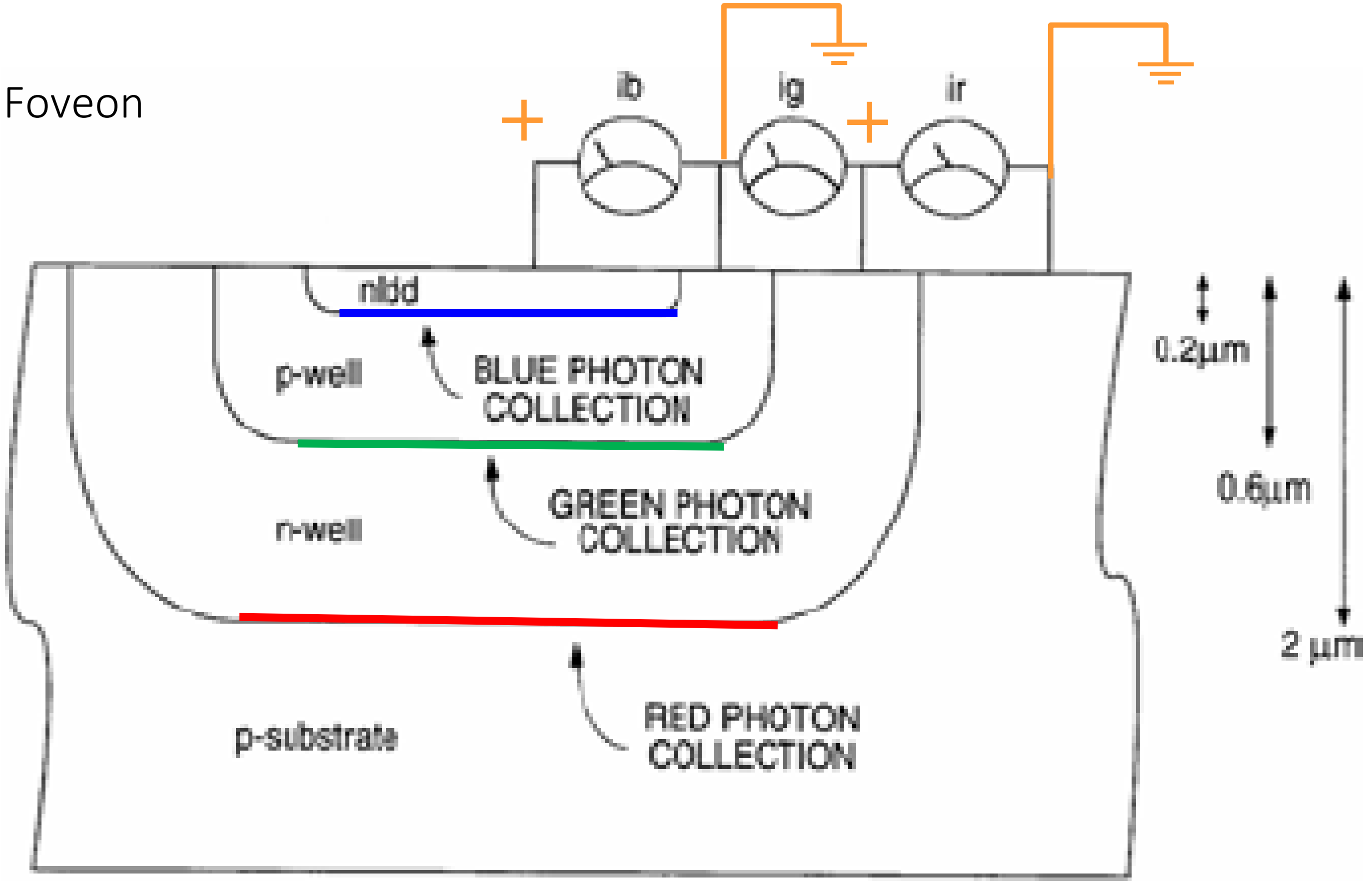


N KAKO, Sensors and Actuators, 4 (1983) 655 - 660

5.4 Foveon X3: Pixel Design on Silicon



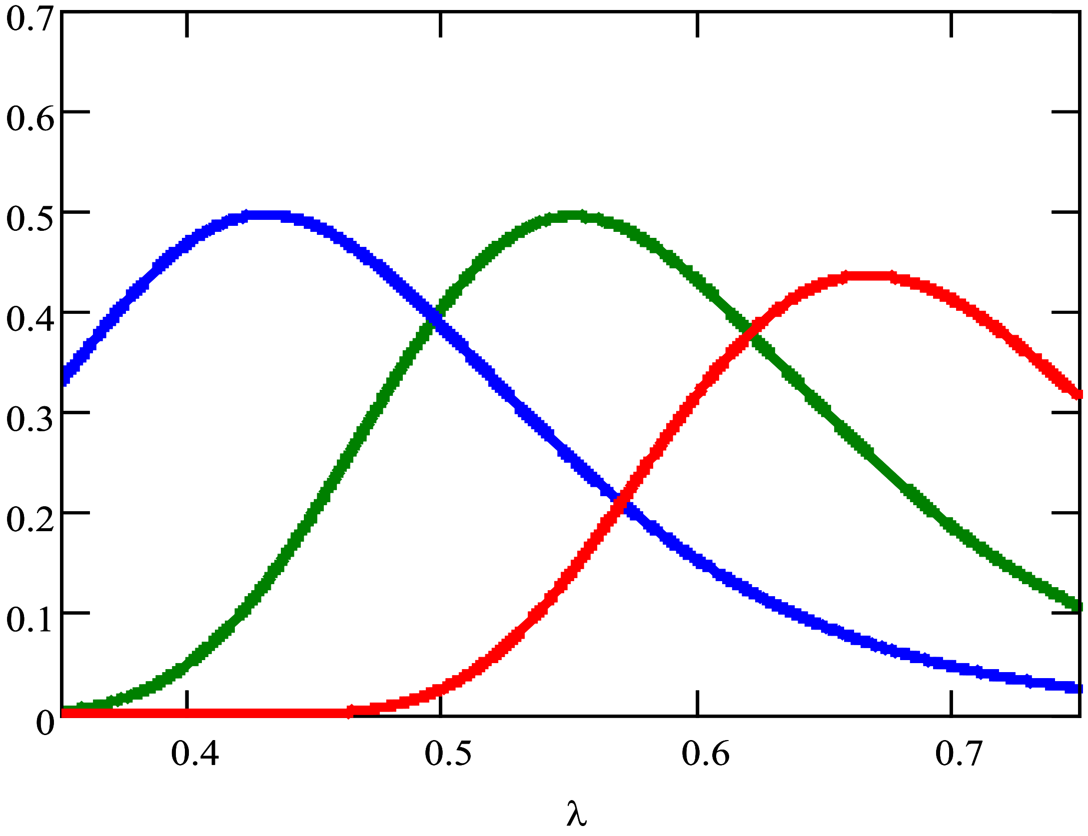
Foveon



Three junctions in reverse!
No colour filters.

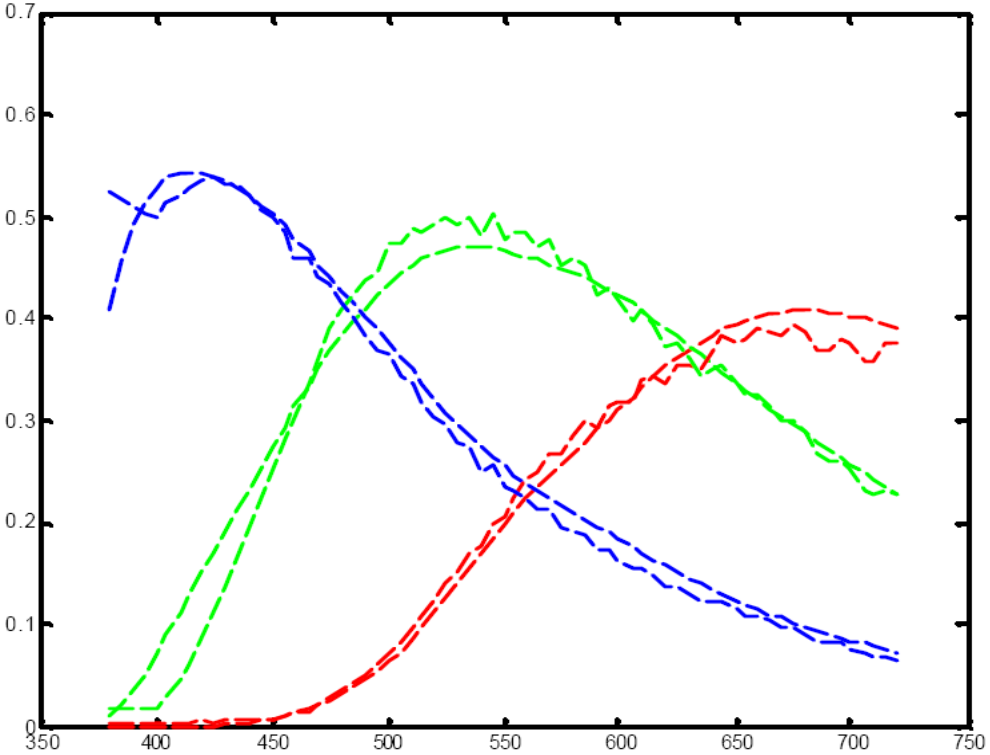
R.F. Lyon and P. M. Hubel: « Eyeing the camera: into the next century », 10th Color Imaging Conference, 2002

5.4 Spectral Response



Our simple model

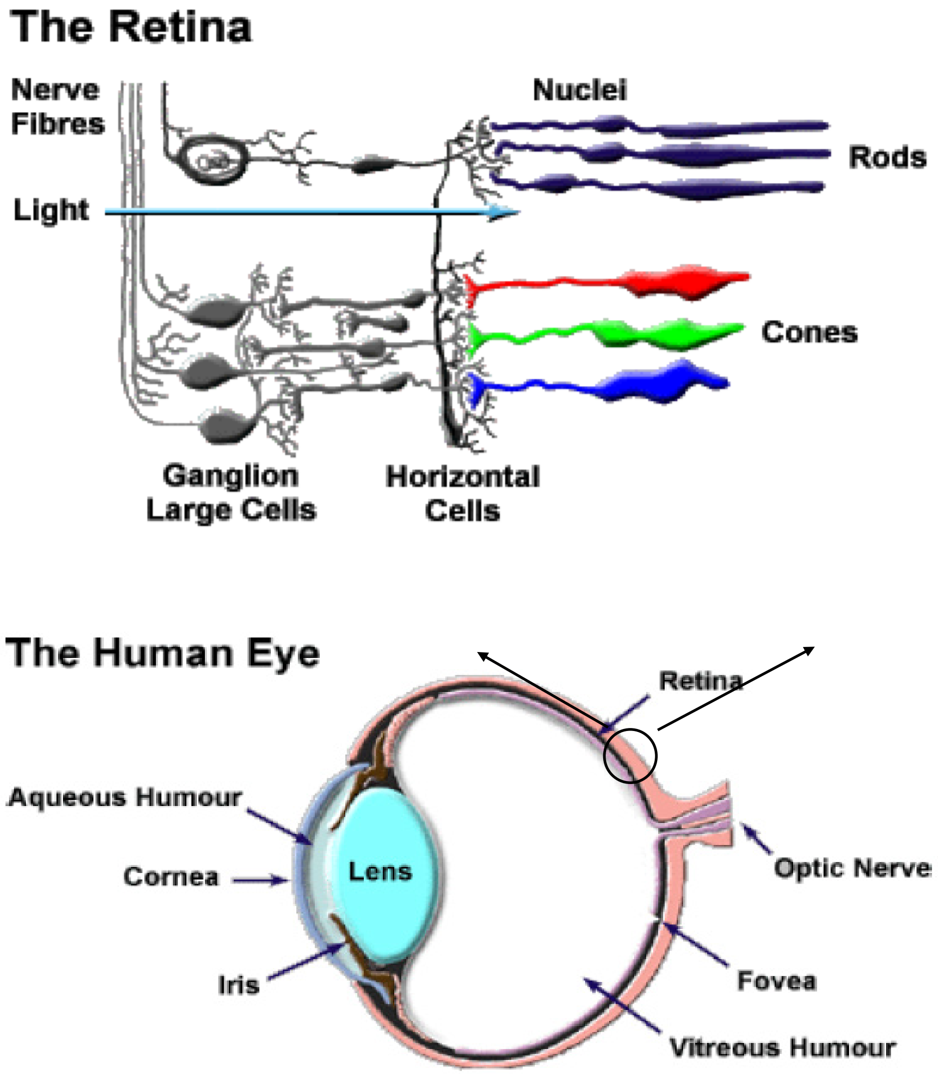
Any other sensor behaving like this?



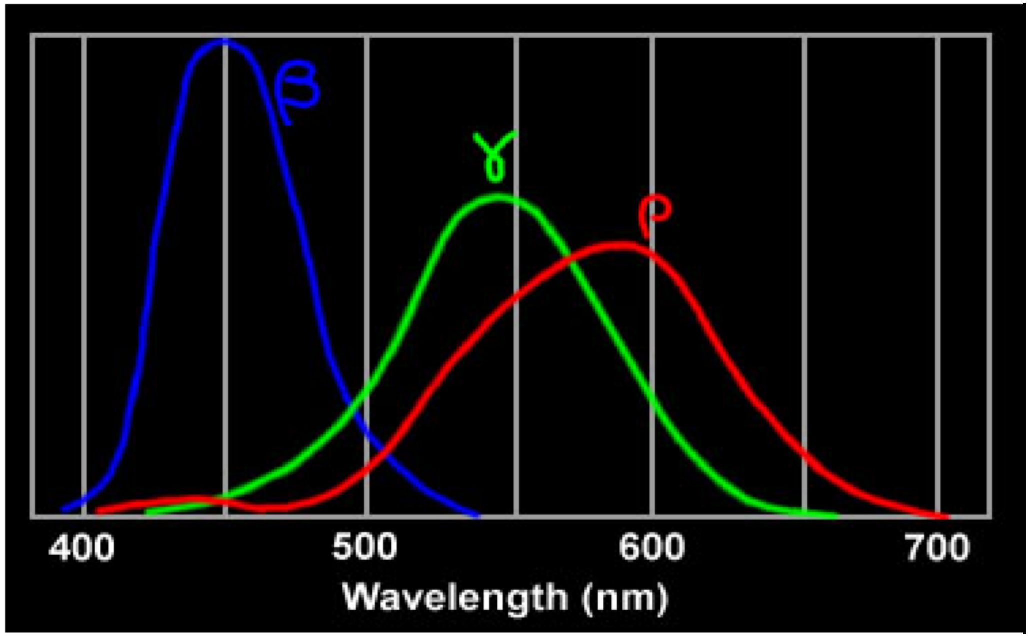
Foveon publication:
Measurements and model

P. Hubel: «Foveon technology and the changing landscape of digital cameras », 13th IS&T Color Imaging Conference pp. 314-317, 2005

