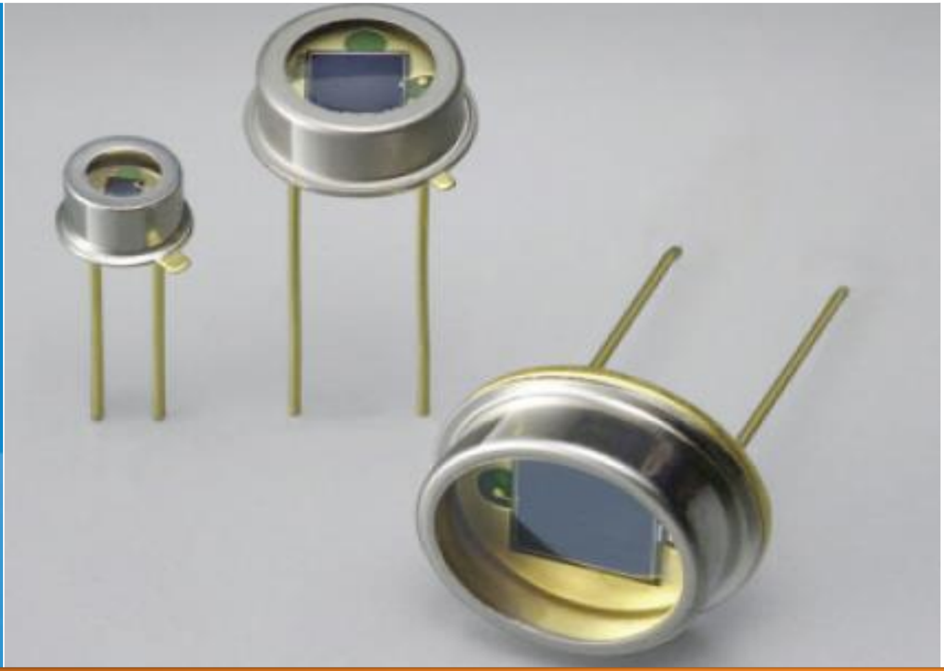
Lecture 10

Photodetectors

ECE 325

OPTOELECTRONICS



Kasap – 5.1, 5.4, 5.5, 5.6, and 5.12

May 08, 2019

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Principle of *pn* junction photodiode

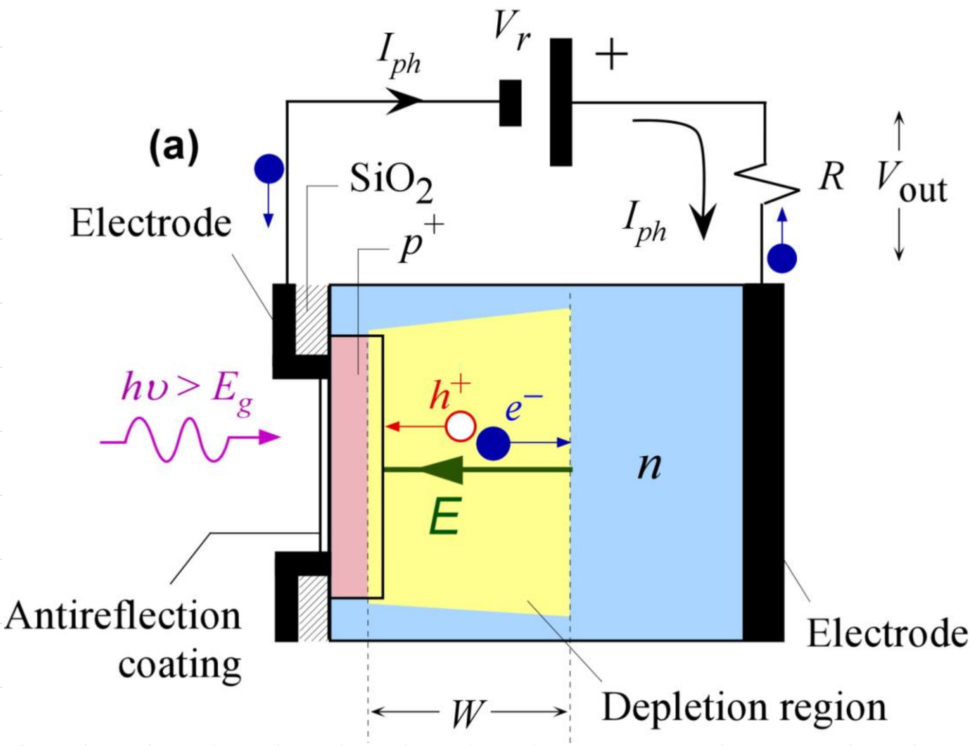
- Photodetectors convert light signal into an electrical signal such as voltage or current.

- Typical *pn* photodiode has a p^+n type junction
  - The Acceptor concentration (N_a) in the p side is **much greater than** the donor concentration (N_d) on the n side.

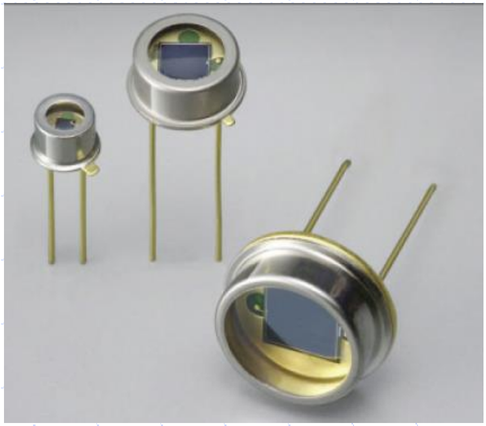
- The illuminated side has an **annular** (ring-shaped) electrode open in the center for light absorption.

- A Si_3N_4 **antireflective coating** is present on Silicon photodiodes to increase transmission of light into the diode.

Principle of *pn* junction photodiode



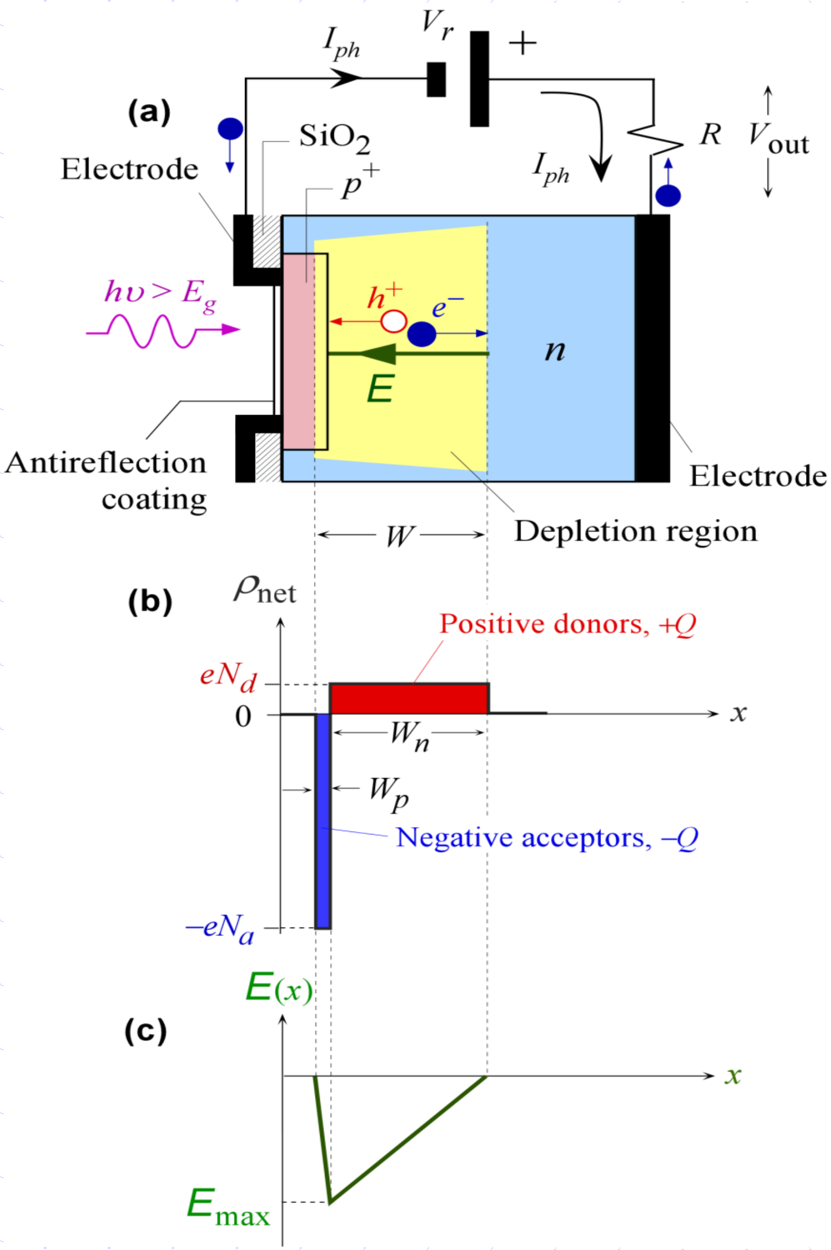
A schematic diagram of a reverse biased *pn* junction photodiode.



Courtesy of Hamamatsu

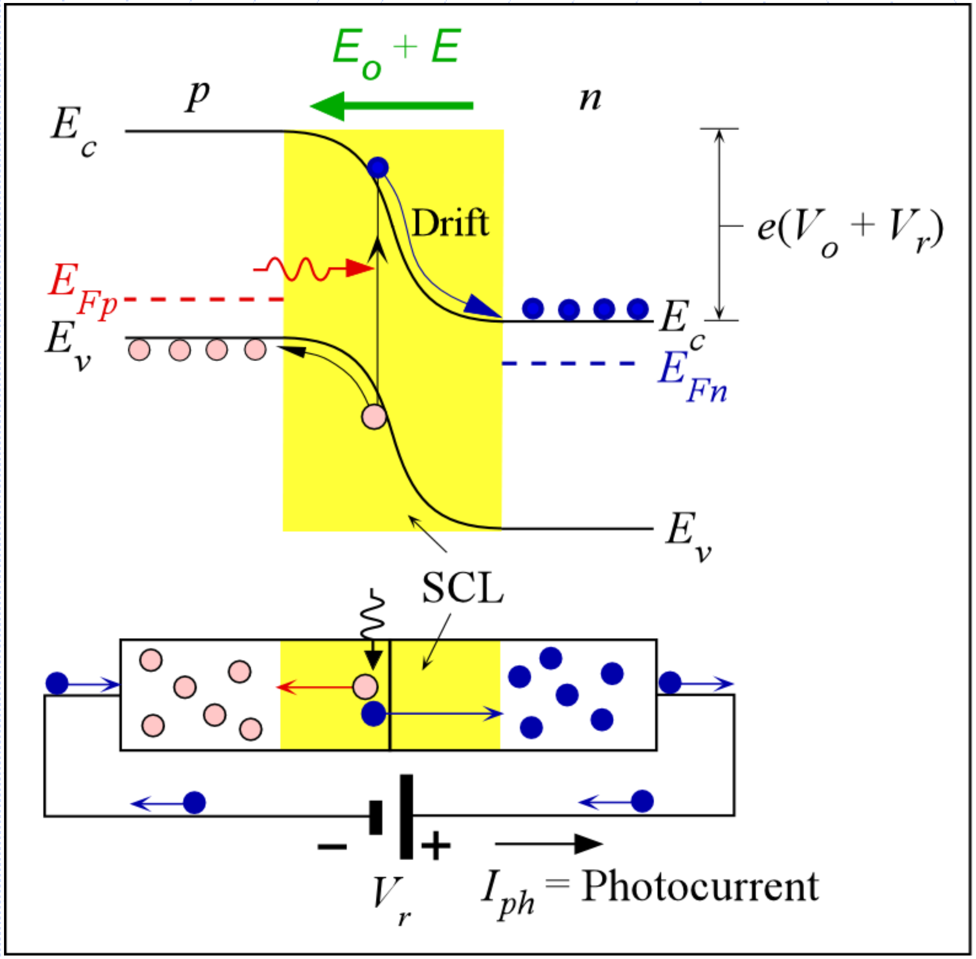
- *pn* photodiodes are reversed biased
- A strong negative bias is generated over a very small lateral dimension in the $p+$ side
- The depletion region extends deep into the thickness of the n side of the device

Principle of *pn* junction photodiode



- Schematic diagram of a **reverse biased** p-n junction photodiode
  - Photocurrent is depend on number of EHP and drift velocity.
  - The electrode do not inject carriers but allow excess carriers in the sample to leave and become collected by the battery.
- **Net space charge** across the diode in the depletion region. N_d and N_a are the donor and acceptor concentrations in the *p* and *n* sides.
- The **field** in the depletion region.

