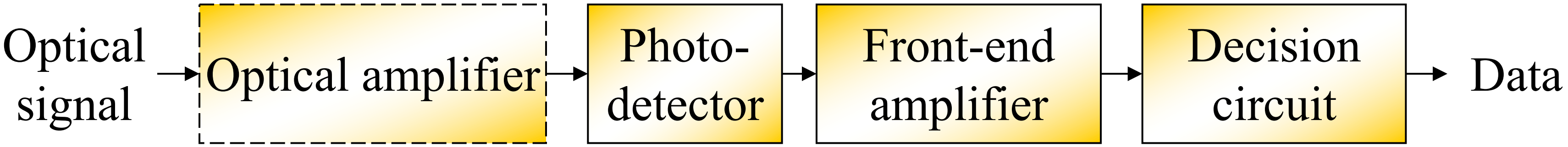
Photo-Detectors

- **Photodetector**: Generates an electrical current proportional to the incident optical power
- **Front-end amplifier**: Increases the power of the generated **electrical** signal to a usable level
- **Decision circuit**: Estimates the data from the output of the front-end amplifier
  - The design depends on the modulation scheme used to transmit the data
- **Optical amplifier**: Optionally placed **before** the photodetector to act as a preamplifier

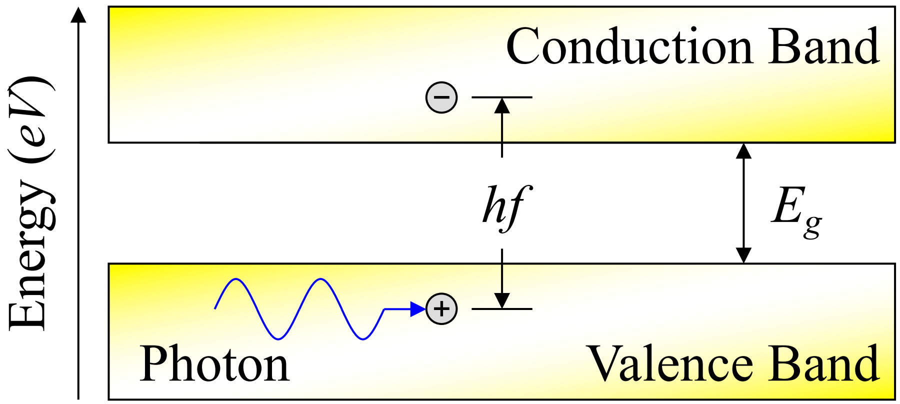


Optical signal → Optical amplifier → Photo-detector → Front-end amplifier → Decision circuit → Data

Block diagram of a receiver in a digital communication system

Photodetectors

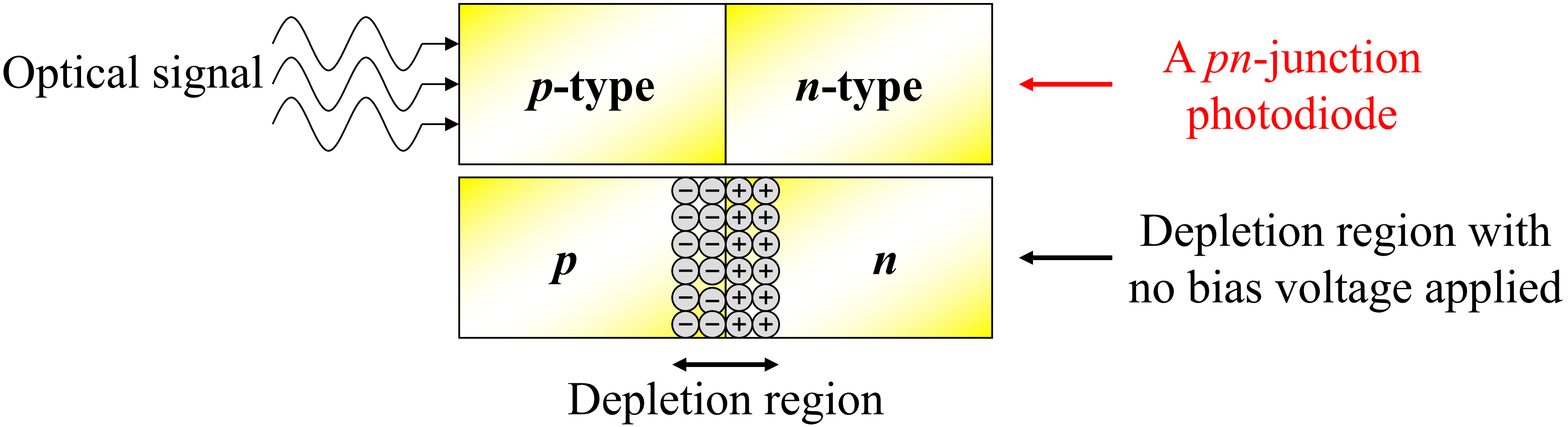
- **Photodetectors** are made of **semiconductor materials**
- **External voltage** is applied to the semiconductor ⇨ The electron-hole pairs give rise to a **photocurrent**
- Quantum mechanics principle: Each electron can absorb only one photon to transit between energy levels
- **Energy** of the incident photon: **at least equal to E_g**
- Photodetector constraint: $\boxed{hf_c = \frac{hc}{\lambda} \geq eE_{gc}}$
  - E_{gc} (J/Cb): Bandgap normalized to the electric charge
  - c: velocity of light
  - e: electric charge



- **Cutoff wavelength (λ_{cutoff})**: The largest λ for which the relation is satisfied
- Silicon photodetectors: Widely used in 0.8 μm band

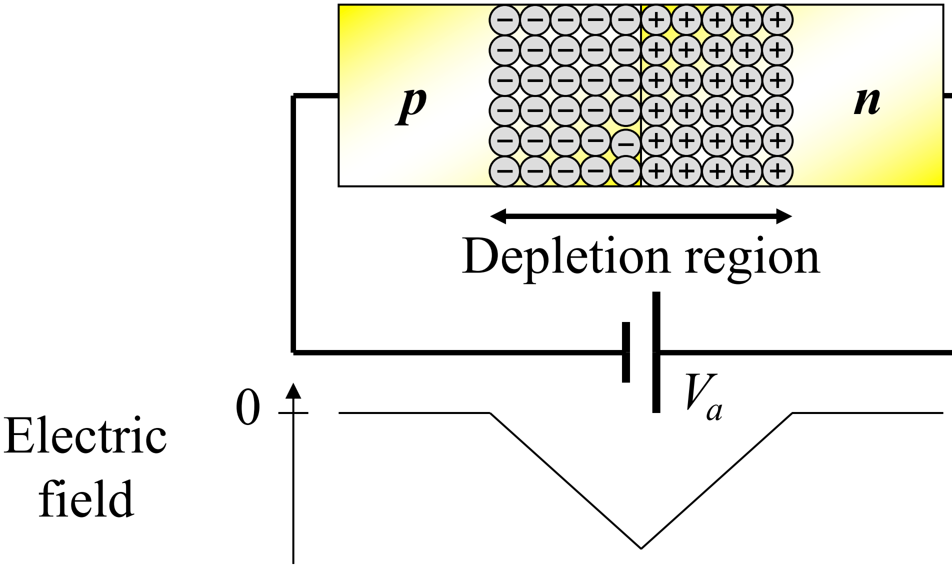
Photodetectors

- In practice, the use of a **semiconductor slab** as a photodetector **does not achieve high efficiencies**
- It is necessary to **sweep the generated conduction band electrons rapidly out of the semiconductor**
- Solution: Impose an **electric field** in the region where electrons are generated
- **Photodiode**: Uses a ***pn*-junction semiconductor** and applies a **reverse-bias voltage** to it
- The depletion region creates a built-in electric field



Photodetectors

- Both the depletion region and the built-in electric field can be enhanced by applying a reverse-bias voltage
- **Drift**: The electrons generated by photon absorption within or close to the depletion region will be swept into the *n*-type semiconductor before they recombine with the holes in the *p*-type semiconductor ⇨ Current in the external circuit