5.4 Human Vision

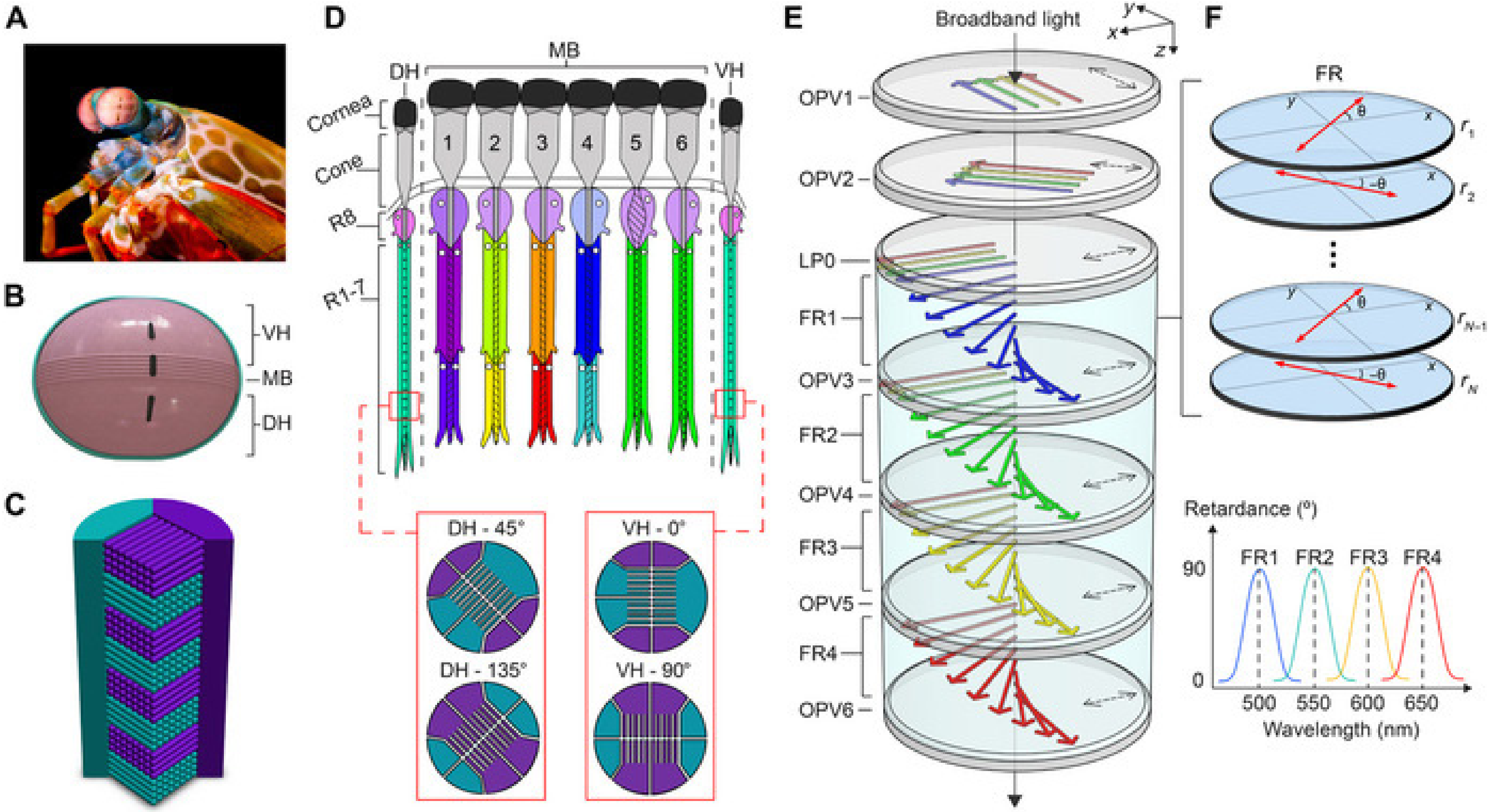


Spectral response of the cones



http://www.photo.net/photo/edscott/vis00010.htm

5.4 An example from nature: the Mantis shrimp

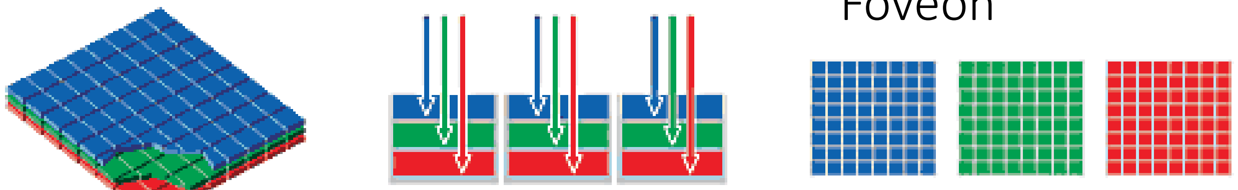


Mantis shrimp–inspired organic photodetector for simultaneous hyperspectral and polarimetric imaging, Volume: 7, Issue: 10, DOI: (10.1126/sciadv.abe3196)

5.4 Vertical or Mosaic Structure

Foveon X3® Capture

Foveon



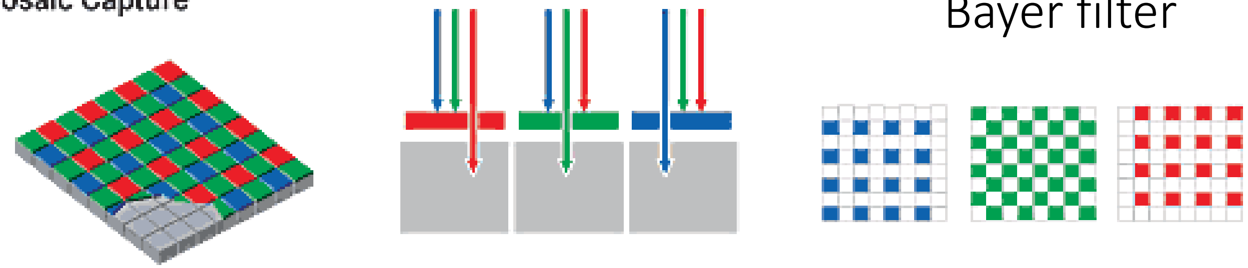
A Foveon X3 direct image sensor features three separate layers of pixel sensors embedded in silicon.

Since silicon absorbs different wavelengths of light at different depths, each layer records a different color. Because the layers are stacked together, all three colors are captured.

As a result, only Foveon X3 direct image sensors capture red, green, and blue light at every pixel location.

Mosaic Capture

Bayer filter



In conventional systems, color filters are applied to a single layer of pixel sensors in a tiled mosaic pattern.

The filters let only one wavelength of light–red, green, or blue–pass through to any given pixel location, allowing it to record only one color.

As a result, mosaic sensors capture only 25% of the red and blue light, and just 50% of the green.

http://www.foveon.com/article.php?a=69

http://www.foveon.com/article.php?a=113

Polaroid x530

4.5 Megapixels → 5.5 Megapoints

Sigma SD14

14.1 Megapixels → 4.7 Megapoints

http://www.sigma-photo.com/cameras/

«RAW» mode vs 3x fitted/interpolated colour pixels (vs monochrome!)

Take-Home Messages/W5-2

5.3 pin photodiodes:

- What are the advantages of PIN photodiodes and which is their structure?
- How is the quantum efficiency influenced by using this type of structure?

5.4 Heterojunctions:

- What is a heterojunction and why are heterojunctions used to fabricate high-performance photodiodes?

5.5 Colour sensors:

- Describe the photon absorption in a semiconductor as function of the wavelength of the light.
- How can a color sensor be fabricated with photodiodes?

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5.5 Solar cells → moved to Appendix A5.2

5.6 Electronic circuits, cut-off frequencies, noise

5.7 Avalanche photodiodes

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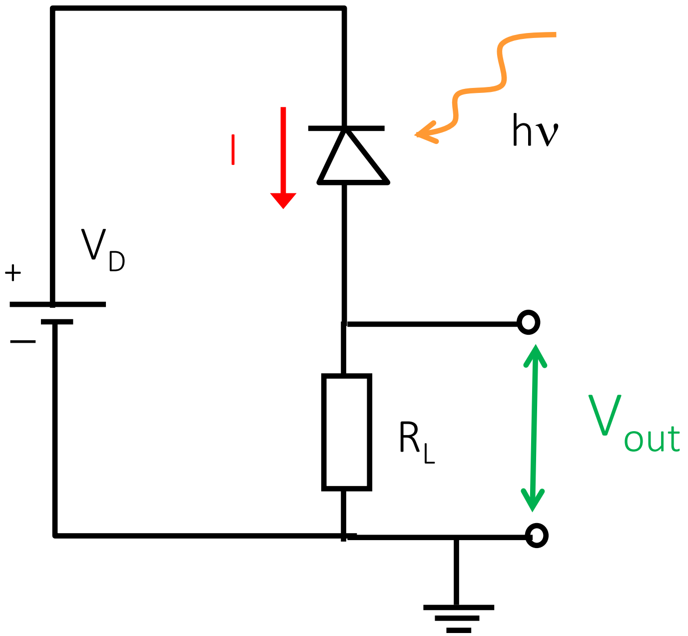
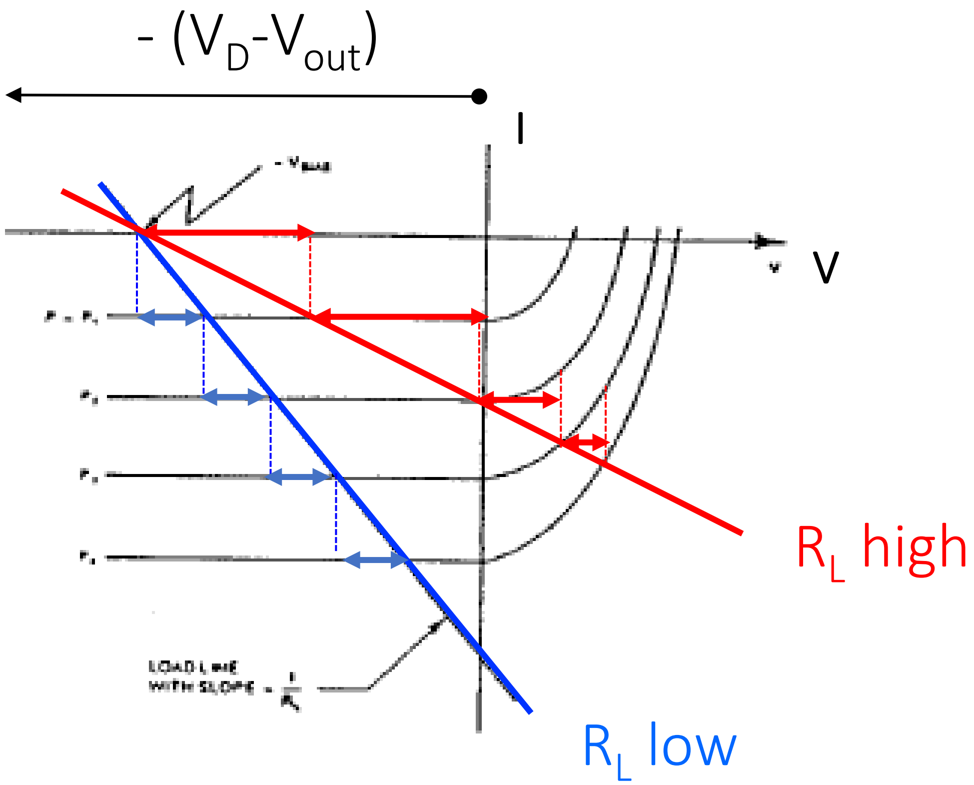
5.6 Measuring Circuit (1): Load Resistance



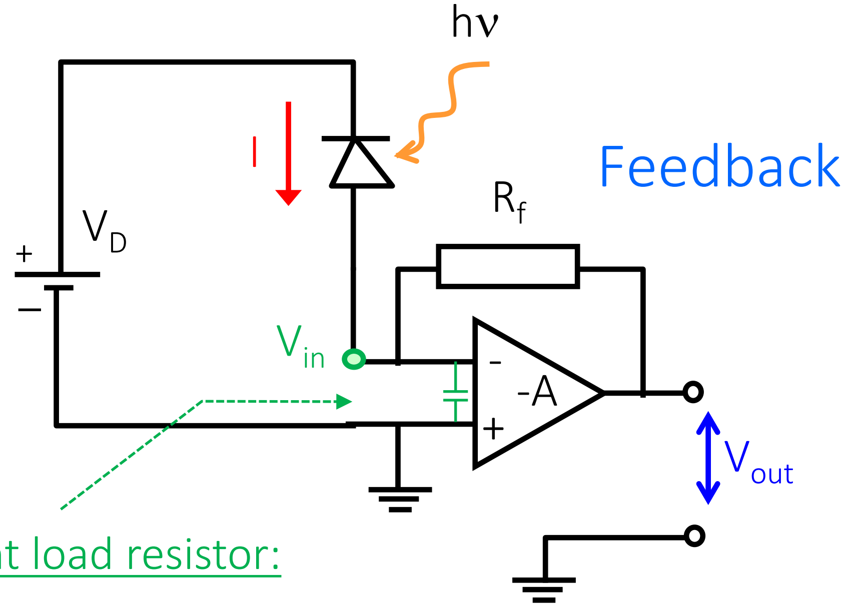


$$V_{out} = R_L \cdot I$$

Only rough measurements possible, small dynamic range

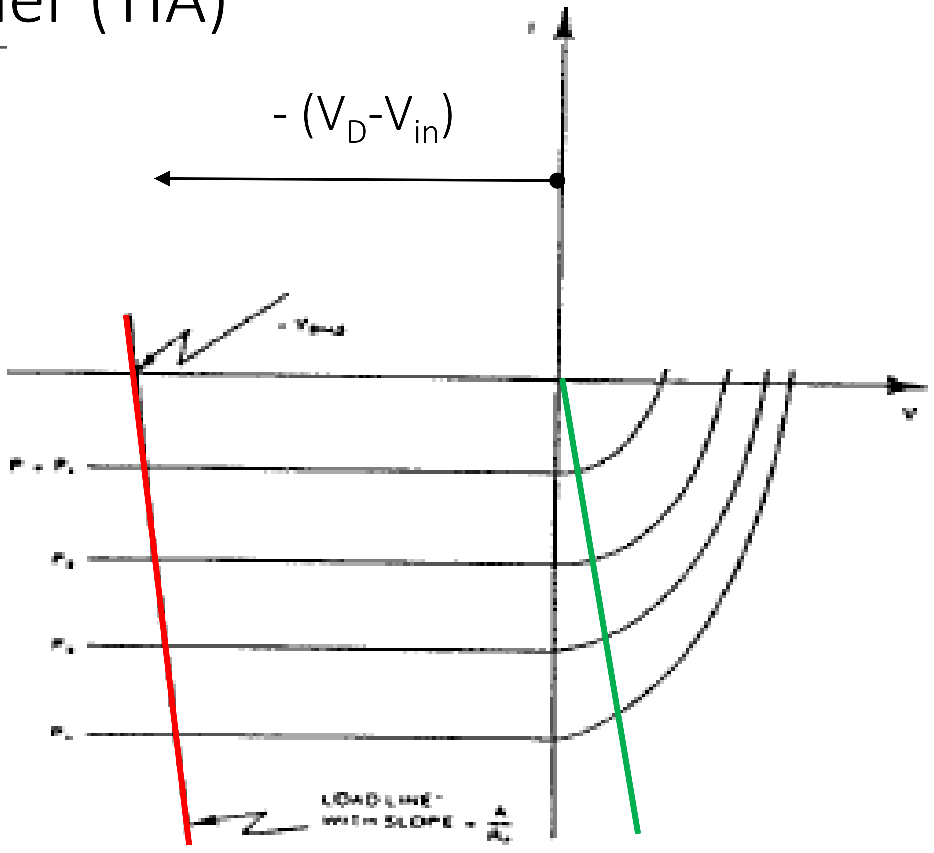
Load line (slope): $1/R_L$

5.6 Measuring Circuit (2): Transimpedance amplifier (TIA)



Feedback

Equivalent load resistor:



$$R_f I = V_{in} - V_{out} = (1 + A) \cdot V_{in} \qquad -A \cdot V_{in} = \boxed{V_{out} \cong -R_f \cdot I}$$

