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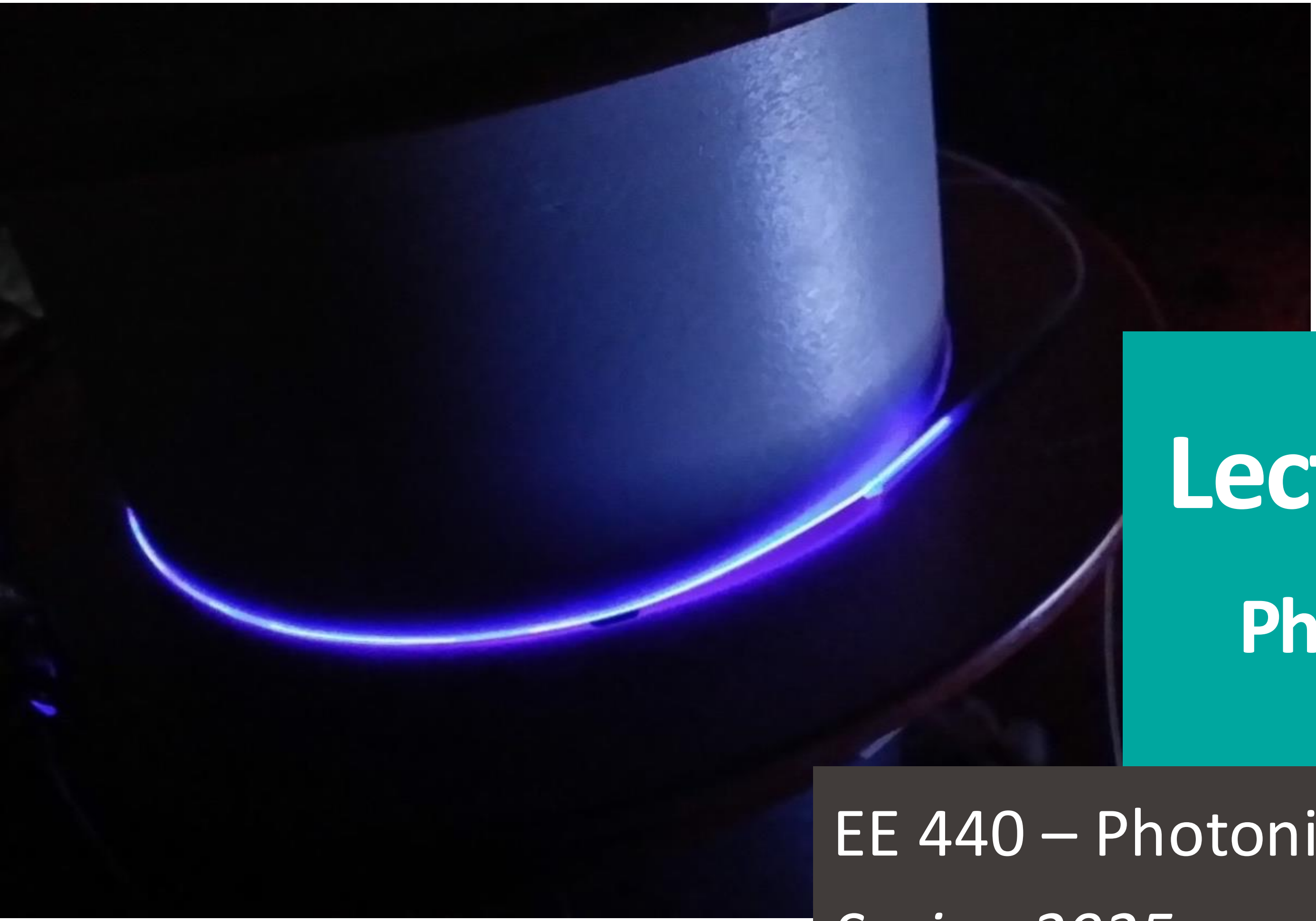

Lecture 8

Photodetectors

EE 440 – Photonic systems and technology

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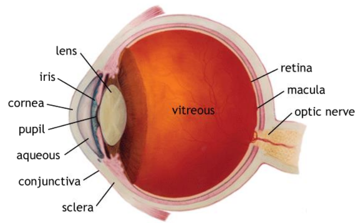
Basic operation principle

Photodetector

Photodetectors convert light (power) into an electrical signal (photocurrent)

- Uses the photoelectric effect.



The eye is a photodetector:

- Spectral response is limited to wavelength of 0.4 μm to 0.7 μm

For telecommunication need:

- Good sensitivity (responsivity) at the desired wavelength of operation.
- Fast response to be able to handle high speed data.
- Low noise to avoid distortions to the signal.
- Compatible physical dimensions with the entire systems
- Long operating life and reasonable cost

Only **photodiodes** are used in optical communication systems

Photodiode basics

All detectors for optical communication use optical absorption in a **depletion region.**

- Light absorption occurs when energy of incident photons exceeds bandgap energy

Photon energy hν > Bandgap energy

- Convert photons to electron-hole pairs .
- Can then sense the number of electron-hole pairs generated.

