# Single Photon detectors

# Outline

- **Motivation for single photon detection**
- Semiconductor; general knowledge and important background
- Photon detectors: internal and external photoeffect
- Properties of semiconductor photo-detector
- Photo-conductor
- Photodiodes
- Avalanche photodiodes
- Noise
- Advantages and disadvantages in the existing device
- New devices research

# Quantum theory- explaining a wide range of phenomena

- More then 100 years ago- Planck described accurately the form of emission from glowing hot object by assuming the light is multiple of a certain quantum
- 1905- Einstein explain the photoelectric effect

- **Counting individual photons provides method of measuring a weak optical signal**

# Single photon detection is employed in a wide range of application in science and technology

- X-ray and radioisotope imaging
- Medical imaging
- Laser optical imaging
- Lifetime fluorescence measurements **using SPC**
- Laser ranging, tracing and imaging
- Industrial scanning and process control
- Particle physics, astrophysics and material science
- Quantum information technology

# Optical detectors convert light into an electrical signal

- Most conventional detectors; vacuum photomultiplier (PMT) and avalanche photodiode (APD)
- Photo-excited electron is multiplied using avalanche process to produce a detectable current

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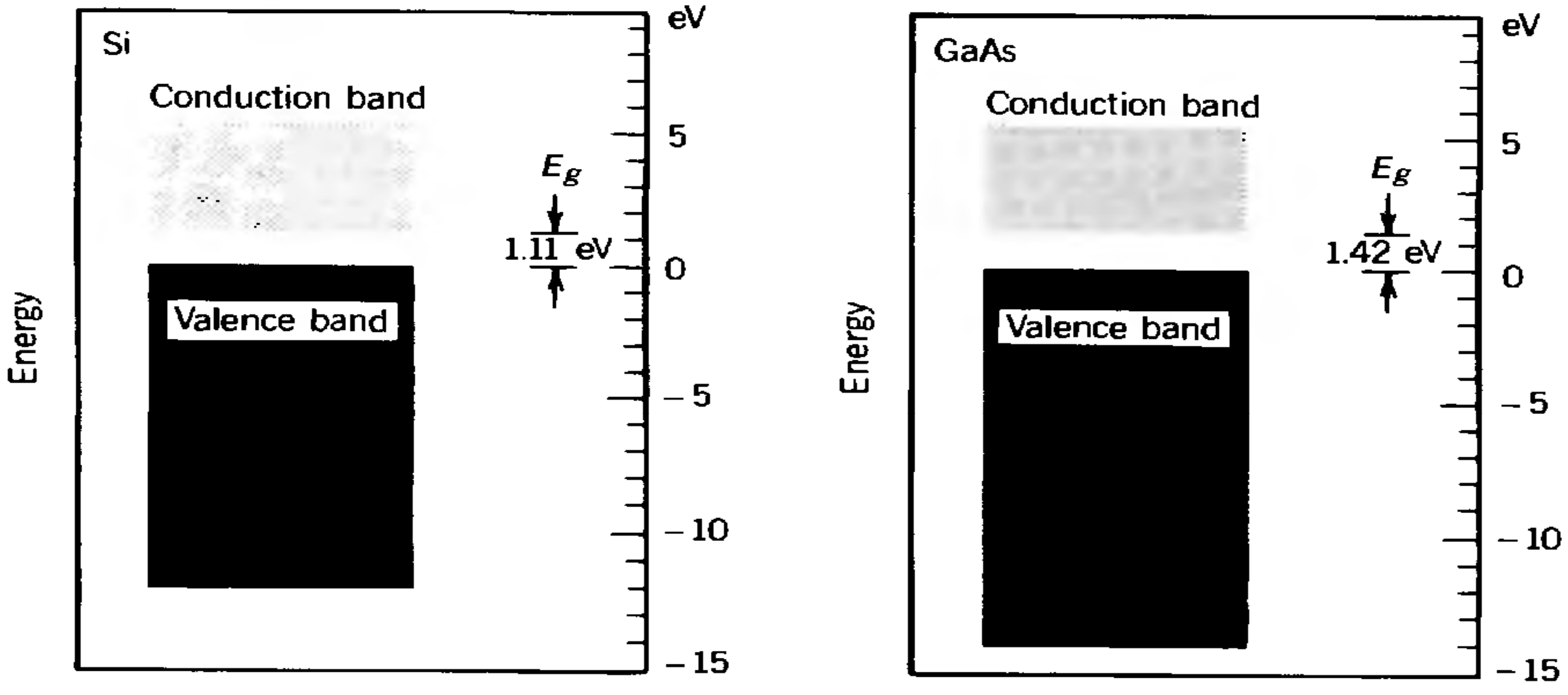
# Electronic and photonic are joined together in semiconductor optoelectronic device

- The proximity of the atoms in solid results in one set of energy levels
- In semiconductors when T=0 the energy levels are or fully occupied by electrons- the valance band or empty- conduction band
- Thermal and optical interaction can cause a jump of electron from the valance to the conduction band- leaving an empty place (hole)

