Photodetectors

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Course Overview

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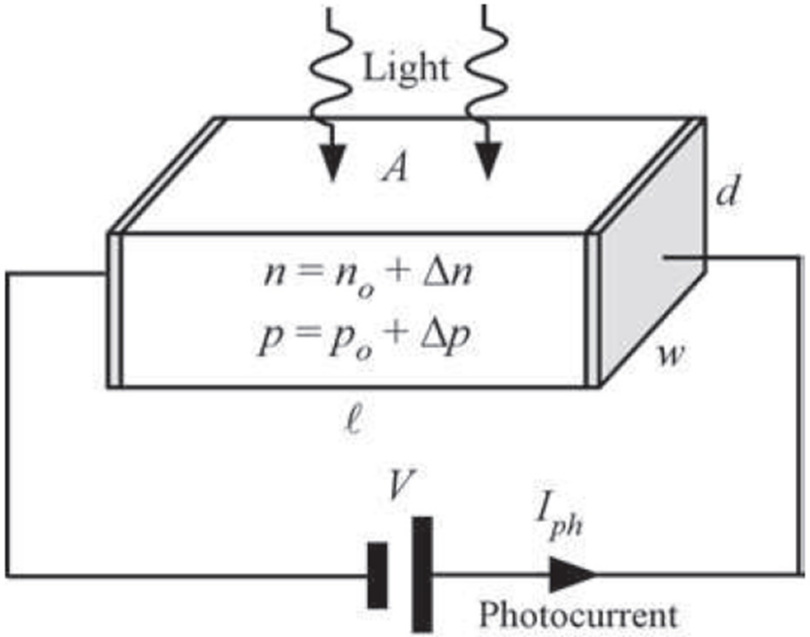
Ref:
Kasap, Optoelectronics and Photonics (Ed. 2), Chapter 5;
Shun Lien Chuang, Physics of Photonic Devices, Chapter 15.