A voltage applied across the device sets an electric field in the depletion region: electron-hole pairs give rise to a measurable photocurrent i_p

- The figure of merit of the photodiode is the responsivity R (in A/W) defined as:

$$i_p = RP_{in}$$

Quantum efficiency

Responsivity of a photodiode can be expressed in terms of the diode's *quantum efficiency* η

$$\eta = \frac{\#\ electrons\ from\ photocurrent\ generation}{\#\ photons\ incident}$$

$$\eta = \frac{i_p/q}{P_{in}/h\nu} = \frac{h\nu}{q}\frac{i_p}{P_{in}} = \frac{h\nu}{q}R$$

With q = electronic charge

Rewrite responsivity:

$$R = \frac{\eta q}{h\nu}$$

$$R \approx \frac{\eta\lambda}{1.24}, \lambda\ in\ \mu m$$

Responsivity

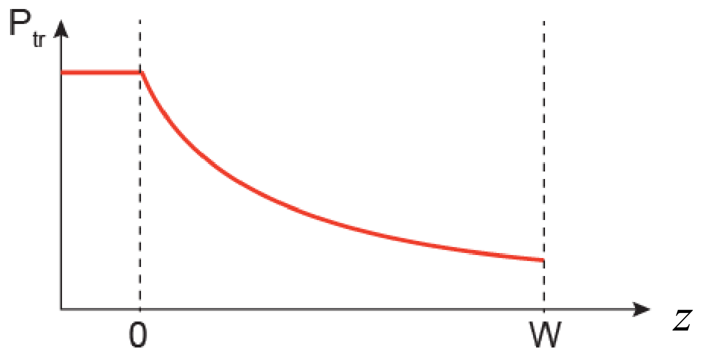
Absorption coefficient

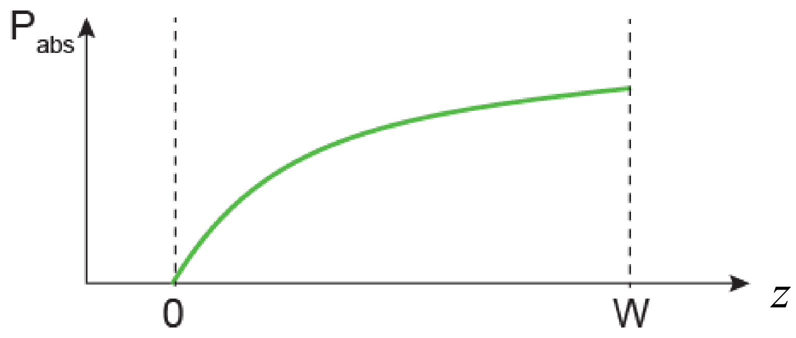
As the photon flux goes through the semiconductor of thickness W, it will be absorbed as it progresses through the material.

- Given absorption coefficient α, transmitted (P_{tr}) and absorbed powers (P_{abs}) are:

$$P_{tr}(z) = P_{in}\exp(-\alpha z)$$

$$P_{abs}(z) = P_{in} - P_{tr}(z) = P_{in}[1 - \exp(-\alpha z)]$$





Quantum efficiency

Since each absorbed photon creates an electron-hole pair we define an absorption quantum efficiency:

$$\eta_{abs} = \frac{P_{abs}(W)}{P_{in}(W)} = 1 - \exp(-\alpha W)$$

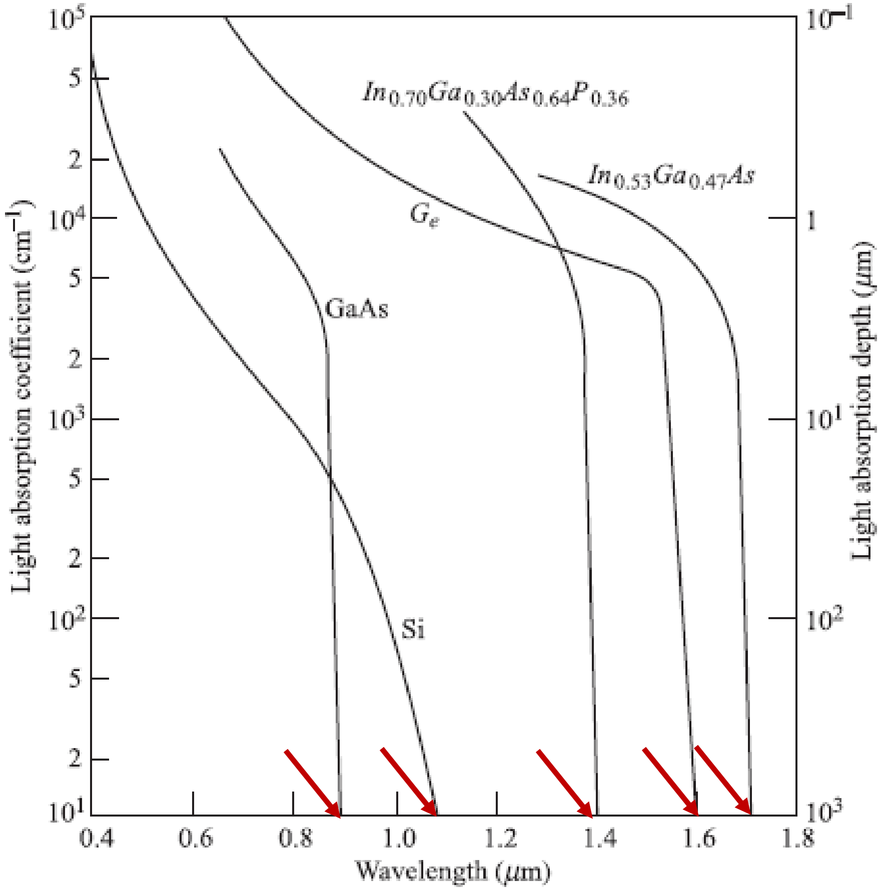
Photodiodes also have an internal quantum efficiency η_{int}

