Physics of Semiconductor Devices

Lecture 12

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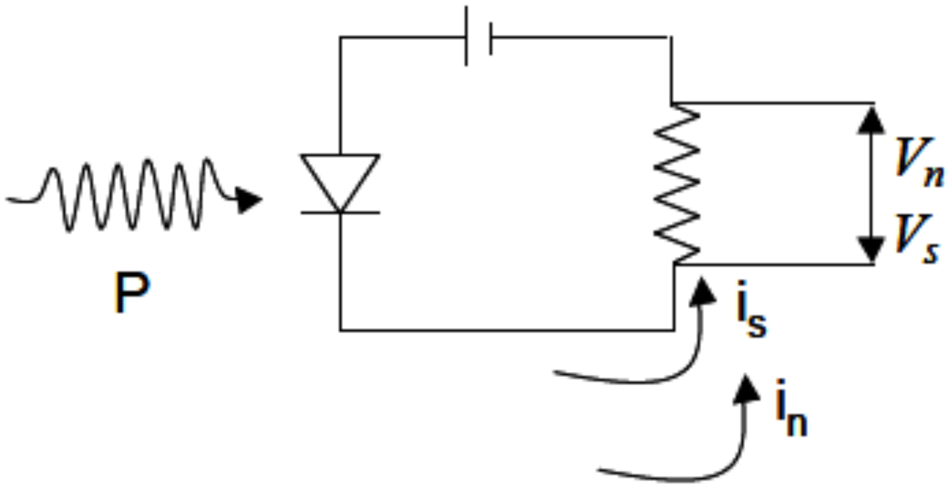
Photodetectors

- Convert light signals to a voltage or current.
- The ***absorption*** of photons creates electron hole pairs.
- Electrons in the CB and holes in the VB.
- A $p^{+}n$ type junction describes a heavily doped p-type material(acceptors) that is much greater than a lightly doped n-type material (donor) that it is embedded into.
- Illumination window with an annular electrode for photon passage.
- Anti-reflection coating (Si_3N_4) reduces reflections.

Basic Properties of Photodetectors



1. *Responsivity*: How much signal is obtained per unit of optical power? This is usually specified in Amps/Watt (A/W) or in Volts/Watt (V/W). For example we can write:

$$i_s = PR$$

where P is the optical power, R is the responsivity, and i_s is the signal current generated in the circuit.

2. *Spectral Response*: How the responsivity varies with wavelength.

3. *Sensitivity*: Following “Optical Radiation Detectors” by Dereniak and Crowe we define the following figures of merit for detector sensitivity:

   a. NEP $\equiv$ The “Noise Equivalent Power” $\equiv$ The optical power required to generate a signal current i_s that is equal to the root mean square noise current $i_{rms} = \sqrt{\langle i_n^2 \rangle}$.

$$i_{rms} = NEP \times R$$

   b. Detectivity, D $\equiv$ 1/NEP (smaller NEP is better but bigger D is better)

c. D^* (pronounced "Dee Star") = $(A\ \Delta f)^{1/2}$ D, where A is the detector area and Δf is the detector bandwidth. The noise in most photodetectors is proportional to $(A\ \Delta f)^{1/2}$, and including this factor in the definition of D^* takes this into account – if two photodetectors have the same D, the one with the larger $(A\ \Delta f)^{1/2}$ is considered better and gets a larger D^*.

4. *Time Response (Frequency Response)*: How fast does the detector respond to a change in signal?

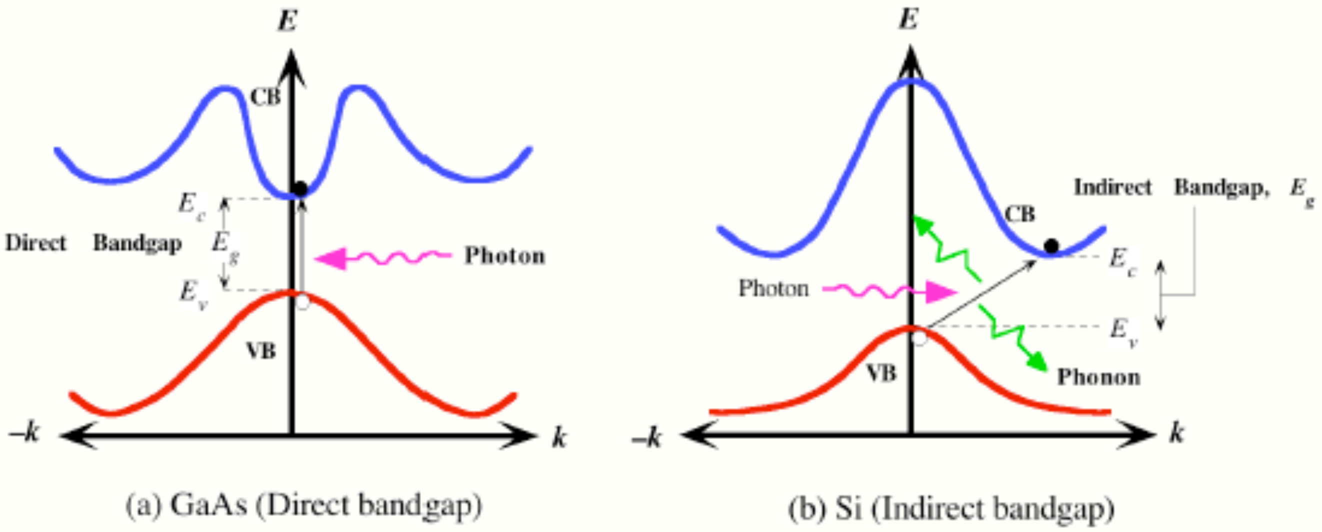
5. Quantum Efficiency: Number of electrons-hole pairs collected (created and separated to the n and p regions) for each photon.

$$QE = \frac{\text{Electron-Hole Pairs Collected}}{\text{Number of Photons}}$$

a. External Quantum Efficiency – We calculate with the number of photons incident on the front surface of the detector.

b. Internal Quantum Efficiency – We calculate with the number of photons that enter the photodetector.