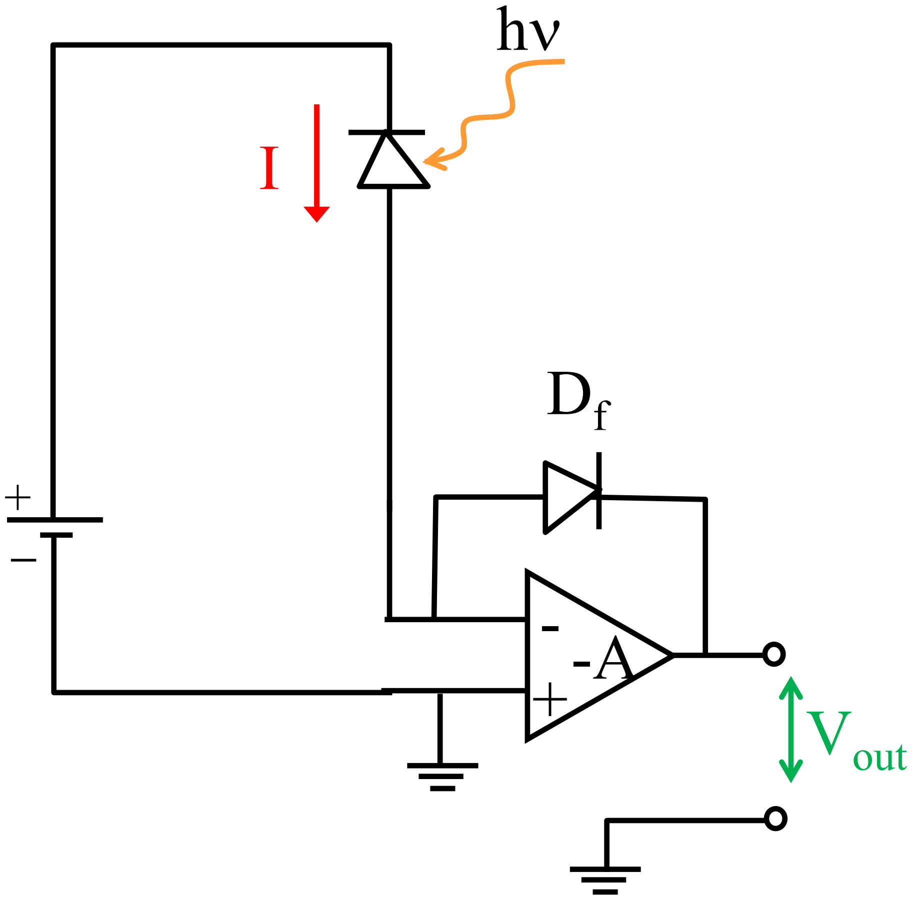
$$V_{in} = \frac{R_f}{A+1} \cdot I \equiv R_L \cdot I \quad \Rightarrow \quad \boxed{R_L \equiv \frac{R_f}{A+1}}$$

Load line: $1/R_L$

Improved linearity (R_L small)

with high gain (R_f large)

5.6 Measuring Circuit (3): Transimpedance and Logarithmic Output



Diode current:

$$I \cong I_0 \cdot e^{\frac{-qV_{out}}{kT}}$$

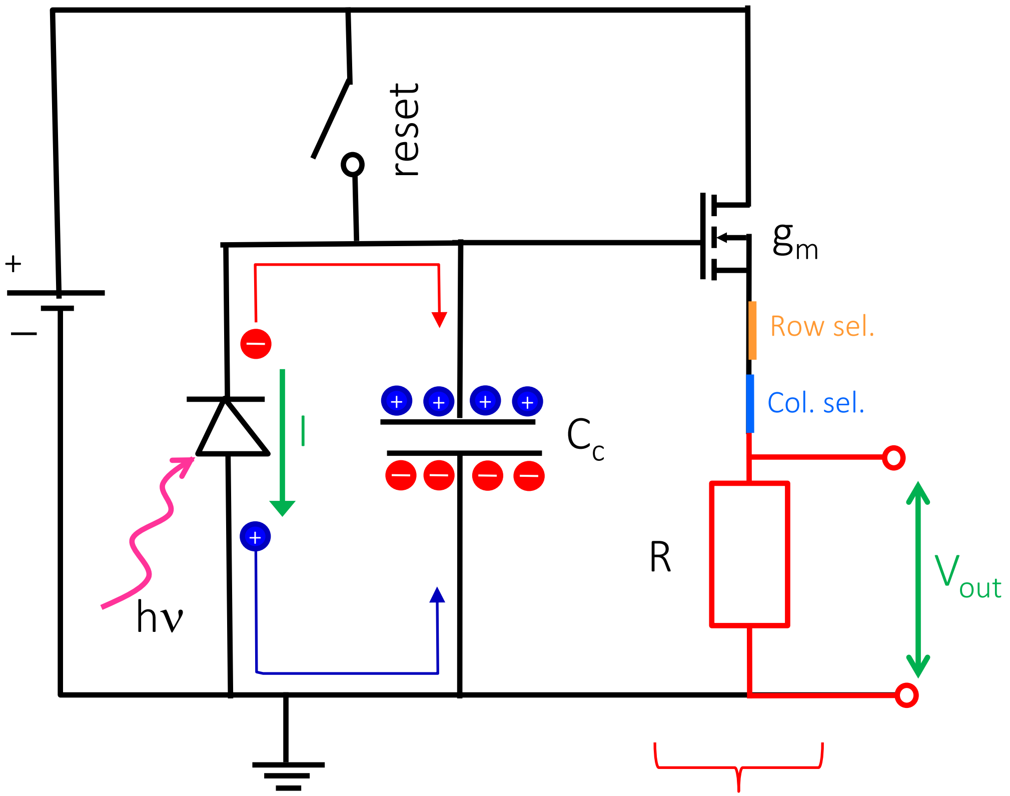
$$\Downarrow$$

$$V_{out} \cong V_0 - \frac{kT}{q}\ln(I) \quad < 0$$

$$V_0 \cong \frac{kT}{q}\ln(I_0)$$

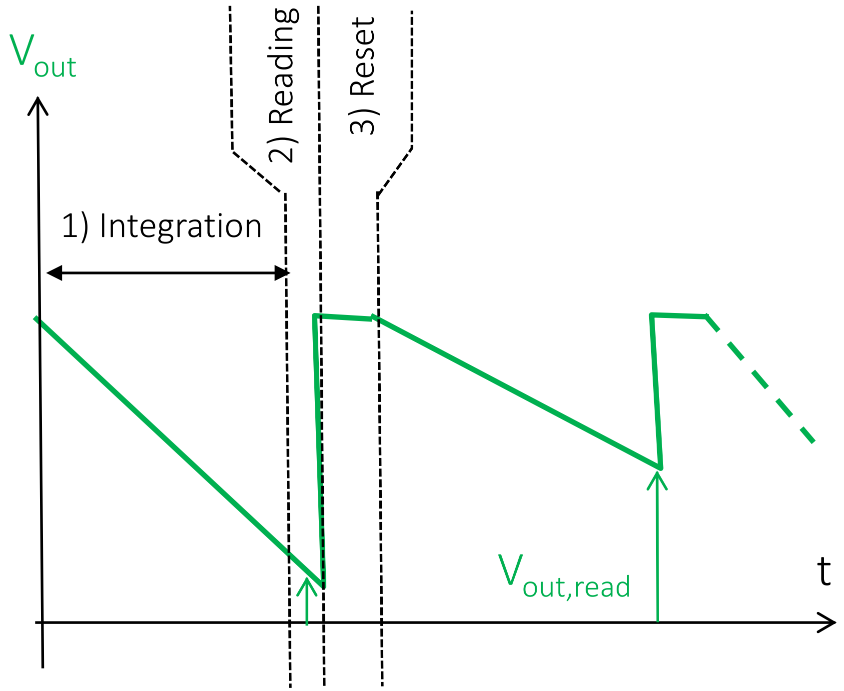
5.6 Measuring Circuit (4): Integration and Current-to-Voltage Conversion

3T APS – basic idea of CMOS camera pixel (one single pixel shown here)



Source Follower

NMOS transistors



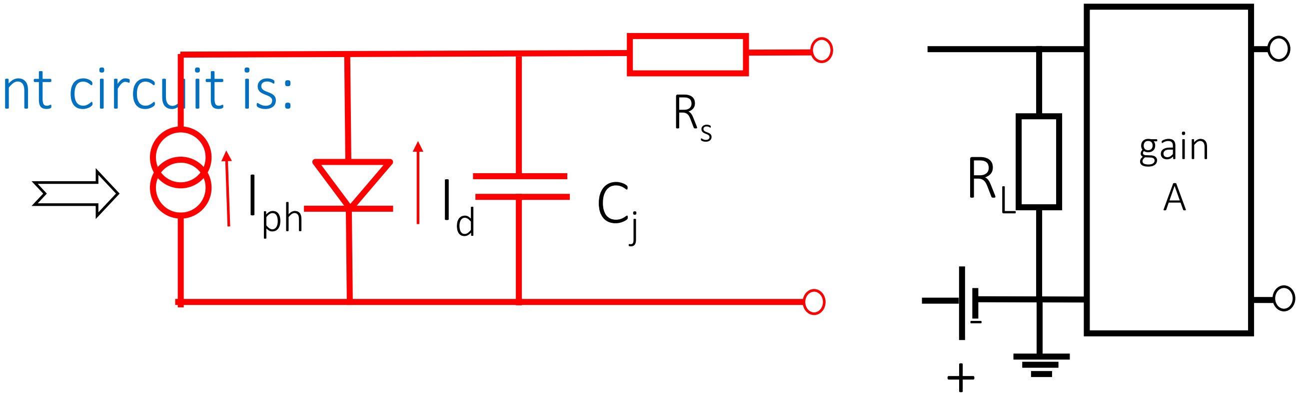
$$V_{out,read} = V_0 - \frac{Q}{C_c} = V_0 - \frac{1}{C_c} \cdot \int_0^{\tau} I \cdot dt$$

Charge integration

5.6 Cut-off Frequencies

1) The cutoff frequency of the equivalent circuit is:

$$f_2 = \frac{1}{4(R_s + R_L)C_j}$$



2) The drift time in the depletion region induces a cutoff frequency:

$$\tau_d \cong W / v_{sat} \quad \Rightarrow \quad f_{2d} \cong \frac{1}{2 \cdot \tau_d} = \frac{v_{sat}}{2 \cdot W}$$

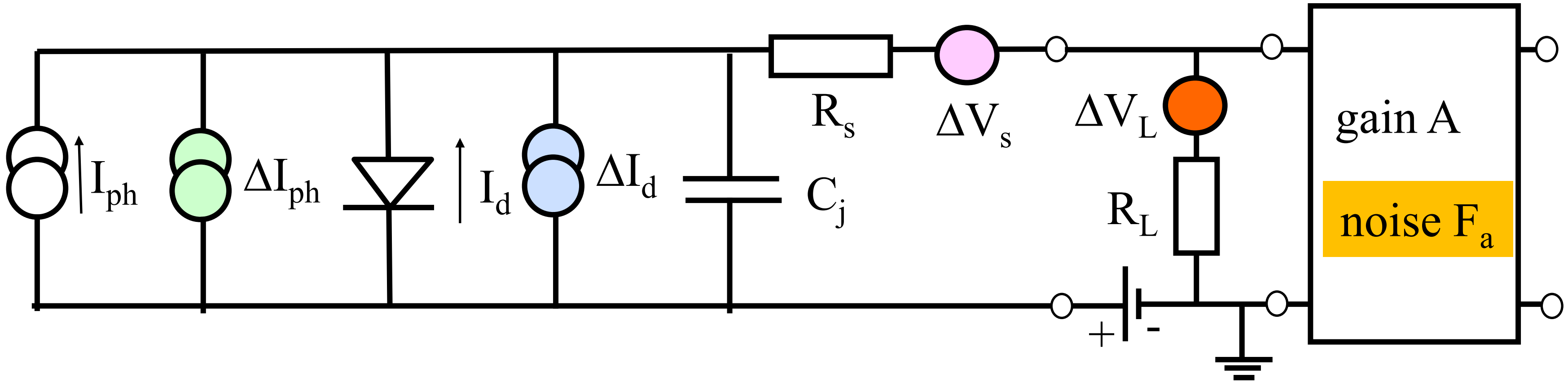
Typically ~ τ_d=10 ps

3) The diffusion time in the diffusion regions is «very long»:

$$\tau_D \cong \frac{L^2}{D} \quad \Rightarrow \quad f_{2D} \cong \frac{1}{2\tau_D} = \frac{D}{2L^2}$$

Typically ~ τ_D=100 ns

5.6 Equivalent Circuit with Noise Sources



$$F_a = \frac{(S/N)^2_{in}}{(S/N)^2_{out}}$$

Photonic (shot) noise:

$$\Delta I_{ph}^2 = 2q\left(|I_0| + \left|I_{background}\right|\right)\Delta f$$

Thermal noise on the resistances:

$$\Delta V_s^2 = 4kTR_s\Delta f$$

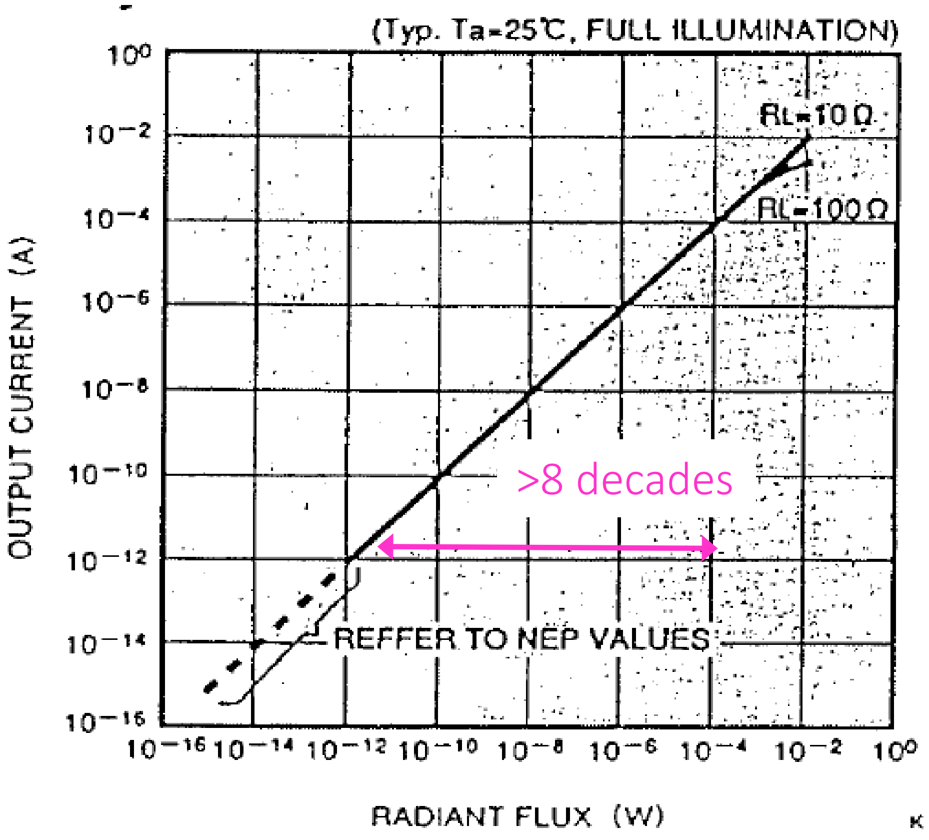
$$\Delta V_L^2 = 4kTR_L\Delta f$$

Dark current noise:

$$|\Delta I_{dark}|^2 = 2\frac{q}{\Gamma}|I_{dark}|\left(e^{qV/\Gamma kT} + 1\right)\Delta f$$

$$NB: for\ a\ practical\ diode:\ I = I_0\left(e^{qV/\Gamma kT} - 1\right)\ with\ \Gamma = ideality\ factor\ [1-2]$$