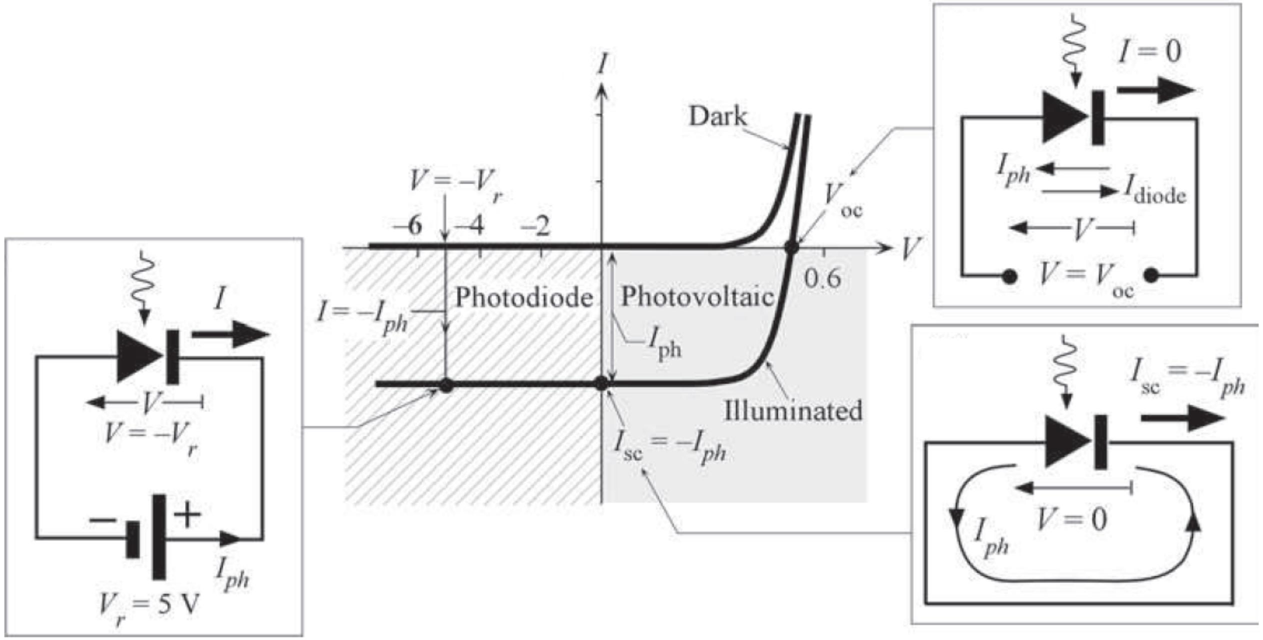
1. Photoconductivity

Two electrodes are attached to a semiconductor that has the desired absorption coefficient and quantum efficiency over the wavelengths of interest. A bias voltage V is applied to the electrodes. Incident photons become absorbed in the semiconductor and photogenerate electron-hole pairs. The result is an increase in the conductivity of the semiconductor and hence an increase in the external current. The increased conductivity is called photoconductivity.

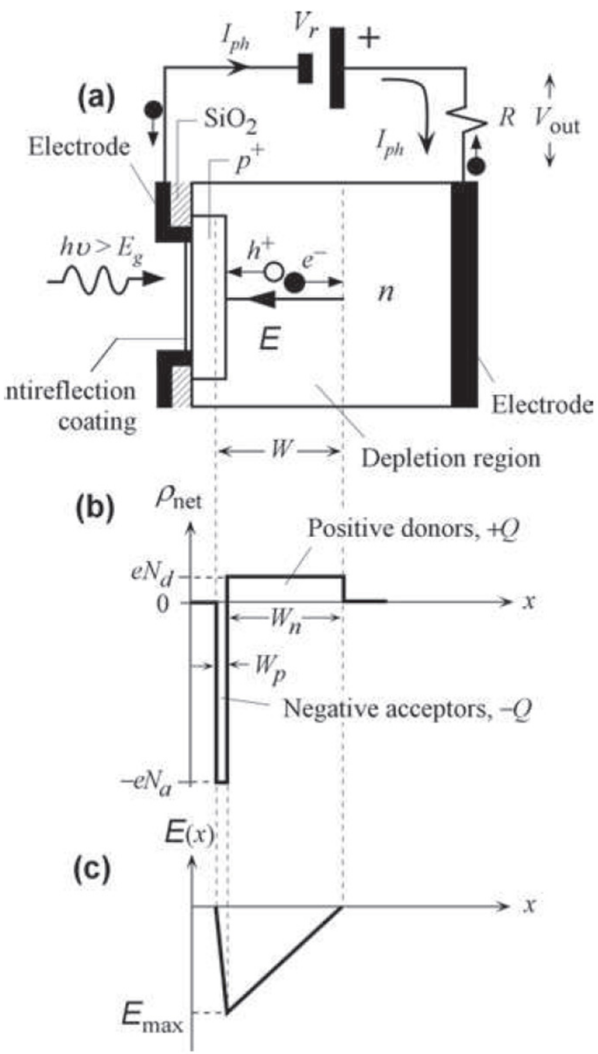


2. Photodetection Mode

The regions of the *pn* junction *I*–*V* characteristics that are bound by the positive *V* and negative *I* axes represent a **photovoltaic mode of operation.** The region bound by the negative *V*-axis and the negative *I*-axis represents a reverse biased **photodiode mode of operation**; this is the most common mode of operation for the detection of light.



3. P-N Junction Based Photodiode



total width of depletion region

$$W = \sqrt{\psi_{bi}\left(\frac{2\varepsilon_r\varepsilon_0}{q}\right)\left(\frac{N_A + N_D}{N_A N_D}\right)}$$