Principle of *pn* junction photodiode



A reverse biased *pn* junction. Photogeneration inside the SCL generates an electron and a hole. Both fall their respective energy hills (electron along E_c and hole along E_v) *i.e.* they drift, and cause a photocurrent I_{ph} in the external circuit.

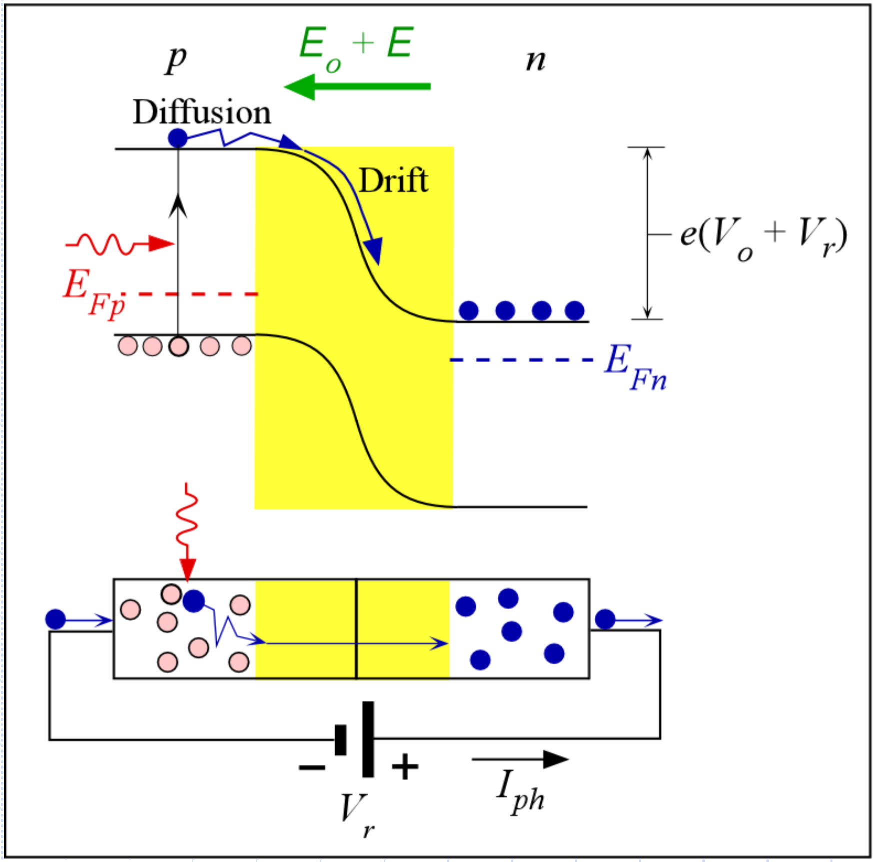
The potential hill, is the change in *Ec* from the *Ec* on the *n*-side to that on the *p*-side in the SCL

The drift corresponds to the electron rolling down the energy hill (along *Ec*) toward the *n*-side, whereas the hole rolls down the energy hill toward the *p*-side.

Principle of *pn* junction photodiode

- The **total bias** in the device $V = V_o + V_r$, where V_o is the built in voltage inherent in the junction
- When a photon of energy greater than the bandgap ($\boldsymbol{hv > E_g}$) is incident, it becomes absorbed and is said to photogenerate a free electron hole pair (EHP).
- Usually the energy of the photon is such that the photgeneraotion takes place in the depletion layer.
- The **electric field** present in the depletion layer pulls the EHP apart until they reach the neutral regions of the device.
- **Motion** of the electrons photgenerated in the device by the electric field produces a **photocurrent**, I_{ph} in the device.

Principle of *pn* junction photodiode

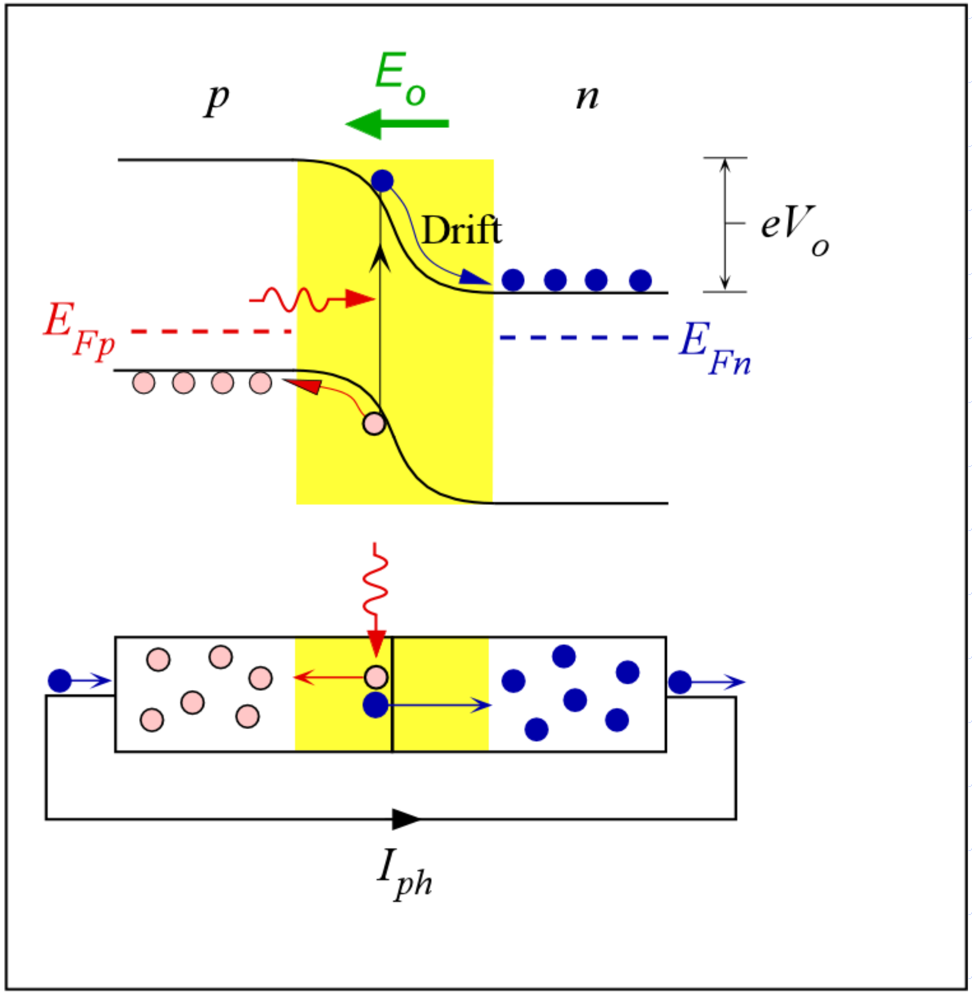


Photogeneration occurs in the neutral region. The electron has to diffuse to the depletion layer and then roll down the energy hill *i.e.* drift across the SCL.

An EHP is created in the *p*-side within the diffusion length L_e of an electron in this *p*-side. The electron can only reach the SCL by diffusion. The photogenerated electron diffuses (by "random walk") to the SCL where the internal field then drifts the electron over to the *n*-side.
The drift creates the photocurrent.

The photocurrent due to photogeneration in the neutral region is **weaker than** that due to photogeneration in the depletion region; in the latter, the field separates and drifts the carriers immediately.
Photodetector designs **prefer** the photogeneration process to take place in the **depletion region**, which is the reason for keeping the p_+-layer as thin as possible.

Principle of *pn* junction photodiode



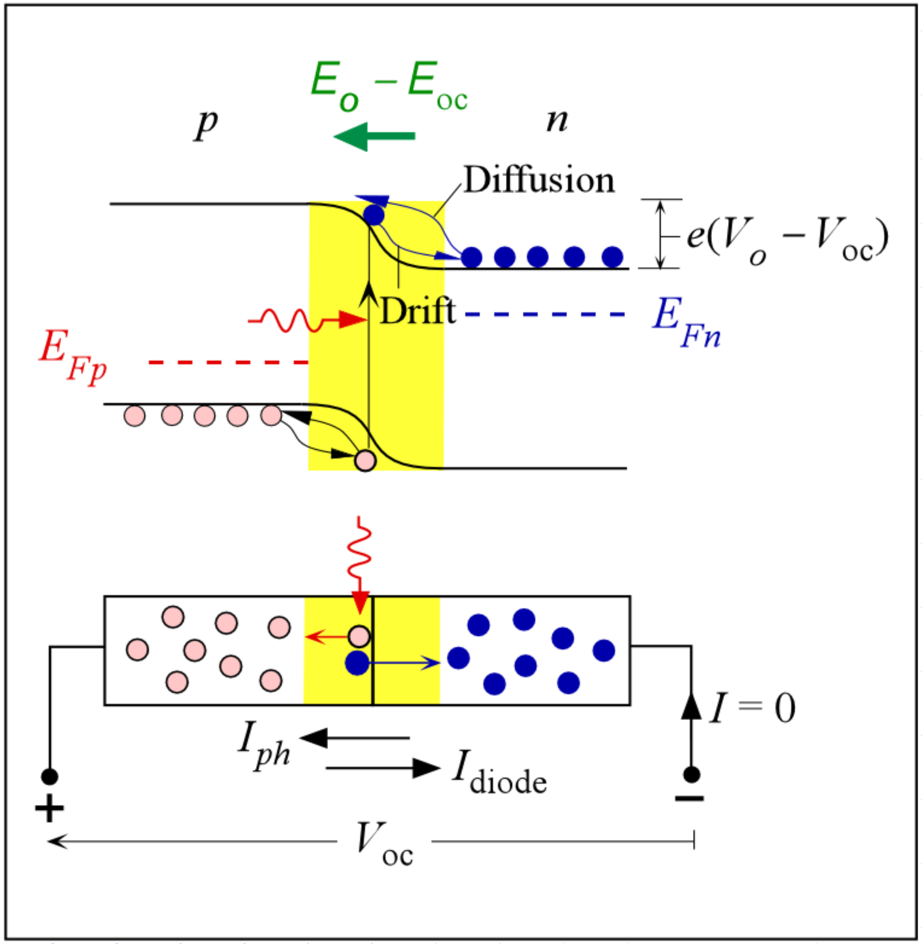
photovoltaic operation

A shorted *pn* junction. The photogenerated electron and hole in the SCL roll down their energy hills, *i.e.* drift across the SCL, and cause a current I_{ph} in the external circuit.