**-semiconductors absorb and emit photons by undergoing transition between the allowed energy levels;**

***absorption and recombination***

# Semiconductor is solid materiel with electrical conductivity is intermediate between isolator and conductor



*(a)* *(b)*

**Figure 15.1-1** Energy bands: (*a*) in Si, and (*b*) in GaAs.

# When temperature is increases some electron will be thermally existed to unoccupied states in the conduction band

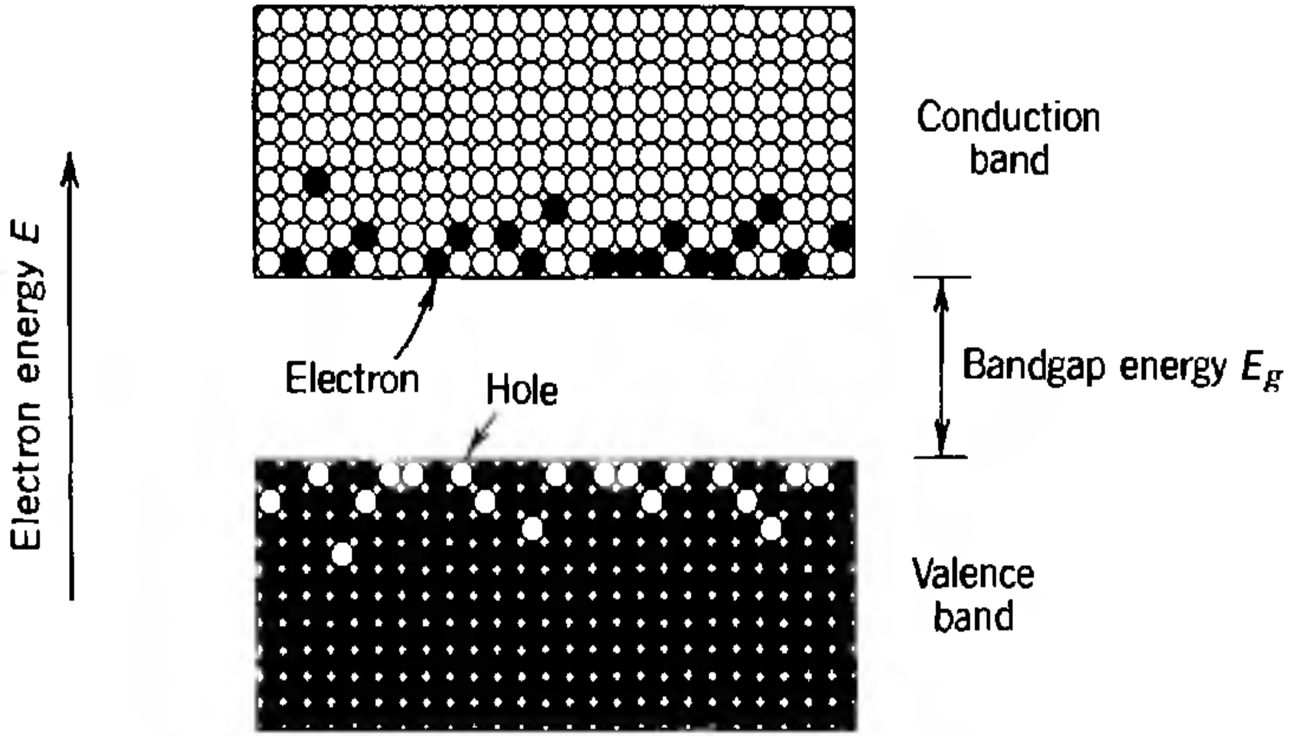


**Figure 15.1-2** Electrons in the conduction band and holes in the valence band at $T > 0$ K.

# Device can come in as elemental material (Si, Ge) or as compound semiconductor

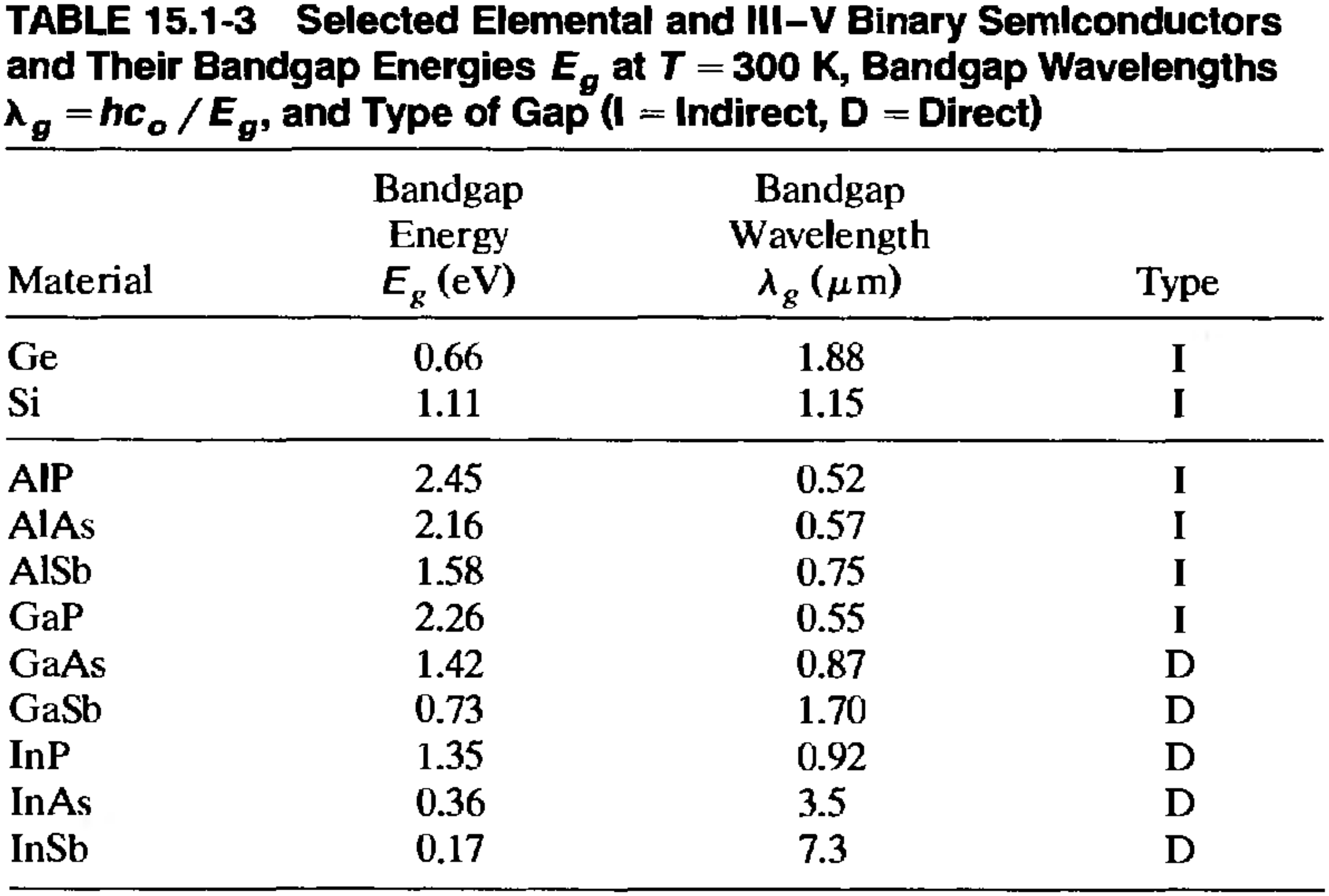


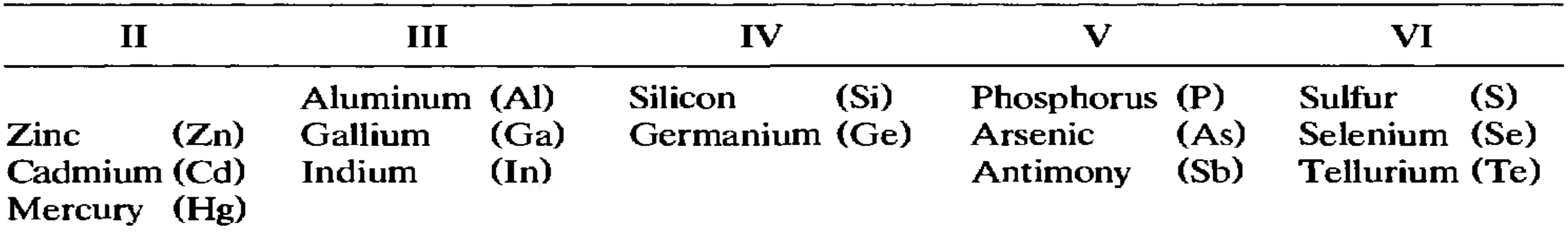
**TABLE 15.1-3 Selected Elemental and III–V Binary Semiconductors and Their Bandgap Energies $E_g$ at $T = 300$ K, Bandgap Wavelengths $\lambda_g = hc_o / E_g$, and Type of Gap (I = Indirect, D = Direct)**

| Material | Bandgap Energy $E_g$ (eV) | Bandgap Wavelength $\lambda_g$ ($\mu$m) | Type |