- Not all electron-hole pairs will contribute to the photocurrent.

The quantum efficiency is therefore given by:

$$\eta = \eta_{int}\eta_{abs} = \eta_{int}[1 - \exp(-\alpha W)]$$

Absorption coefficient α



Large values of α (10^4 cm^{-1}) can be realized in most semiconductors

Photodetectors can be made of indirect bandgap semiconductor (Si, Ge)

- Absorption edge is not as sharp

Absorption becomes tends to zero at the cut-off wavelength λ_c

$$\lambda_c = \frac{hc}{E_g}$$

Example

A photodiode has a quantum efficiency of 50% at a wavelength of 900 nm.

What is its responsivity at 900 nm ?

What is the optical power if the mean photocurrent is 10 uA?

Given that the absorption is $10^3\ \mathrm{cm}^{-1}$, and assume 100% internal quantum efficiency, what is the the length of the active medium ?

Types of photodiodes

Photodiode types

p-n photodiodes

- Electron-hole pairs created in the depletion region of a p-n junction in proportion to the optical power
- Electrons and holes are swept out by the electric field leading to a current (in photoconductive mode)

p-i-n photodiodes

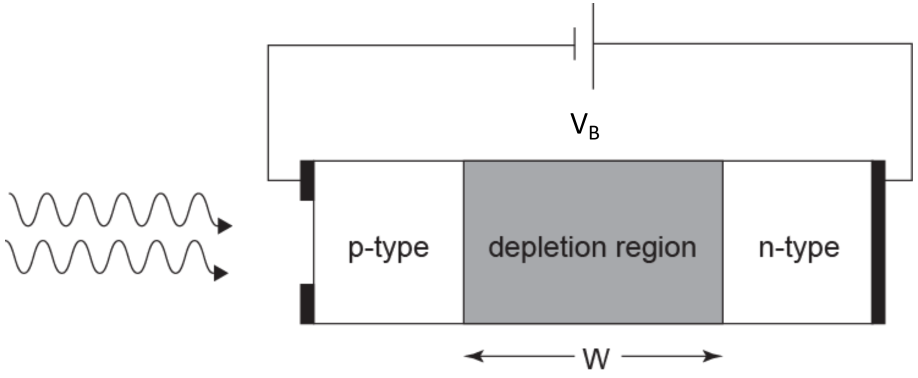
- Electric field is concentrated in an intrinsic (i) layer

Avalanche photodiodes (APD)

- Like p-i-n photodiodes but have an additional layer
- An average of M secondary electron-hole pairs are generated through impact ionization for each primary pair

p-n photodiodes

A p-n photodiode is a p-n junction whose reverse current increases when it absorbs photon



Photons are absorbed everywhere with absorption coefficient α, is resulting in electron-hole pairs

Under an electric field the generated charge carriers can be transported

- For a p-n junction, electric field is only in the depletion region
- The depletion region is therefore where it is desirable to generate photo-carriers.

Bias of p-n photodiode

As an electronic device, the photodiode under illumination has an $i - V$ relation given by:

$$i = i_0 \left[\exp\left(\frac{qV}{k_B T} \right) - 1 \right] - i_p$$

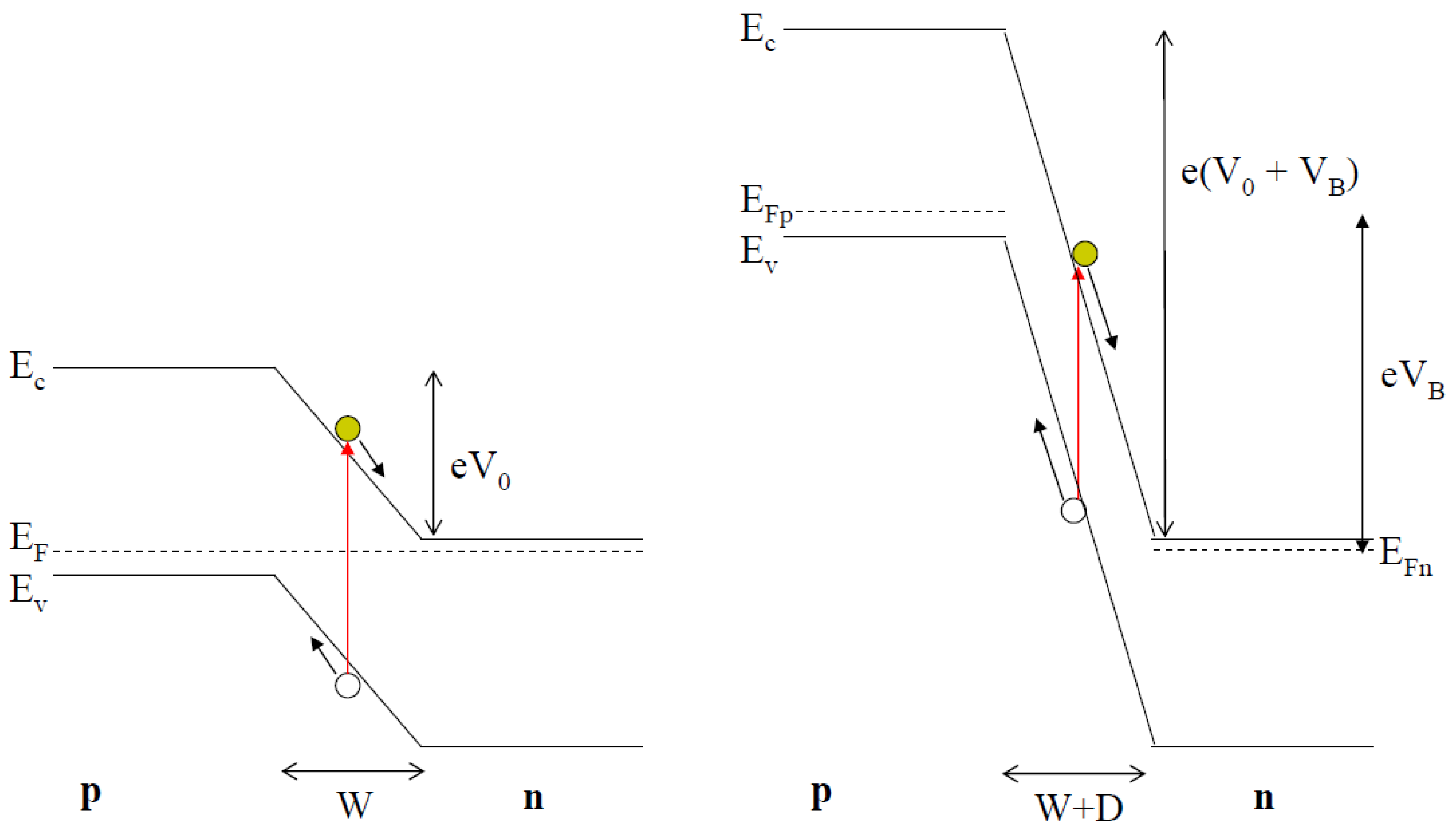
i: is the injection current under a forward bias V

i_0: is the dark current representing thermal generated free carrier which flow through the junction

There are two modes of operation for a junction photodiode

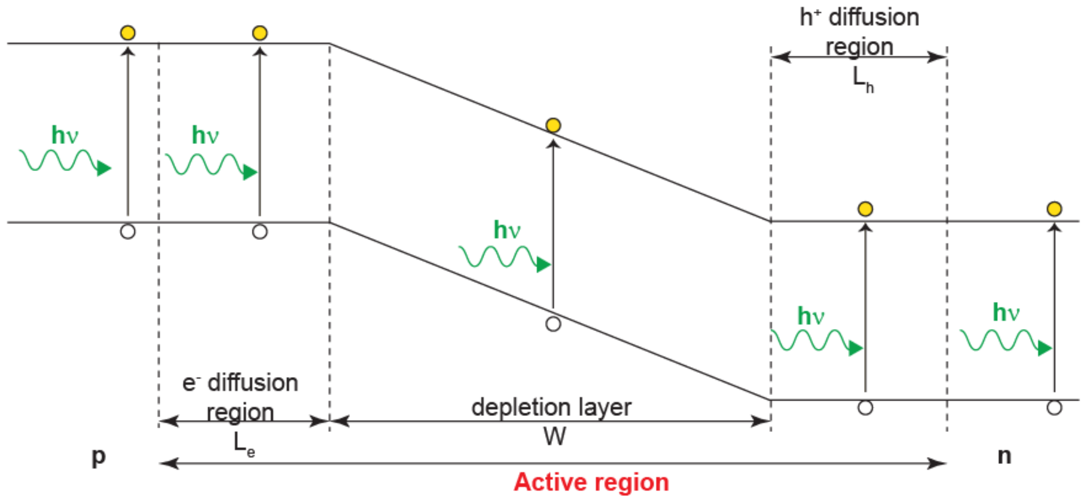
- Photoconductive mode – including short circuit condition (current source)
- Photovoltaic mode – including open circuit condition (voltage source)

Reverse bias p-n junction



Reverse biased mode: photoconductive

e⁻-h pairs can be generated in *3 possible locations*



<u>Depletion region</u>

Charges quickly drift in opposite directions under influence of strong E field and *contribute* to the reverse photocurrent i_p