Photogeneration in the SCL will create an electron and a hole and these will now be driven by the built-in field E_o.

As the electron and hole drift, they generate a photocurrent I_{ph} in the external circuit.

Principle of *pn* junction photodiode

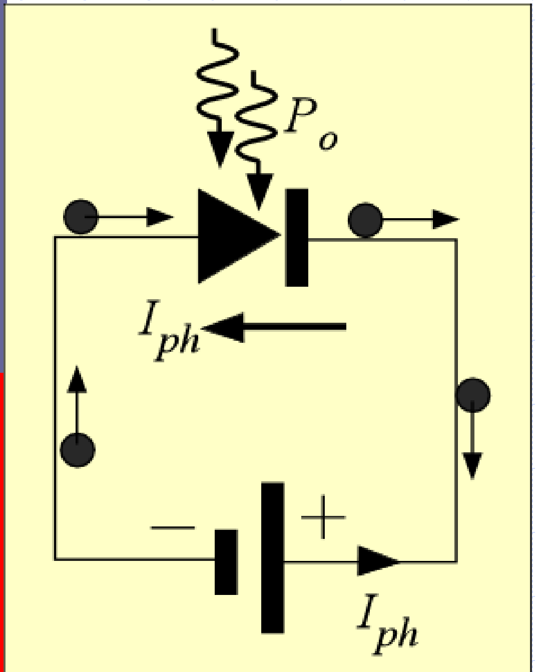


photovoltaic operation

The *pn* junction in open circuit. The photogenerated electron and hole roll down their energy hills (drift) but there is a voltage V_{oc} across the diode that causes them the diffuse back so that the net current is zero.

The voltage V_{oc} appears as a forward bias across the junction. Such forward bias would inject electrons from the *n*- to the *p*-side and holes from the *p*- to the *n*-side as in normal diode operation, and hence result in a diode current I_{diode}.

The current I_{diode} is actually in the opposite direction to the photocurrent I_{ph} and its magnitude is such that the total current I is zero, as it must be in an open circuit.

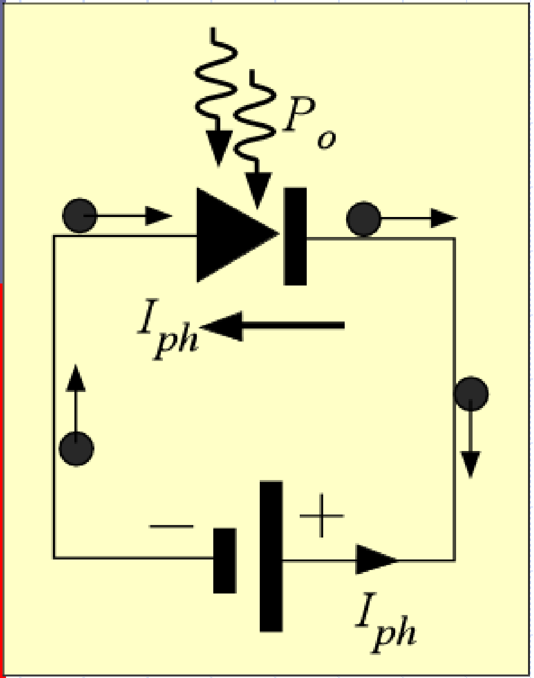


External quantum efficiency (QE) h_e of the detector

$$\eta_e = \frac{\text{Number of free EHP generated and collected}}{\text{Number of incident photons}}$$

$$\eta_e = \frac{I_{ph} / e}{P_o / h\upsilon}$$

Responsivity R

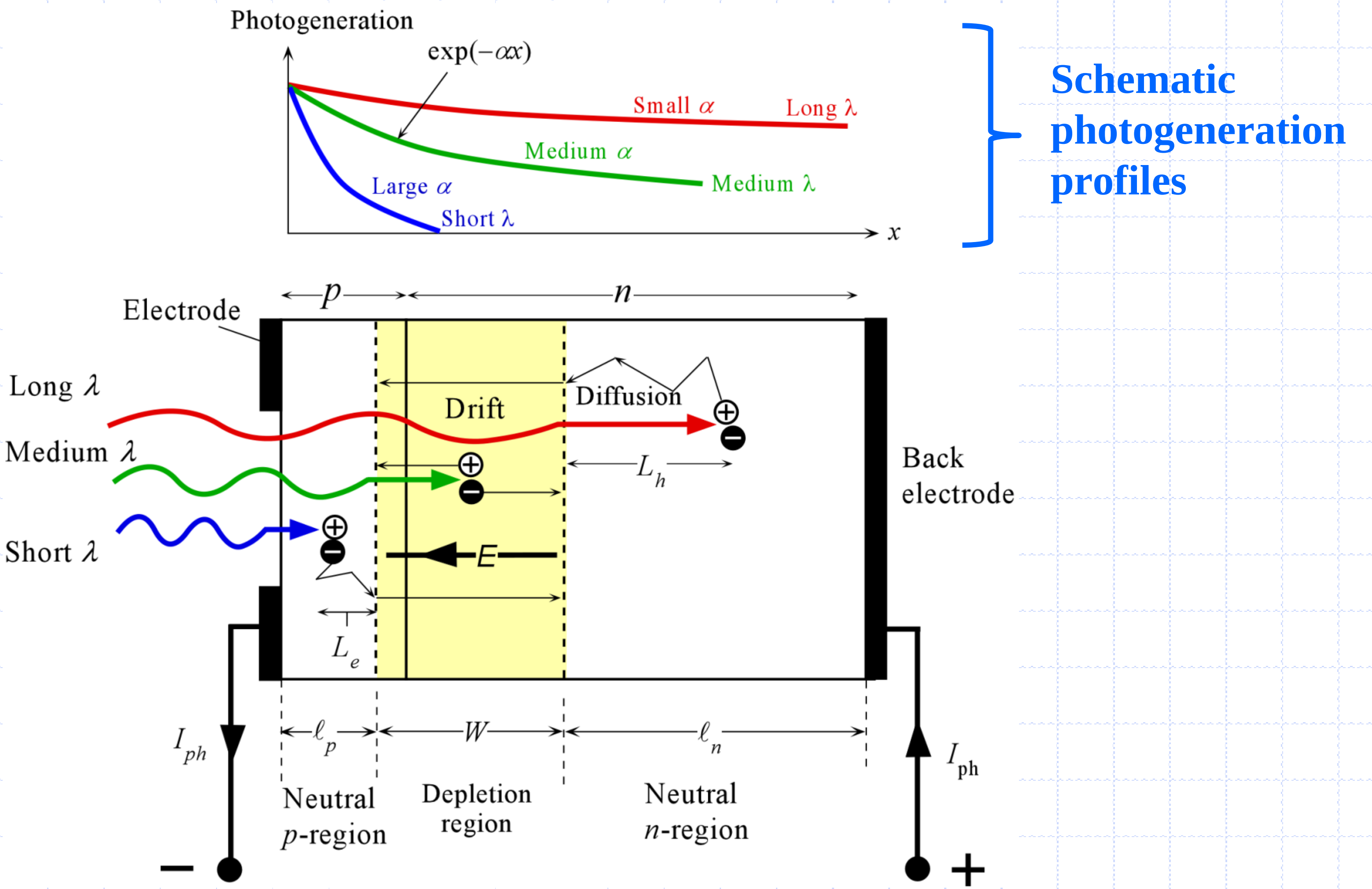


Responsivity characterizes the performance of a photodiode in terms of photocurrent generated per unit of optical power

$$R = \frac{\text{Photocurrent (A)}}{\text{Incident Optical Power (W)}} = \frac{I_{ph}}{P_o}$$

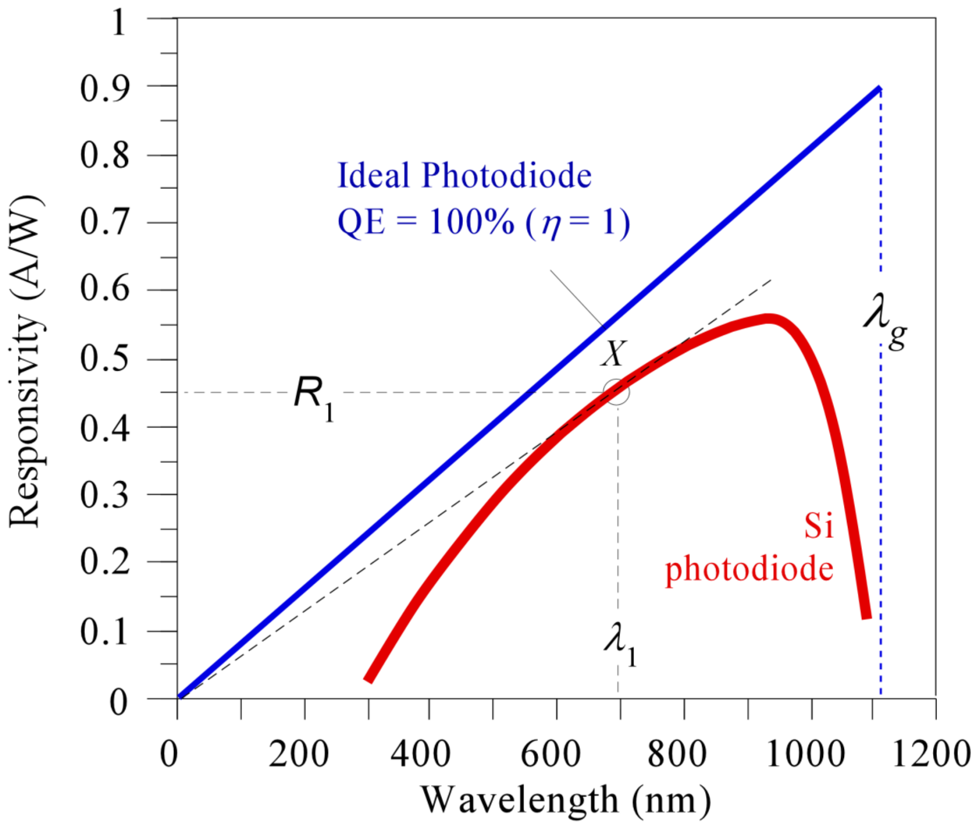
$$R = \eta_e \frac{e}{h\upsilon} = \eta_e \frac{e\lambda}{hc}$$

External Quantum Efficiency and Responsivity



Different contributions to the photocurrent I_{ph}. Photogeneration profiles corresponding to short, medium and long wavelengths are also shown.