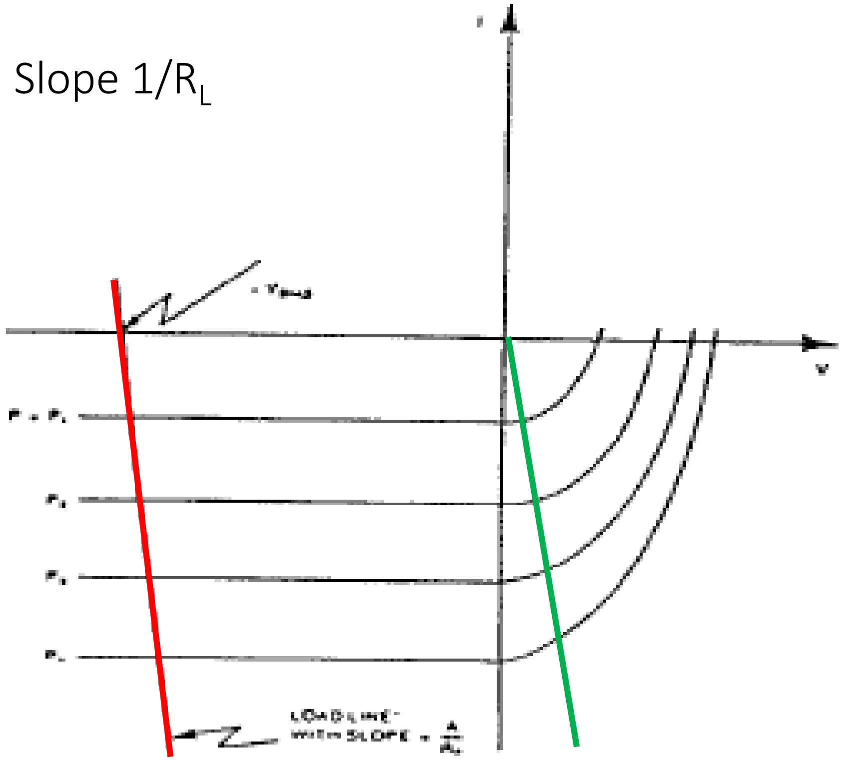
5.6 Dynamic Range



>8 decades

$$NEP = \frac{\sqrt{F_a} \cdot \sqrt{\Delta I_{ph}^2 + \Delta I_{dark}^2 + \frac{\Delta V_s^2 + \Delta V_L^2}{R_L^2}}}{\eta q / h\nu}$$

Slope $1/R_L$



Small R_L → less saturation effect

5.6 Photodiodes: Summary

Quantum Efficiency:	almost optimal	> 90%
Gain	no	1
Noise	electronic	Load resistance
Voltage	zero or small	0-10 V reverse
Spectrum	adaptable	UV - VIS - IR

Compatible with CMOS → cameras (see the respective chapters)

Outline

5.1 p-n junctions (review)

5.2 p-n photodiodes

5.3 PIN photodiodes

5.4 Case study: color sensors

5.5 Solar cells

5.6 Electronic circuits, cut-off frequencies, noise

5.7 Avalanche photodiodes

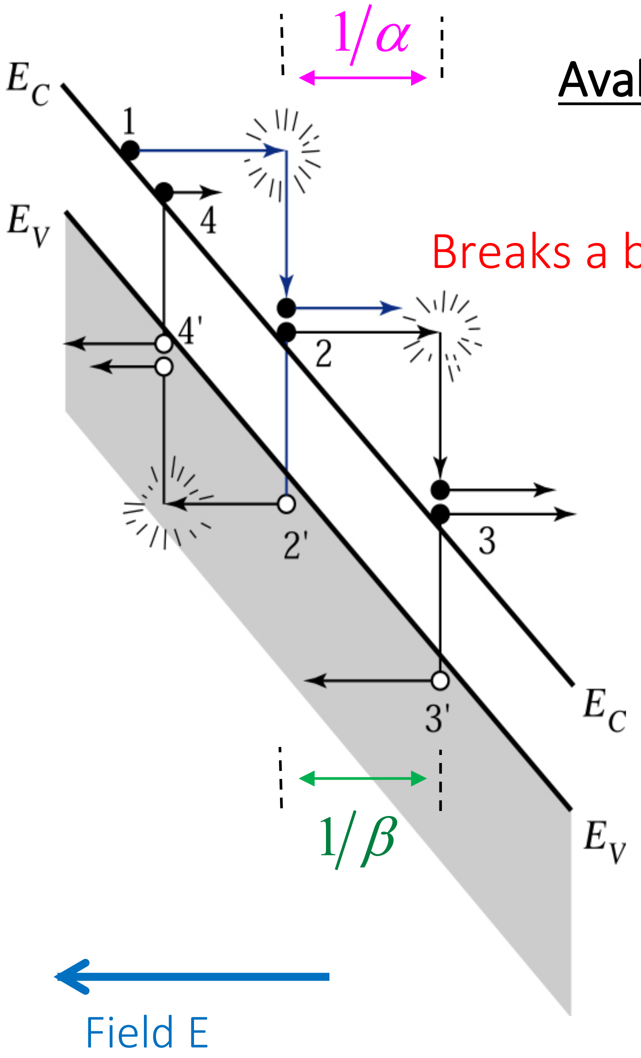
5.7 Avalanche Effect

α = ionisation coefficient
of electrons [1/cm]
(much more efficient than holes)

Silicon:

$$k \equiv \frac{\beta}{\alpha} \cong 0.1$$

β = ionisation coefficient
of holes [1/cm]



Avalanche

Breaks a bond → e/h pair creation

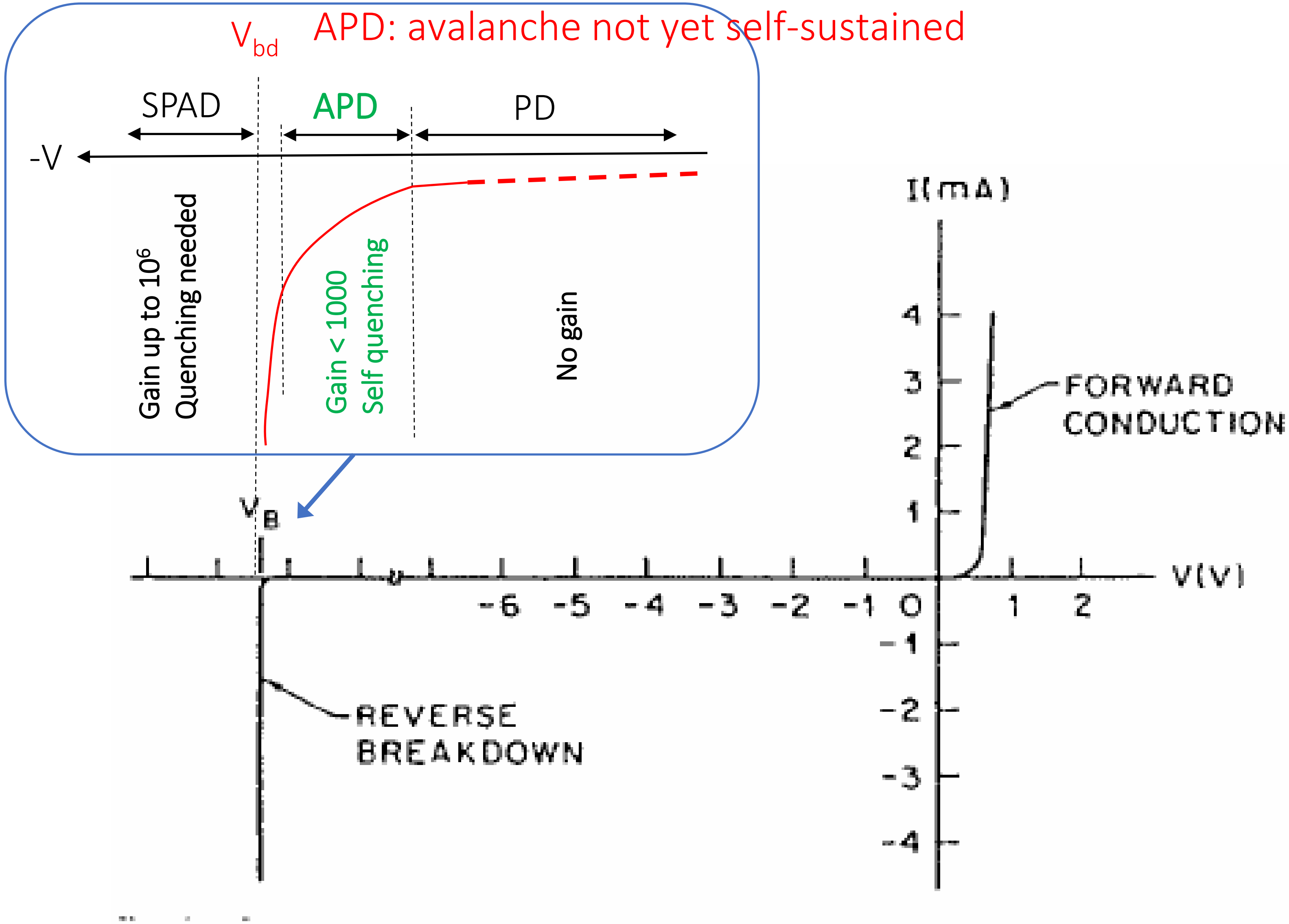
Bi-carriers !

⇩

Self-sustained
above V_{bd}!

S.M. Sze, « Semiconductor devices, physics and technology »

5.7 I(V) Plot



V_{bd}

APD: avalanche not yet self-sustained

SPAD

APD

PD

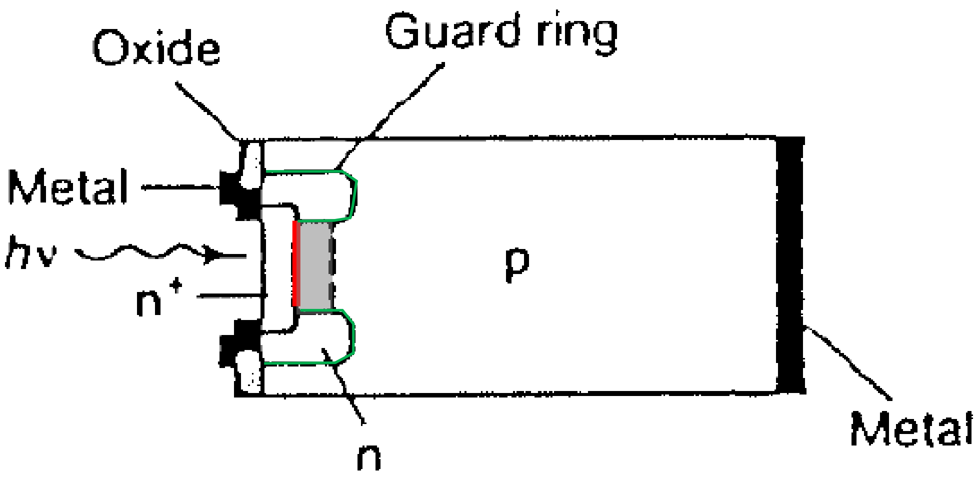
-V

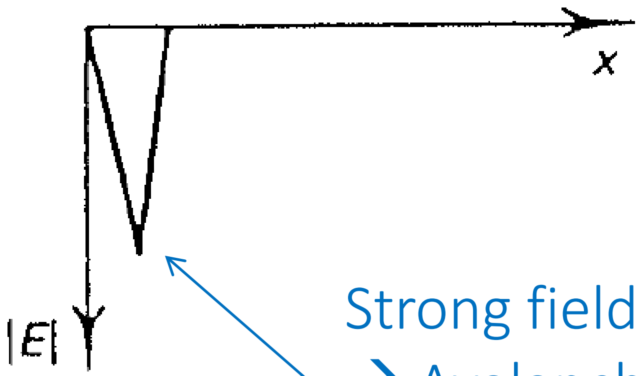
Gain up to 10^6
Quenching needed

Gain < 1000
Self quenching

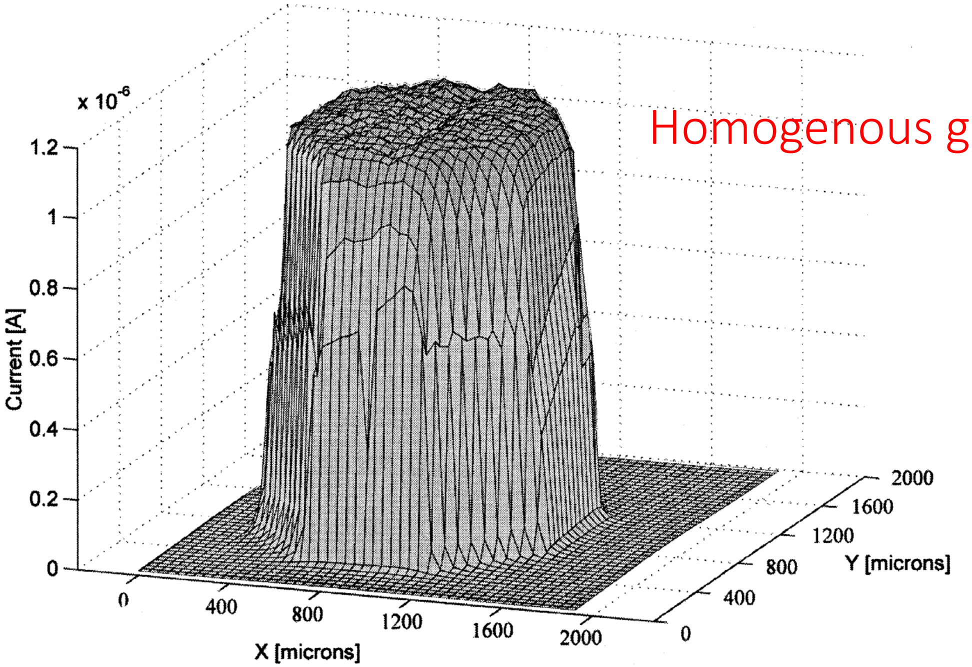
No gain

5.7 Structure with a Guard Ring





Avoids latch-up at the boundaries
(*lightning rod* effect)



Homogenous gain

Strong field (at corners)