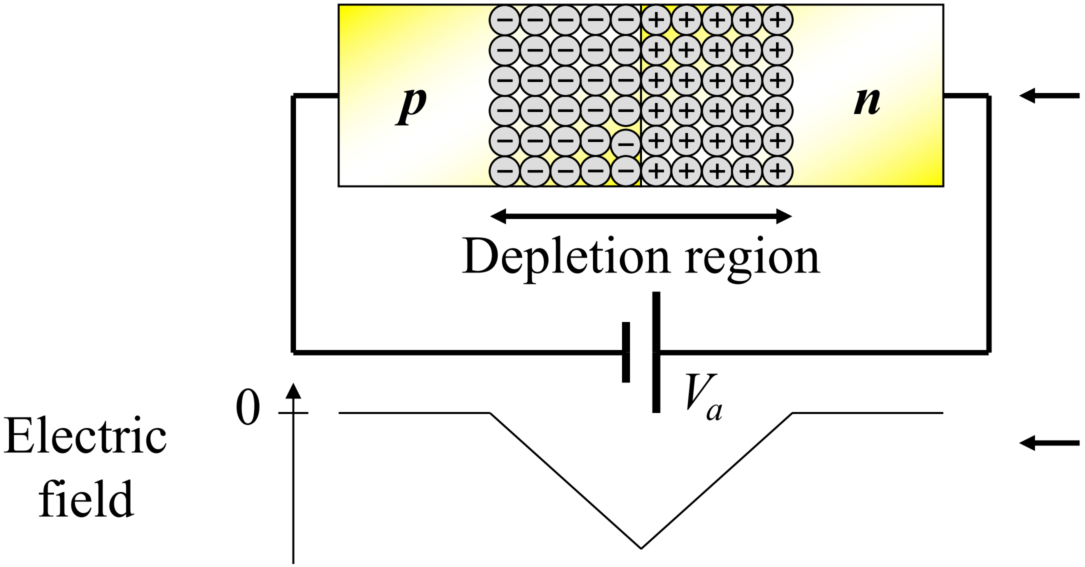


Depletion region with a reverse-bias voltage

Built-in electric field on reverse bias

Photodetectors

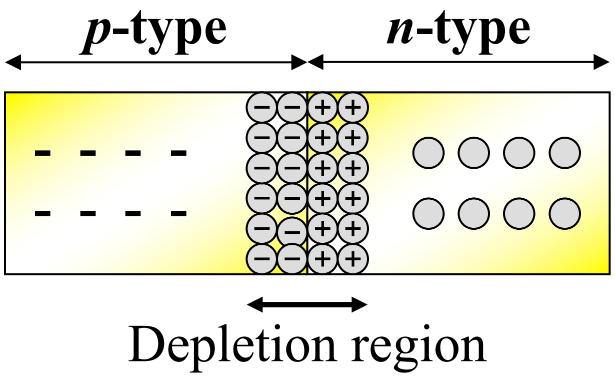
- Electron-hole **pairs generated far away from the depletion region** travel primarily under the effect of **diffusion** and **may recombine without giving rise to a current** in the external circuit
  - This reduces the efficiency η of the photodetector
  - Diffusion is a much slower process than drift ⇨ The diffusion current will not respond quickly to incident optical signal intensity changes ⇨ The photodiode bandwidth is reduced



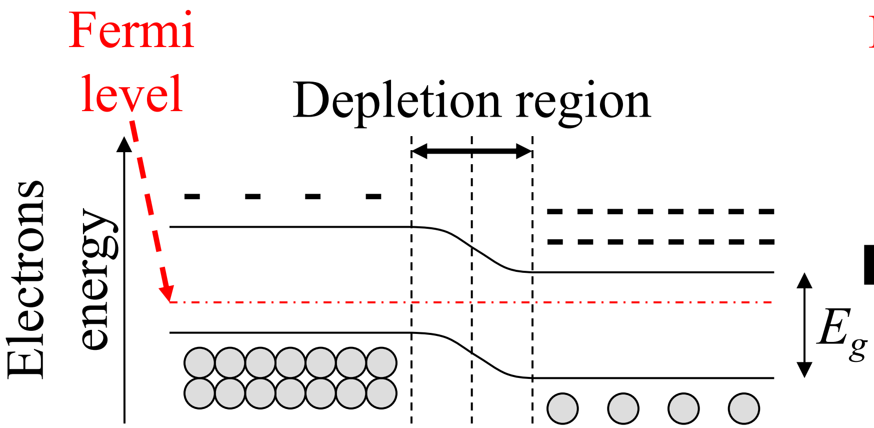
← Depletion region with a reverse-bias voltage

← Built-in electric field on reverse bias

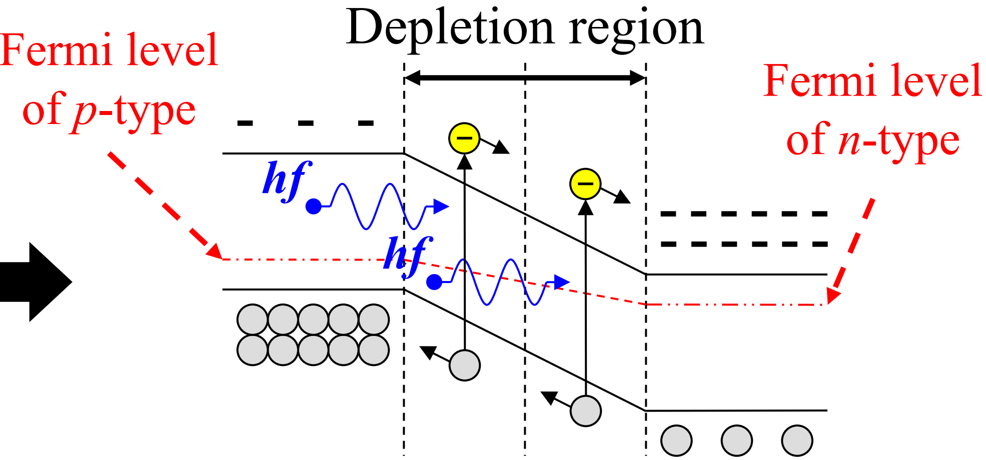
Photodetectors



Concentration of **minority** carriers and depletion region **with no application** of bias voltage



Energy-band diagram **with no application** of bias voltage



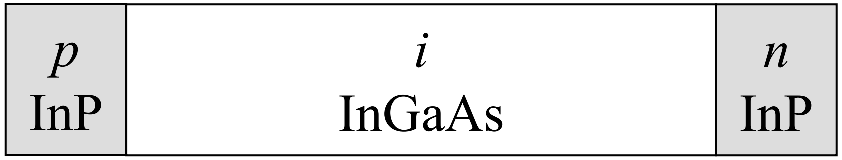
Energy-band diagram **with application** of bias voltage

PIN Photodiodes

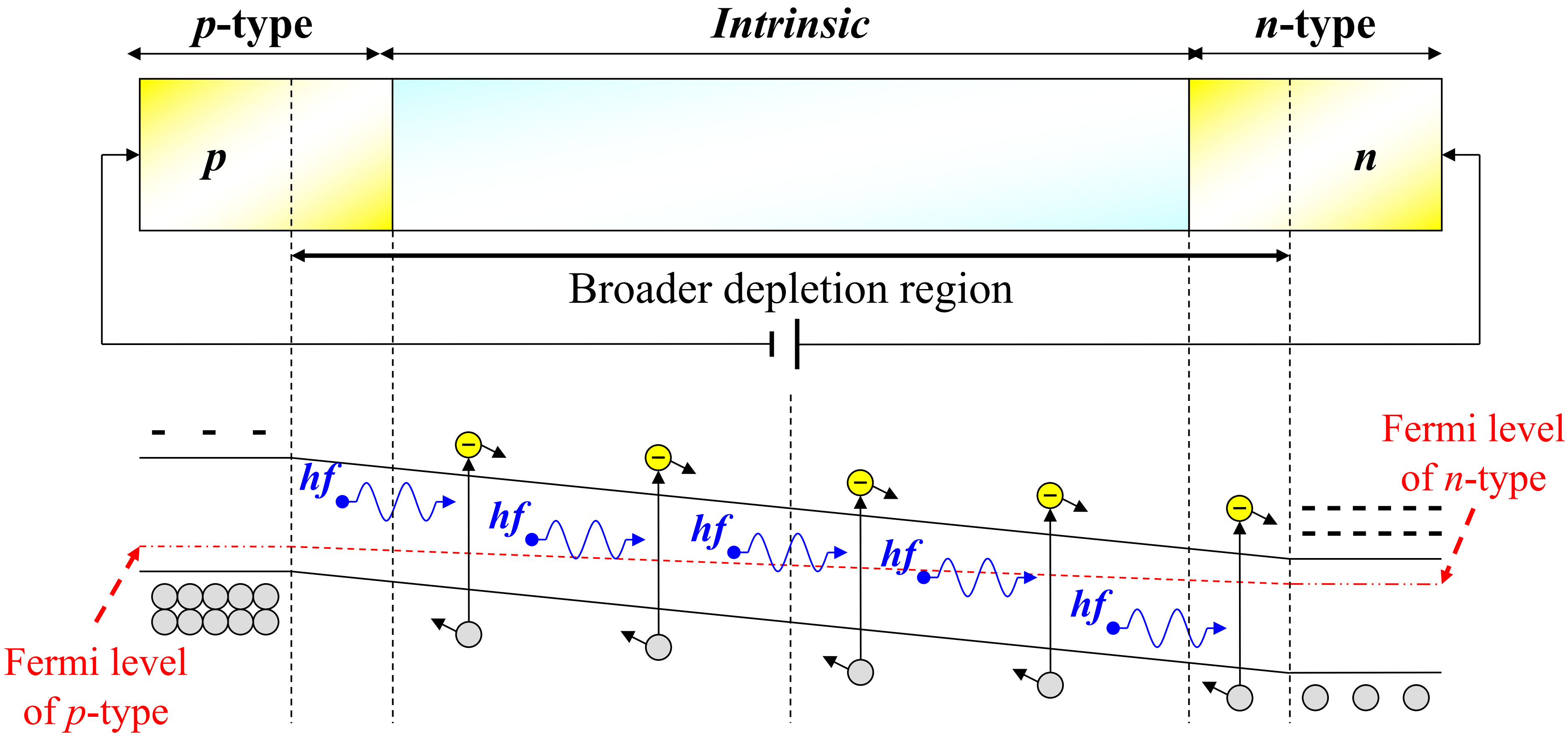
- ***pin* photodiodes: Introduction of a very lightly doped intrinsic semiconductor between the *p*-type and *n*-type semiconductors ⇨ Improves the photodetector efficiency**
- The depletion region extends completely across this intrinsic semiconductor
- The widths of the *p*-type and *n*-type semiconductors are small compared to the intrinsic region ⇨ Increased efficiency and responsivity
- $\lambda_{\text{cutoff,InP}} = 0.92\ \mu\text{m}$
- $\lambda_{\text{cutoff,InGaAs}} = 1.65\ \mu\text{m}$