|---|---|---|---|
| Ge | 0.66 | 1.88 | I |
| Si | 1.11 | 1.15 | I |
| AlP | 2.45 | 0.52 | I |
| AlAs | 2.16 | 0.57 | I |
| AlSb | 1.58 | 0.75 | I |
| GaP | 2.26 | 0.55 | I |
| GaAs | 1.42 | 0.87 | D |
| GaSb | 0.73 | 1.70 | D |
| InP | 1.35 | 0.92 | D |
| InAs | 0.36 | 3.5 | D |
| InSb | 0.17 | 7.3 | D |

# The electrical and optical properties of the semiconductor can be adding small controlled amount of chosen impurities

- **n-type :** dopants with excess valance electrons, create predominance of mobile electron
- **p-type :** dopants with deficiency of valance electrons

**TABLE 15.1-2 A Section of the Periodic Table**



| II | III | IV | V | VI |
|---|---|---|---|---|
| | Aluminum (Al) | Silicon (Si) | Phosphorus (P) | Sulfur (S) |
| Zinc (Zn) | Gallium (Ga) | Germanium (Ge) | Arsenic (As) | Selenium (Se) |
| Cadmium (Cd) | Indium (In) | | Antimony (Sb) | Tellurium (Te) |
| Mercury (Hg) | | | | |