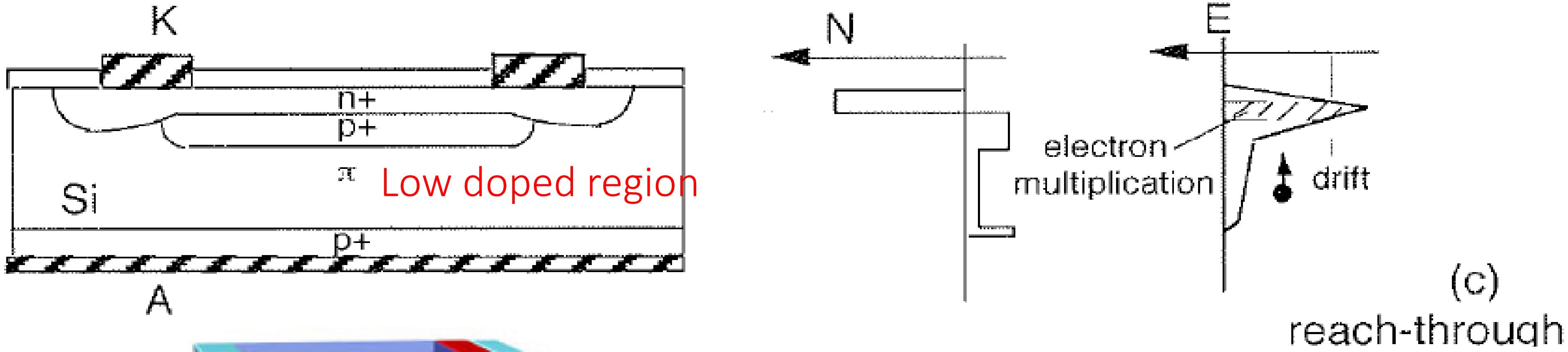
→ Avalanche could take place there

→ introduce a (weakly doped) guard ring to reduce it

A. Pauchard et al., Sensors and Actuators 82 (2000) 128–134

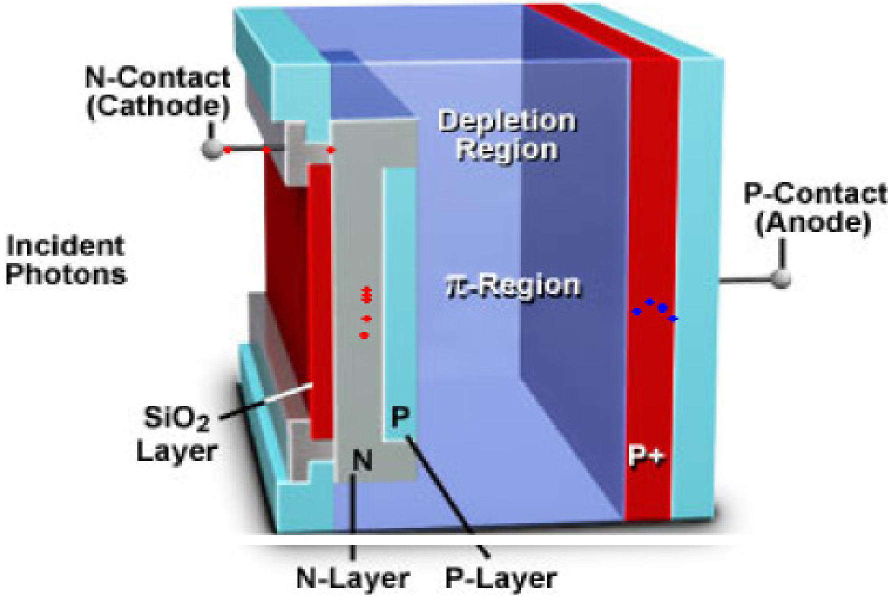
5.7 APD Structure: Reach-Through

S. Donati, « Photodetectors, devices, circuits and applications »

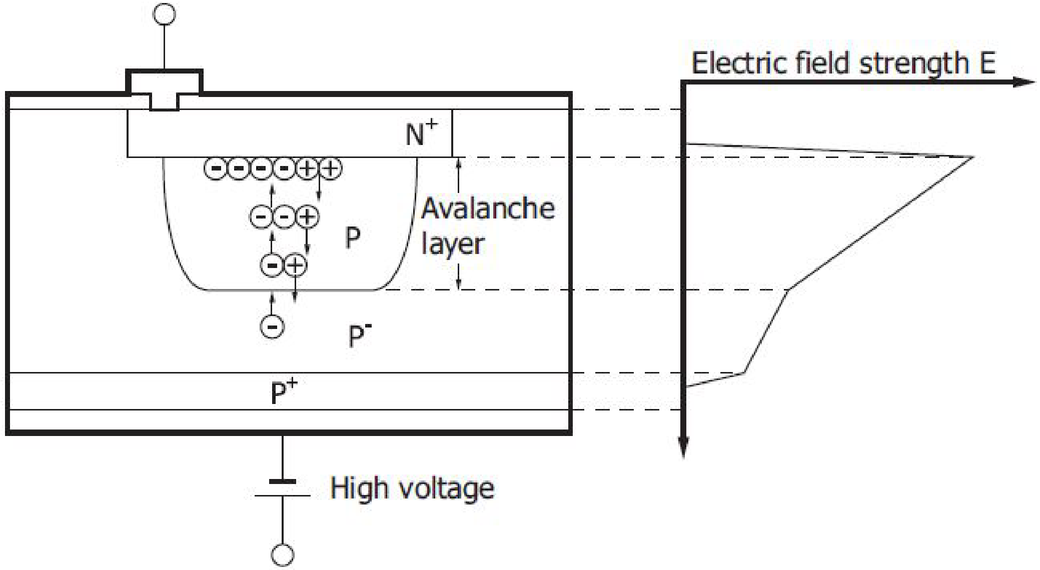


Low doped region

(c)
reach-through

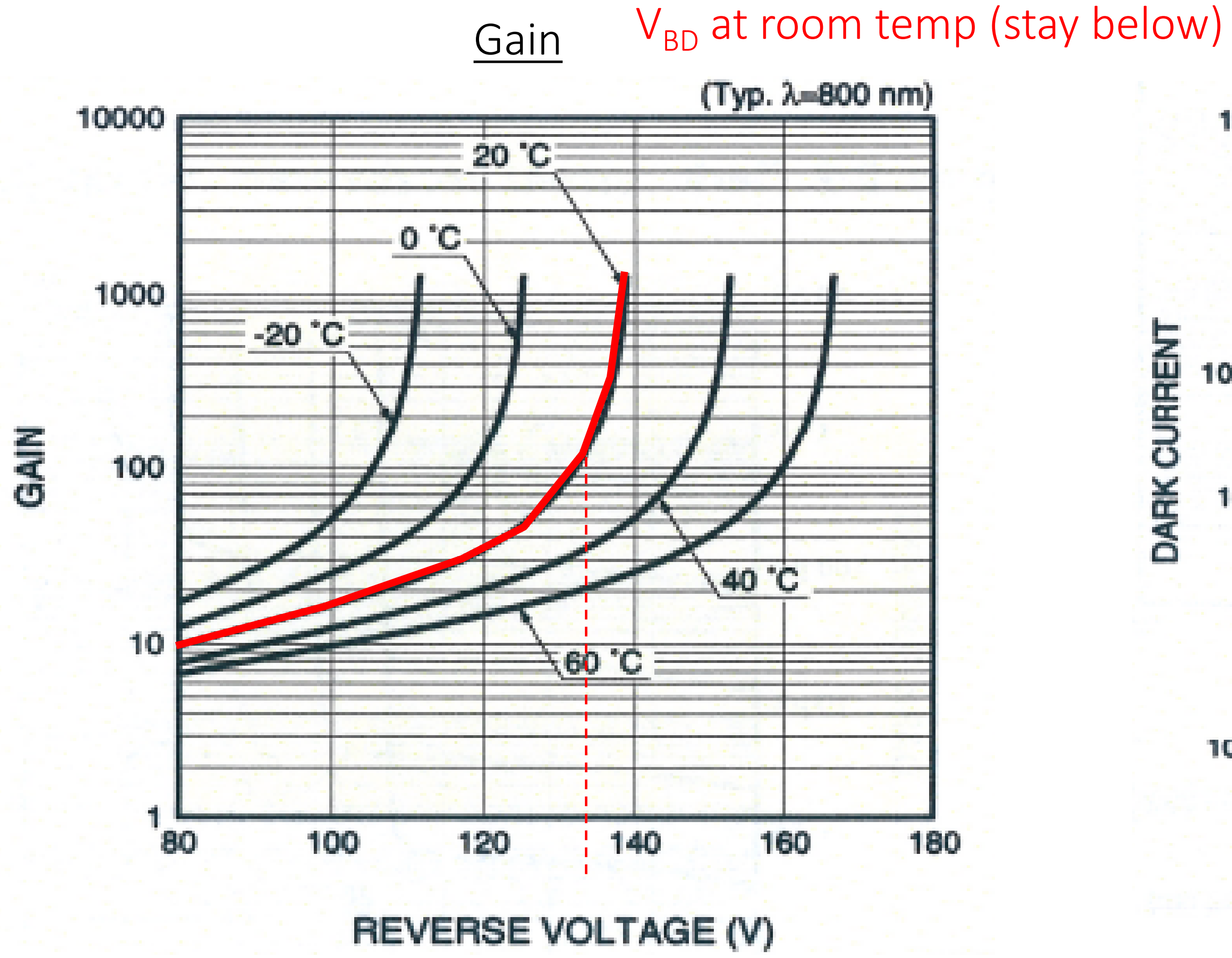


http://micro.magnet.fsu.edu/primer/java/digitalimaging/avalanche/index.html

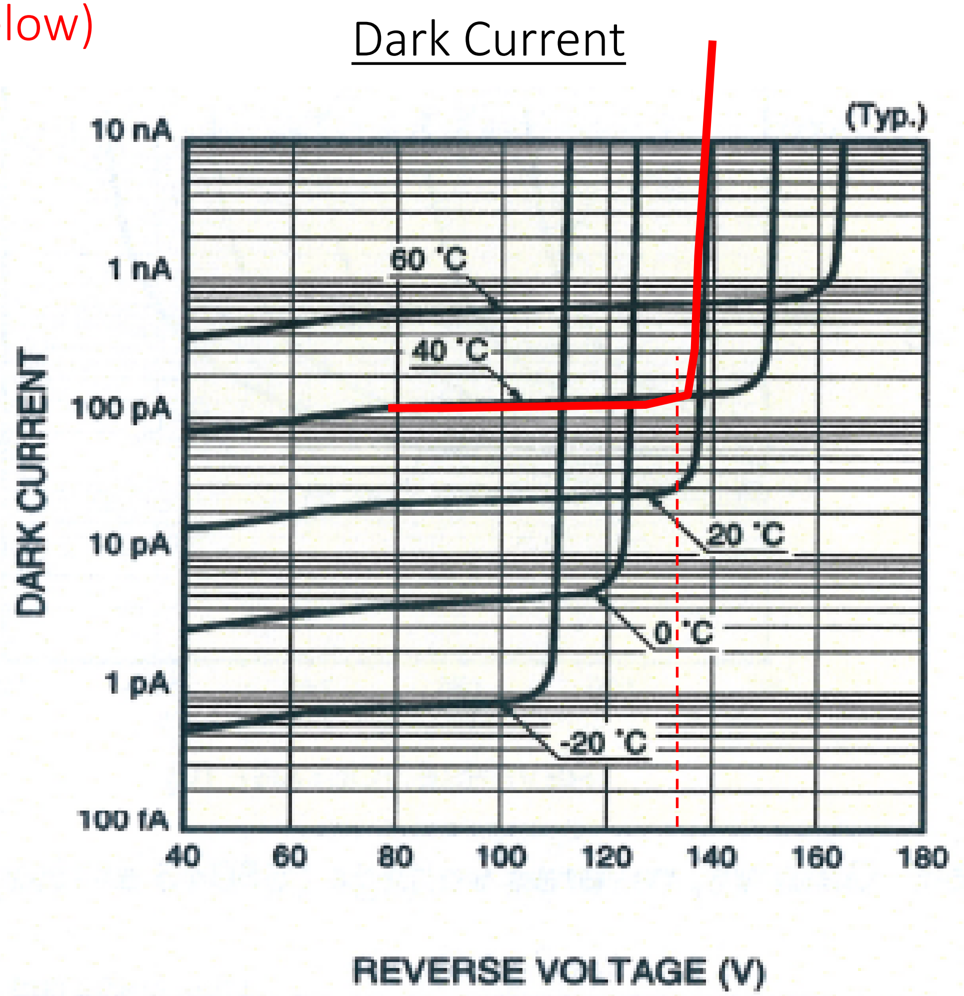


Near IR structure, Hamamatsu, Handbook 2014, chap.3

5.7 APD: Gain and Dark Current



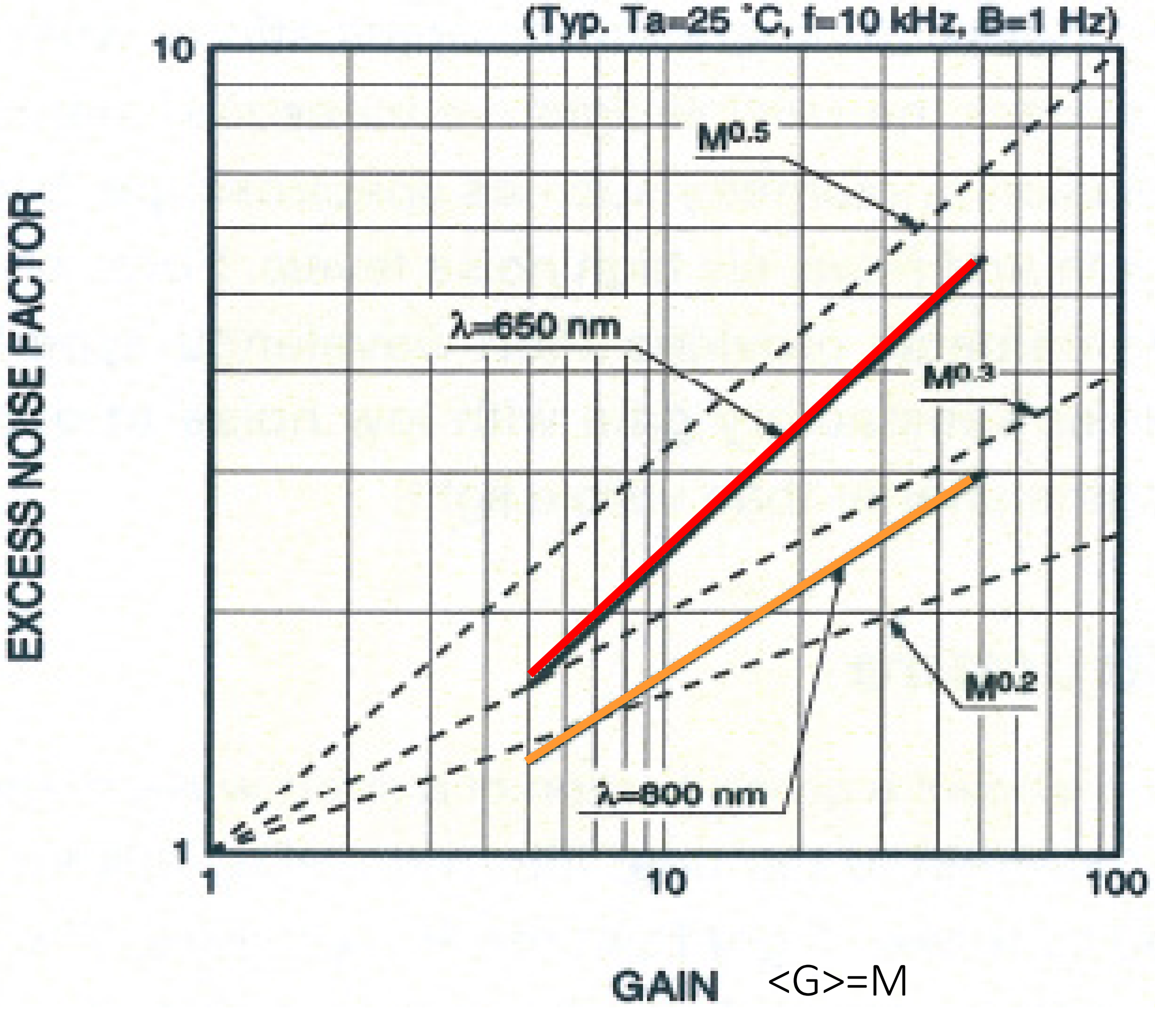
Typically: 100



Typically: 10-100 pA

Hamamatsu
SI APD series S238x

5.7 APD: Noise and Excess Noise Factor F



<G>=M

Hamamatsu SI APD series S238x

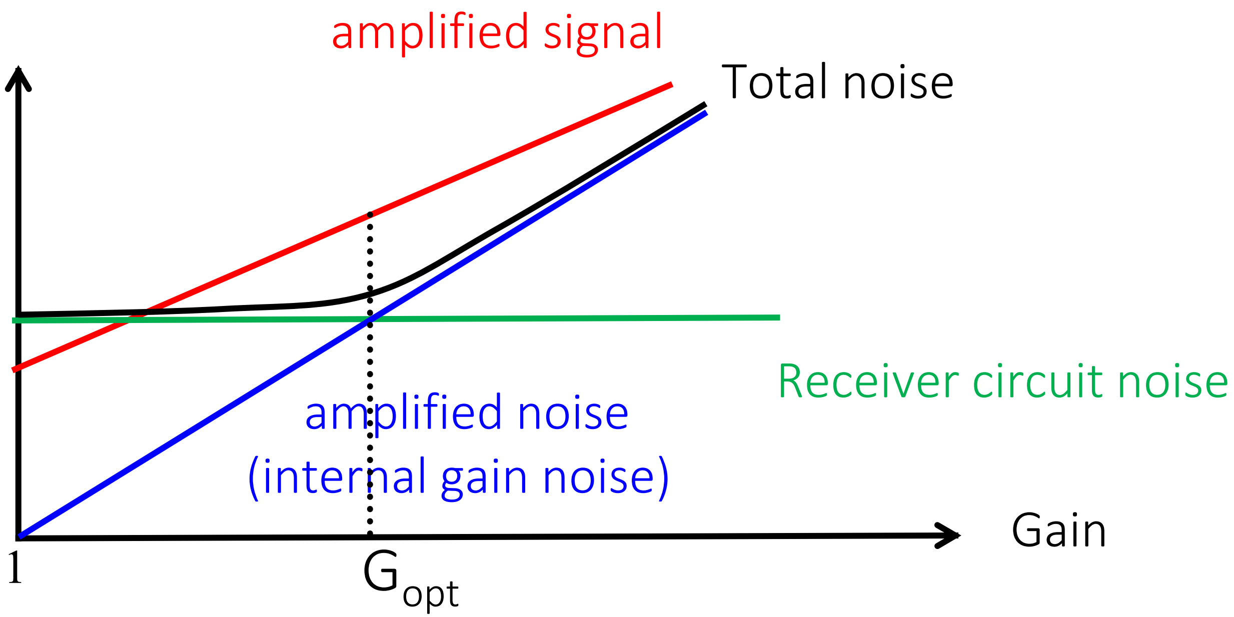
$$F = \frac{(S/N)_{in}^2}{(S/N)_{out}^2}$$

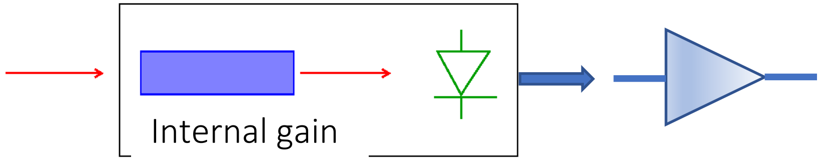
$$F = \frac{\langle G^2 \rangle}{\langle G \rangle^2} \cong \langle G \rangle^x$$

Typically:
x = 0.3
F = 3…5

5.7 Reminder: Optimal Amplification