} *p*-type and *n*-type regions are transparent at the wavelength of interest

PIN photodiode based on a **heterostructure**

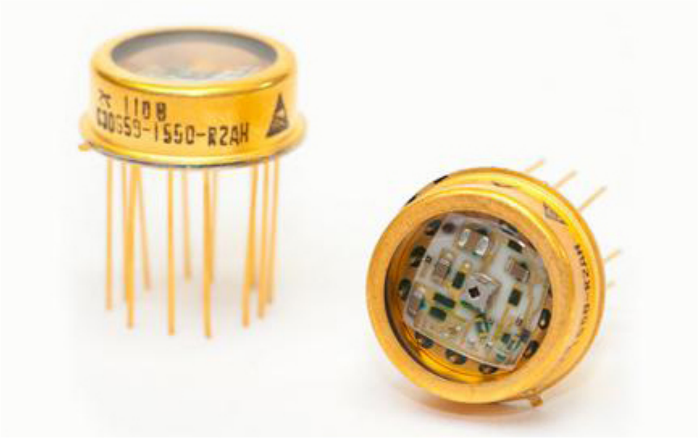


PIN Photodiodes



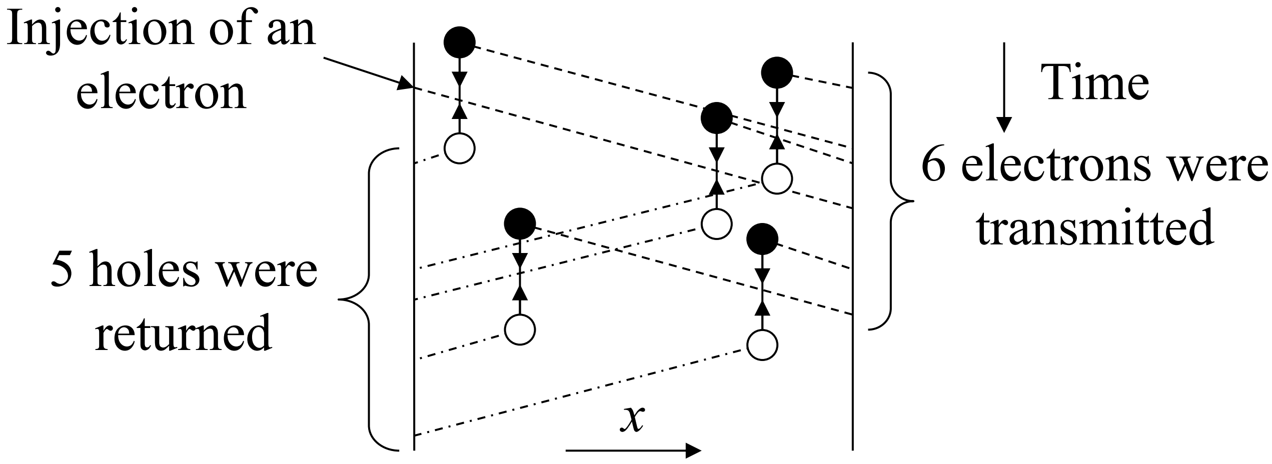
Avalanche Photodiodes

- **In the described photodetectors, one photon can generate only one electron ⇨ Low responsivities**
- **<u>Avalanche Photo-Diode (*APD*)</u>: The generated electron is subjected to a very high electric field ⇨ It can acquire sufficient energy to knock off more electrons from the valence band to the conduction band ⇨ These secondary electron-hole pairs generate even further electron-hole pairs when they are accelerated to sufficient levels**
- **<u>Multiplicative gain (G_m)</u>**: The **mean number of secondary electron-hole pairs** generated by the avalanche multiplication process by a single electron
  - ⇨ This number is random



Avalanche Photodiodes

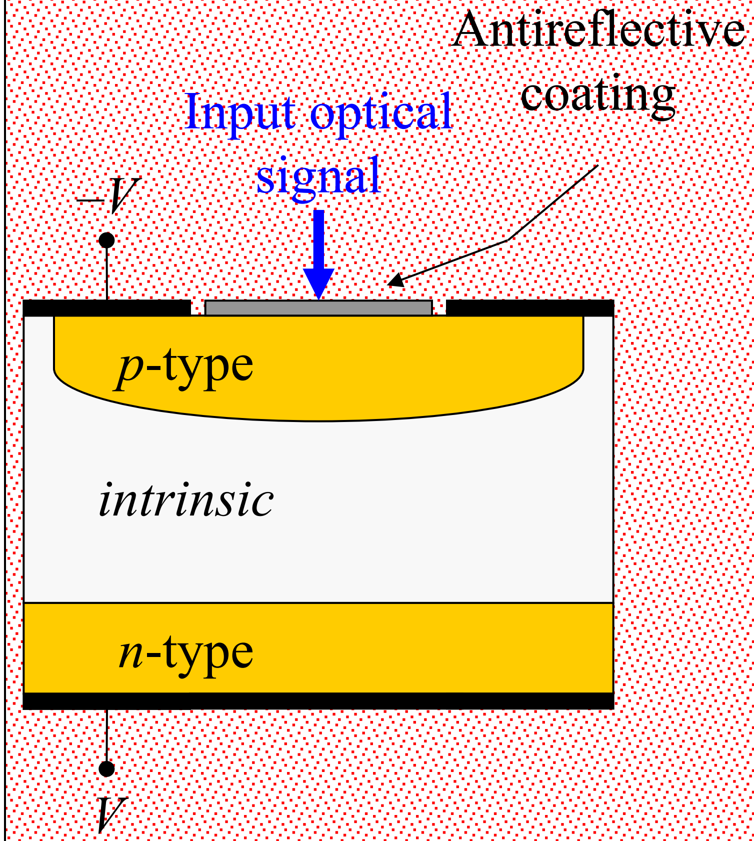
- **Avalanche breakdown**: The APD multiplicative gain is made infinite
- Large G_m ⇨ Larger photocurrent variance ⇨ Affects the APD noise performance
- **Trade-off between the multiplicative gain and the noise factor**: APDs usually have a moderate value of multiplicative gain that optimizes their performance



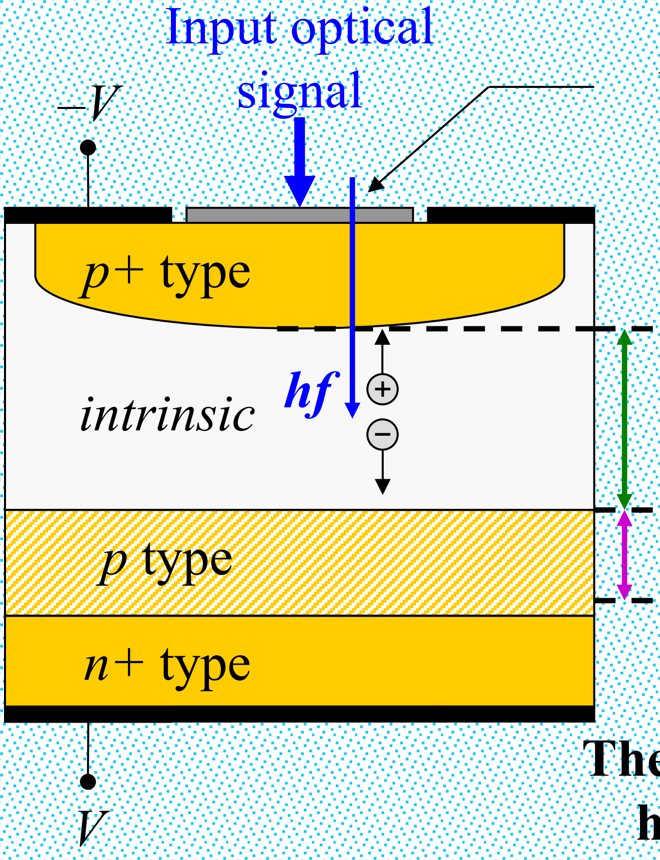
By the impact of a single photon, we achieve an amplification $G_m = 6$