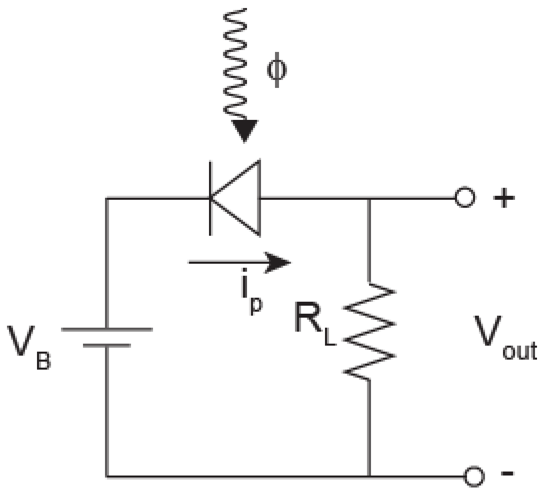
<u>Away from depletion region</u>

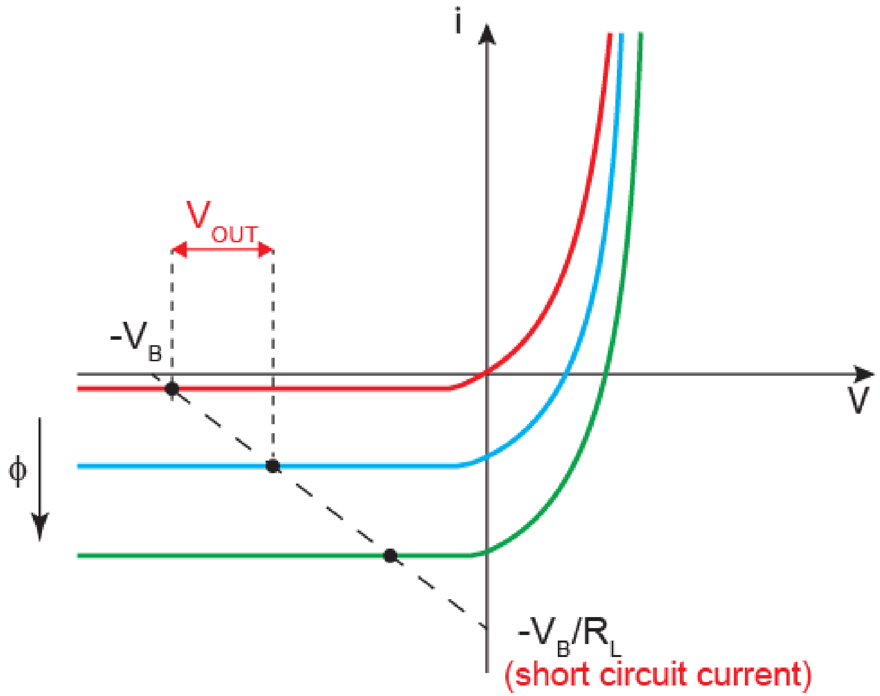
Charged cannot be transported (no E field): wander until recombined, not contributing to the photocurrent i_p

<u>Vicinity of depletion region</u>

Charges can enter depletion region by random diffusion and then *contribute* to the reverse photocurrent i_p

Reverse biased mode: photoconductive



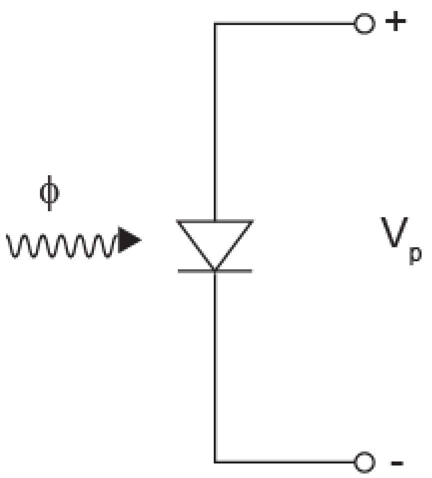


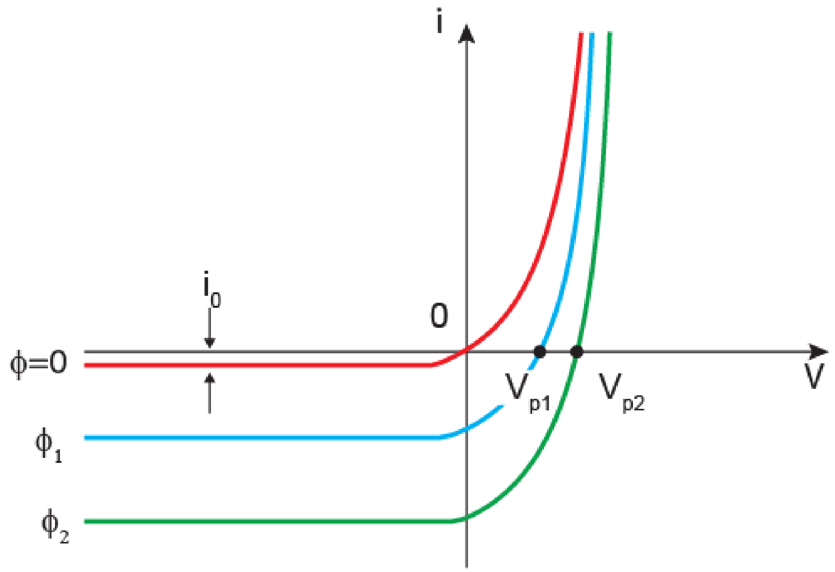
Load resistor R_L is inserted in the circuit