p-type

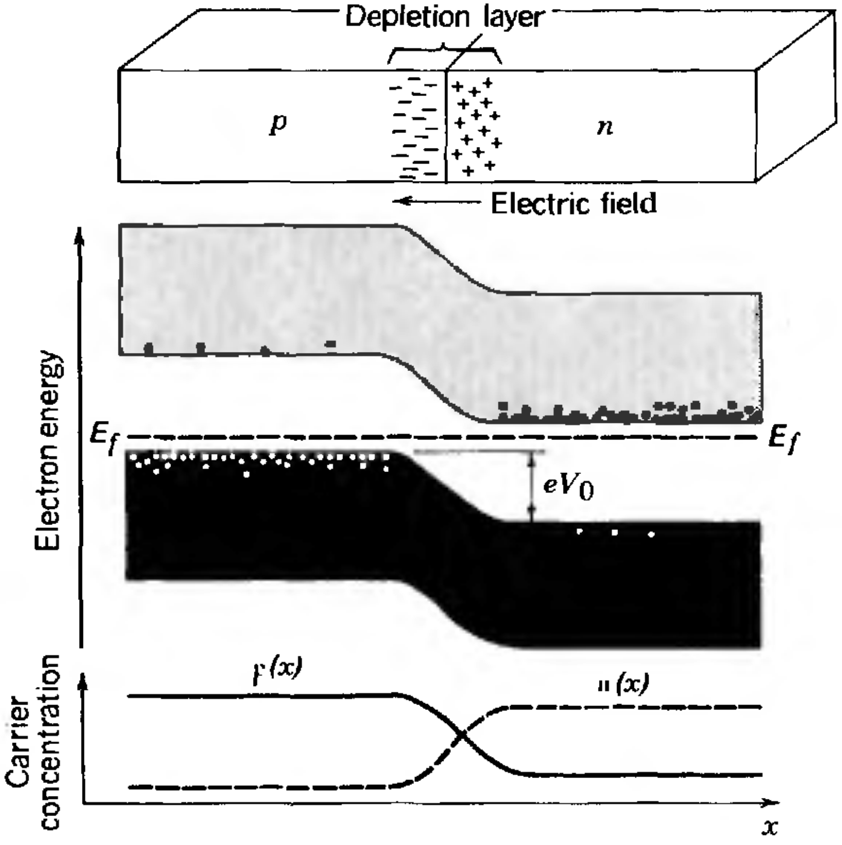
in III-V

n-type

in III-V

**intrinsic-undoped materials , extrinsic- doped materials**

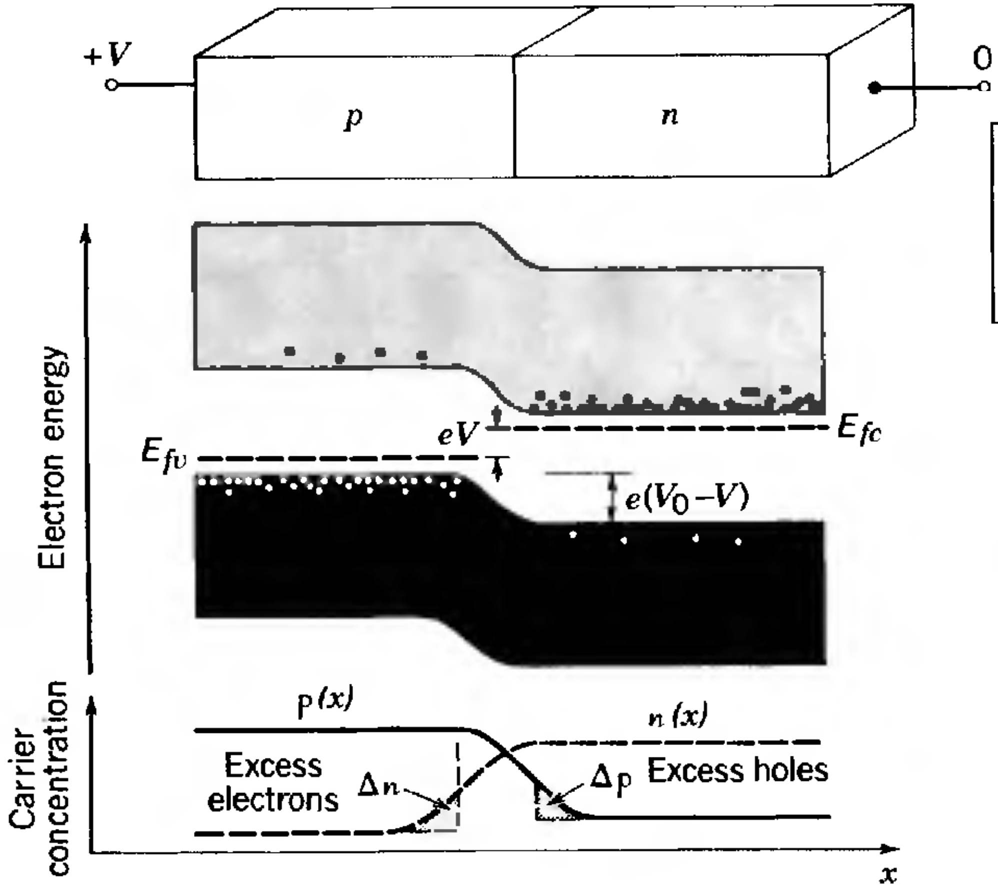
# A p-n junction is a homojunction between p-type and n-type of the same semiconductor



Electrons and hole diffuse from areas with high concentration to areas of low concentration

**Figure 15.1-16** A *p–n* junction in thermal equilibrium at $T > 0$ K. The depletion-layer, energy-band diagram, and concentrations (on a logarithmic scale) of mobile electrons $n(x)$ and holes $p(x)$ are shown as functions of position $x$. The built-in potential difference $V_0$ corresponds to an energy $eV_0$, where $e$ is the magnitude of the electron charge.

