Optoelectronics

Key notes

6/ Detectors

1. Basics

After analysing the formalism for LEDs, there is no secret in the detectors principles. A semiconductor detector behaves exactly equal to a light source but in the other sense: a photon arrives to the semiconductor and produces a pair of carriers (electron+hole). Nevertheless, there are a couple of concepts that must be keep in mind.

First of all, when we want to use a semiconductor junction as a detector we want the carriers to arrive as fast as possible the ends of the semicontuctor and so enter the circuit. In contraposition with LED, now the potential applied to the semiconductor must be reversed to the carriers feel a stronger field and drift faster to the conductors. The stronger the potential V applied the harder will be for carriers to recombinate.

Secondly, as the LEDs emit a minimum wavelength determined by the energy gap of the material, detectors will not absorb photons with energies smaller than this energy gap. Each photodiode will have a characteristic maximum detectable wavelength called the cut-off wavelength $\lambda_c = hc/E_g$.

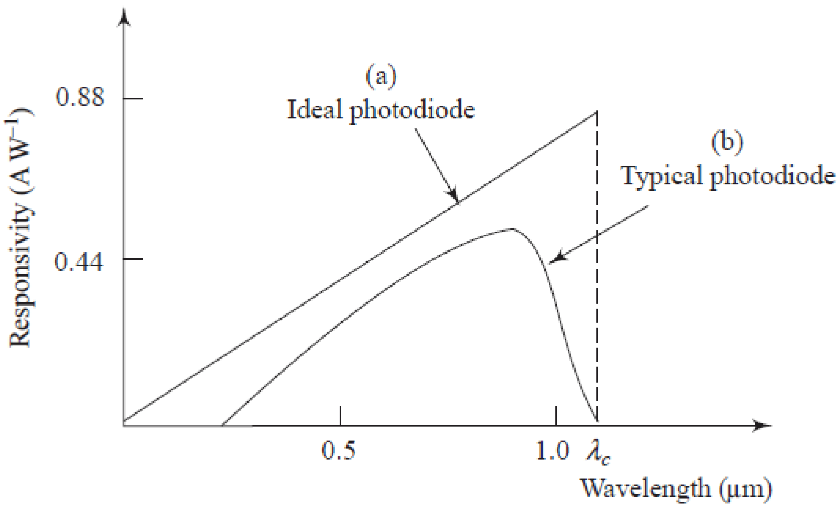
Finally, the photodiode will have a different responsibility for each wavelength $\Re(\lambda)$, this responsibility is the coefficient between the photocurrent I_p (rate of flow of carriers, Amperes) and the incident power arriving to the diode P_{in} (optical power, Watts). The relation between both magnitudes can be expressed as a function of the absorption coefficient $\alpha(\lambda)$, The transmission coefficient between air and the photodiode $T(\lambda) = (1 - R(\lambda))$ and the energy of the photon $E_{ph} = h\nu = hc/\lambda$

$$\Re = \frac{I_p}{P_{in}} = \frac{(1-R)e}{h\nu}\left(1 - e^{-\alpha d}\right)$$

Where we can introduce the quantum efficiency of the detector, η, as:

$$\Re = \frac{I_p}{P_{in}} = \eta\frac{e}{h\nu} = \eta\frac{e}{hc}\lambda$$

Near the cut wavelength the efficiency is usually considered constant even it falls dramatically to 0 at λ_c.