If noise is amplified more than the signal, would it not be better not to amplify at all?

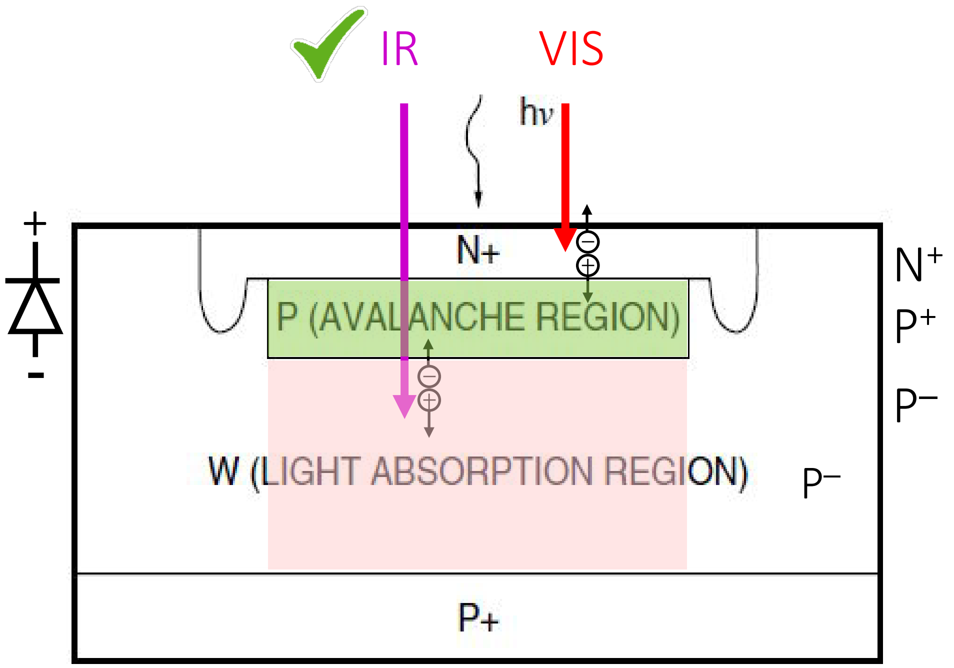




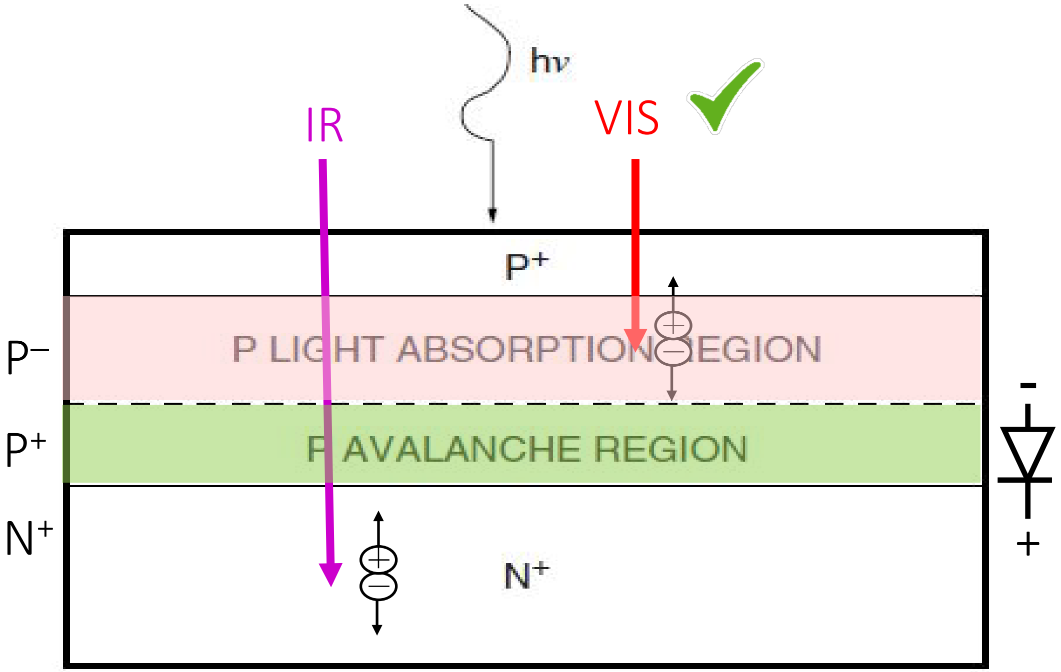
There exists an optimal internal gain, at which the internal gain noise exceeds the receiver circuit noise.

5.7 Front or Backside Illumination?

Frontside illumination



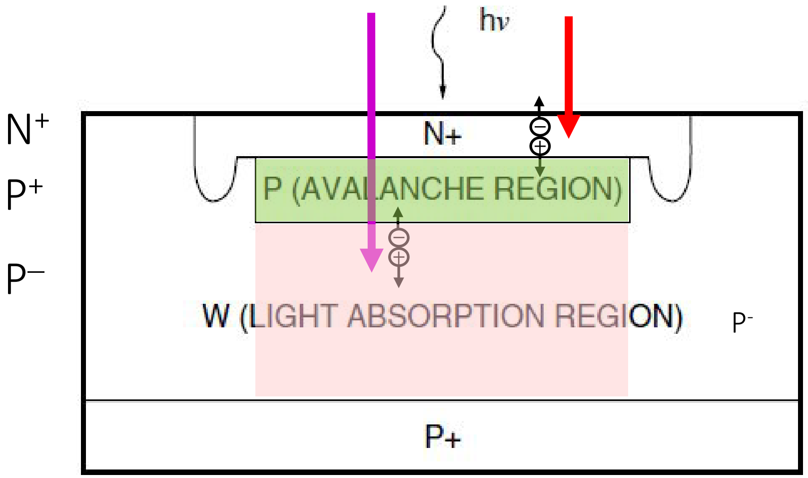
Backside illumination



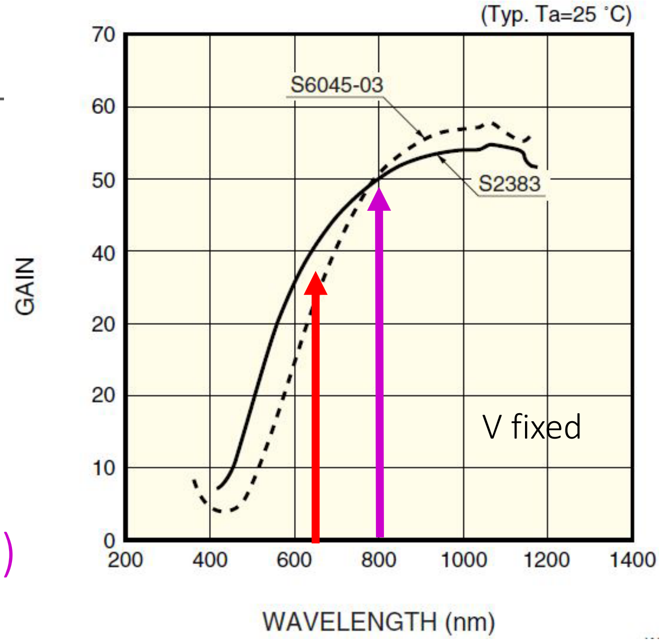
Reminder: electrons have a much better ionization coefficient (and the corresponding excess noise factor is lower than for holes – not demonstrated here)

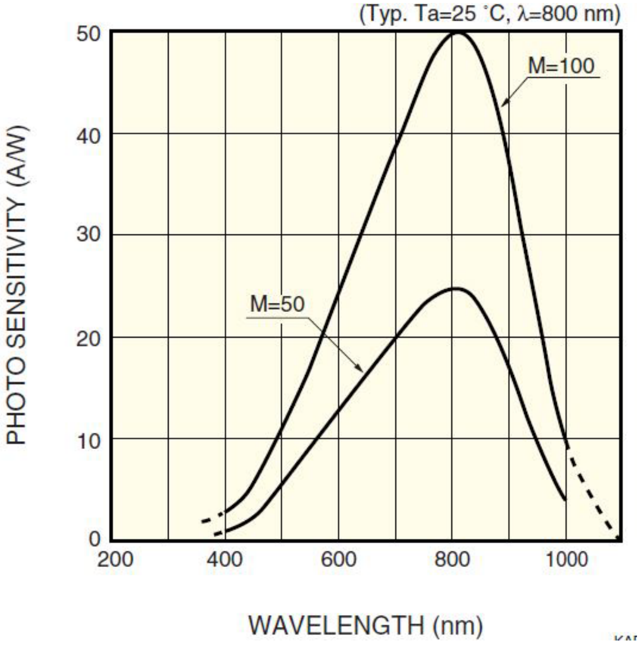
→ Electron injection is required for high gain and low (excess) noise

5.7 APD Structure in Silicon for the Near IR



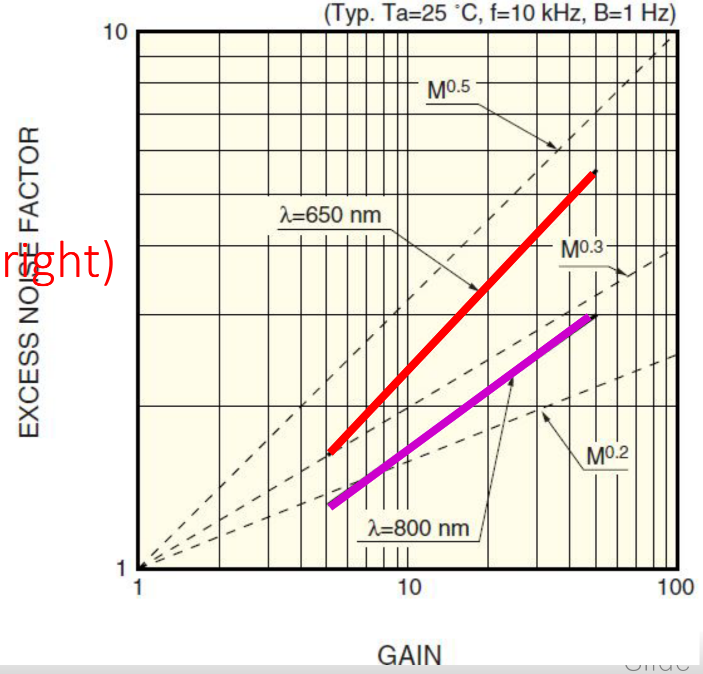
IR: electron injection
large gain (top right)
low noise (bottom right)



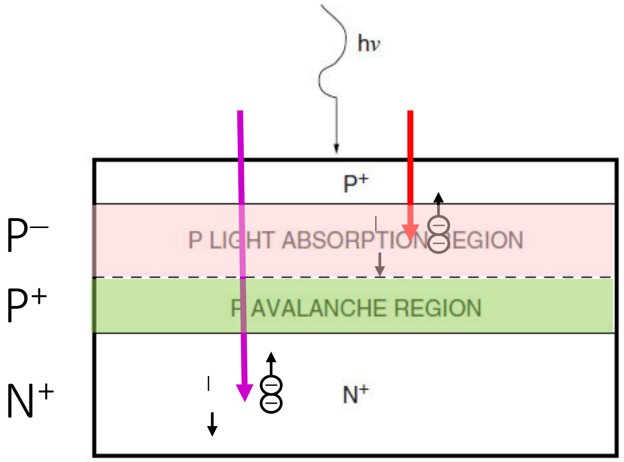


VIS: hole injection
lower gain (top right)
higher noise (bottom right)

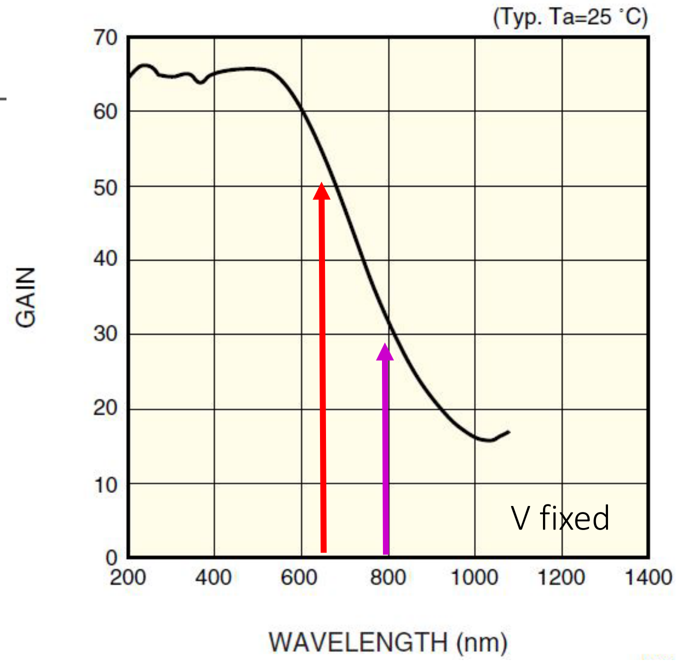
Hamamatsu Solid State division,
«Characteristics and use of Si APD»,
Technical information SD-28