- $R_L < R_i$, the internal resistance of the junction
- Keep $V_{out} < V_B$ so that the diode remains reversed biased

Have $V_{out} = (i_0 + i_p)R_L$

Open circuit mode: photovoltaic





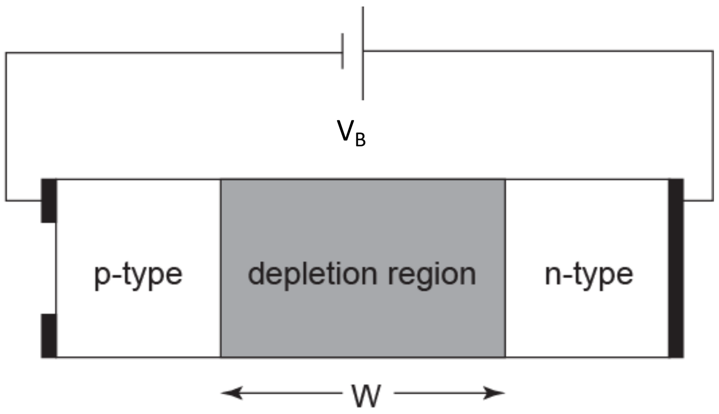
Light generates e⁻-h pairs in depletion region

- Photogenerated majority carriers *forward bias* the junction
- Net result: *photovoltage* V_p across the device

Limit on V_p is the equilibrium contact potential V_0 as drift current vanishes with $V_p = V_0$

Note: responsivity for such device is measured in V/W rather than A/W

Limits of p-n photodiodes



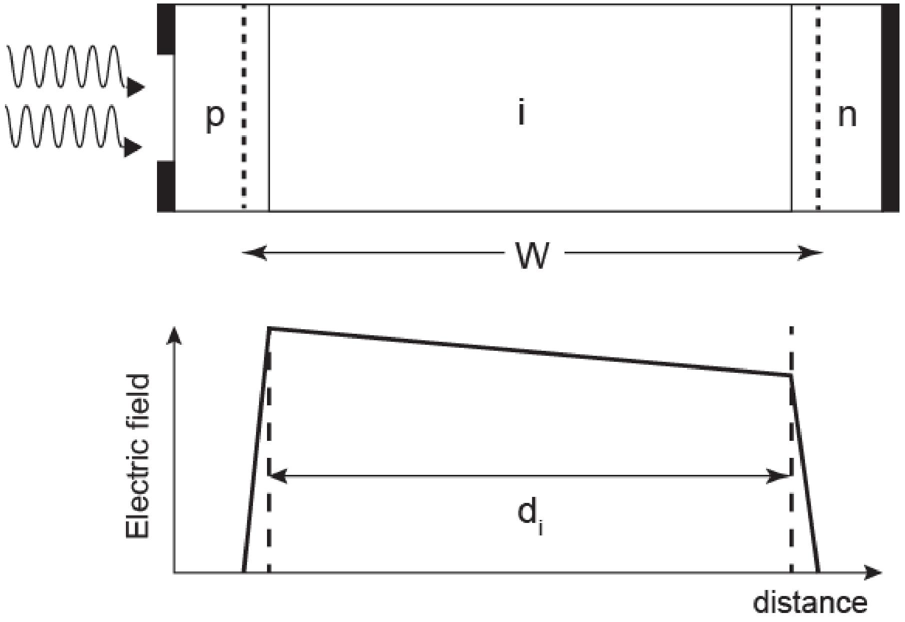
Problem with p-n photodiode is the limited width of depletion region:

- Leads to the presence of a diffusive component in the photocurrent.
- Diffusion is slow process (> ns to diffuse 1µm): distorts response of photodiode.

p-i-n photodiode

A layer of undoped (or slightly doped) semiconductor is inserted between the p-n junction :

- Layer is nearly intrinsic,
- Offers high resistance: large electric field exists in the i-layer.



- All absorption takes place in depletion region
- Depletion layer width W *does not vary* significantly with bias voltage: $W \approx d_i$
- Optimal value of d_i depend on *tradeoff between speed and sensitivity*

Avalanche photodetector

All detectors require a minimum current to operate reliably: have a *minimum power requirement*

$$i_p = RP_{in}$$

Detectors with large responsivity R are preferred

However responsivity of p-i-n photodiodes are limited and take a maximum value for a quantum efficiency $\eta = 1$

$$R = \frac{q}{h\nu} \approx \frac{\lambda}{1.24}$$

Avalanche photodiodes (APD) can have much larger R : they are designed to provide internal current gain