Qualitative Comparison of PIN and Avalanche Photodiodes

pin photodiode



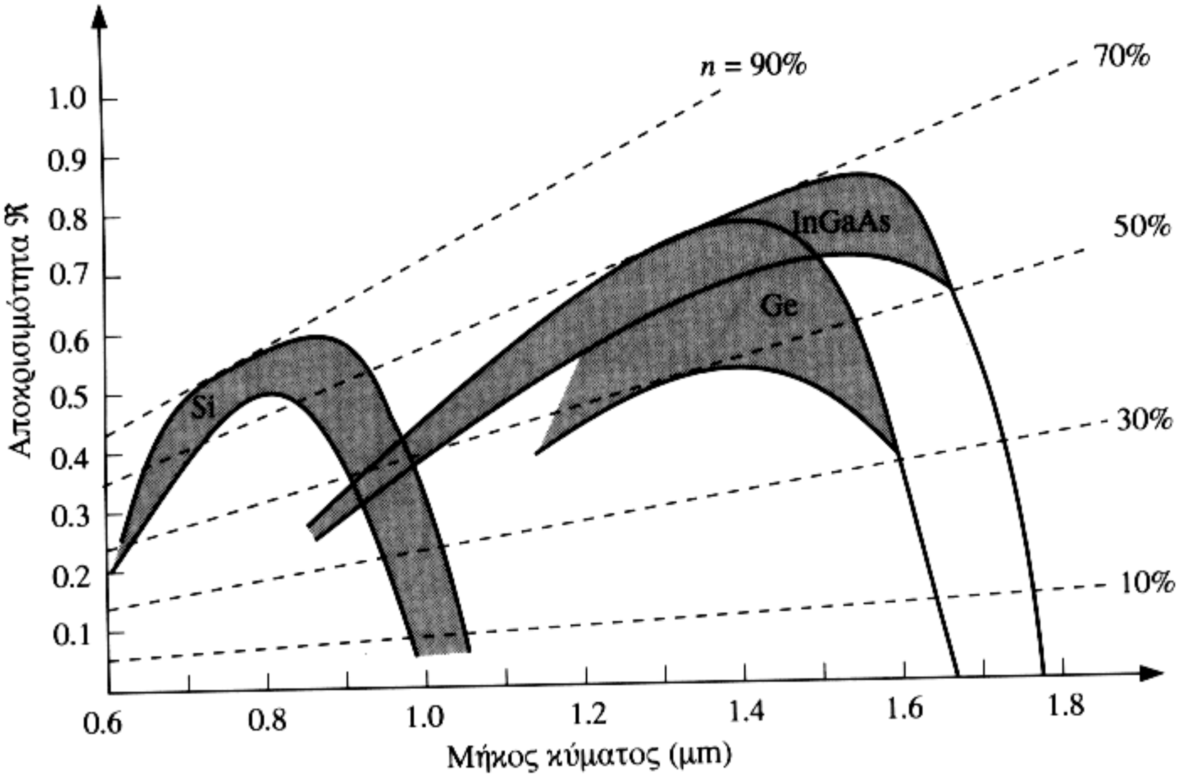
APD photodiode

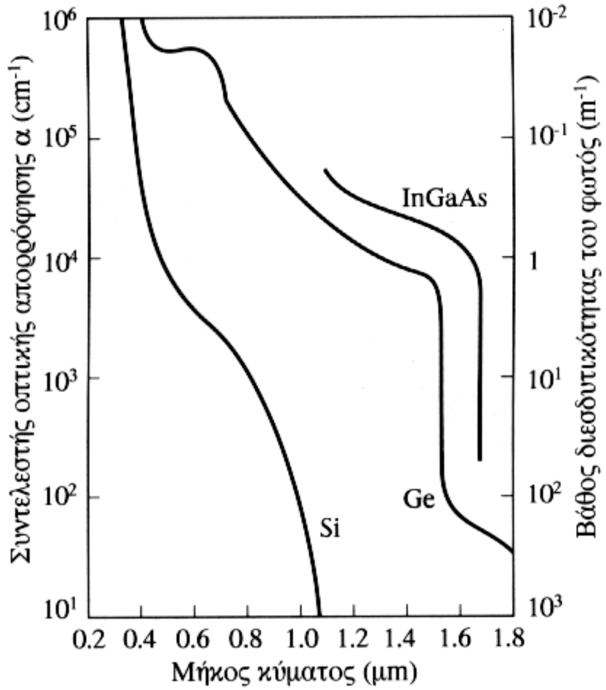


“+” denotes strong doping

The intrinsic region has low doping

Photodetectors





Photodetectors

Bandgap energies and cutoff wavelengths for a number of semiconductor materials

$In_{1-x}Ga_xAs$: a fraction $1-x$ of the Ga atoms in GaAs are replaced by In atoms

$In_{1-x}Ga_xAs_yP_{1-y}$: a fraction $1-y$ of the As atoms are replaced by P atoms

Material	E_g (eV)	λ_{cutoff} (μm)
Si	**1.17**	**1.06**
Ge	**0.775**	**1.6**
GaAs	**1.424**	**0.87**
InP	**1.35**	**0.92**
$In_{0.55}Ga_{0.45}As$	**0.75**	**1.65**
$In_{1-0.45y}Ga_{0.45y}As_yP_{1-y}$	**0.75 – 1.35**	**1.65–0.92**

InGaAs and InGaAsP: photodetectors in the **1310 nm** and **1550 nm bands**

Ge: photodetectors in both these bands, but it has a reduced efficiency

Photodetectors

- **Efficiency, η**: The **fraction of the optical signal energy which is absorbed** giving rise to a photocurrent
- It is important to design the photodetector to achieve an η **as close to 1 as possible**
  - Achieved by using a semiconductor slab of sufficient thickness
- Power absorbed by a semiconductor slab:

$$\boxed{P_{abs} = \left(1 - e^{-aL}\right) P_{in}}$$

  - L (μm): slab thickness
  - P_{in}: incident optical signal power
  - a: material absorption coefficient
    - Depends on the wavelength
    - For $\lambda > \lambda_{cutoff}$, $a = 0$

$$\boxed{\eta = \frac{P_{abs}}{P_{in}} = 1 - e^{-aL}}$$

- Typically α is on the order of 10^4/cm ⇨ To achieve $\eta > 0.99$, the slab's thickness should be on the order of 10 μm

Photodetectors

- Photodetector **area**: **Sufficiently large** ⇨ All the incident optical power can be captured
- Photodetector operating **bandwidth**: **Very wide**
  - A photodetector at some wavelength serves as a photodetector at all smaller wavelengths as well
- **Responsivity, *R***:

$$\boxed{R = \frac{I_p}{P_{in}} \ \mathrm{A/W}}$$

  - I_p (Amperes): mean current produced by a photodetector
  - P_{in} (Watts): incident optical power

$$\boxed{R = \frac{\eta e}{h f_c} \ \mathrm{A/W}}$$

- The responsivity is commonly expressed in terms of λ:

$$\boxed{R = \frac{\eta e \lambda}{hc} = \frac{\eta \lambda}{1.24} \ \mathrm{A/W}}$$

  - λ: expressed in μm
  - R is on the order of 1 A/W in the 1310 nm band and 1.2 A/W in the 1550 nm band

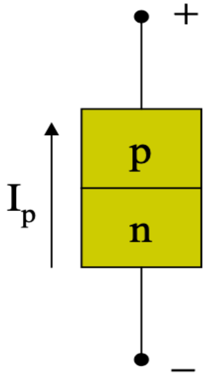
Electronic Properties / PD circuits

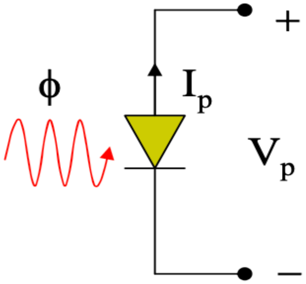
I-V characteristics of an illuminated junction