# An externally applied potential will alter the potential difference between the p- and n- regions



$$i = i_s\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right],$$

**Figure 15.1-17** Energy-band diagram and carrier concentrations in a forward-biased *p–n* junction.

# A p-i-n junction is made by inserting a layer of intrinsic semiconductor between p-type and n-type region

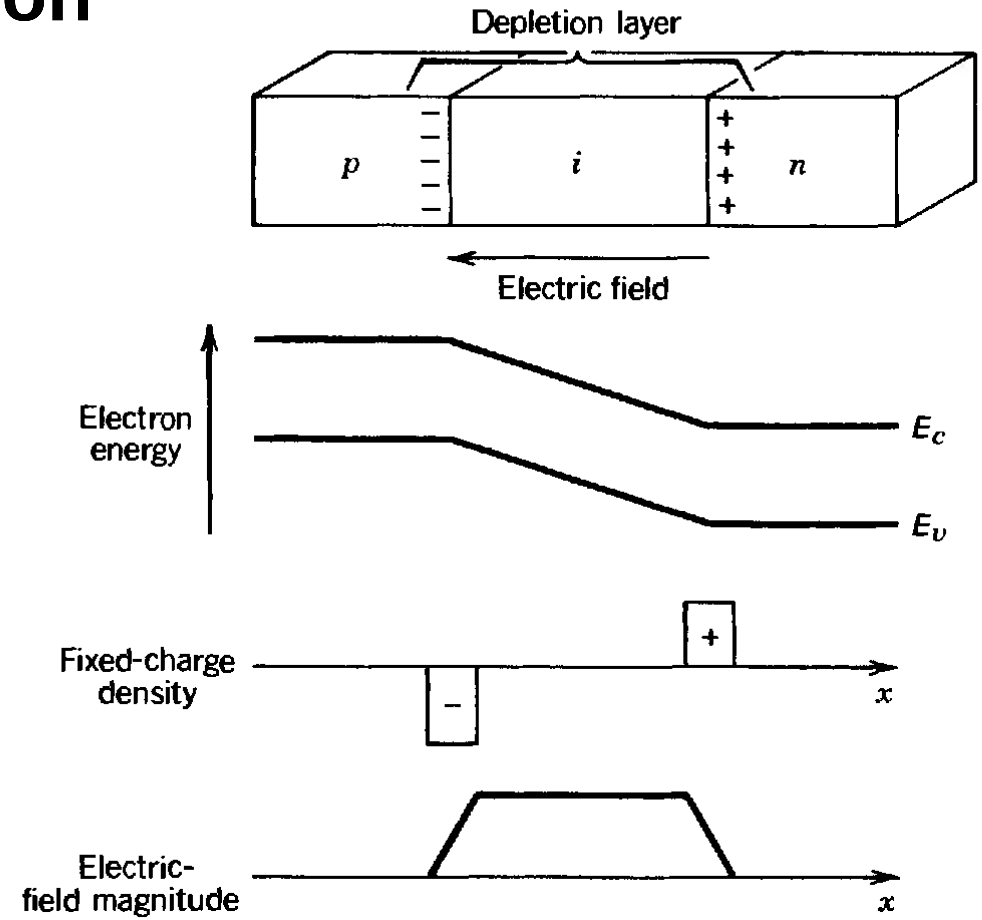


**Figure 15.1-19** Electron energy, fixed-charge density, and electric field magnitude for a *p–i–n* diode in thermal equilibrium.

# Heterojunctions provide substantial improvement in the performance of electronic and optoelectronic devices

- Junction between materials create localized jump in the energy diagram
- It can create energy band discontinuities that accelerate carriers at specific locations (impact ionization)
- Semiconductors with different band gap can be used to select regions of the structures where light is absorbed (part of the device can act as a window layer).

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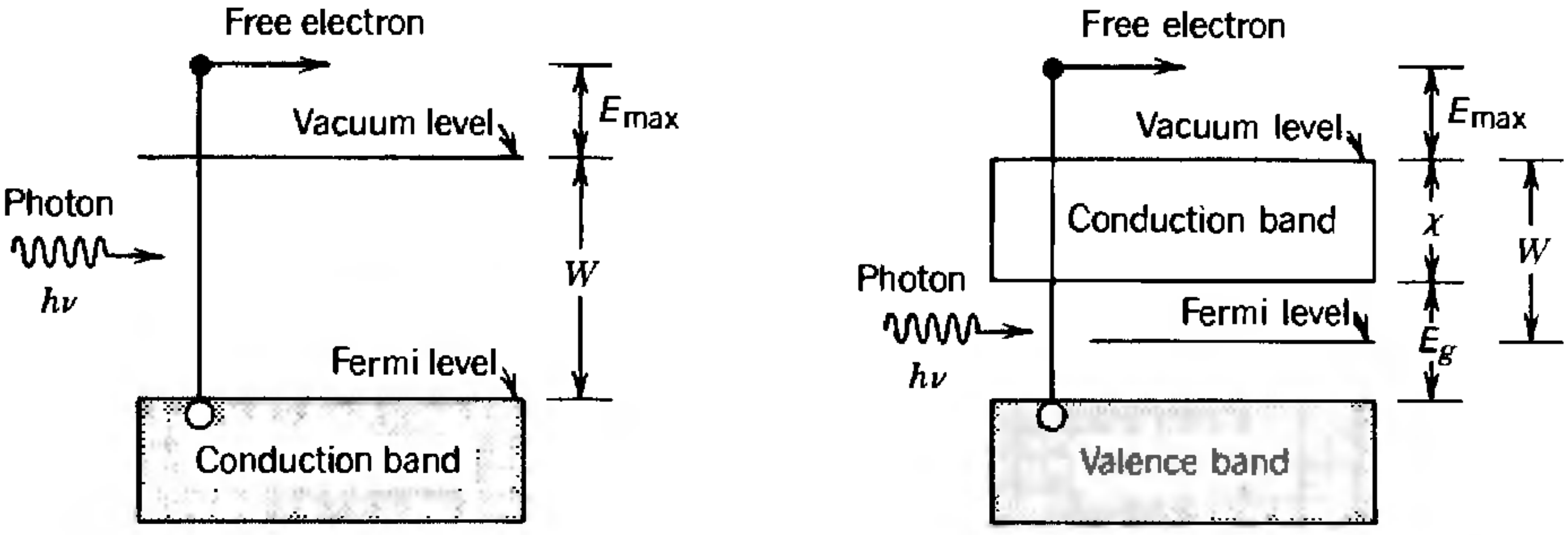
# The photo effect take two forms- external and internal

- **External photo effect**; involves photo emission, photo generated photon escape from the material as free electron.

- **Internal photo effect**; the exited carriers remain within the material and serve to increase its conductivity

# External photo effect: if the energy of a photon is sufficiently large, the exited electron can escape over the potential barrier of the material surface into the vacuum



(a) (b)