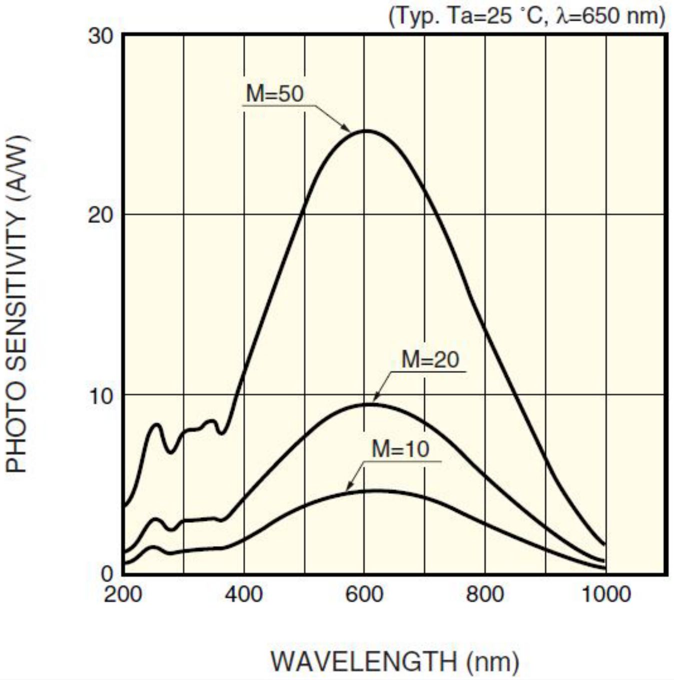


5.7 APD Structure in Silicon for the Visible



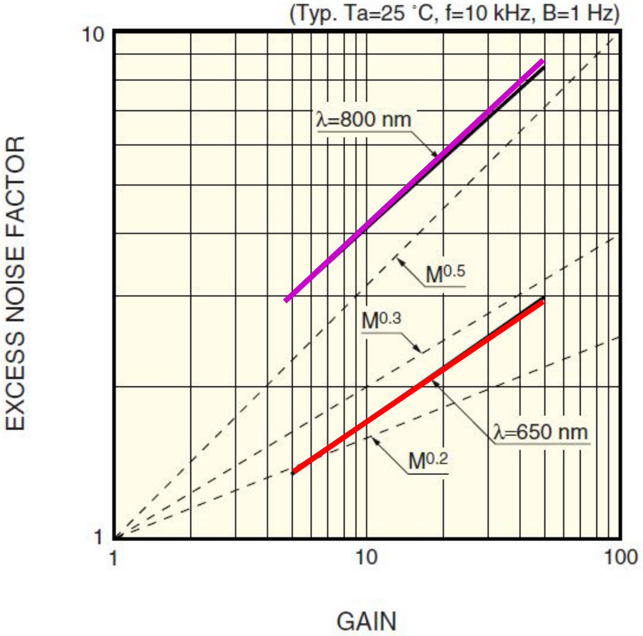
IR: hole injection
lower gain
higher noise





VIS: electron injection
larger gain
lower noise

Hamamatsu Solid State division, «Characteristics and use of Si APD», Technical information SD-28



5.7 Avalanche Photodiode: Summary

Quantum efficiency:	near-optimal	> 90%
Gain	average	50 - 200
Noise	good	dark current or signal shot noise limited
Excess noise	high	F: 3 - 5
Voltage	high	10-200 V
Spectrum	adaptable	UV - VIS - IR
Voltage stabilization		Critical

Photon counting possible

Geiger mode and SPAD for digital detection

Technologically compatible with microelectronics

Take-Home Messages/W5-3

5.6 Photodiode bandwidth & electronic circuits:

- Which phenomena limit the speed of a photodiode? What is the cut-off frequency?
- Which electronic circuits are used with photodiodes? Describe their respective advantages.
- Describe the physical effects limiting the dynamics of a photodiode

5.7 Solar cells:

- How does a solar cell work?

5.8 Avalanche photodiode (APD):

- Describe an avalanche photodiode. Why is a « guard ring » required ?
- What is the « excess noise » in an avalanche photodiode? Explain the optimization of the internal gain as function of the electronic noise

Acknowledgements

Previous course version: P.-A. Besse, 2023

Slide preparation and first revision:

- Edwin Bertschy, EPFL MA
- Victoria Chalain, EPFL MA

Appendix 5.1: Band diagrams and pn junction

A5.1 Fundamental equations (1)

1) Potential energy : $$E_{pot} = E_{vac} = (-q) \cdot \varphi$$ The potential energy is the vacuum level

2) Maxwell :

$$div(\vec{E}) = \frac{\rho}{\varepsilon_0 \varepsilon} = \frac{q\ (p + N_d^+ - n - N_a^-)}{\varepsilon_0 \varepsilon}$$

1D ⇨ $$E_x \propto +\int \rho \cdot dx$$ The electric field is the integral of the net charges

$\propto$ = proportional

3) Maxwell :

$$rot(\vec{E}) = -\frac{\partial \vec{B}}{\partial t} = 0 \quad \Rightarrow \quad \vec{E} = -\overrightarrow{grad}(\varphi) = \frac{1}{q}\,\overrightarrow{grad}(E_{vac})$$

1D ⇨ $$E_x \propto +\frac{\partial E_{vac}}{\partial x}$$ The electric field is the slope of the vacuum level *(first derivative)*

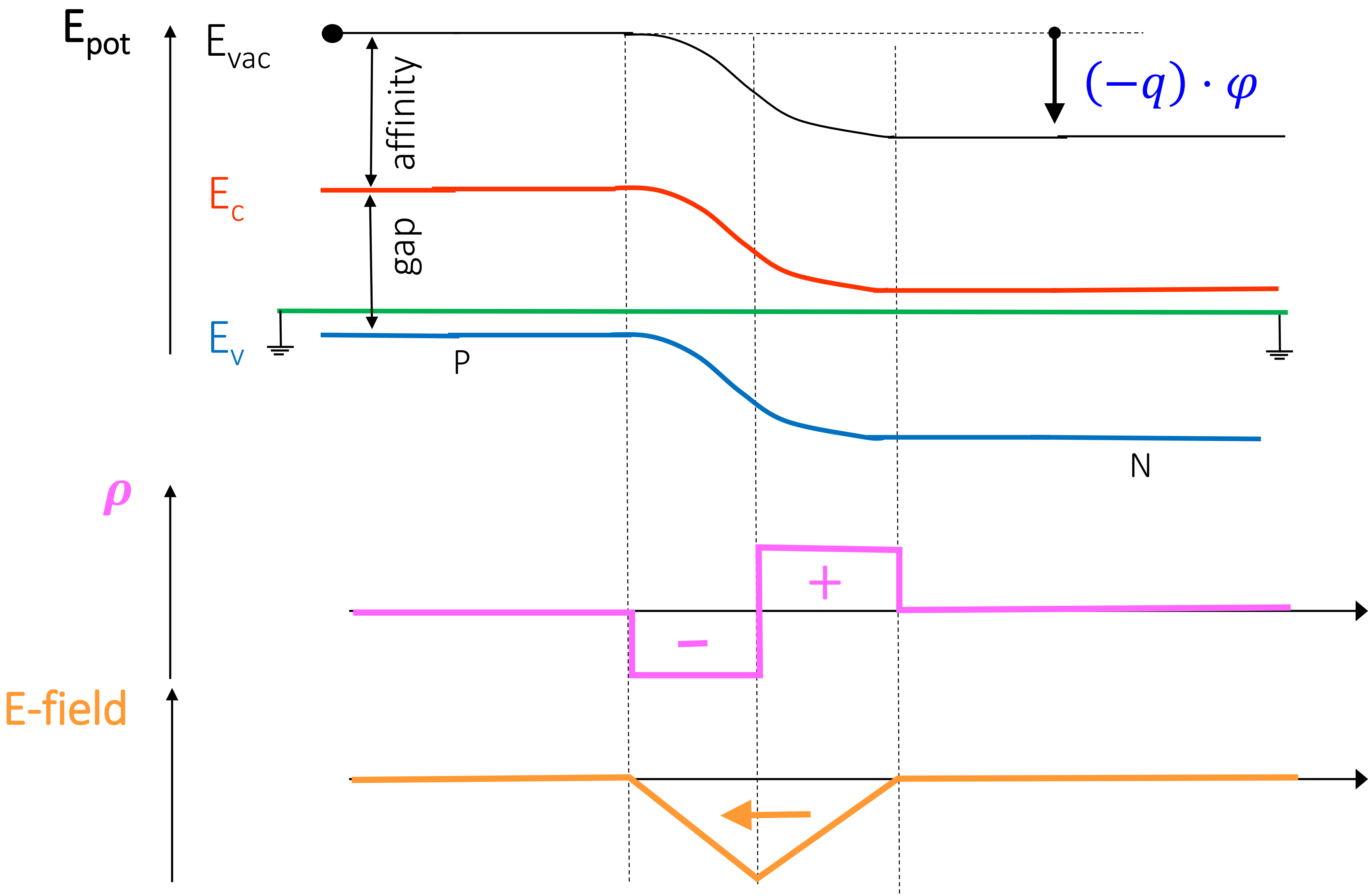
A5.1 Fundamental equations (2)

4) Poisson equation :
from 2) and 3)

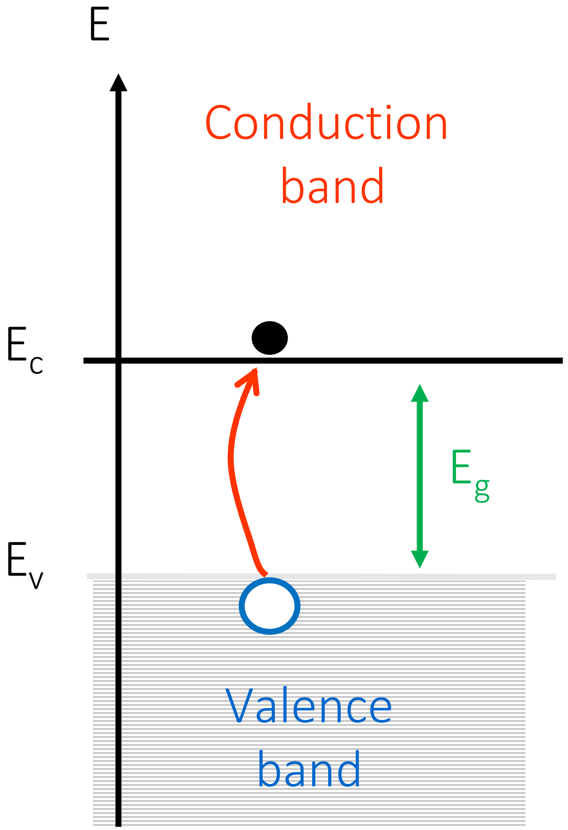
$$\boxed{\Delta\varphi = -\frac{\rho}{\varepsilon_0\varepsilon} = -\ \frac{q\ (p + N_d^+ - n - N_a^-)}{\varepsilon_0\varepsilon} = -\frac{1}{q}\Delta E_{vac}}$$

1D $\Longrightarrow$ $\boxed{\rho \propto +\frac{\partial^2 E_{vac}}{\partial x^2}}$ The net charges are the curvature of the vacuum level *(second derivative)*

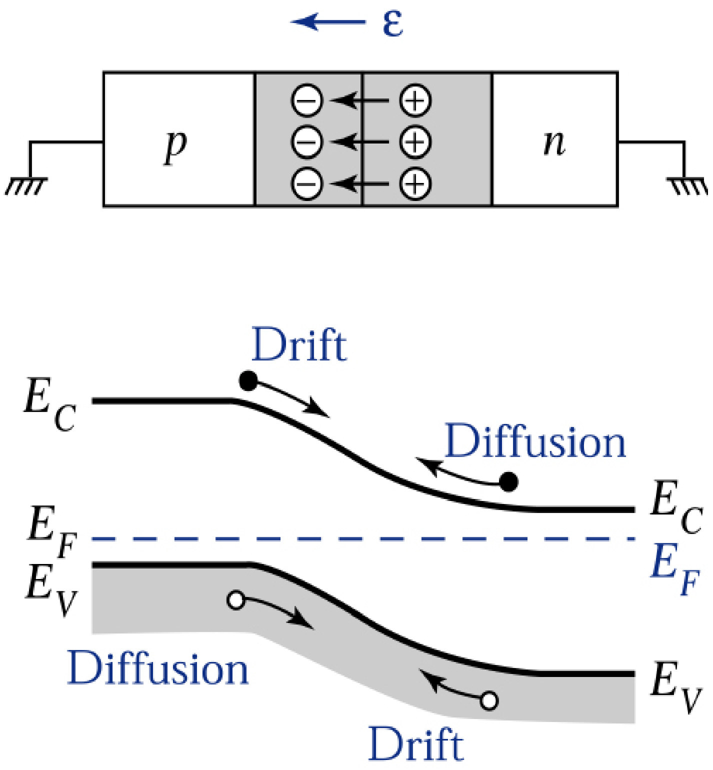
A5.1 Band diagram



A5.1 Band structure

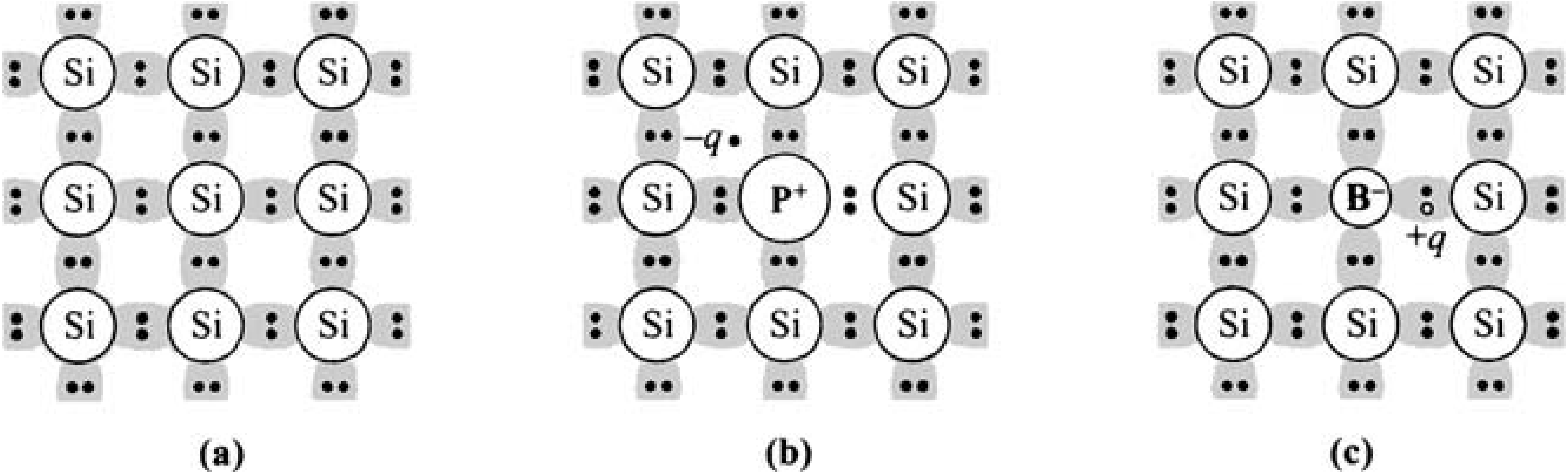


Jonction p/n



S.M. Sze, « Semiconductor devices, physics and technology »