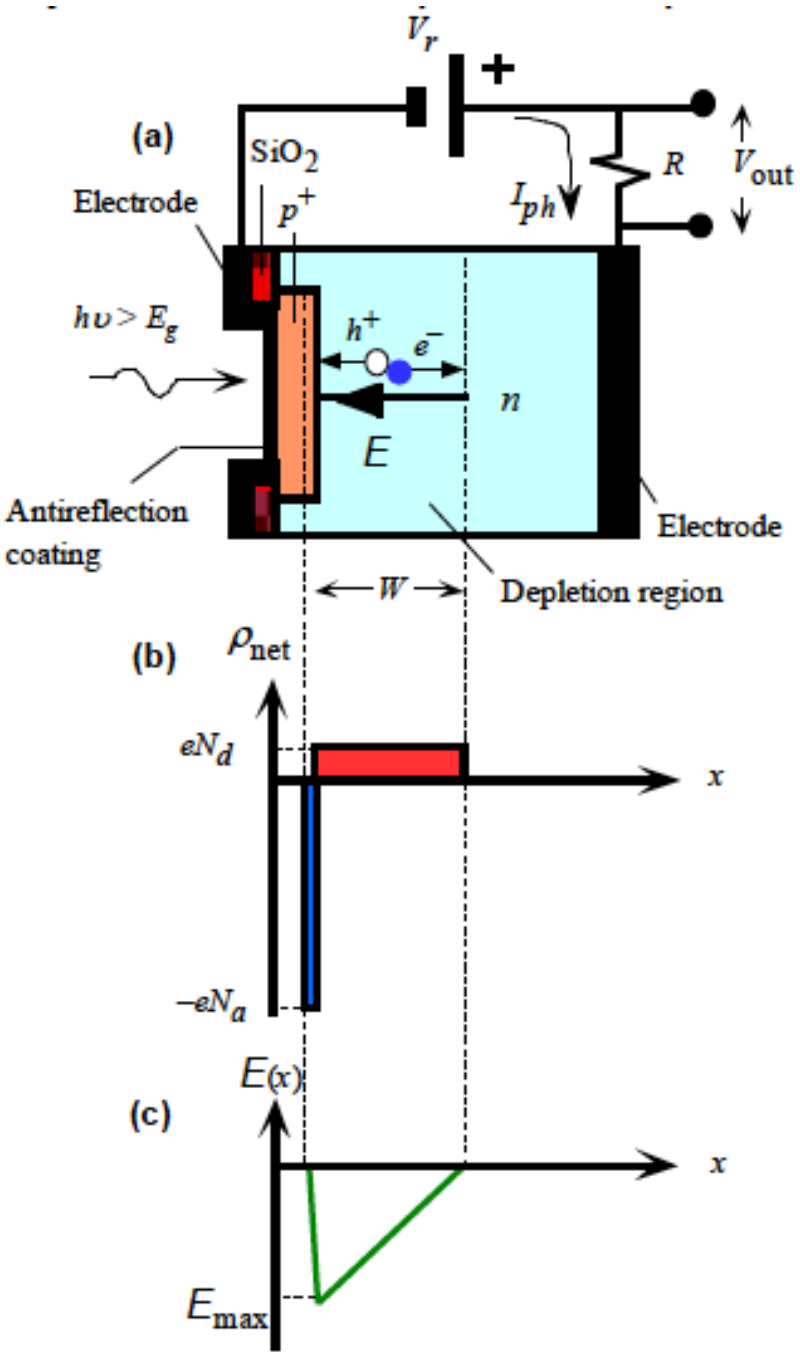
Photodetectors



(a) Photon absorption in a direct bandgap semiconductor. (b) Photon absorption in an indirect bandgap semiconductor (VB, valence band; CB, conduction band)

Regions outside the depletion region (neutral regions) hold majority carriers. These neutral regions can be considered resistive extensions of electrodes to the depletion region.

When a photon with an energy greater than bandgap (E_g) is incident, the photon is absorbed and generates a free EHP in the depletion layer.



Photodiode

ɔtodiodes are compact, inexpensive, sensitive, and t; but they have limited spectral response.

- The p^+ side is on the order of less than a micron thick (formed by planar diffusion into n-type epitaxial layer).
- A ***space charge*** distribution occurs about the junction within the ***depletion layer.***
- The depletion region extends predominantly into the lightly doped n region (up to 3 microns max)

(a) A schematic diagram of a reverse biased *pn* junction photodiode. (b) 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. (c). The field in the depletion region.

Photodetectors

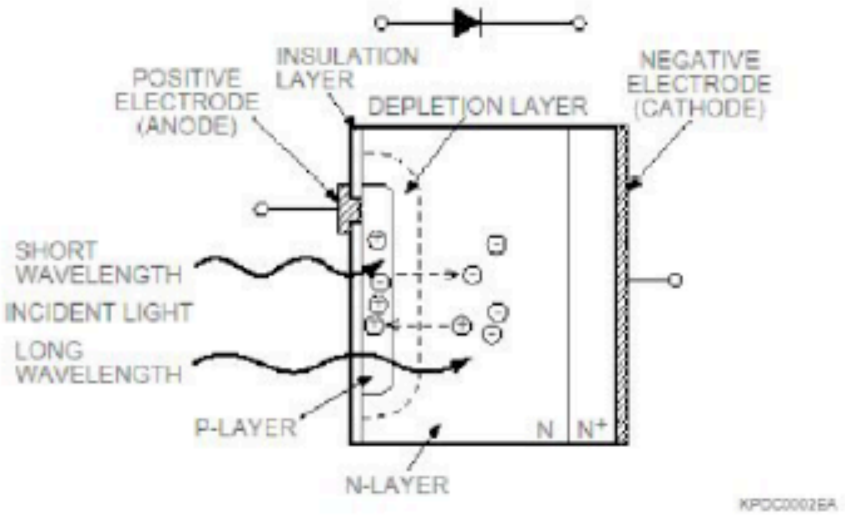
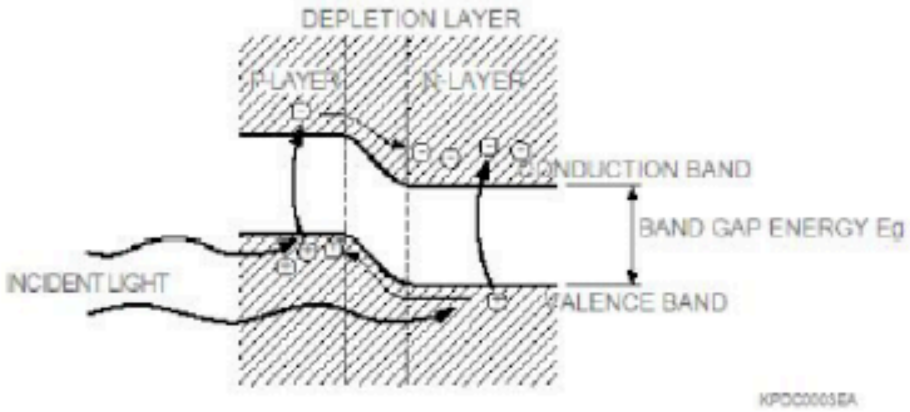


Figure 1-2 Photodiode P-N junction state



Short wavelengths (ex. UV) are absorbed at the surface, and longer wavelengths (IR) will penetrate into the depletion layer.

What would be a fundamental criteria for a photodiode with a wide spectral response?

Thin p-layer and thick n layer.

What does thickness of depletion layer determine (along with reverse bias)?

Diode capacitance.