Responsivity *R*



Responsivity (*R*) vs. wavelength (*l*) for an ideal photodiode with QE = 100% (h_e = 1) and for a typical inexpensive commercial Si photodiode. The exact shape of the responsivity curve depends on the device structure.

EXAMPLE: Quantum efficiency and responsivity

Consider the photodiode shown in Figure 5.7. What is the QE at peak responsivity? What is the QE at 450 nm (blue)? If the photosensitive device area is 1 mm^2, what would be the light intensity corresponding to a photocurrent of 10 nA at the peak responsivity?

Solution

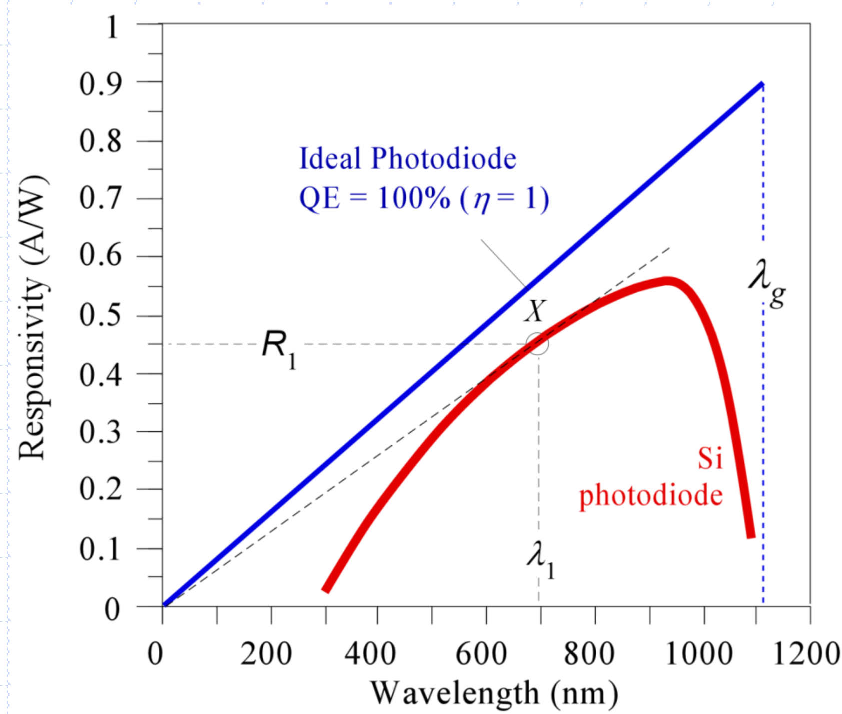
The peak responsibility in Figure 5.7 occurs at about *l* ≈ 940 nm where *R* ≈ 0.56 A W^{-1}. Thus, from Eq. (5.4.4), that is ***R* =*h*$_e$*el* / *hc***, we have

$$0.56\text{AW}^{-1} = \eta_e \frac{(1.6\times10^{-19}\ \text{C})(940\times10^{-9}\ \text{m})}{(6.63\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})}$$

i.e. *h*$_e$ = 0.74 or **74%**

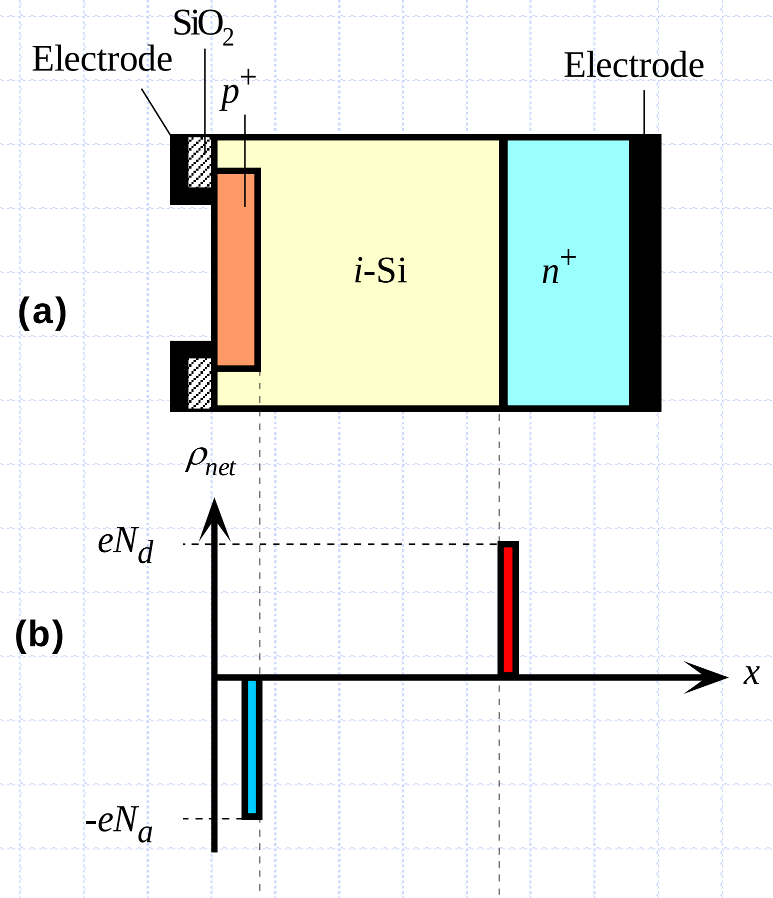
We can repeat the calculation for *l* = 450 nm, where *R* ≈ 0.24 AW^{-1}, which gives *h*$_e$ = 0.66 or 66%.

From the definition of responsivity, ***R* = *I*$_{ph}$/*P*$_o$**, we have 0.56 AW^{-1} = (10 × 10^{-9} A)/*P*$_o$, *i.e.* *P*$_o$ = 1.8 × 10^{-8} W or 18 nW. Since the area is 1 mm^2 the intensity must be 18 nW mm^{-2}.

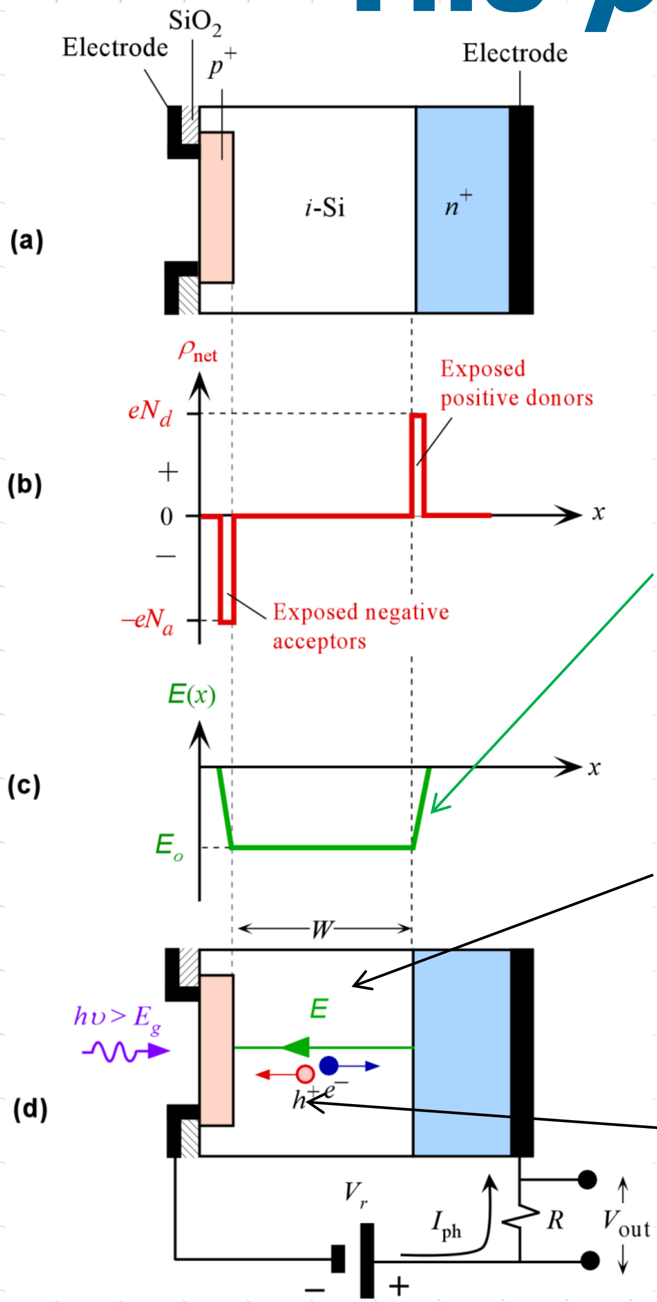


The *pin* Photodiode

- The *pn* junction photodiode has two drawbacks:
  - Depletion layer capacitance is not sufficiently small to allow photodetection at high modulation frequencies (RC time constant limitation).
  - Narrow SCL (at most a few microns) □long wavelengths incident photons are absorbed outside SCL □low QE
- The *pin* photodiode can significantly reduce these problems.



The *pin* Photodiode



The schematic structure of an idealized pin photodiode (b) The net space charge density across the photodiode. (c) The built-in field across the diode. (d) The pin photodiode reverse biased for photodetection.

$$E = E_o + \frac{V_r}{W} \approx \frac{V_r}{W}$$

$$C_{\text{dep}} = \frac{\varepsilon_o \varepsilon_r A}{W}$$

- **Small depletion layer capacitance** gives **high modulation frequencies**.
- **High Quantum efficiency**.