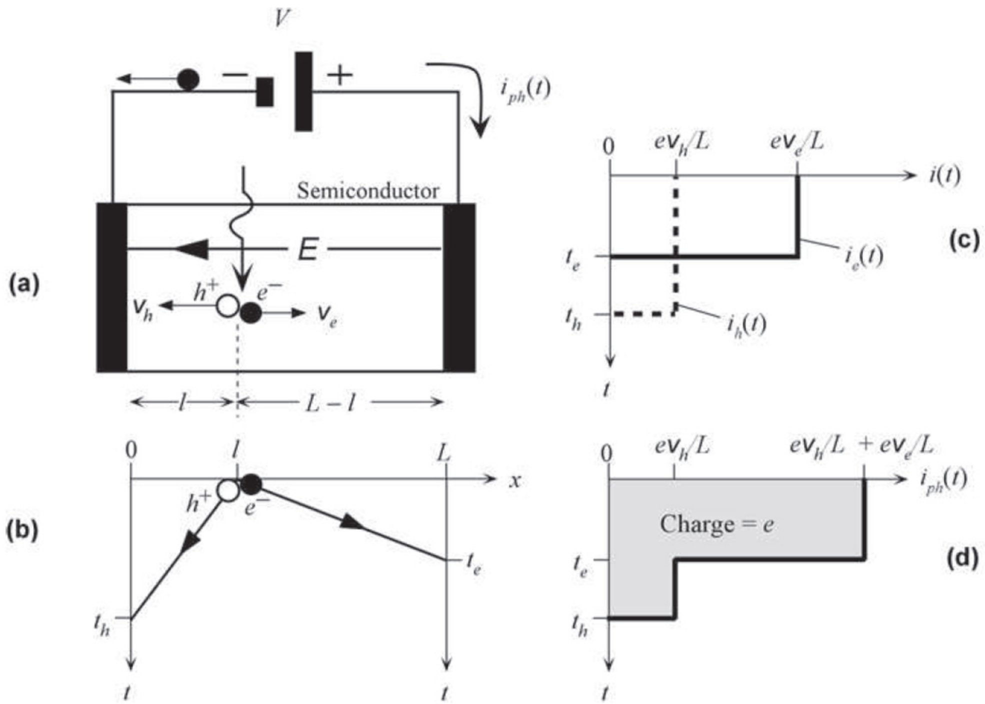
The photocurrent due to photogeneration in the neutral region is weaker than that due to photogeneration in the depletion region; in the latter, the field separates and drifts the carriers immediately.

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.

The drift current of electrons and holes creates a photocurrent I_{ph}, which is the quantity detected in the external circuit. It lasts for the duration of the drift of the electrons and holes.

At the wavelength of radiation, the absorption occurs over a depth covering the depletion layer so that the photogenerated e-h pairs can be separated and drifted by the field, and collected at the electrodes.

4. Shockley-Ramo Theorem



Consider a semiconductor material with a negligible dark conductivity that is electrode and biased. The electrodes do not inject carriers but allow excess carriers to leave and become collected by the battery (Schottky contact). The E field is uniform (intrinsic region of p-i-n structure).

The electron and hole transit times $t_e = \left(L - l \right) / v_e, \quad t_h = l / v_h$

Work done by external circuit $eEdx = Vi_e(t)dt \quad E = V / L, \quad v_e = dx / dt$

electron and hole photocurrent $i_e(t) = ev_e / L, \; t < t_e; \;\; i_h(t) = ev_h / L, \; t < t_h$

total collected charge $\int_0^{te} i_e(t) + \int_0^{th} i_h(t) = e$

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5. Quantum Efficiency and Responsivity (1)

quantum efficiency
(IPCE in solar cell)

$$\eta_e = \frac{\text{Number of collected electrons at detector terminals}}{\text{Number of incident photons}}$$