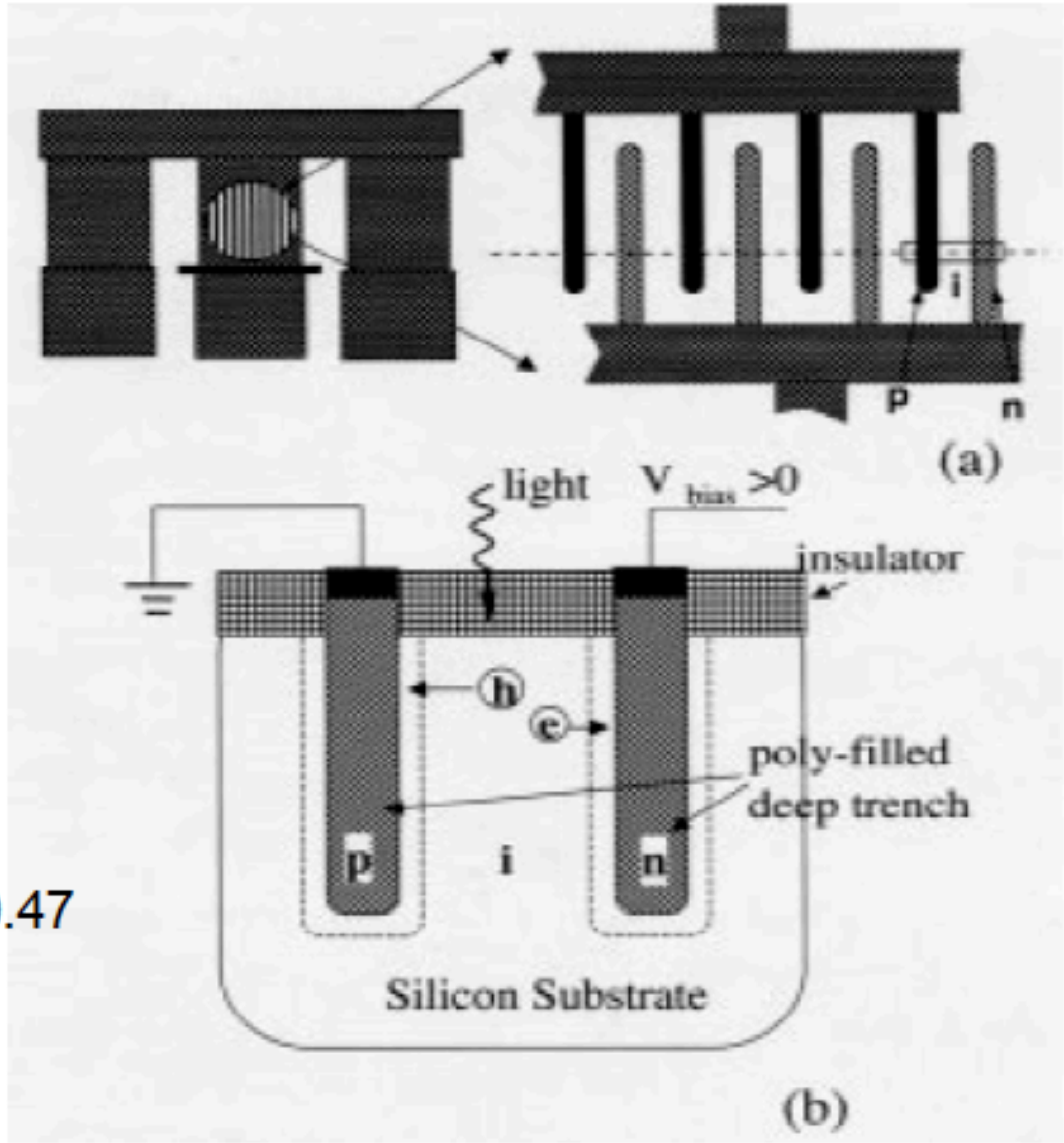
What does capacitance dictate?

Response time.

Silicon Photodetectors -- Interdigitated Lateral Trench

Interdigitated electrodes are often used to increase the active region area while optimizing the electric fields in the carrier collection region. Electrode can either be p+/n+ or just metal.

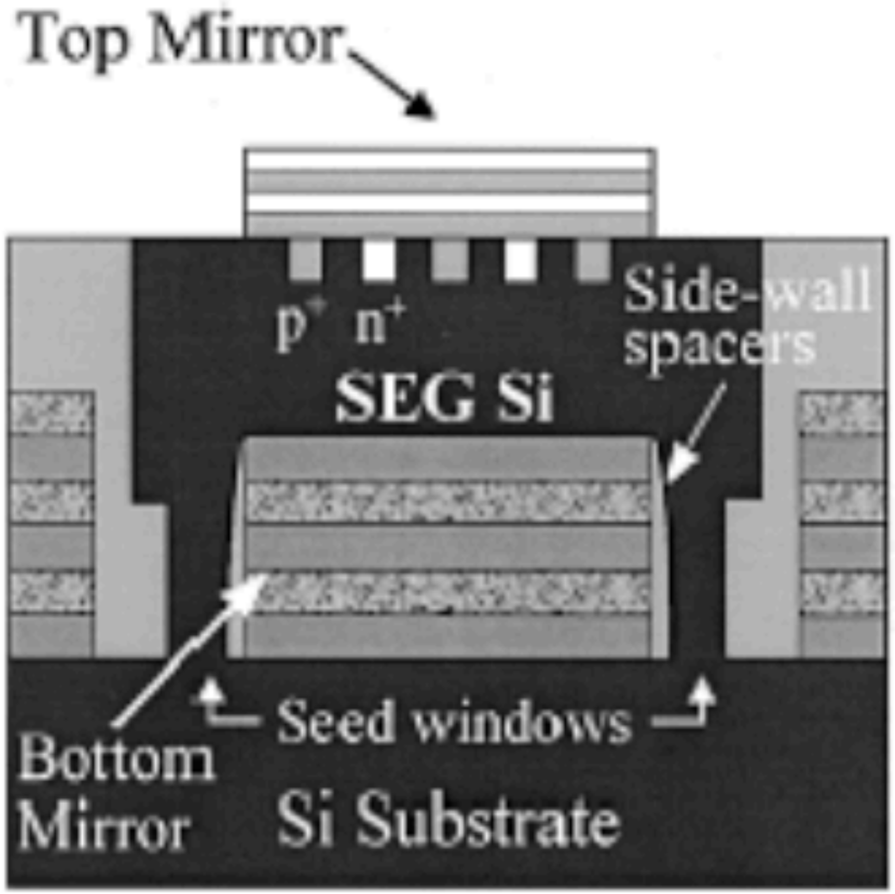
Finger space = 3.3 μm
Trench depth = 8 μm
Finger size = 0.35 μm
For λ=845 nm,
BW=1.5 GHz, Responsivity = 0.47 A/W at 5V