**Figure 17.0-1** Photoelectric emission from (*a*) a metal and (*b*) a semiconductor.

$$E_{max} = h\nu - W,$$

$$E_{max} = h\nu - (E_g + \chi)$$

**The lowest work function in metal is ~2eV, useful for visible and ultraviolet**

**For semiconductor the barrier can get as low as 1.4eV**

# Photodetectors based on the photo electric emission usually take the form of vacuum tubs called phototubes

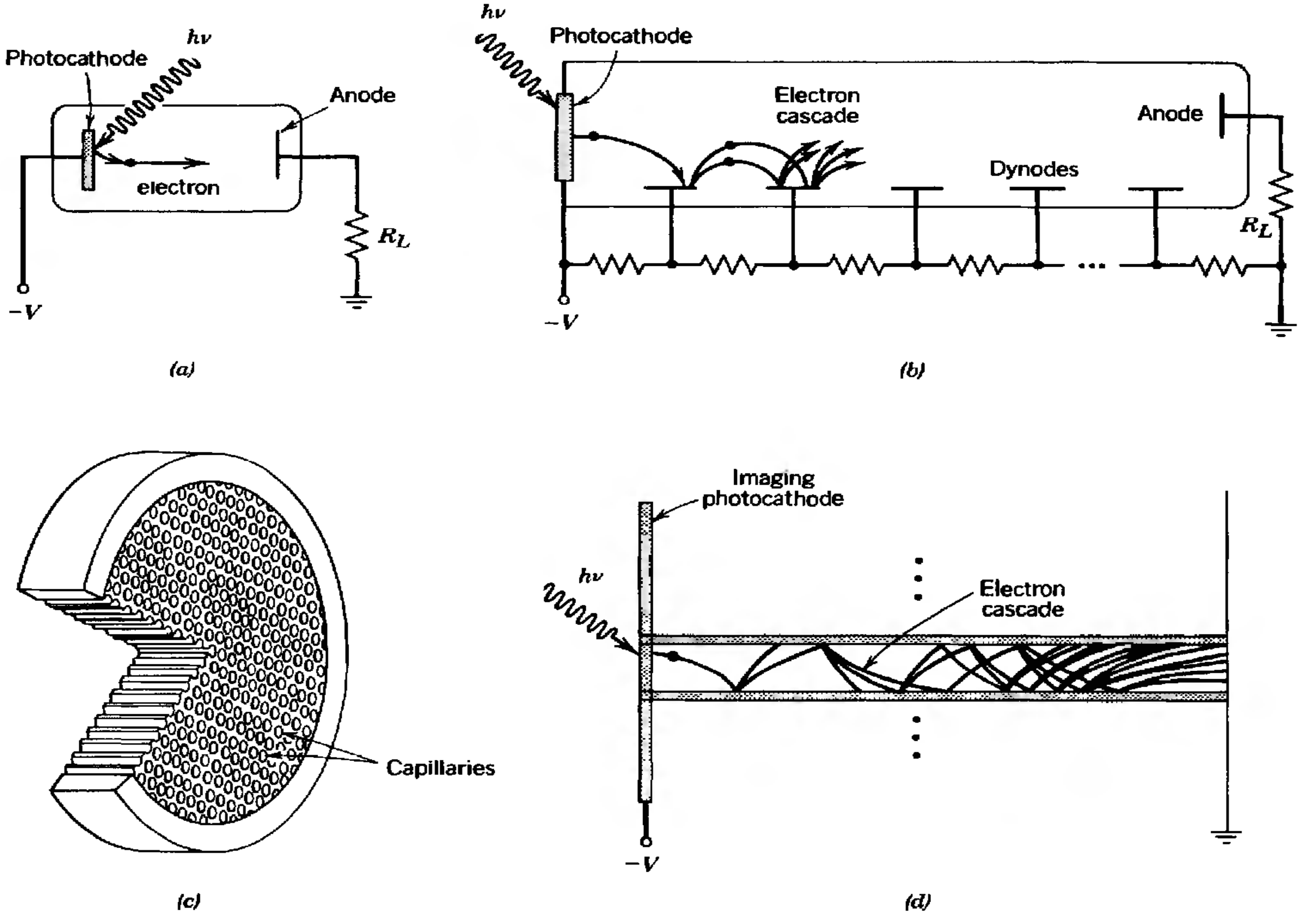


**Figure 17.0-2** (*a*) Phototube. (*b*) Photomultiplier tube with semitransparent photocathode. (*c*) Cutaway view of microchannel plate. (*d*) Single capillary in a microchannel plate.

# Internal photo effect: photoconductor detectors relay on the light increasing the photoconductivty

- Generation- absorbed photon generate free carriers
- Transport- an applied electric field induce moving of the carriers, results in a circuit current
- Amplification- induced avalanche by impact ionization

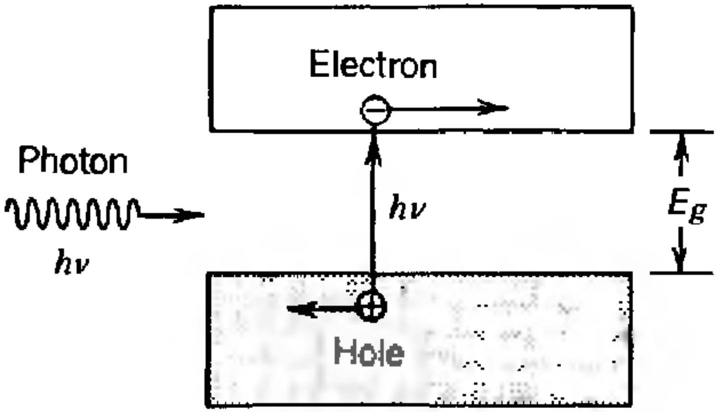


**Figure 17.0-3** Electron–hole photogeneration in a semiconductor.

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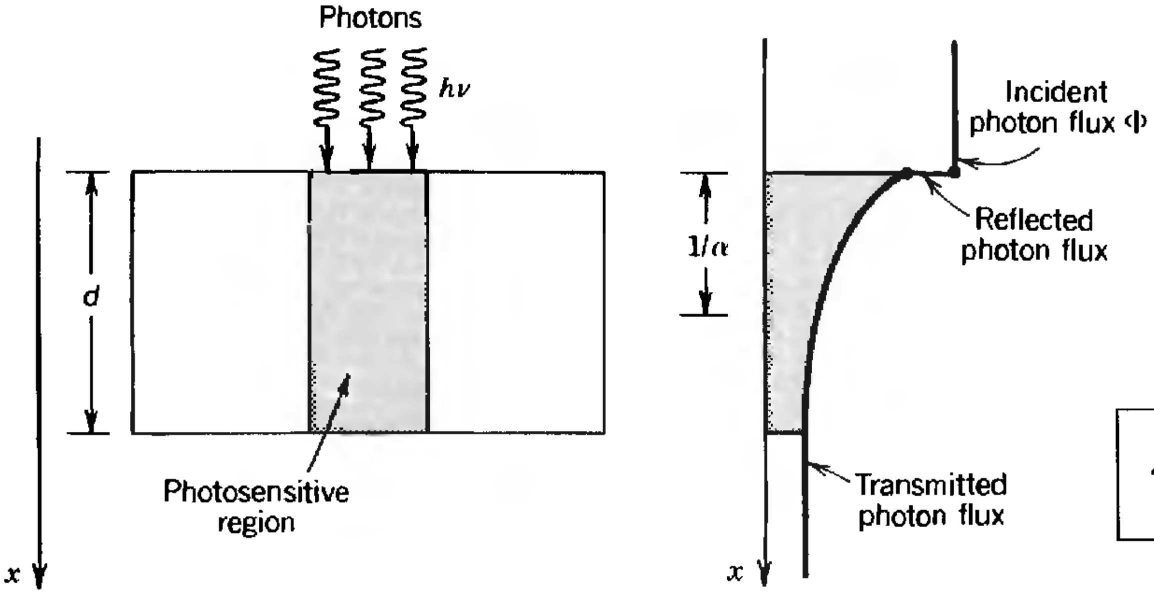
# Certain fundamental rules govern all semiconductors detectors