$$\eta = \frac{I_{ph} / e}{P_0 / h\nu}$$

P_0 is the incident optical power

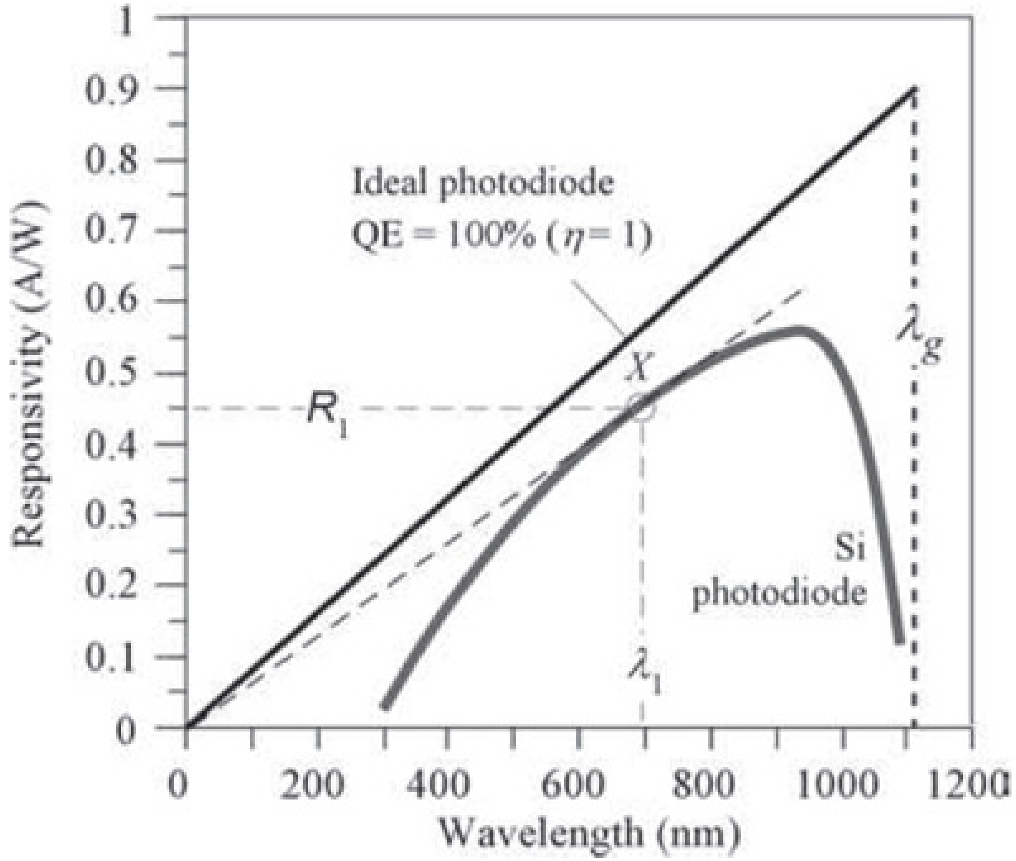
QE can be increased by reducing the reflections at the semiconductor surface, increasing absorption within the depletion layer and preventing the recombination or trapping of carriers before they are collected.

Internal quantum efficiency is the number of free electron-hole pairs photogenerated per absorbed photon and is typically quite high for many devices.

5. Quantum Efficiency and Responsivity (2)

The **responsivity** R of a photodiode characterizes its performance in terms of the photocurrent generated (I_{ph}) per incident optical power (P_0) at a given wavelength