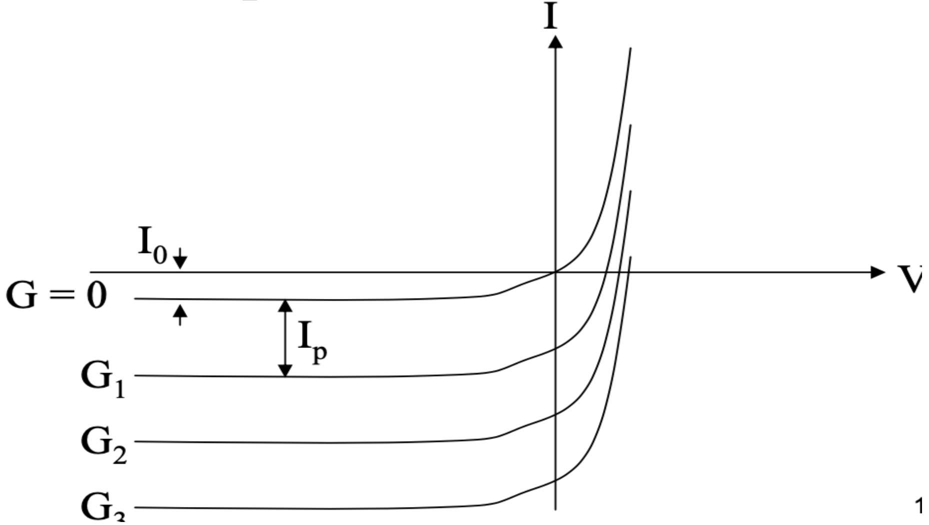
- The photodiode therefore has an I-V characteristic:

$$I = I_0(\exp(eV/k_BT) - 1) - I_p$$

- This is the usual I-V curve of a p-n junction with an added photocurrent $-I_p$ proportional to the photon flux.

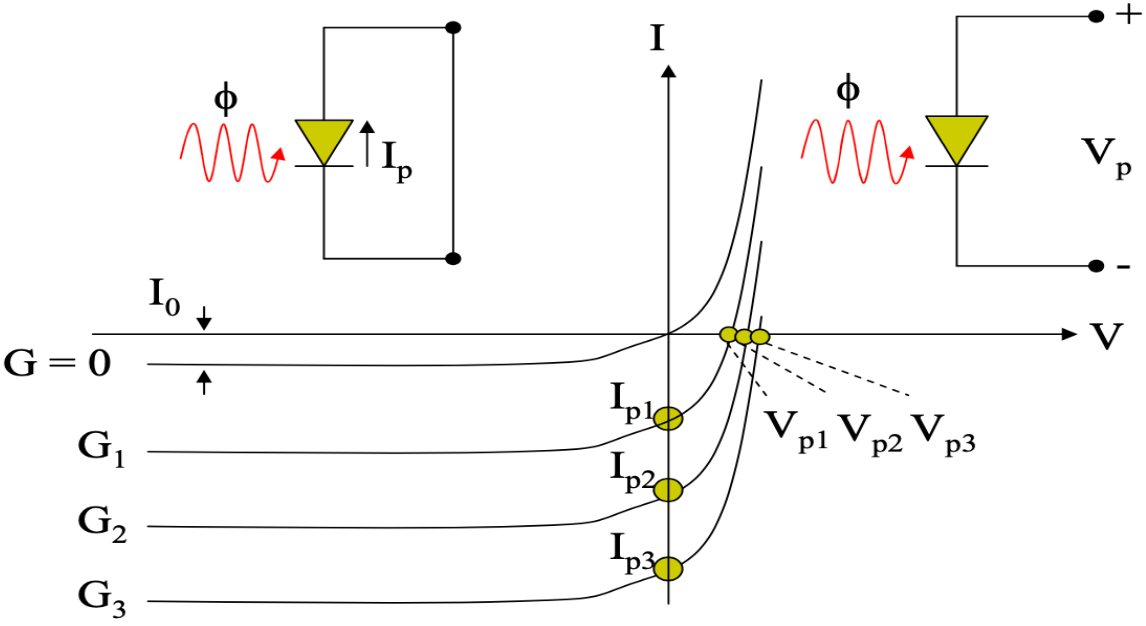






Electronic Properties / PD circuits

Short-circuit current and open-circuit voltage

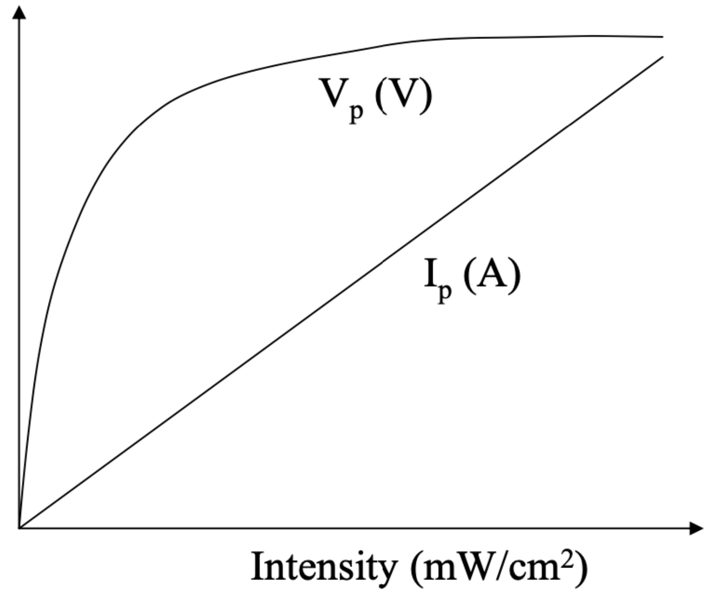


- The *short-circuit current* (V = 0) is the *photocurrent* I_p.
- The *open-circuit voltage* (I = 0) is the *photovoltage* V_p.

$$(I = 0) \Rightarrow \quad V_p = (k_B T/e)\ln(I_p/I_0 + 1)$$

Electronic Properties / PD circuits

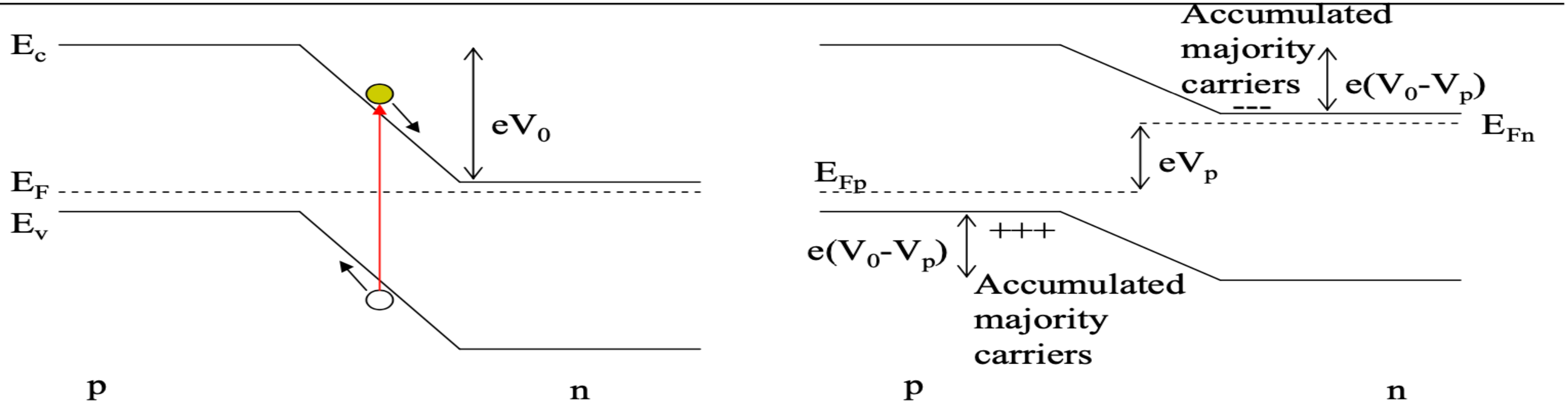
Photocurrent and photovoltage



- ☐ As the light intensity increases, the short-circuit current increases linearly ($I_p \propto G$);
- ☐ The open-circuit voltage increases *only logarithmically* ($V_p \propto \ln(I_p/I_0)$) and limits by the *equilibrium contact potential*.