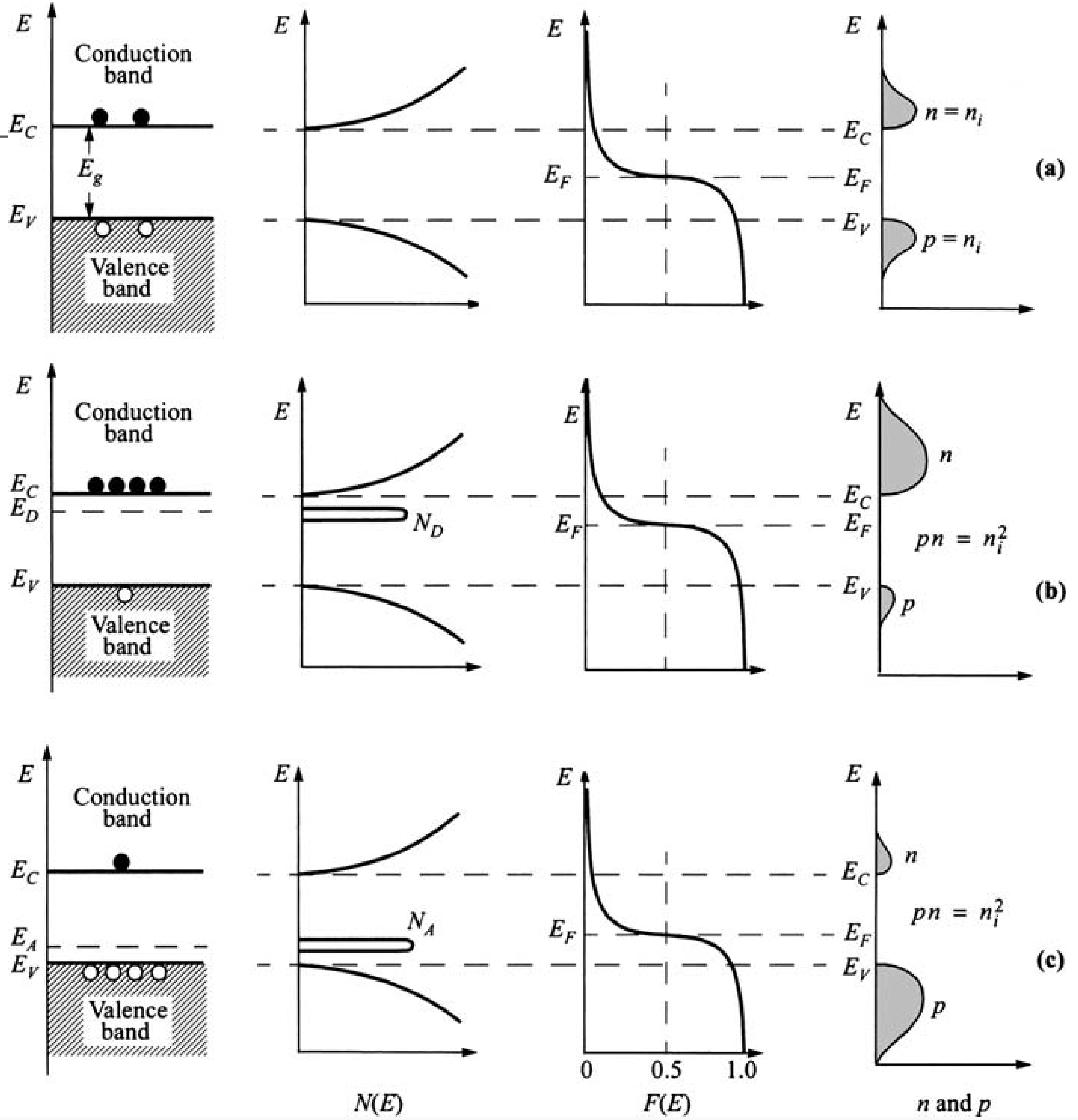
A5.1 Semiconductor doping



Three basic bond pictures of a semiconductor. (a) Intrinsic Si with no impurity. (b) n-type Si with donor (phosphorus). (c)p-type Si with acceptor (boron).

S.M. Sze, K.K. Ng, « Physics of Semiconductor devices », 3rd edition

A5.1 Mass-action law



Nondegenerate semiconductors:

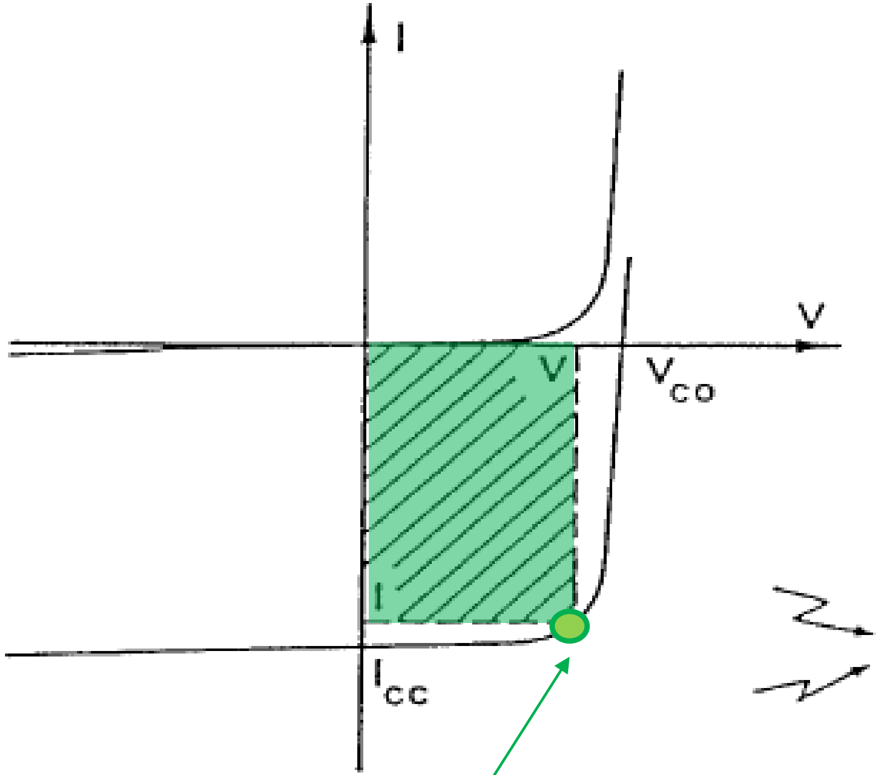
$$p \cdot n = N_C N_V \exp\left(-\frac{E_g}{kT}\right) = n_i^2$$

S.M. Sze, K.K. Ng, « Physics of Semiconductor devices », 3rd edition

Appendix 5.2: Solar Cells

A5.2 Solar Cells

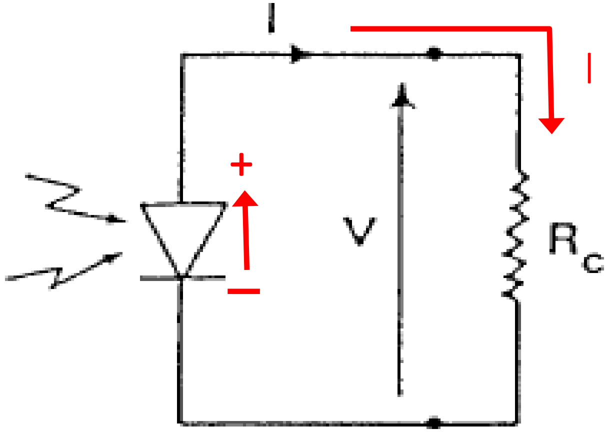
$$P_{el} = U \cdot I$$



Power = shaded area (rectangle) – direct power generation

Optimal load resistance R$_c$:

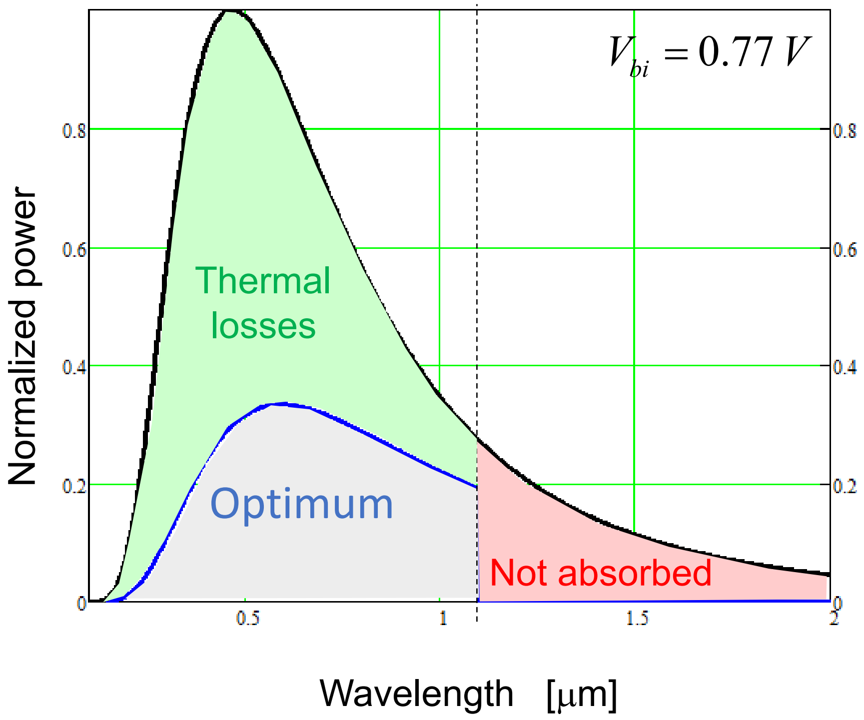
$$R_c = \frac{V_{\max}}{I_{\max}}$$



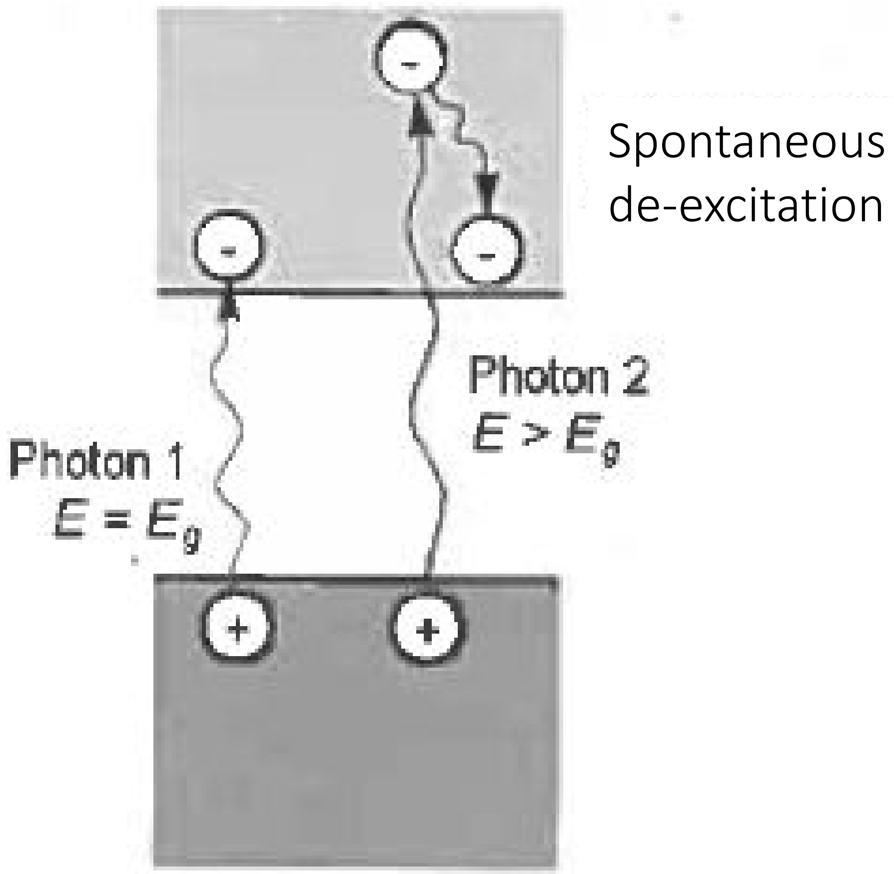
$$P_{el} \cong V_{bi} \cdot I_{ph} = V_{bi} \cdot R_I P_{opt}$$

A5.2 Maximum Efficiency of Solar Cells

Monocrystaline Si



η_{tot} = 31 % (E_g=1.1 eV)



Spontaneous de-excitation

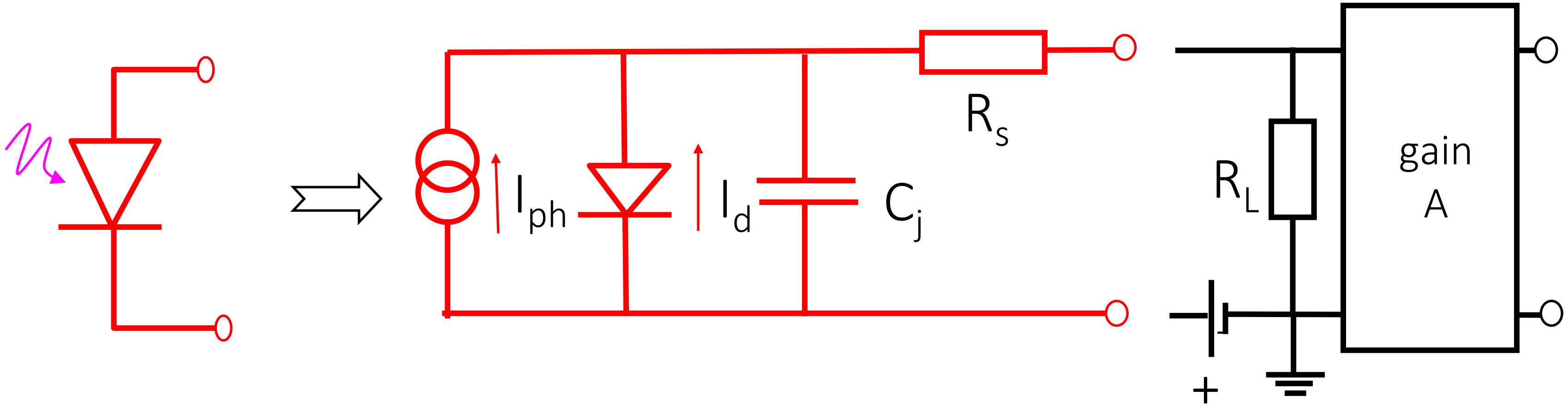
Thermal losses: we generate «only» the bandgap energy

A. Labouret, M. Villoz,
« installations photovoltaiques »,
Dunod, 2012

A5.2 Equivalent Circuit of a Photodiode

R_d = differential (shunt) resistance =

$$1/\frac{\delta I_d}{\delta V}$$



C_j = junction capacitance

R_L = load resistance

R_S = series contact resistance

- Dark current: I_d (thermal generation)

- Photocurrent: $I_{ph} = I_{sig\text{-}AC} + I_{sig\text{-}DC} + I_{bg}$