$$R = \frac{I_{ph}}{P_0}$$



R is also called the **spectral responsivity** or **radiant sensitivity**

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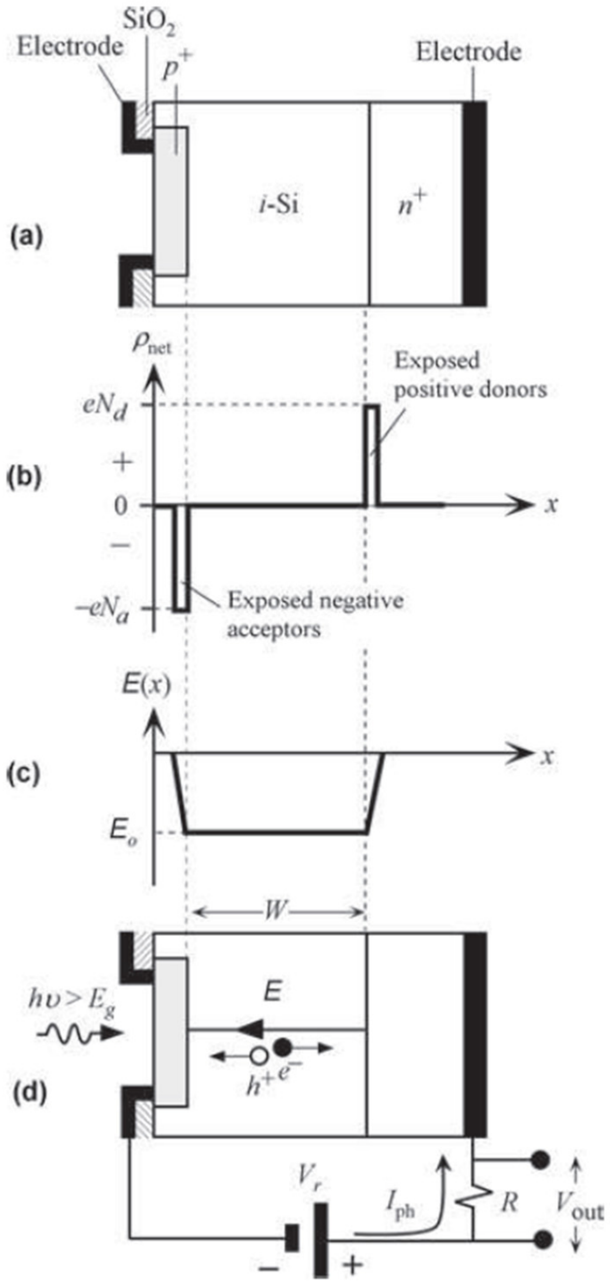
6. P-I-N Photodiode



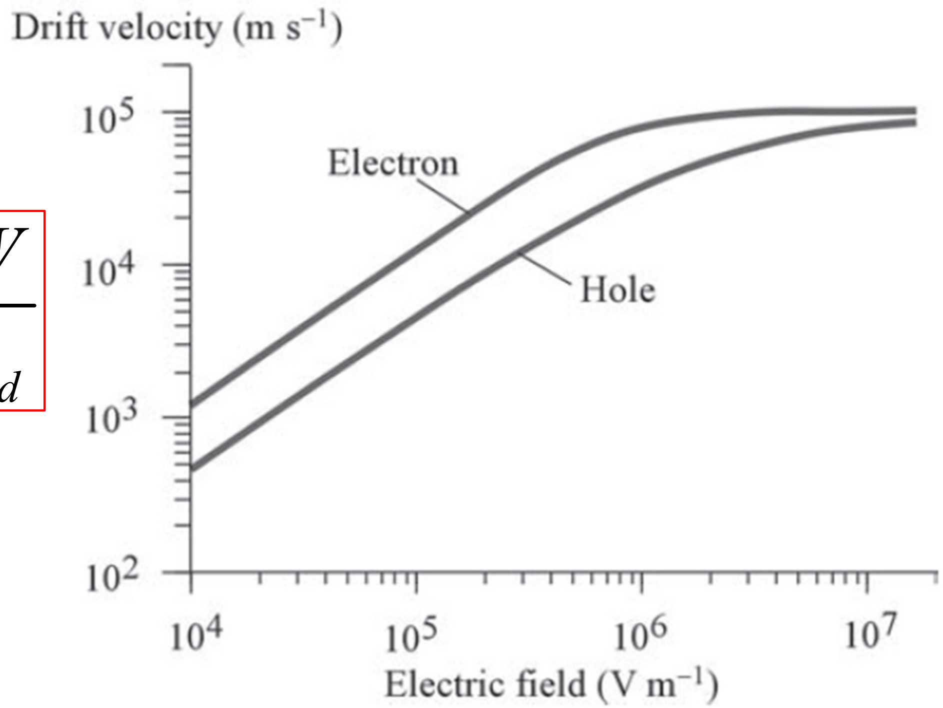
Drawback of P-N Photodiode: 1. Its junction capacitance is not sufficiently small to allow photodetection at high modulation frequencies. This is an <u>*RC* time constant limitation</u>. 2. its depletion layer is at most a few microns. This means that at long wavelengths where the penetration depth is greater than the depletion layer width, the majority of photons are absorbed outside the depletion layer where there is no field to separate and drift the e-h pairs.