Avalanche photodetector

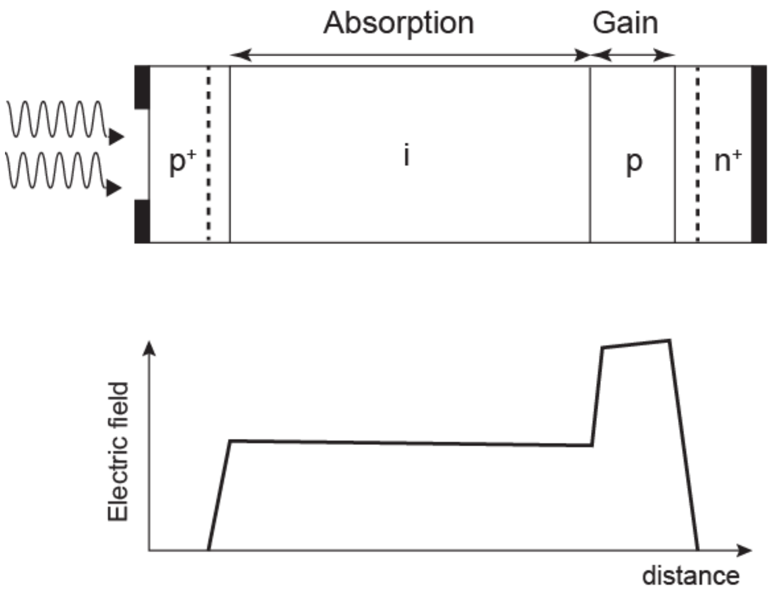
Internal gain of APD is obtained by having a high electric field

- Accelerating electron (hole) can acquire sufficient energy to generate a new electron-hole pair
- These high energy electrons (holes) ionize bound electrons in the valence band upon colliding with them
- Known as impact ionization

Net result of this mechanism

- A primary electron generated through photon absorption creates secondary electrons
- Secondary electrons can also cause further impact ionization: avalanche effect
- All generated electrons contribute to the photodiode current i_p

APD structure



p-i-n structure with an additional layer

i layer still acts as depletion region where most incident photons are absorbed

- Primary electron holes pair

Under reverse bias high E field exists in the added p-type layer

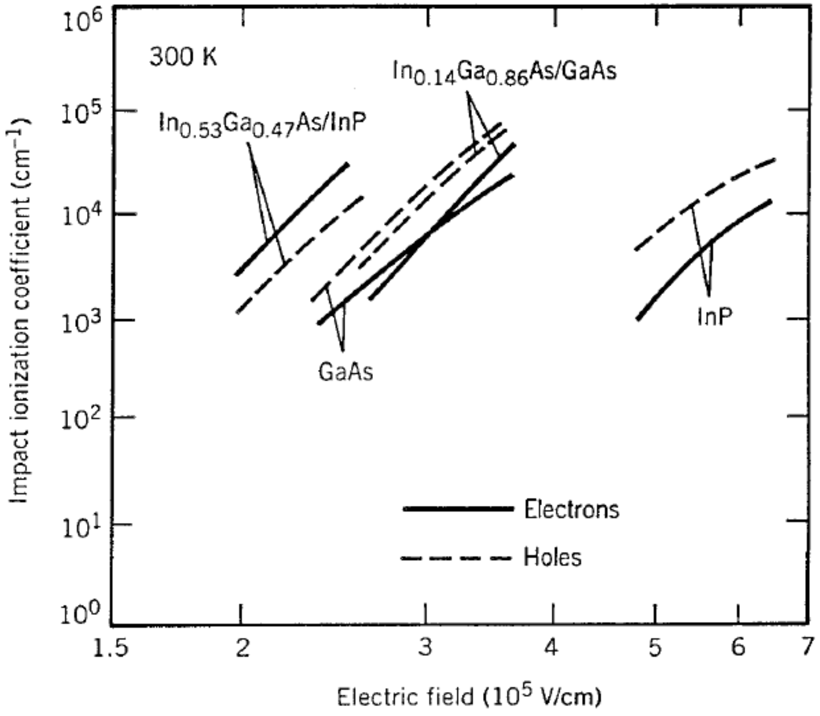
- Secondary electron hole pairs

APDs are characterized by a gain multiplication factor M

$$R_{APD} = MR = M\frac{\eta q}{h\nu}$$

Impact ionization

Rate of generation is governed by the *impact-ionization coefficients* of electron and hole ($\alpha_e,\ \alpha_h$)



Value of $\alpha_e,\ \alpha_h$ depend on

- Semiconductor material
- Accelerating electric field

Values of 10^4 cm^{-1} are obtained for field within the range 2- 4 x 10^5 V/cm

- Need voltages near 100 V for APD.

$$k_A\ ionization\ factor = \begin{cases} \frac{\alpha_h}{\alpha_e}\ for\ \alpha_h < \alpha_e \\ \frac{\alpha_e}{\alpha_h}\ for\ \alpha_h > \alpha_e \end{cases}$$

Average current gain M

Rate equations: both electrons and holes produce new electron/hole pairs during the impact ionization

Electron current i_e :
$$\frac{di_e}{dx} = \alpha_e i_e + \alpha_h i_h$$

Opposite direction hole current i_h :
$$-\frac{di_h}{dx} = \alpha_e i_e + \alpha_h i_h$$

Total current is:
$$I = i_e(x) + i_h(x)$$

Average current gain M

$$\frac{di_e}{dx} = \alpha_e i_e + \alpha_h(I - i_e) = (\alpha_e - \alpha_h)i_e + \alpha_h I$$