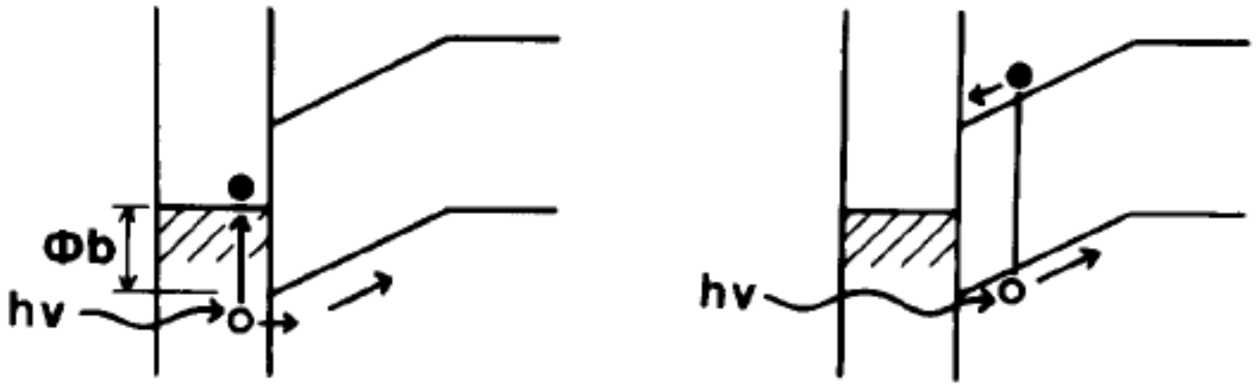
Silicon Photodetectors -- Resonant-cavity-enhanced

Why? High Speed

Uses three pair of quarter wavelength SiO_2 and polysilicon at bottom (LPCVD). SiO_2 Side-wall to prevent defects at the edge of poly.
Two pairs of ZnSe-MgF on top (evaporated).



Silicon Photodetectors -- Schottky Barrier



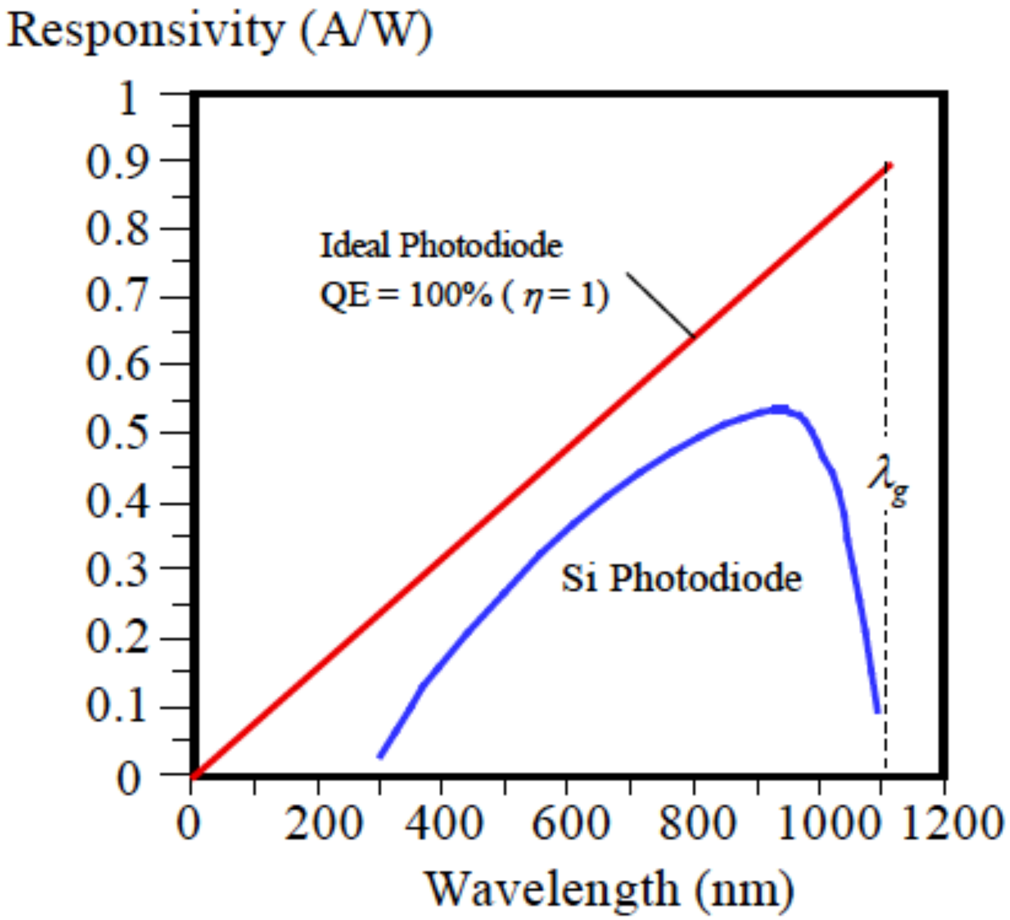
(a) (b)

- High dark current, has to operate at low temperature (40 ~ 80 K).
- Low quantum efficiency (QE).

$$QE = C_1 \frac{(h\nu - q\phi_B)^2}{h\nu} = 1.24 C_1 \lambda \left(\frac{1}{\lambda} - \frac{1}{\lambda_C} \right)^2$$

High λ_C gives high QE. To expand the spectrum, need to decrease the barrier height.

Responsivity for a Photodiode:

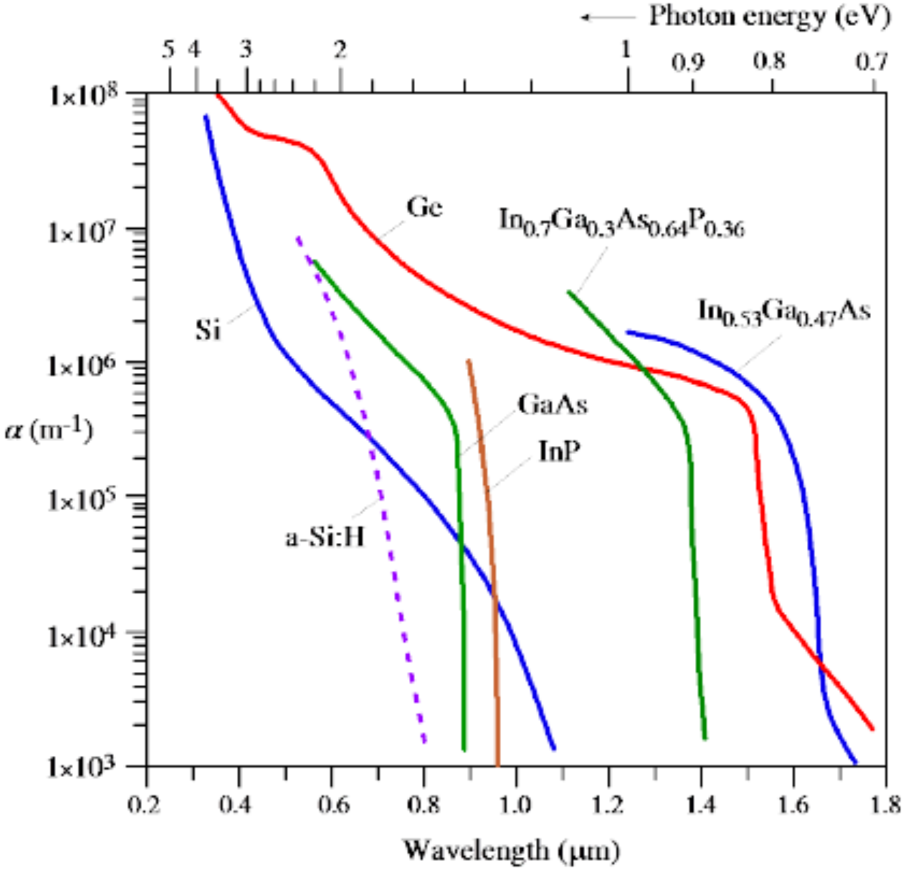


Responsivity (R) vs. wavelength (λ) for an ideal photodiode with QE = 100% ($\eta = 1$) and for a typica commercial Si photodiode.

Note 1. R is small beyond a cut-off wavelength corresponding to the semiconductor band gap.

Note 2. R decreases at shorter wavelengths because the number of photogenerated electrons = $\eta P/h\nu = \eta P\lambda/hc$, which decreases with wavelength.

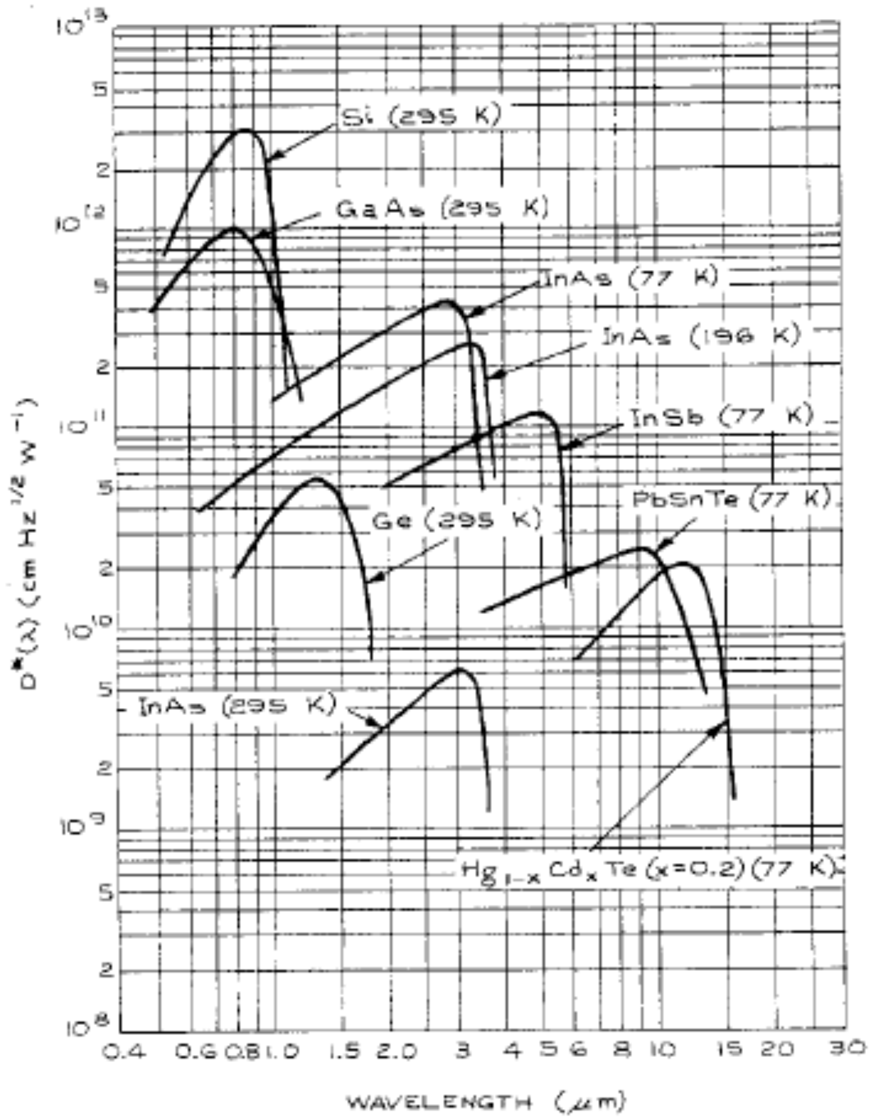
Note 3. Choosing the correct semiconductor material for a photodiode includes selecting one with a small enough band gap but sensitivity must also be taken into account (see next section)



Absorption coefficient (α) vs. wavelength (λ) for various semiconductors
(Data selectively collected and combined from various sources.)

From <u>Optoelectronics and Photonics</u>, Kasap

Photodiode Sensitivity



Note: The peak D^* is larger for photodiodes made from semiconductors with larger band gap because there is less generation of electrons-hole pairs across the gap by background radiation.

Time Response for a Photodiode

The temporal response is limited by:

1. Drift Time
2. Diffusion Time
3. RC Time Constant, $\tau = RC$

For high-speed operation, diffusion is minimized and photodiode area is kept small to minimize the RC Time Constant.

Commercial photodiodes have bandwidth up to 40 GHz (InGaAs pin photodiodes available from Opto Speed).