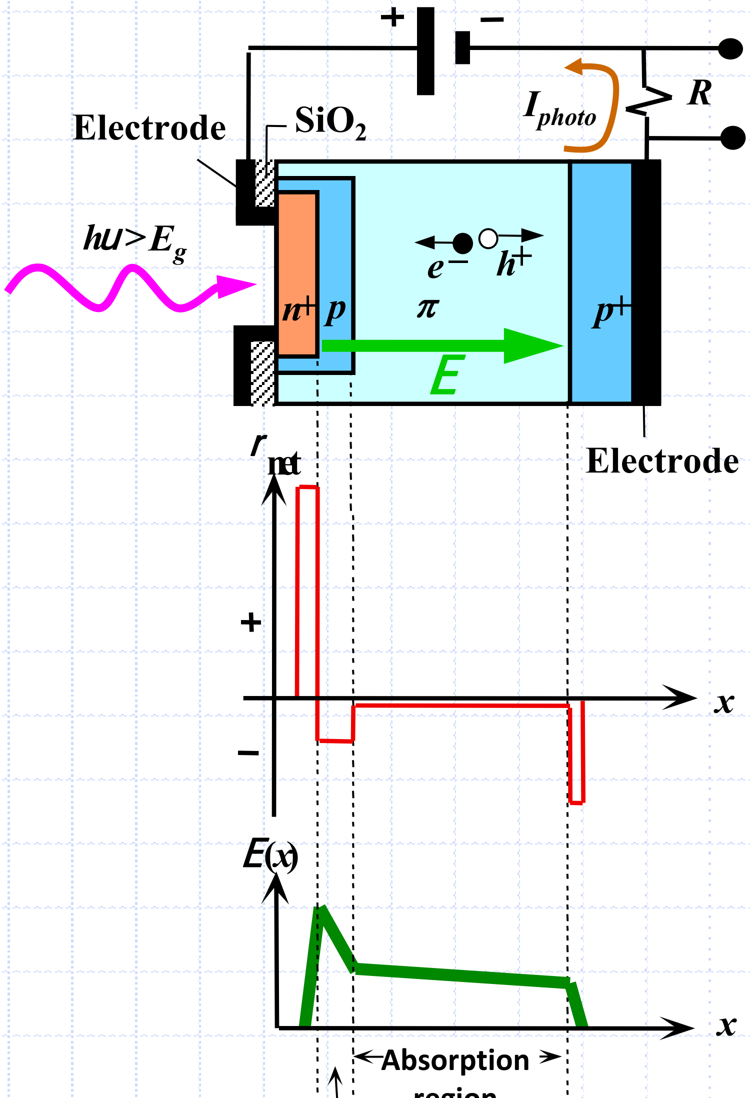
$$t_{\text{drift}} = \frac{W}{v_d}$$

Response time

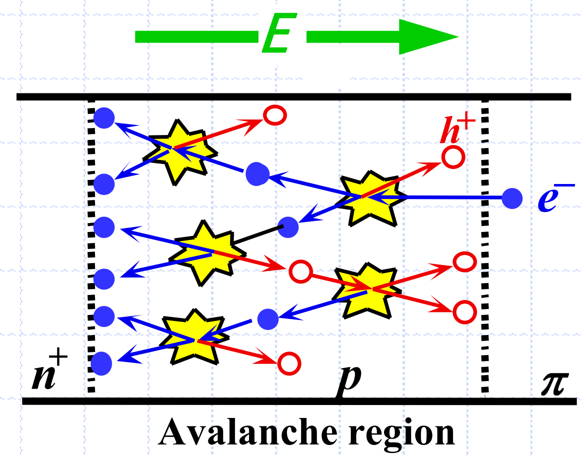
Avalanche Photodiode

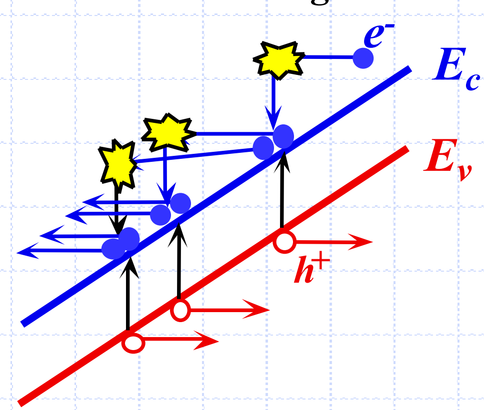
- APD has an internal gain obtained by having a **high electric field** that energizes photo-generated electrons and holes
- These electrons and holes ionize bound electrons in the valence band upon colliding with them
- This mechanism is known as **impact ionization**
- The newly generated electrons and holes are also accelerated by the high electric field and they gain enough energy to cause further impact ionization
- This phenomena is called the **avalanche effect**

Avalanche Photodiode



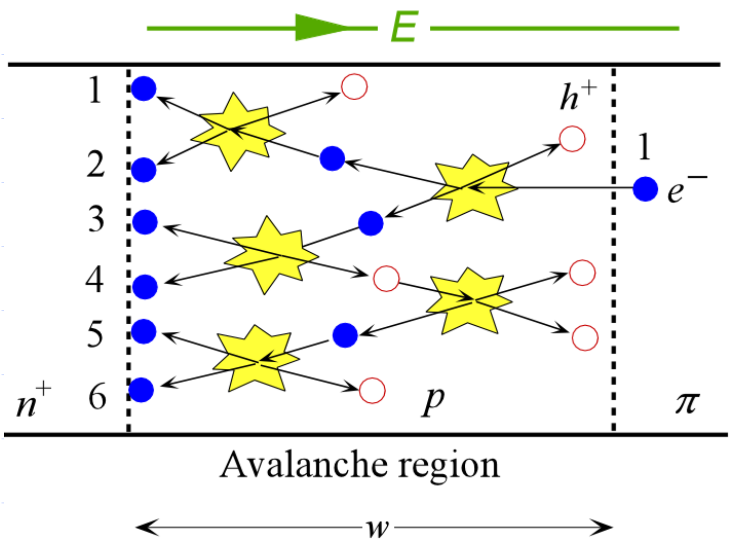
- Impact ionization processes resulting avalanche multiplication





- Impact of an energetic electron's kinetic energy excites VB electron to the CV.

Avalanche Photodiode Gain or Multiplication *M*

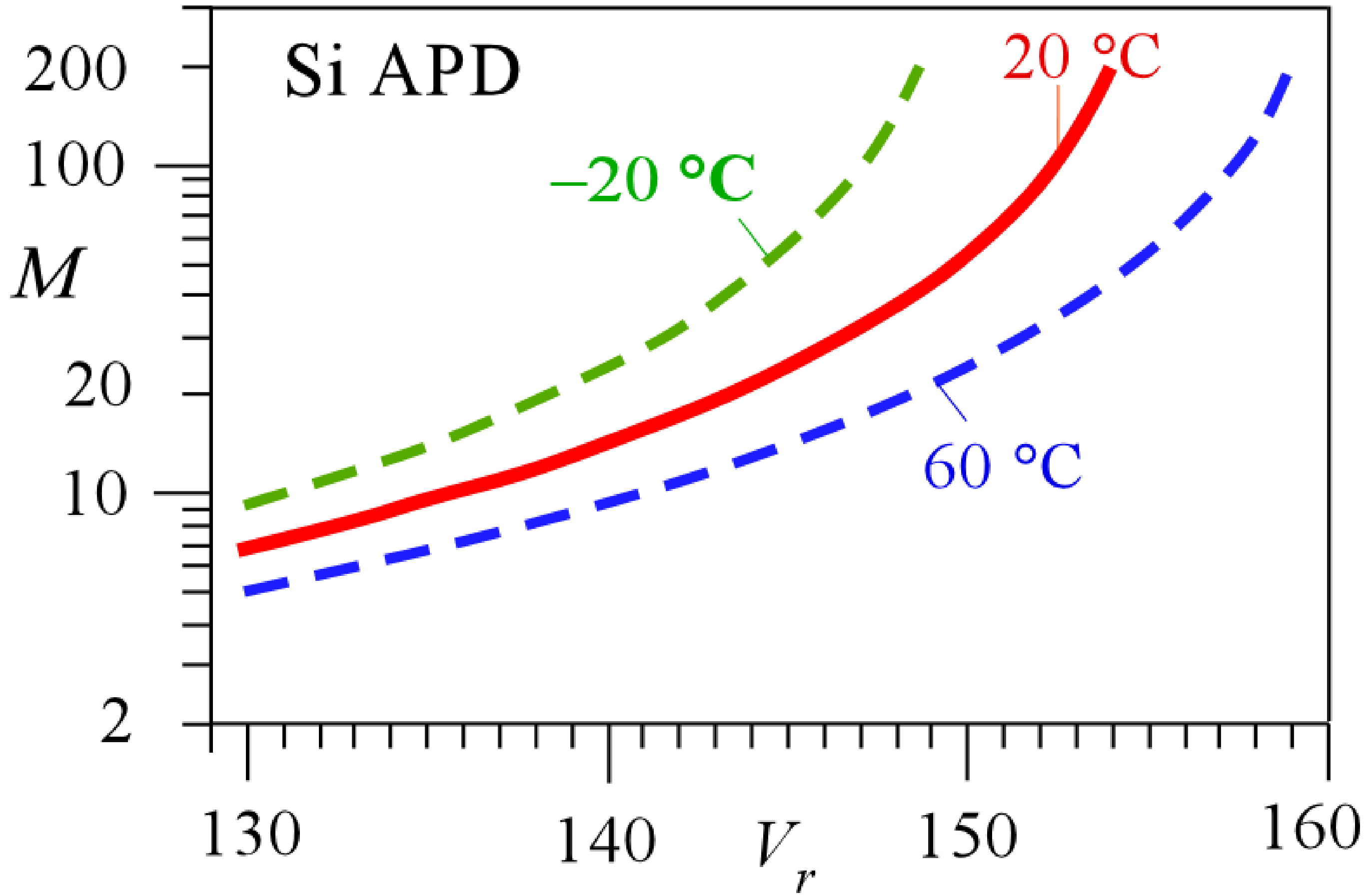


$$M = \frac{\text{Multiplied photocurrent}}{\text{Primary unmultiplied photocurrent}} = \frac{I_{ph}}{I_{pho}}$$

$$M = \frac{1}{1 - \left(\frac{V_r}{V_{br}}\right)^m}$$

V_{br} is a parameter called the **avalanche breakdown voltage** and *m* is a characteristic index that provides the best fit to the experimental data. Both V_{br} and *m* are temperature dependent.

Avalanche Photodiode



Typical multiplication (gain) *M* vs. reverse bias characteristics for a typical commercial Si APD, and the effect of temperature. (*M* measured for a photocurrent generated at 650 nm of illumination)

EXAMPLE: InGaAs APD Responsivity

An InGaAs APD has a quantum efficiency (QE, η_e) of 60 % at 1.55 μm in the absence of multiplication (M = 1). It is biased to operate with a multiplication of 12. Calculate the photocurrent if the incident optical power is 20 nW. What is the responsivity when the multiplication is 12?

Solution

The responsivity at M = 1 in terms of the quantum efficiency is

$$R = \eta_e \frac{e\lambda}{hc} = (0.6)\frac{(1.6\times10^{-19}\ \text{C})(1550\times10^{-9}\ \text{m})}{(6.626\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})} \qquad = \mathbf{0.75\ A\ W^{-1}}$$

If I_{pho} is the primary photocurrent (unmultiplied) and P_o is the incident optical power then by definition, $R = I_{pho}/P_o$ so that

$$I_{pho} = RP_o$$
$$= (0.75\ \text{A W}^{-1})(20\times10^{-9}\ \text{W})$$
$$= 1.5\times10^{-8}\ \text{A or 15 nA.}$$

The photocurrent I_{ph} in the APD will be I_{pho} multiplied by M,

$$I_{ph} = MI_{pho}$$
$$= (12)(1.5\times10^{-8}\ \text{A})$$
$$= 1.80\times10^{-7}\ \text{A or 180 nA.}$$

The responsivity at M = 12 is

$$R' = I_{ph}/P_o = MR = (12) / (0.75) = \mathbf{9.0\ A\ W^{-1}}$$

EXAMPLE: Silicon APD

A Si APD has a QE of 70 % at 830 nm in the absence of multiplication, that is $M = 1$. The APD is biased to operate with a multiplication of 100. If the incident optical power is 10 nW what is the photocurrent?