Electronic Properties / PD circuits

Open-circuit voltage



- ☐ The photogenerated, field-separated, majority carriers (+ve charge on the p-side, -ve charge on the n-side) forward-bias the junction.
- ☐ The appearance of a forward voltage across an illuminated junction (photovoltage) is known as the photovoltaic effect.
- ☐ The limit on V_p is the equilibrium contact potential V_0 as the contact potential is the maximum forward bias that can appear across a junction. (drift current vanishes with $V_p = V_0$)

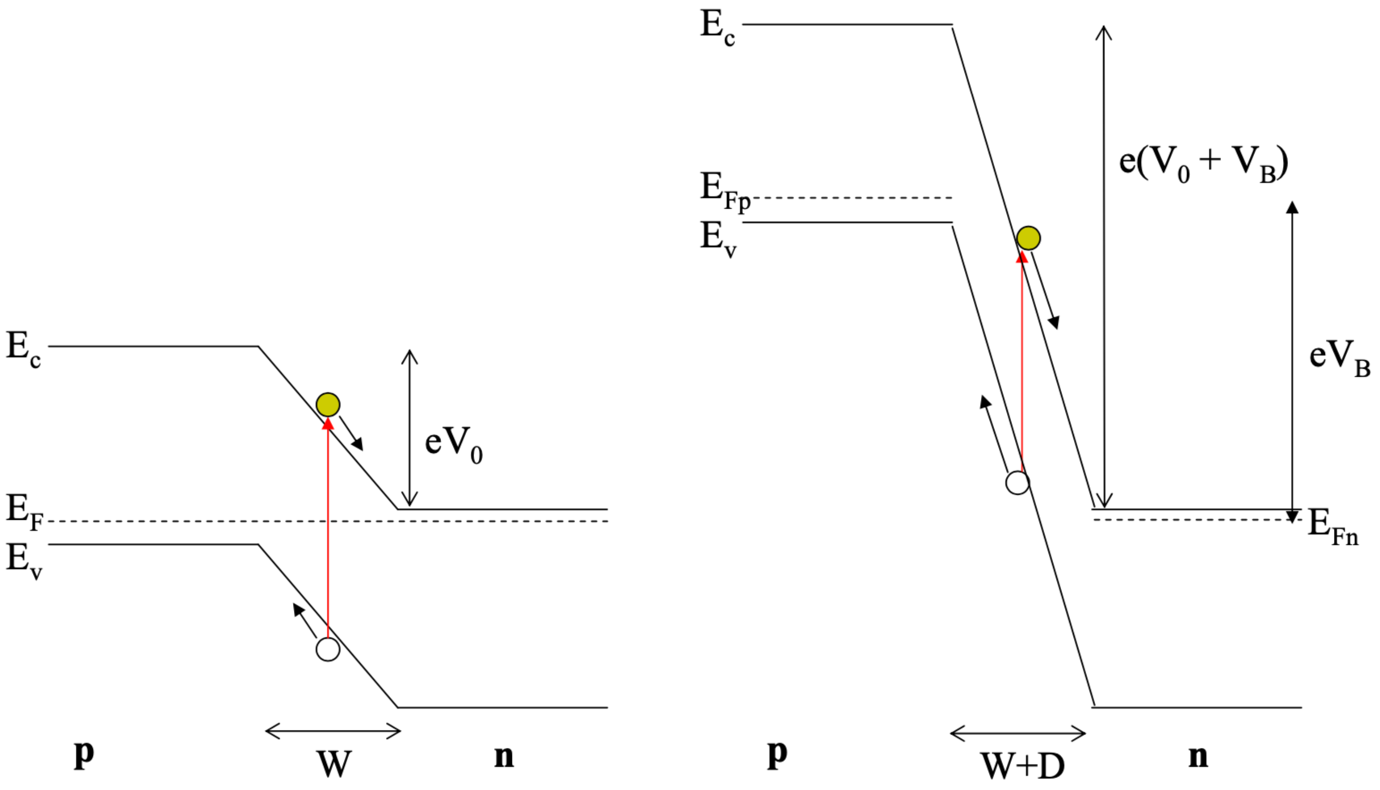
Electronic Properties / PD circuits

Photoconductive and photovoltaic modes

- There are *two* modes of operation for a junction photodiode: *photoconductive* and *photovoltaic*
- The device functions in *photoconductive* mode in the *third* quadrant of its current-voltage characteristics, including the *short-circuit condition* on the vertical axis for V = 0. (*acting as a current source*)
- It functions in *photovoltaic* mode in the *fourth* quadrant, including the *open-circuit condition* on the horizontal axis for I = 0. (*acting as a voltage source with output voltage limited by the equilibrium contact potential*)
- The mode of operation is determined by the *bias condition* and the *external circuitry*.

Electronic Properties / PD circuits

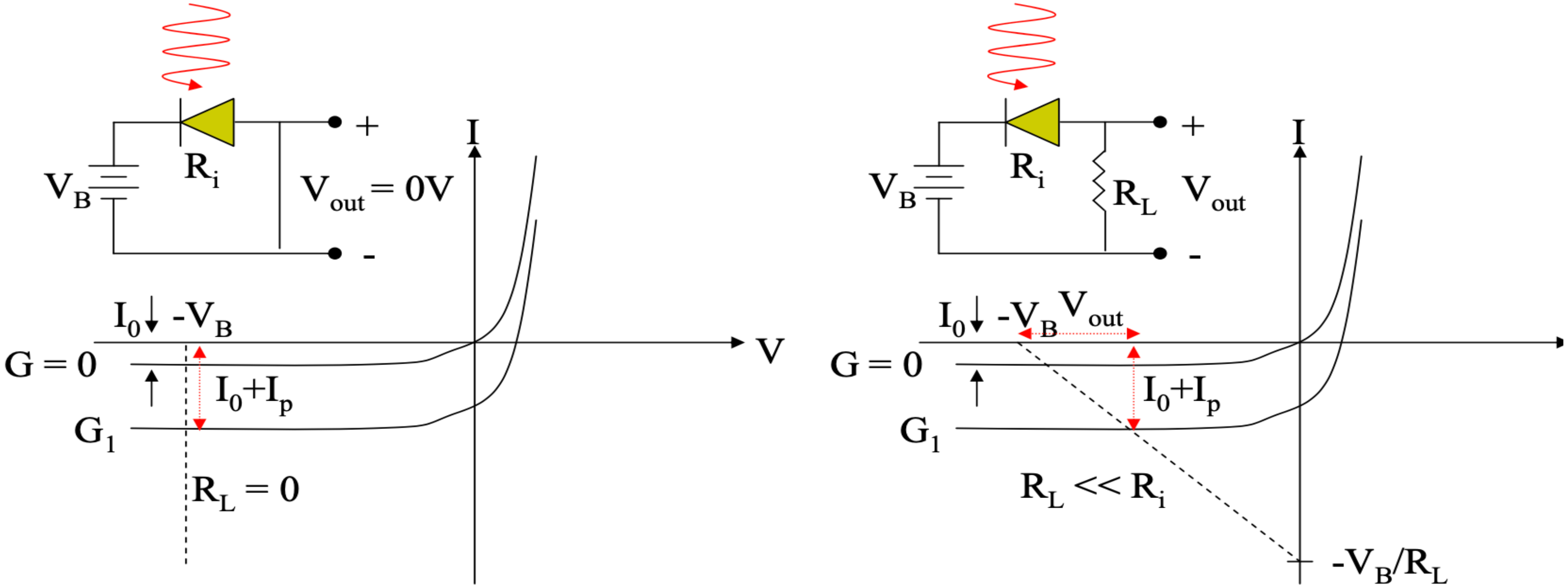
Photoconductive mode under reverse bias



For silicon photodiodes, $V_0 \approx 0.7$ V, V_B can be up to -5 – -10 V)

Electronic Properties / PD circuits

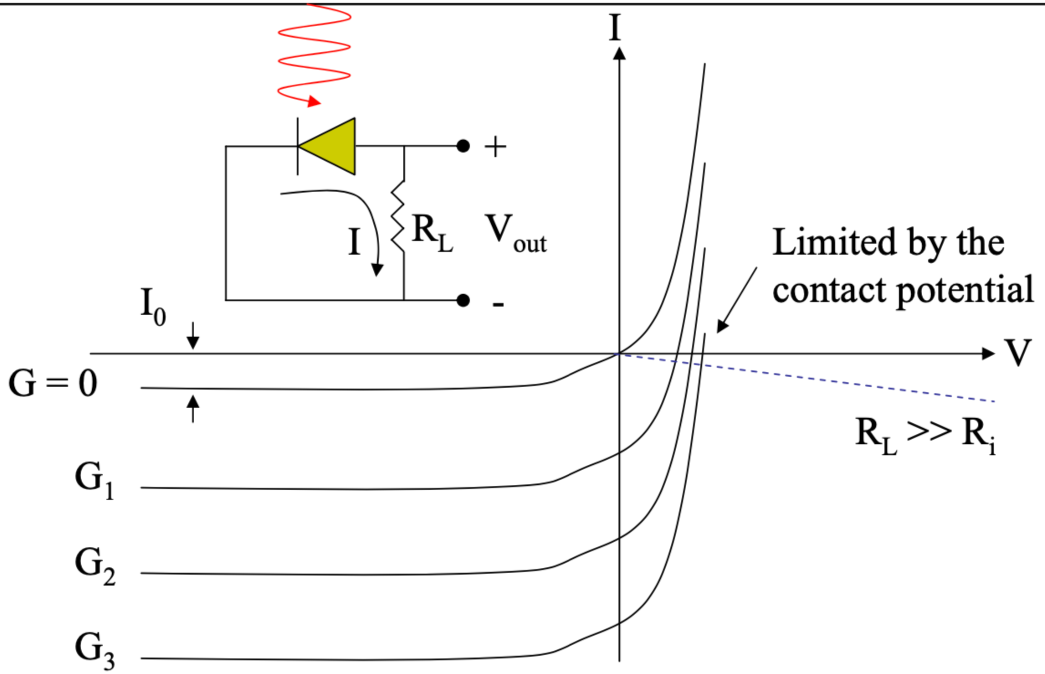
Basic circuitry and load line for the photoconductive mode