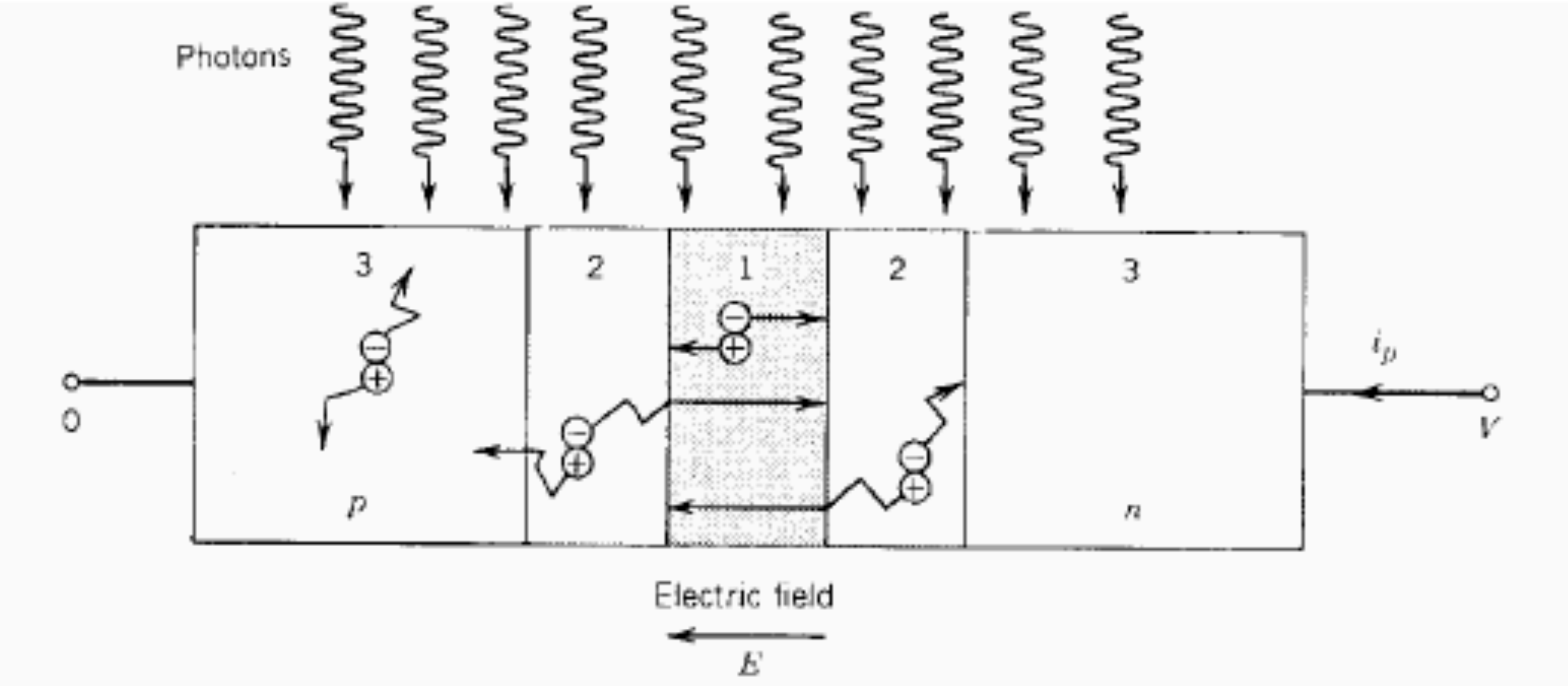


Figure 17.3-1 Photons illuminating an idealized reverse-biased p-n photodiode detector. The drift and diffusion regions are indicated by 1 and 2, respectively.

Light Emitting Diode (LED)

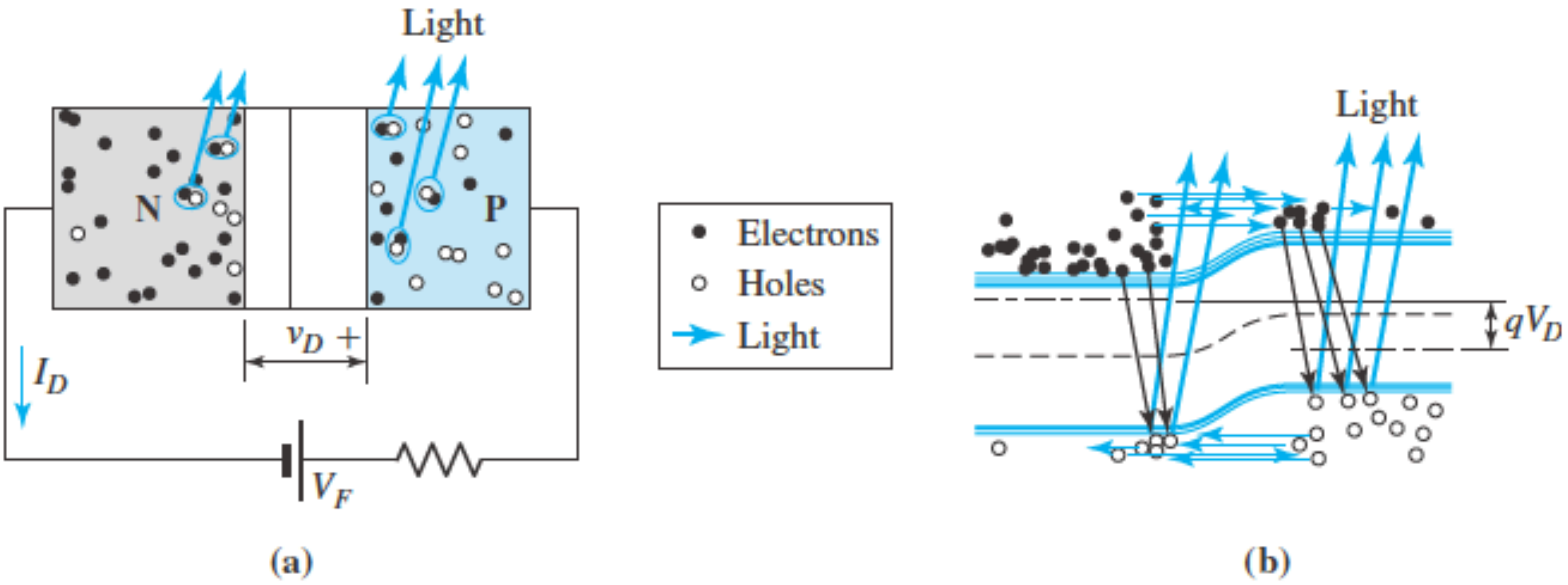


Figure 12.1 (a) Cross section and (b) energy-band diagram of a forward-biased LED, illustrating emission of photons due to the electron–hole recombination.