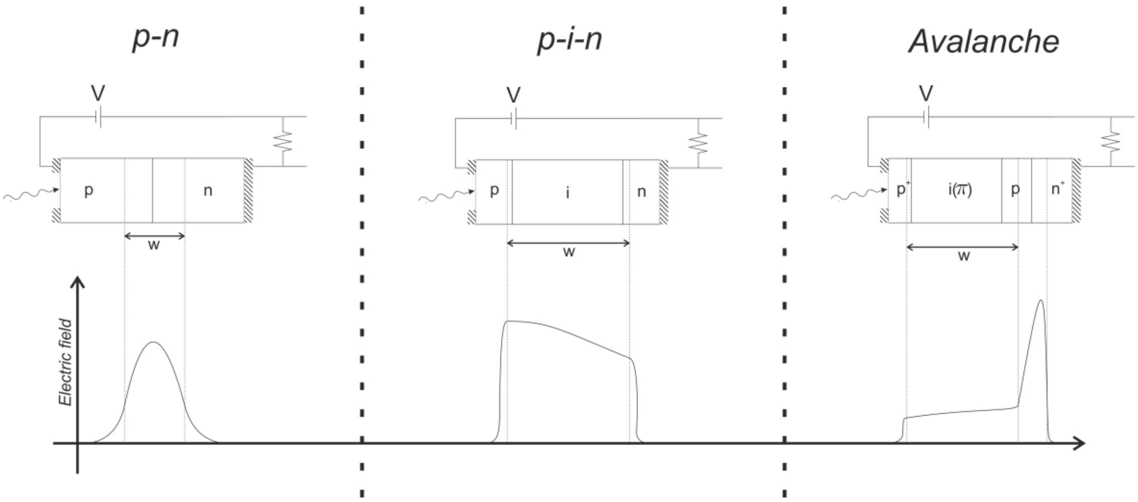
2. Detector types

There are mainly 2 types of photodetectors based on semiconductors: photodiodes, that use the depletion region as detection zone as explained before; and photoconductors, doped semiconductors which vary their conductivity as function of the received light.

- **p-n Photodiode**. This is the simplest case in which a p-n homojunctions is used as detector. The depletion region in between the p and n regions absorbs light and generate pairs of carriers. The width of the depletion region is a function of the semiconductor properties and is defined as:

$$w = \sqrt{\frac{2\epsilon}{e}(V_d + V)\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$$

- **p-i-n Photodiode**. In the previous case, the detection region will vary with the voltage applied to the diode. In order to avoid this and have an almost constant width of detection, an intrinsic semiconductor is introduced in between the p and n regions. This zone will act as detection zone because there is an almost constant field along it. Usually this type of photodiodes are heterojunctions to the input face do not absorb the desired photons and only the intrinsic produce pairs.
- **Avalanche photodiode**. This type of photodiode consists in two region heavily doped n^+ and p^+, and very slightly positive doped region considered intrinsic $i(\pi)$ and a p region. This peculiar structure shown in the figure has been design so there is a small region with a really intense field. The electrons created in the intrinsic region get accelerated when arriving the interphase $p - n^+$ providing them with an extra momentum. These accelerated electrons can create extra pairs of carriers multiplying the final current. This effect is called avalanche effect.



- **Photoconductors**. As mentioned before, this last type only uses a negatively doped semiconductor in which the electrons have enough mobility to be considered a conductor. The light is absorbed by the semiconductor, a temporal electron appears increasing the conductivity (reducing the resistivity) and so incrementing the current in the circuit for a short period of time.

3. Noise considerations

To conclude, it is interesting to identify the main types of noise that this kind of detectors can be affected by. There are 3 types:

- **Dark current noise**. Noise produced by an almost constant background of photons that are being absorbed by the detector.
- **Quantum or shot noise**. This type of noise is produced by random arrival of photons in the detector, for example cosmic rays.
- **Thermal noise**. As seen along the previous section, the diodes properties are very sensitive to variations in the temperature. Detectors are no exceptions as the responsibility will change with temperature.

Recommended bibliography:

- Anil K. Maini, << Lasers and Optoelectronics: Fundamentals, Devices and Applications>>, 2013 John Wiley and Sons Ltd, ISBN: 978-1-118-45887-7, Chapter (5, 9, 10)
- John P. Dakin and Robert G.W. Brown, << Handbook of Optoelectronics, Second Edition: Concepts, Devices and Techniques – Volume One>>, 2018 Taylor & Francis Group, ISBN: 978-1-4822-4178-5, Chapter (10,11,12,19)
- Giovanni Ghiones, <<Semiconductor Devices for High-Speed Optoelectronics>>, 2009 Cambridge University Press, ISBN: 978-0-511-63420-8, Chapter (4-5)