- **Quantum efficiency**: the probability that a single photon will generates a photo carrier pair that contributes to the detector current
- **Responsivity**: the relation between the electron current to incident optical power
- **Response time**: the charge delivered to external circuit by carriers motion occupies an extended time

**Quantum efficiency**: the probability that a single photon will generates a photo carrier pair that contributes to the detector current



$$\eta = (1 - \mathscr{R})\zeta[1 - \exp(-\alpha d)],$$

**Figure 17.1-1** Effect of absorption on the quantum efficiency $\eta$.

The quantum efficiency is a function of the wave length. The band gap wave length is the **long wave length limit** of the material.

**Responsivity**: the relation between the electron current to incident optical power

$$G = \frac{q}{e},$$

$$\boxed{i_p = \eta q \Phi = G\eta e \Phi = \frac{G\eta e P}{h\nu}}$$

(17.1-5)
Photocurrent

$$\boxed{\Re = \frac{G\eta e}{h\nu} = G\eta \frac{\lambda_o}{1.24},}$$

(17.1-6)
Responsivity in the Presence of Gain (A/W)
($\lambda_o$ in $\mu$m)

# **Response time**: the charge delivered to external circuit by carriers motion occupies an extended time

$$\boxed{i(t) = -\frac{Q}{w}v(t).} \qquad (17.1\text{-}7)$$

Ramo's Theorem

This important formula, known as **Ramo's theorem**, can be proved with the help of an

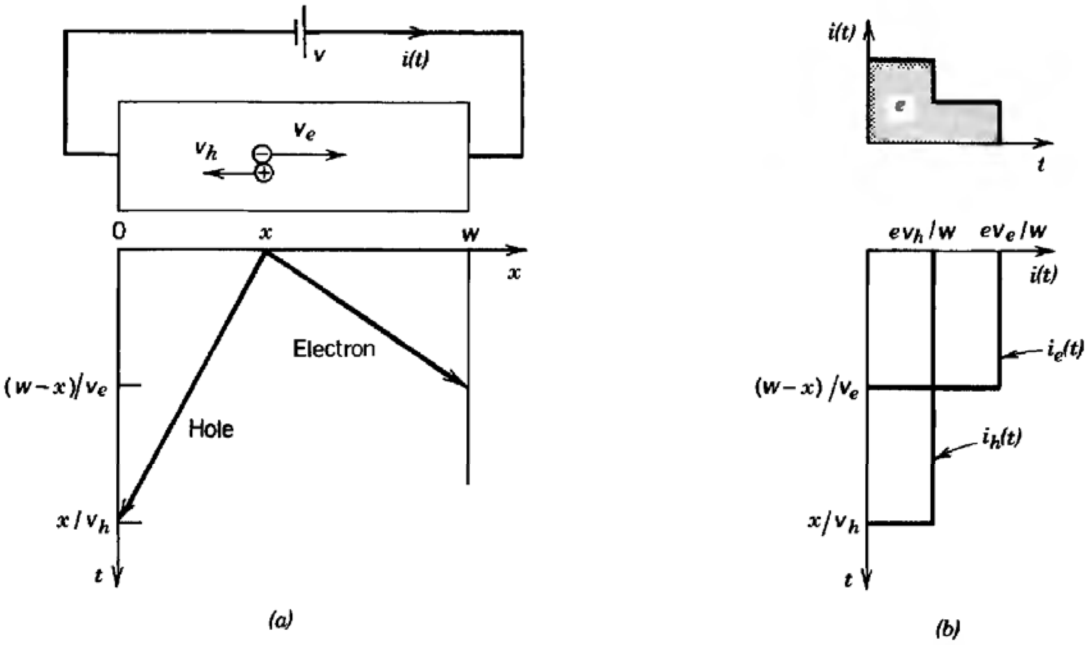


**Figure 17.1-3** (*a*) An electron–hole pair is generated at the position $x$. The hole moves to the left with velocity $v_h$ and the electron moves to the right with velocity $v_e$. The process terminates when the carriers reach the edge of the material. (*b*) Hole current $i_h(t)$, electron current $i_e(t)$, and total current $i(t)$ induced in the circuit. The total charge induced in the circuit is $e$.

# Three main type of internal photo effect

- **Photoconductor**- registering either the photocurrent or the voltage drop across a load resistor placed in series with the circuit
- **Photodiode-** based on photo genratod charge carriers in materials junctions.
- **Avalanche photodiode-** relay on impact ionization inside the device to get gain in the diode current.