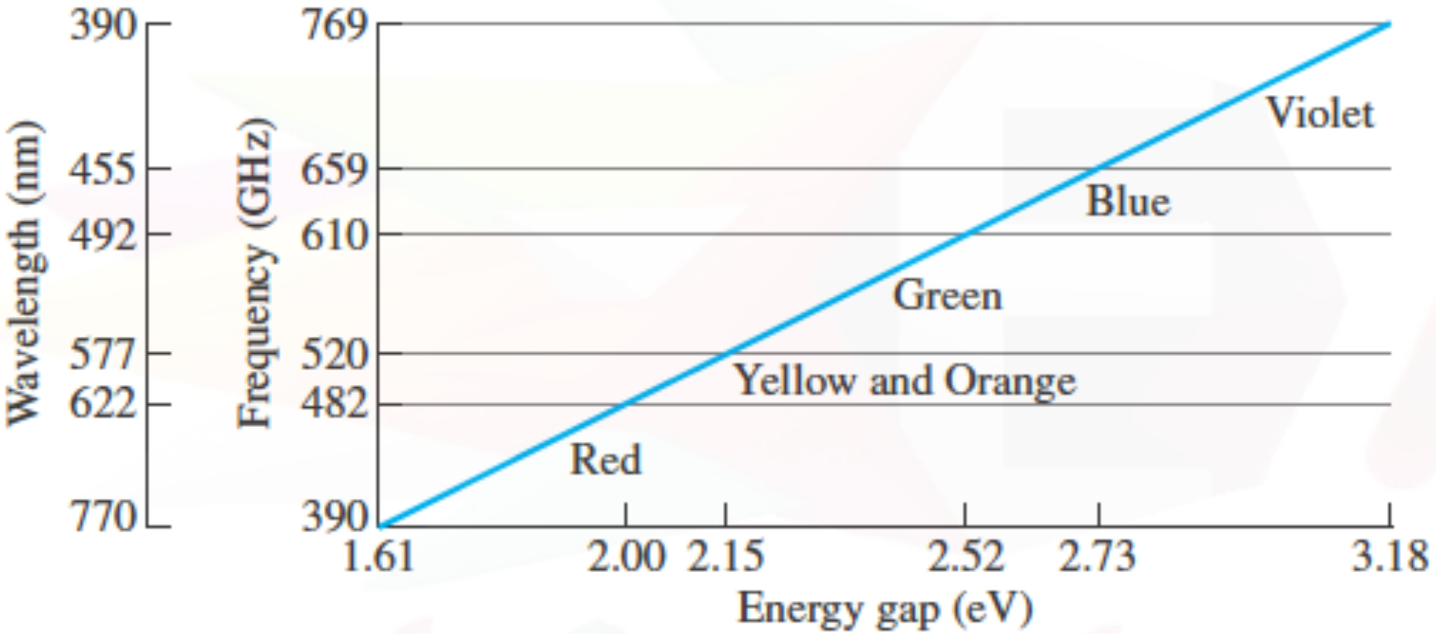


Figure 12.2 Different energy gaps are needed to produce LEDs emitting light of different colors.

$$E_{photon} = h\nu = \frac{hc}{\lambda}$$

$$\frac{P_{opt}}{h\nu} A_J = \frac{\eta_Q}{q} I_D$$

The parameter η_Q expresses the efficiency of an LED and is referred to as *radiative recombination efficiency*.

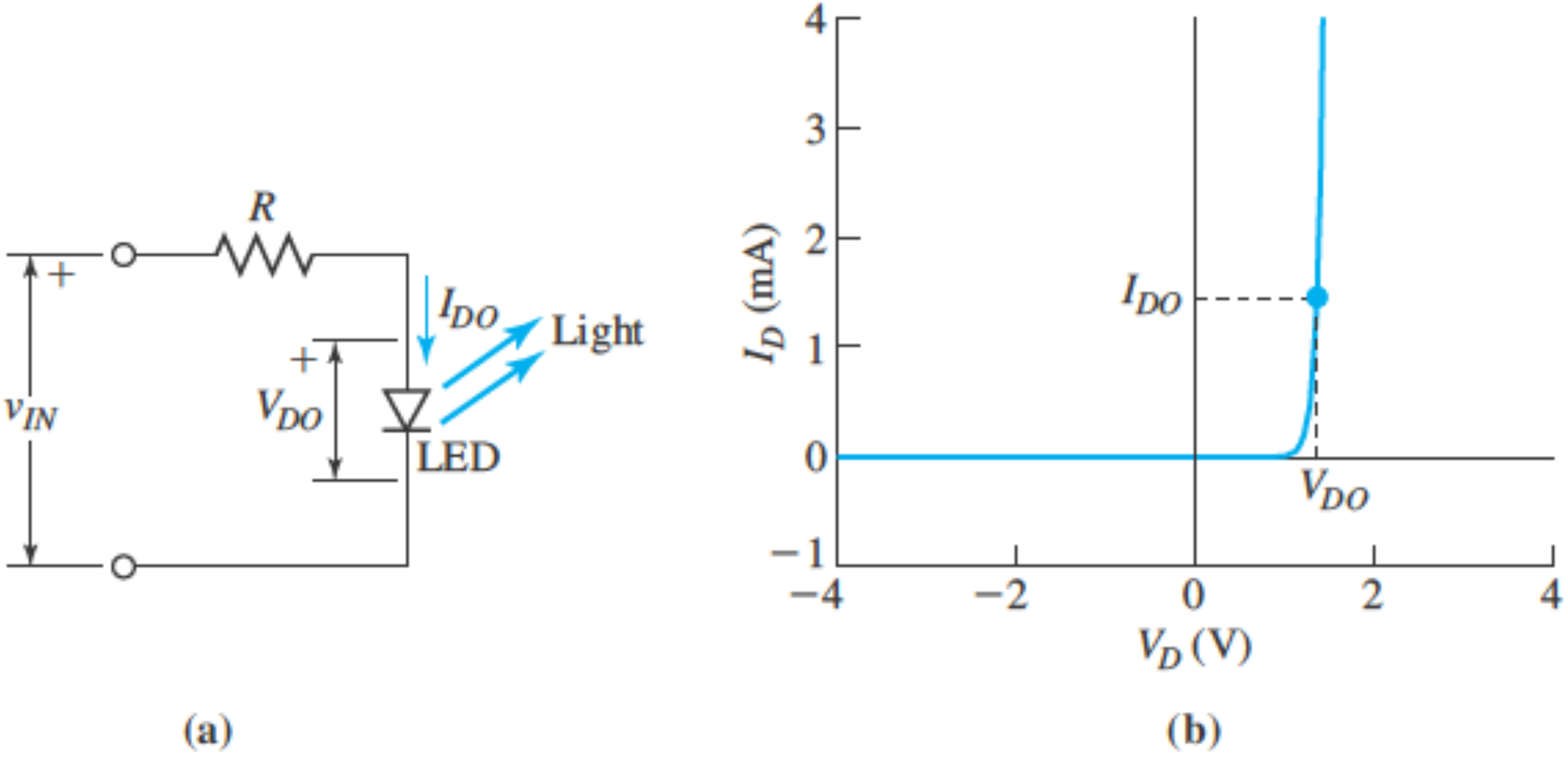


Figure 12.3 (a) LED driving circuit. (b) Operating point.

$$\text{Light intensity} \propto I_{DO} = \frac{v_{IN} - V_{DO}}{R} \approx \frac{v_{IN}}{R}$$