- "Photoconductive" mode – ***reverse** biasing* the photodiode
- With a *series* load resistor $R_L < R_i$ gives the load line
- Keep $V_{out} < V_B$ so that the photodiode is *reverse* biased (V_B *is sufficiently large*)
- Under these conditions and before it saturates, a photodiode has the following *linear response*: $V_{out} = (I_0 + I_p)\,R_L$

Electronic Properties / PD circuits

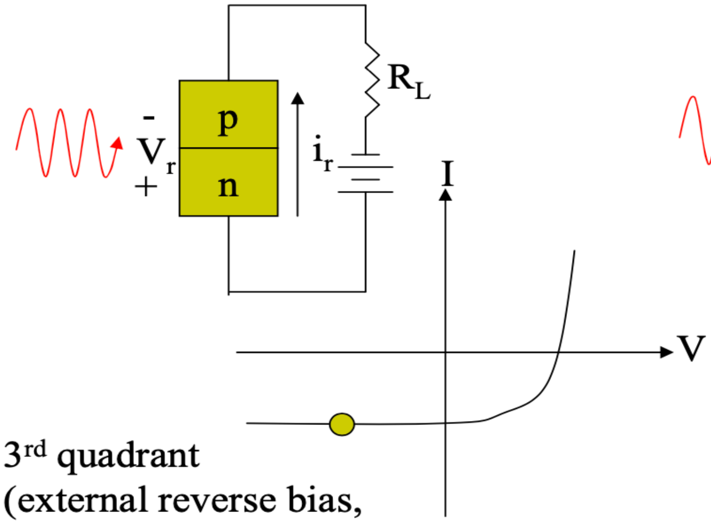
Basic circuitry and load line for the photovoltaic mode



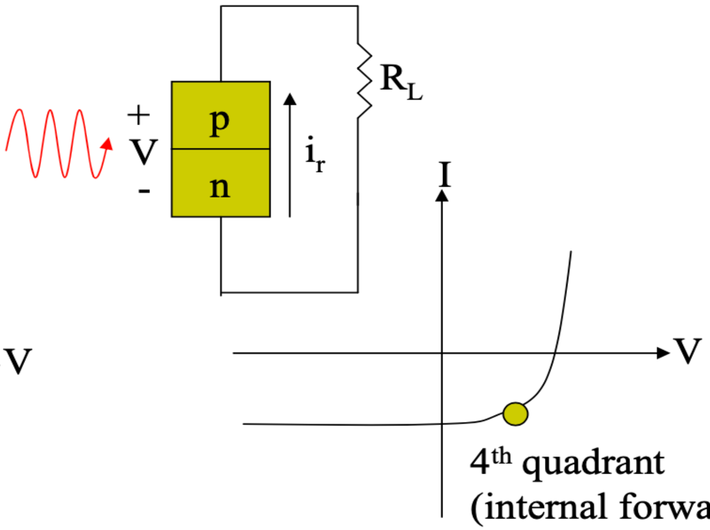
- *Does not require a bias voltage* but requires a ***large load resistance***.
- $R_L >> R_i$, so that the current I flowing through the diode and the load resistance is negligibly small.

Electronic Properties / PD circuits

Operation regimes of an illuminated junction



3rd quadrant
(external reverse bias,
reverse current)



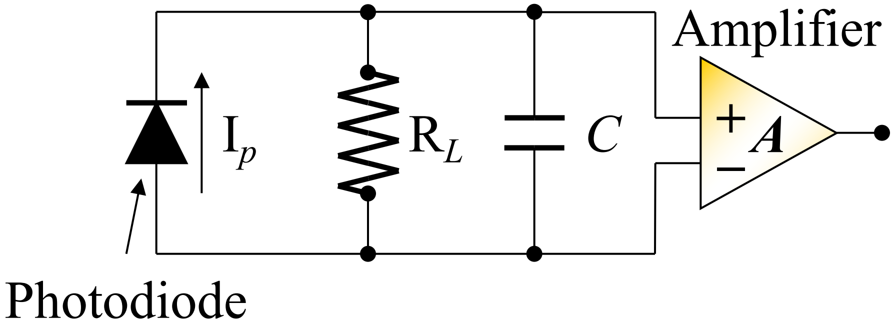
4th quadrant
(internal forward bias,
reverse current)

Photoconductive:
Power (+ve) is delivered *to the device by the external circuit* (photodetector)

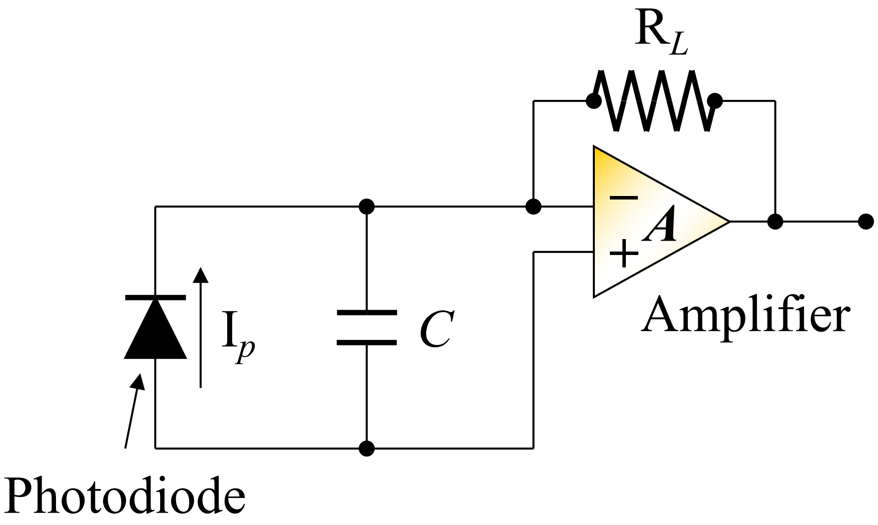
Photovoltaic:
Power (-ve) is delivered *to the load by the device*
(solar cell/ energy harvesting)

Front-End Amplifiers (1/4)

- Two kinds of front-end amplifiers are used in optical communication systems:
  - High-impedance front end amplifier
  - Transimpedance front end amplifier