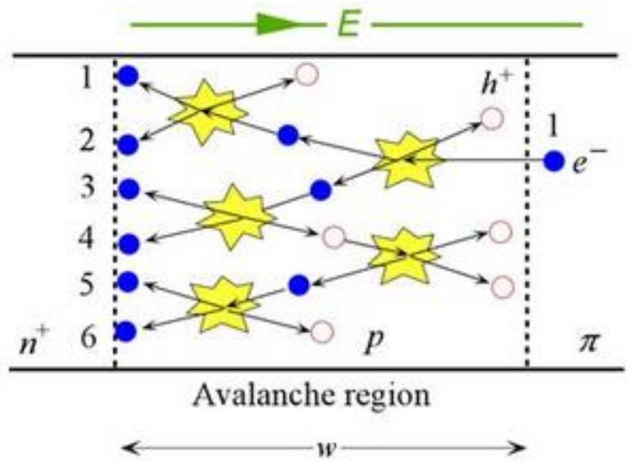
$$\frac{di_e}{dx} + (\alpha_h - \alpha_e)i_e = \alpha_h I$$

Solution of the form: $$i_e = \frac{\alpha_h}{(\alpha_h - \alpha_e)} I + k\exp[-(\alpha_h - \alpha_e)x]$$

k determined by boundary condition

Electron current *grows exponentially* when moving into the gain region

Average current gain M



Boundary condition: Only electrons go into the n+ region: $i_e(d) = I$ and $i_h(d) = 0$

Get multiplication factor M:

$$M = \frac{i_e(d)}{i_e(0)} = \frac{1 - k_A}{\exp[-(1 - k_A)\alpha_e d] - k_A}$$

$$\text{with } k_A = \frac{\alpha_h}{\alpha_e} \; for \; \alpha_h < \alpha_e$$

Example

A Si APD has a quantum efficiency of 70% at 830 nm when M = 1. When illuminated with radiation it produces an output photocurrent of 10 uA after avalanche gain with a multiplication factor of 250.

What is the received optical power to the device ?

How many photons per second does this correspond to ?

Speed and bandwidth

Rise time and bandwidth

The photodiode bandwidth is determined by the speed at which the device responds to variations in incident optical power.

Rise time T_r: time over which the current builds up from 10% to 90% of its final value when incident power is changed abruptly.

Photodetector response time has two components:

- *Transit time of the photocurrent* τ_{tr} : time taken by electrons and holes to travel to electrical contacts of photodiode.
- *RC-limited time constant* τ_{RC} : response time of the electrical circuit processing the photocurrent.

<u>Note:</u> photodiode operating in photovoltaic mode has large RC constant, only photoconductive diodes are suitable for high speed or broadband applications

Photo-carrier response time – drift component

Drift of carriers is a fast process

Constant electric field in the depletion region causes the photogenerated carriers to accelerate.

- Motion of carrier is at an average velocity called drift velocity v_d

When field in depletion exceeds a saturation value, carriers travel at maximum drift velocity called saturation velocity

Longest transit time $\tau_{tr,drift}$ is when (slowest) carriers traverse entire depletion layer of width W

$$\tau_{tr,drift} = \frac{W}{v_d}$$

Photo-carrier response time – diffusion component

Carriers generated outside the depletion region but sufficiently close take time to diffuse into it.

- Relatively slow process in comparison with drift.
- Maximum times allowed for this process are the carrier lifetimes.
- Given a diffusion speed of v_{diff} the diffusion time is:

$$\tau_{diff} = \frac{L_{e/h}}{v_{diff}}$$

Example: hole diffusion through 10 mm of silicon is 40 ns. Electron diffusion time is 8 ns

- For high speed photodiode, this diffusion mechanism has to be eliminated

RC limited response time

Photodiode has internal resistance R_i and capacitance C_j

- Under strong reverse bias: $C_j = \frac{\varepsilon_0 \varepsilon_r A}{W}$ (A : area of junction, W: width)

Other resistances, capacitances or inductances are parasitic and due to contact, packaging or wire connections

- Can be minimized by careful design and packaging.

Frequency response of the equivalent circuit : $\tau_{RC} \approx R_L C_j$

RC limited 3dB bandwidth: $\Delta f_{RC} = \frac{1}{2\pi\tau_{RC}}$

Total bandwidth can be approximated by:

$$\Delta f = \frac{1}{[2\pi(\tau_{tr} + \tau_{RC})]}$$

APD bandwidth

Intrinsic bandwidth also depends on M

- Transit time increases significantly
- For $\alpha_h << \alpha_e$, effective transit time in the multiplication layer is:

$$\tau_{eff,M} \approx k_A M \tau_{tr,M}$$

$$\text{with } \tau_{tr,M} = \frac{d}{v_d}$$

Assuming $\tau_{RC} \ll \tau_{eff,M}$ and $\tau_{tr,i} \ll \tau_{eff,M}$ then : $\Delta f \approx \frac{1}{2\pi\tau_{eff,M}}$

Tradeoff between gain & bandwidth (speed & sensitivity), better to have k_a<<1