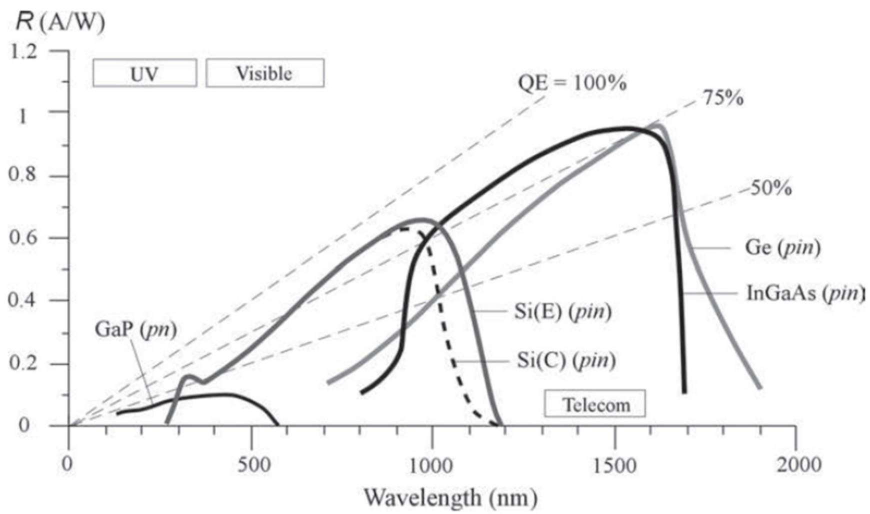
Merits of P-I-N Photodiode: 1. Its junction capacitance is small to allow photodetection at high modulation frequencies. RC~50 ps. 2. Its intrinsic layer has <u>uniform E-field</u> and large thickness (photon absorption and collection are improved).

7. Response Time

<u>response time</u> of the pin photodiode is determined by the transit times of the photogenerated carriers across the width *W* of the i-Si layer. Increasing *W* allows more photons to be absorbed, which increases the quantum efficiency but it slows down the speed of response as carrier transit times become longer.

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





Both Si and InGaAs *pin* photodiodes are widely available in the market, covering a range of wavelength from around 300 nm to 1700 nm.

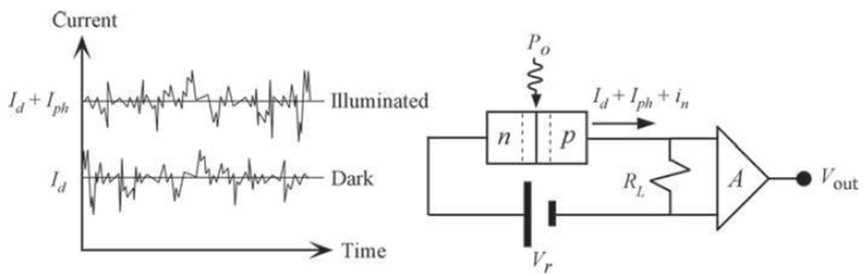
8. Noise Issue (1)

The thermal generation of electron-hole pairs will generate dark current. The *root mean square* (rms) value of the fluctuation in the dark current represents the shot noise current (there is a statistical distribution in the transit times of the carriers across the photodiode)

$$i_{n-dark} = [2eI_d B]^{1/2}$$

The quantum nature of the photon gives rise to a statistical randomness in the e-h pair photogeneration process. This type of fluctuation is called quantum noise or photon noise (there is an unavoidable random fluctuation in the rate of arrival of photons)

$$i_{n-quantum} = [2eI_{ph} B]^{1/2}$$



8. Noise Issue (2)

In photodetector design, we are often interested in the **signal to noise ratio**, SNR, which is defined as the ratio of signal power to noise power

$$SNR = \frac{i_{ph}^2}{i_n^2}$$

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

The **noise equivalent power** (NEP) is defined as the required optical input power to achieve a SNR of 1 within a bandwidth of 1 Hz. The **detectivity** *D* is defined as the reciprocal of noise equivalent power (NEP). It is a measure of detector's sensitivity taking into account various noise contributions.

$$\text{NEP} = \frac{P_1}{B^{1/2}} = \frac{1}{R}\left[2e(I_d + I_{ph})\right]^{1/2}$$