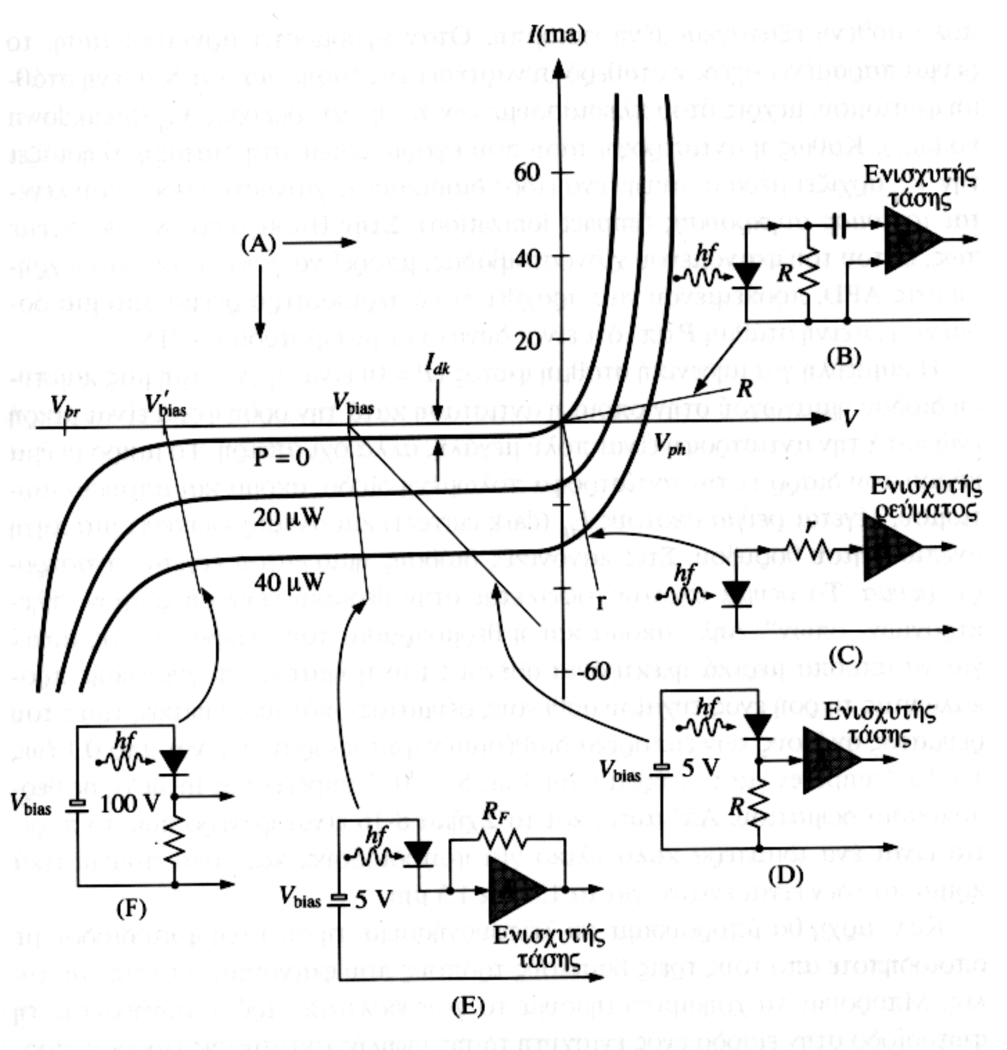
Equivalent circuit for a **high-impedance front-end amplifier**



Equivalent circuit for a **transimpedance front-end amplifier**

- The capacitance C includes:
  - –the capacitance due to the photodiode
  - –the amplifier input capacitance
  - –other parasitic capacitances

Operating regimes



A: Καμπύλες I-V υπό ορθή και ανάστροφη πόλωση

B: Λειτουργία σε Φ/Β τρόπο ανοικτού κυκλώματος

C: Λειτουργία σε βραχυκυκλωμένο τρόπο

D: Λειτουργία με ανάστροφη πόλωση σε ενισχυτή τάσης

E: Λειτουργία σε μορφή ενισχυτή διαντιστάσεως

F: Λειτουργία ως δίοδος Χιονοστοιβάδος

Front-End Amplifiers

- Main design issue: the choice of the **load resistance R_L**
- The **thermal noise current** is **inversely proportional to R_L**
- The **bandwidth** of the photodiode is **inversely proportional to R_p**
  - R_p: the output load resistance seen by the photodiode
- **High-impedance front end amplifier**: $R_p = R_L$
  - We must choose R_L small enough to accommodate the bit rate of the system ⇨ Trade-off between the photodiode bandwidth and its noise performance
- **Transimpedance front end amplifier**: $R_p = R_L/(A+1)$
  - A: the amplifier gain
  - Advantage: Increased bandwidth
  - Drawback: Higher thermal noise current
    - Quite moderate increase: usually a factor < 2
- Thus the **transimpedance front end is chosen over the high-impedance** one for most optical communication systems

Front-End Amplifiers

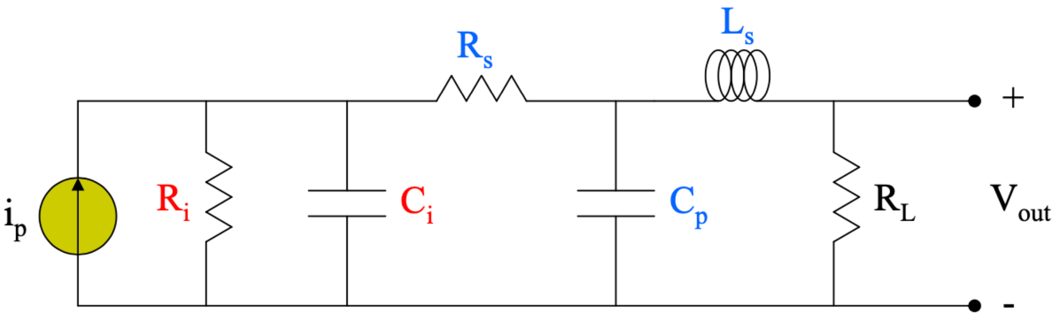
- **Dynamic range**: The **difference between the largest and smallest signal levels** that the front-end amplifier can handle
- Not an important consideration for many optical communication links
  - The power level seen by the receivers is usually more or less fixed
- Very important consideration for networks where the received signal level can vary by a few orders of magnitude, depending on the location of the source in the network

Front-End Amplifiers

- **The transimpedance amplifier has** a significantly **higher dynamic range** than the high-impedance one
  - Transimpedance amplifier: A change ΔI_p in the photocurrent ⇨ A change in voltage $\Delta I_p R_L$ across the resistance R_L ⇨ A voltage change across the inputs of the amplifier of only $\Delta I_p R_L/(A+1)$
  - High-impedance amplifier: Voltage change across the amplifier inputs = $\Delta I_p R_L$
- **Field-Effect Transistor (*FET*)**: Has a very high input impedance ⇨ Is often used as the amplifier in the front end
- *pin*FET device: A *pin* photodiode and an FET integrated on the same semiconductor substrate

Front-End Amplifiers

Small-signal equivalent circuits

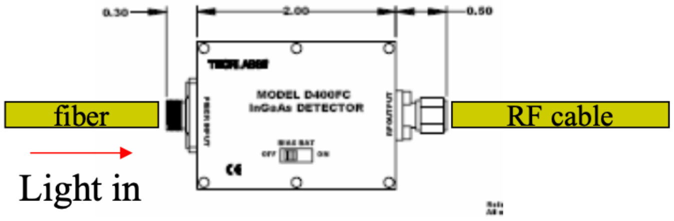


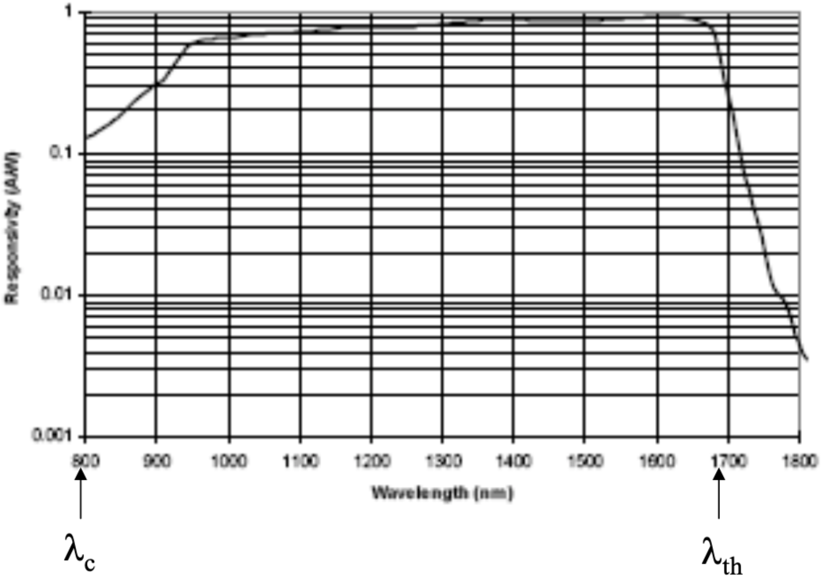
- A photodiode has an *internal resistance* R_i and an *internal capacitance* C_i *across its junction*.
- The *series resistance* R_s takes into account both resistance in the *homogeneous regions* of the diode and *parasitic resistance* from the contacts.
- The *external parallel capacitance* C_p is the *parasitic capacitance* from the contacts and the package.
- The series inductance L_s is the parasitic inductance from the wire or transmission-line connections.
- The values of R_s, C_p, and L_s can be minimized with careful design, processing, and packaging of the device.

Front-End Amplifiers

InGaAs fiber-optic pin photodetector

(Thorlabs D400FC)





Spectral response	800 – 1700 nm
Peak response	0.95 A/W @ 1550 nm
Rise/fall time	0.1 ns
Diode capacitance	0.7 pF (typ)
NEP @ 1550 nm	1.0 x 10^{-15} W/√Hz
Dark current	0.7nA (typ), 1.0nA (max)
PD Active diameter	0.1 mm
Bandwidth	1 GHz (min)
Damage threshold	100 mW CW
Bias (reverse)	12V battery
Coupling lens	0.8” dia. Ball lens
Coupling efficiency	92% (typ) from both single- and multi-mode fibers over full spectral response