PhotoVoltaic Cell or Solar Cell

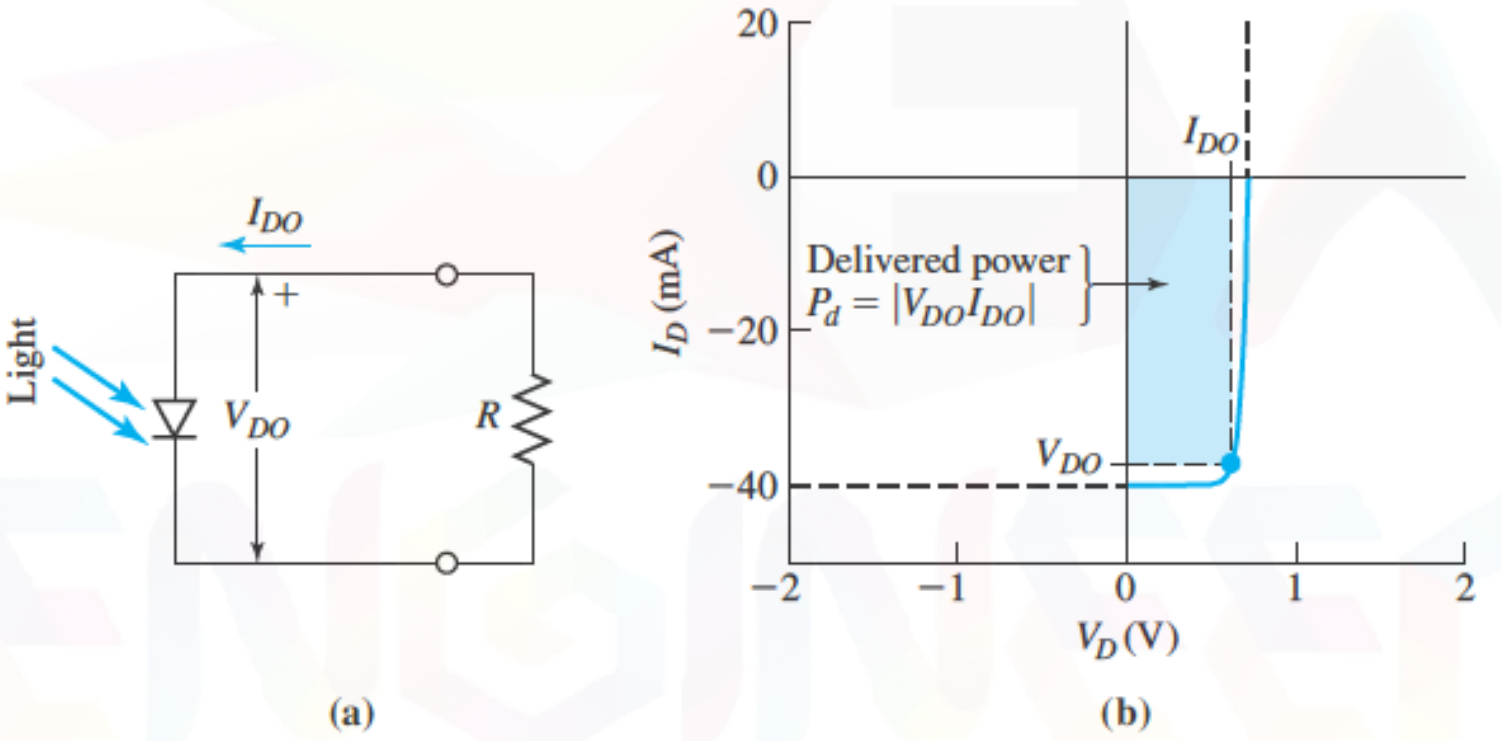


Figure 12.5 A solar-cell diode is directly connected to a loading element. (a) The electric circuit. (b) The operating point (I_{DO}, V_{DO}) is in the quadrant of negative currents and positive voltages (forward bias).

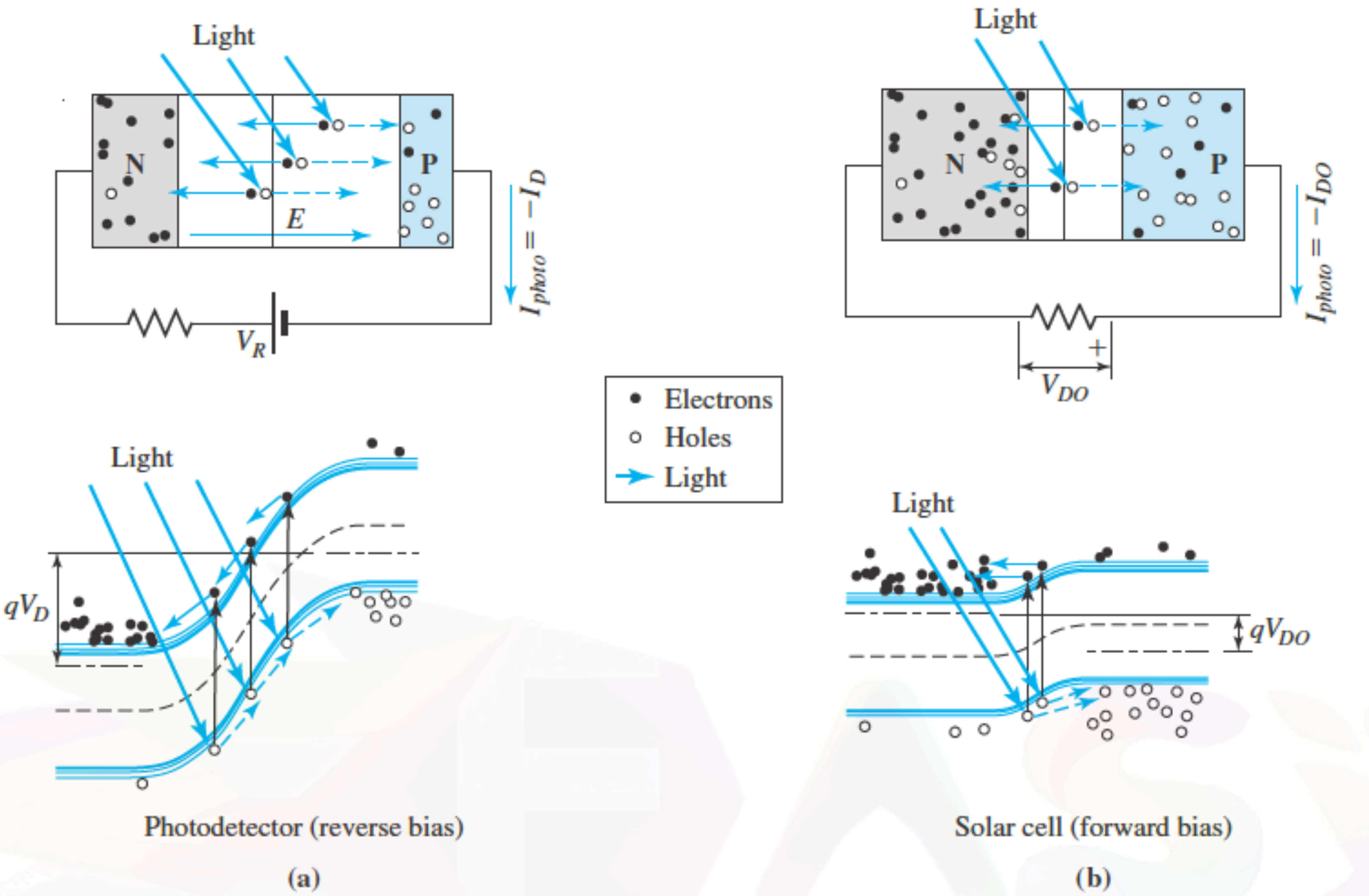


Figure 12.6 Energy-band diagrams of (a) a photodetector and (b) a solar cell, accompanied by their respective application circuits, where the diode symbols are replaced by diode cross sections.