Solution

The unmultiplied responsivity is given by,

$$R = \eta_e \frac{e\lambda}{hc} = (0.70)\frac{(1.6\times10^{-19}\ \text{C})(830\times10^{-9}\ \text{m})}{(6.626\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})} = 0.47\ \text{A W}^{-1}$$

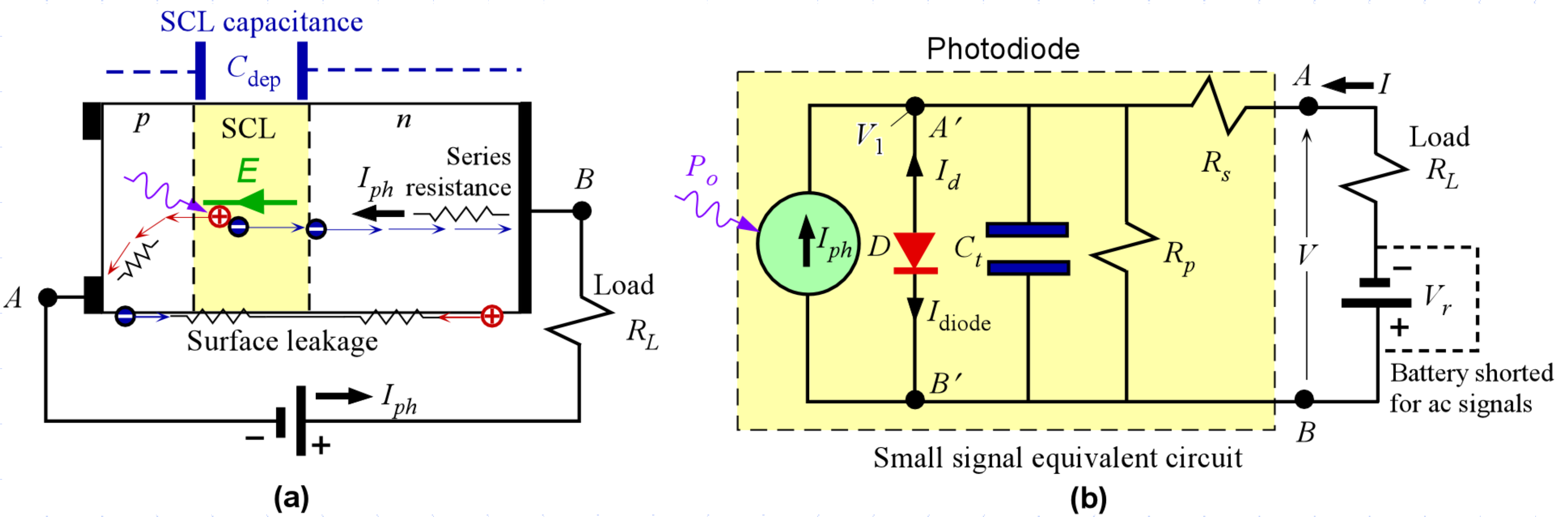
The unmultiplied primary photocurrent from the definition of R *is*

$$I_{pho} = RP_o = (0.47\ \text{A W}^{-1})(10\times10^{-9}\ \text{W}) = 4.7\ \text{nA}$$

The multiplied photocurrent is

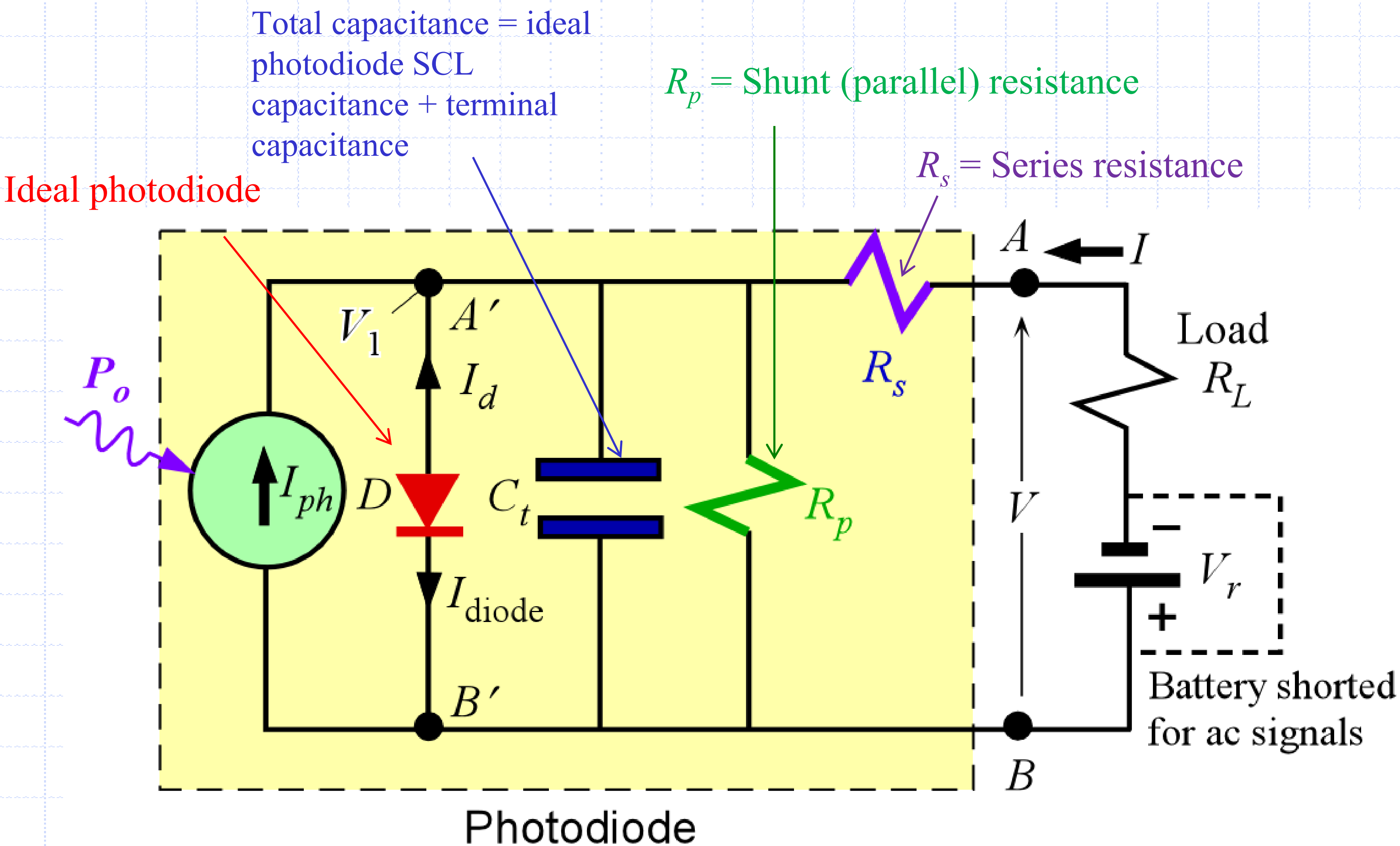
$$I_{ph} = MI_{pho} = (100)(4.67\ \text{nA}) = \mathbf{470\ nA} \text{ or } \mathbf{0.47\ mA}$$

Photodiode Equivalent Circuit

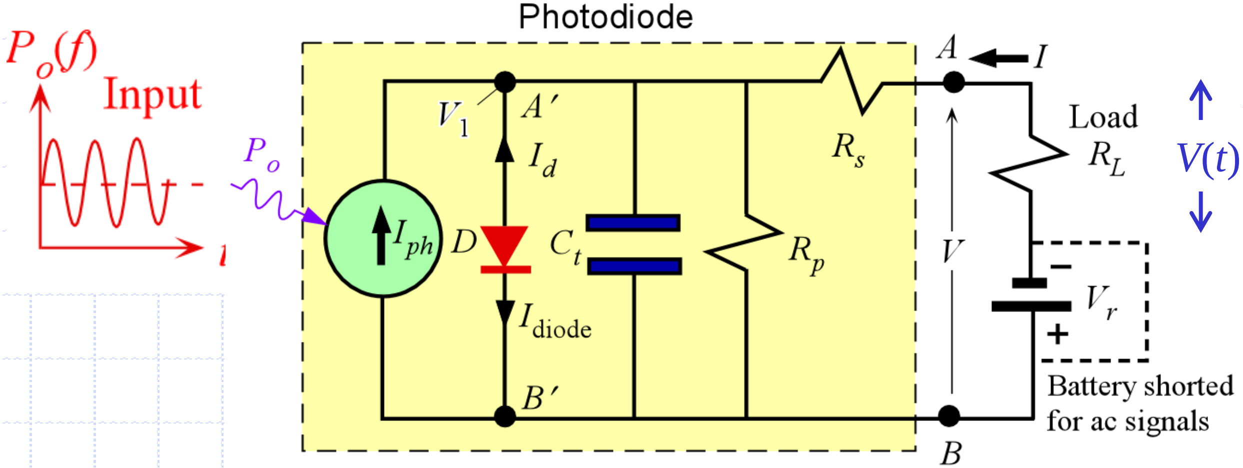


(a) A real photodiode has series and parallel resistances R_s and R_p and a SCL capacitance C_{dep}. A and C represent anode and cathode terminals. (b) The equivalent circuit of a photodiodes. For ac (or transient) signals, the battery can be shorted since ac signals will simply pass through the battery.

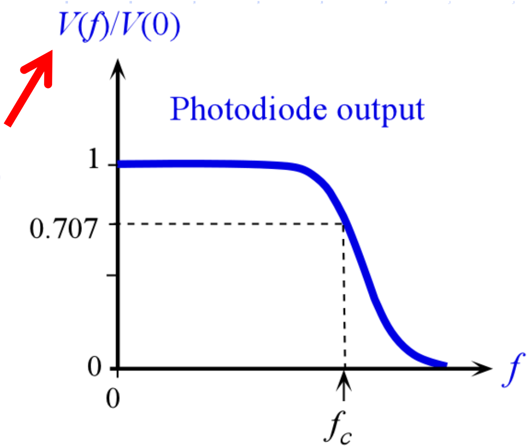
Reverse Biased Photodiode Equivalent Circuit



Cutoff Frequency f_c



Small signal equivalent circuit



The cutoff frequency or the bandwidth of the PD

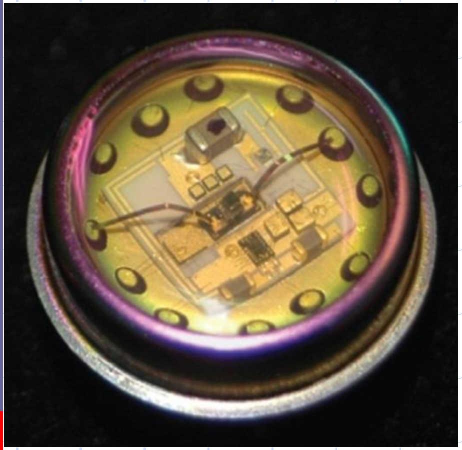
$$f_c = \frac{1}{2\pi R_{\text{eq}} C_t} \approx \frac{1}{2\pi (R_s + R_L) C_t} \approx \frac{1}{2\pi R_L C_t}$$

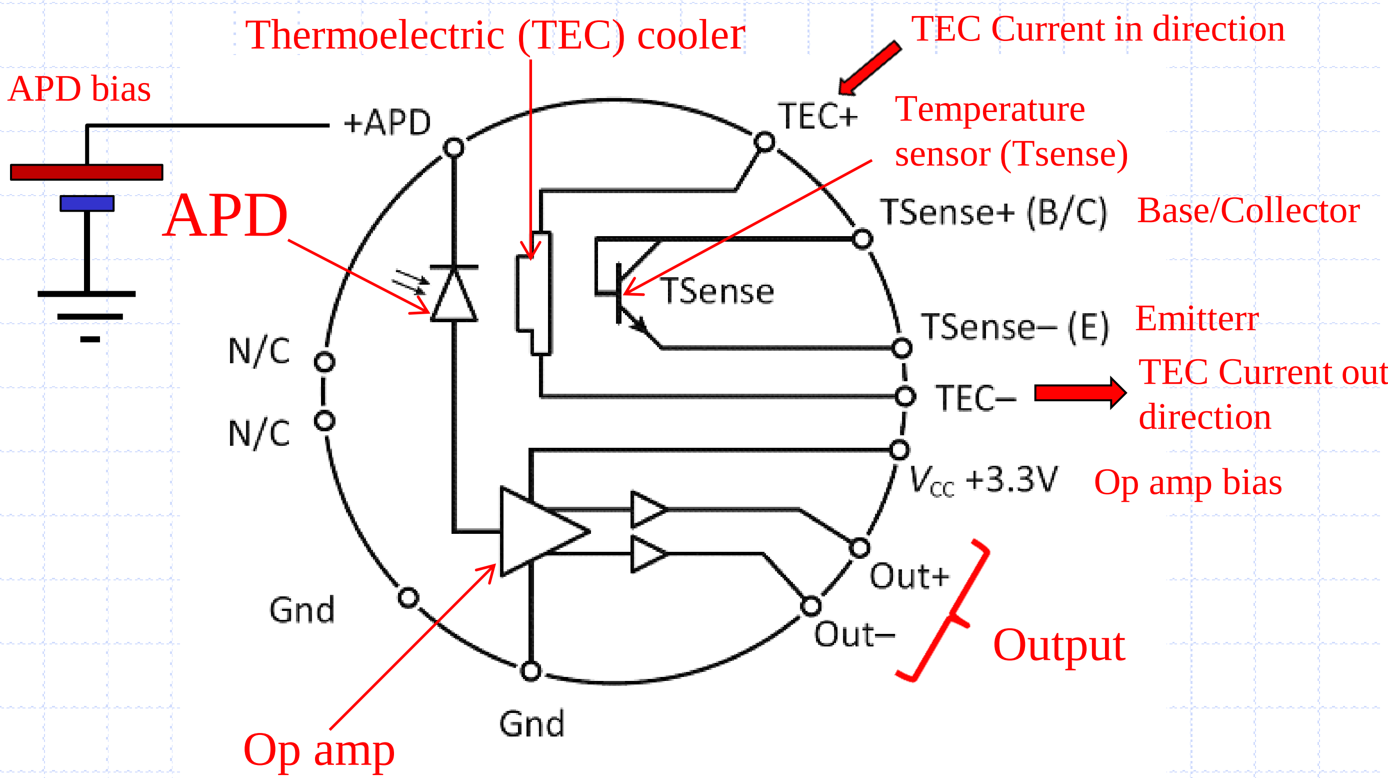
R_{eq} is equivalent resistance and represents $(R_s + R_L)$ in parallel with R_p

Assumption

Drift time of carriers is much less than $1/f_c$.
Response is not limited by drift and diffusion times of caries within the device.

A Commercial Photoreceiver

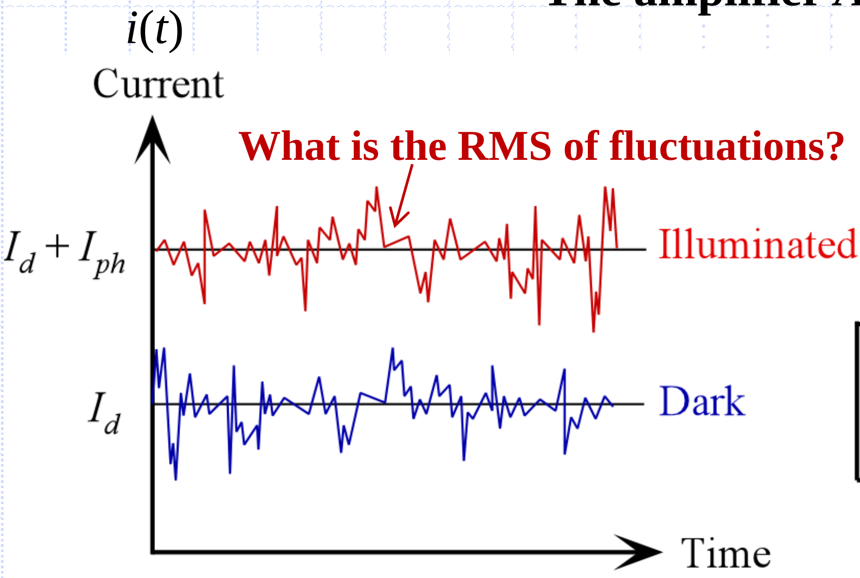


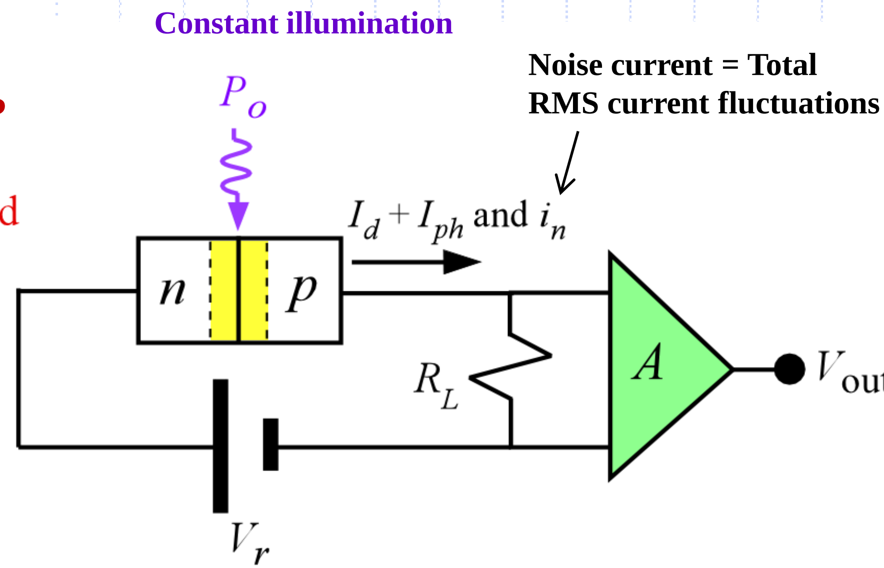


A photoreceiver that has an InGaAs APD and peripheral electronics (ICs) to achieve high gain and high sensitivity. There is also a thermoelectric cooler (TEC) and a temperature sensor (TSense). Courtesy of Voxtel Inc (www.voxtel-inc.com)

Noise in Photodiodes

Consider a receiver with a photodiode and a sampling resistor R_L
The amplifier A is assumed noiseless





Consider **constant illumination P_o**

Total current without noise = Dark current (I_d) + Photocurrent (I_{ph}) = "Constant"

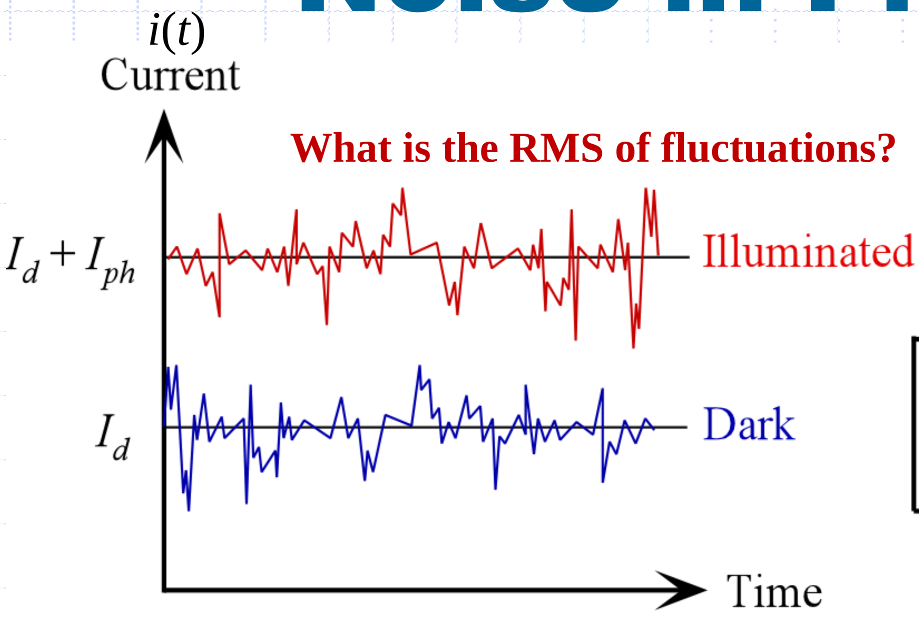
Observed Current = Dark current + Photocurrent **and** **Fluctuations (Noise)**

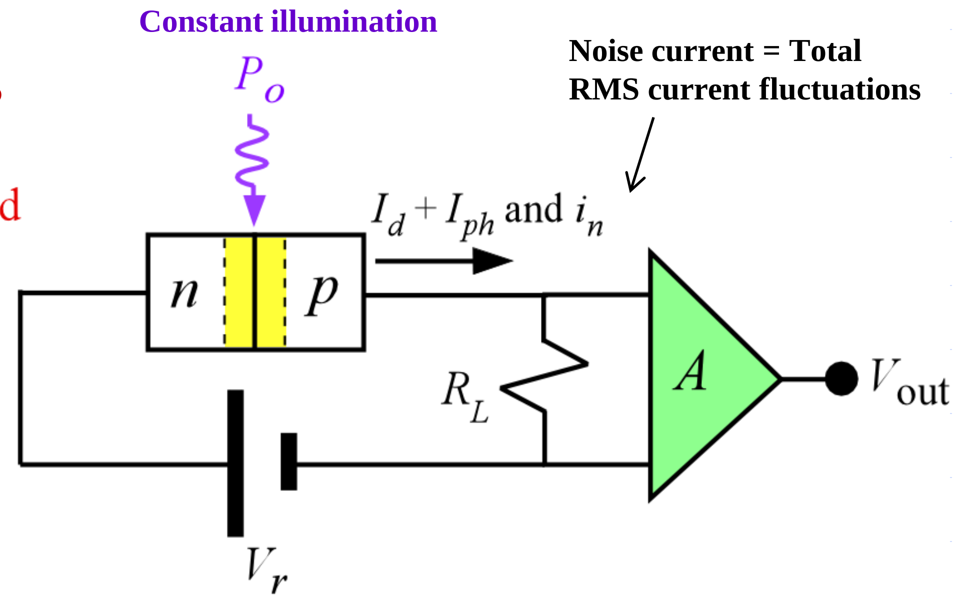
What is this "Noise" ?

We can represent the "noise current" by the RMS of fluctuations

$$\text{RMS of fluctuations} = \sqrt{\overline{i(t)^2}}$$

Noise in Photodiodes





The dark current has **shot noise** or fluctuations about I_d,

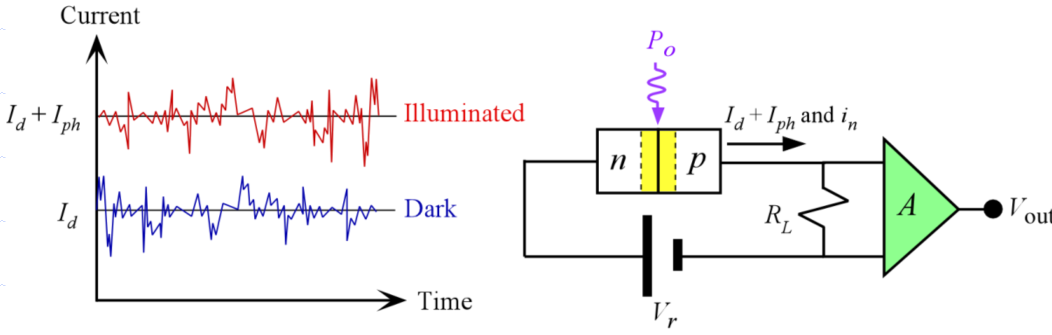
$$i_{n\text{-dark}} = (2eI_dB)^{1/2}$$

B = Bandwidth

Quantum noise is due to the photon nature of light and its effects are the same as **shot noise**. Photocurrent has quantum noise or shot noise

$$i_{n\text{-quantum}} = (2eI_{ph}B)^{1/2}$$

Noise in Photodiodes



Total shot noise current, i_n

$$i_n^2 = i_{n-\text{dark}}^2 + i_{n-\text{quantum}}^2$$

$$i_n = [2e(I_d + I_{ph})B]^{1/2}$$

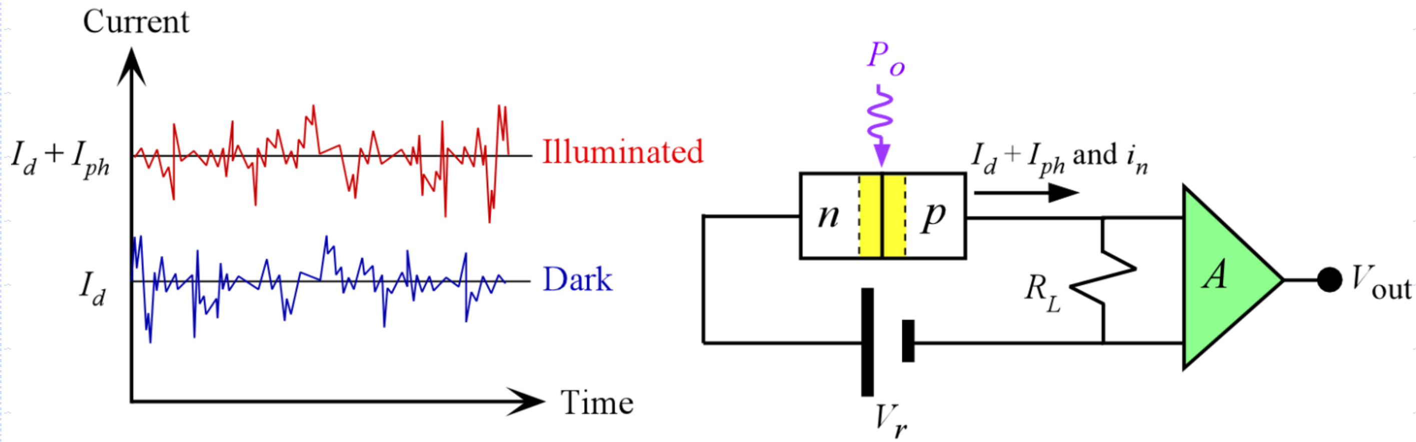
We can conceptually view the photodetector current as

$$I_d + I_{ph} + i_n$$

This flows through a load resistor R_L and voltage across R_L is amplified by A to give V_{out}

The noise voltage (RMS) due to shot noise in PD = $i_n R_L A$

Noise in Photodiodes



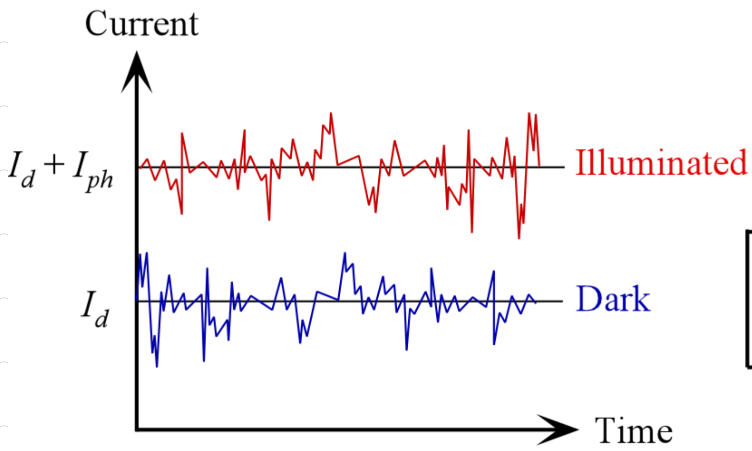
Total current flowing into R_L has three components:

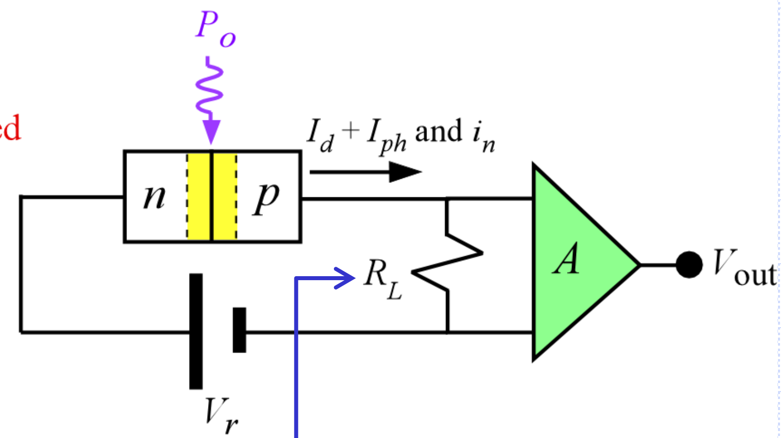
I_d = Dark current. In principle, we can subtract this or block it with a capacitor *if* I_{ph} is an ac (transient) signal.

I_{ph} = Photocurrent. This is the signal. We need this. It could be a steady or varying (ac or transient) signal.

i_n = Total shot noise. Due to shot noise from I_d and I_{ph}. We cannot eliminate this.

Noise in Photodiodes





The resistor R_L exhibits **thermal noise (Johnson noise)**

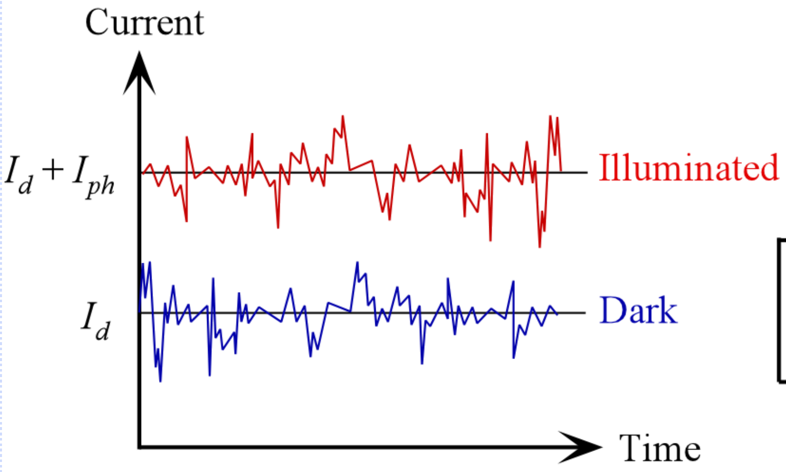
Power in thermal fluctuations in $R_L = 4k_BTB$

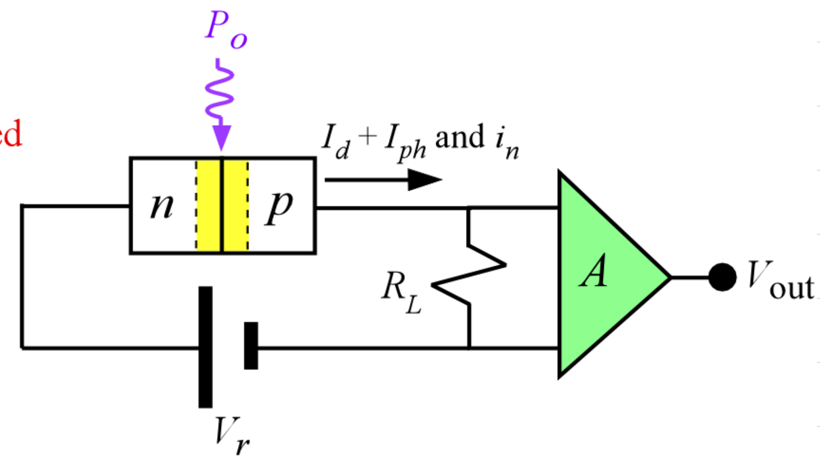
$$\therefore \quad R_L\overline{i^2} = 4k_BTB \qquad i = \text{Current in } R_L$$

$$\sqrt{\overline{i^2}}$$

$$i_{\text{th}} = \text{Thermal noise current from } R_L = \left[\frac{4k_BTB}{R_L}\right]^{1/2}$$

Signal to Noise Ratio



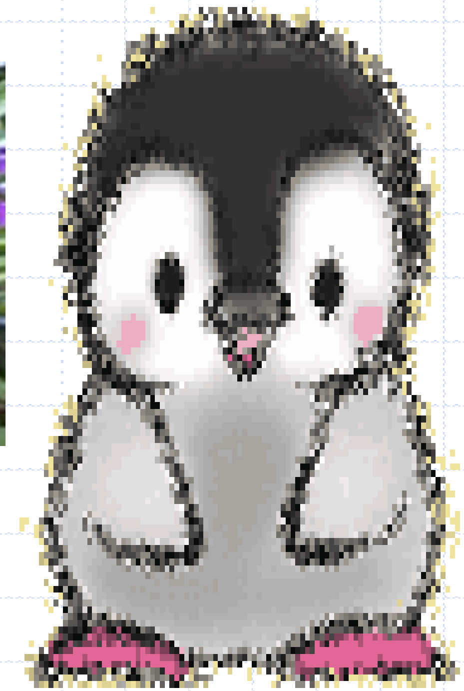


$$\text{SNR} = \frac{\text{Signal Power}}{\text{Noise Power}}$$

$$\text{SNR} = \frac{I_{ph}^2 R_L}{i_n^2 R_L + 4k_B TB} = \frac{I_{ph}^2}{\left[2e(I_d + I_{ph})B\right] + \frac{4k_B TB}{R_L}}$$

Important Note: Total noise is always found by first summing the average powers involved in individual fluctuations *e.g.* **power in shot noise + power in thermal noise**

Thank you



Have a nice day !