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# **Photoconductor**- registering either the photocurrent or the voltage drop across a load resistor placed in series with the circuit

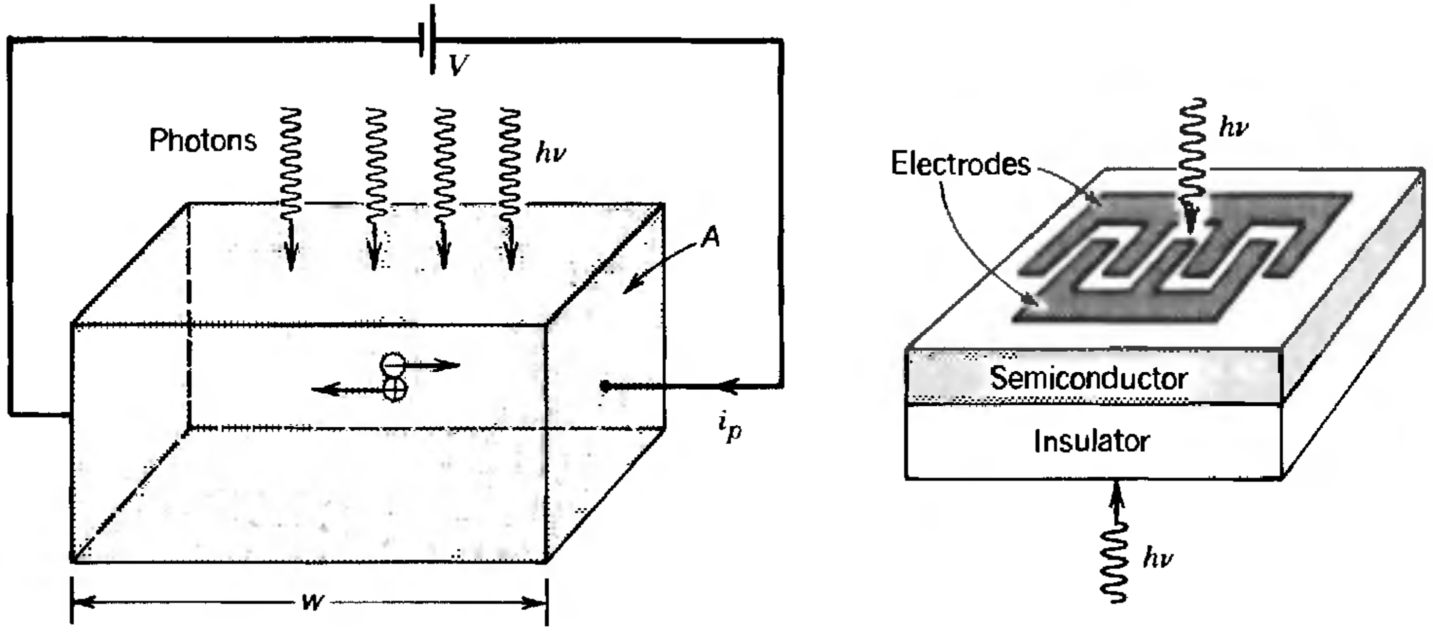

**Figure 17.2-1** The photoconductor detector. Photogenerated carrier pairs move in response to the applied voltage $V$, generating a photocurrent $i_p$ proportional to the incident photon flux. The interdigitated electrode structure shown is designed to maximize both the light reaching the semiconductor and the device bandwidth (by minimizing the carrier transit time).

$$\Delta\sigma = e\Delta n(\mu_e + \mu_h) = \frac{e\eta\tau(\mu_e + \mu_h)}{wA}\Phi,$$

$$i_p \approx e\eta\frac{\tau}{\tau_e}\Phi.$$

**The device exhibits an internal gain because the recombination life time and transient time generally differ**

$$i_p \approx e\eta \frac{\tau}{\tau_e}\Phi. \Longrightarrow G = \frac{\tau}{\tau_e}$$

$$\boxed{\Re = \frac{G\eta e}{h\nu} = G\eta \frac{\lambda_o}{1.24},}$$

# The spectral sensitivity of photoconductors is governed by the long wave length limit

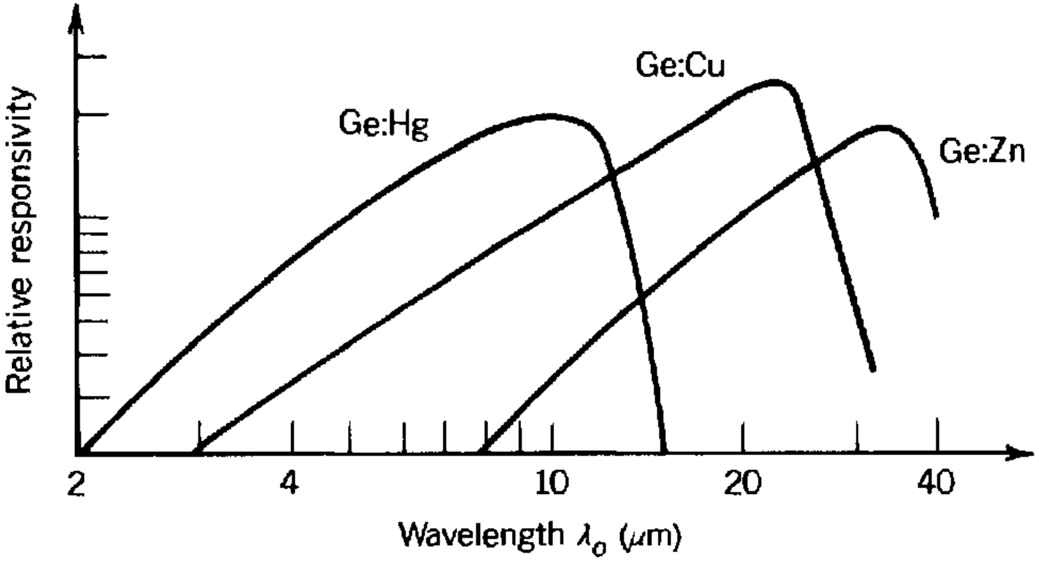

**Figure 17.2-2** Relative responsivity versus wavelength $\lambda_o$ (μm) for three doped-Ge extrinsic infrared photoconductor detectors.

The response time of photocondactor detector constrained by the transit time and RC time constant

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# **Photodiode p-n junction:** reverse current increases when absorbs photon

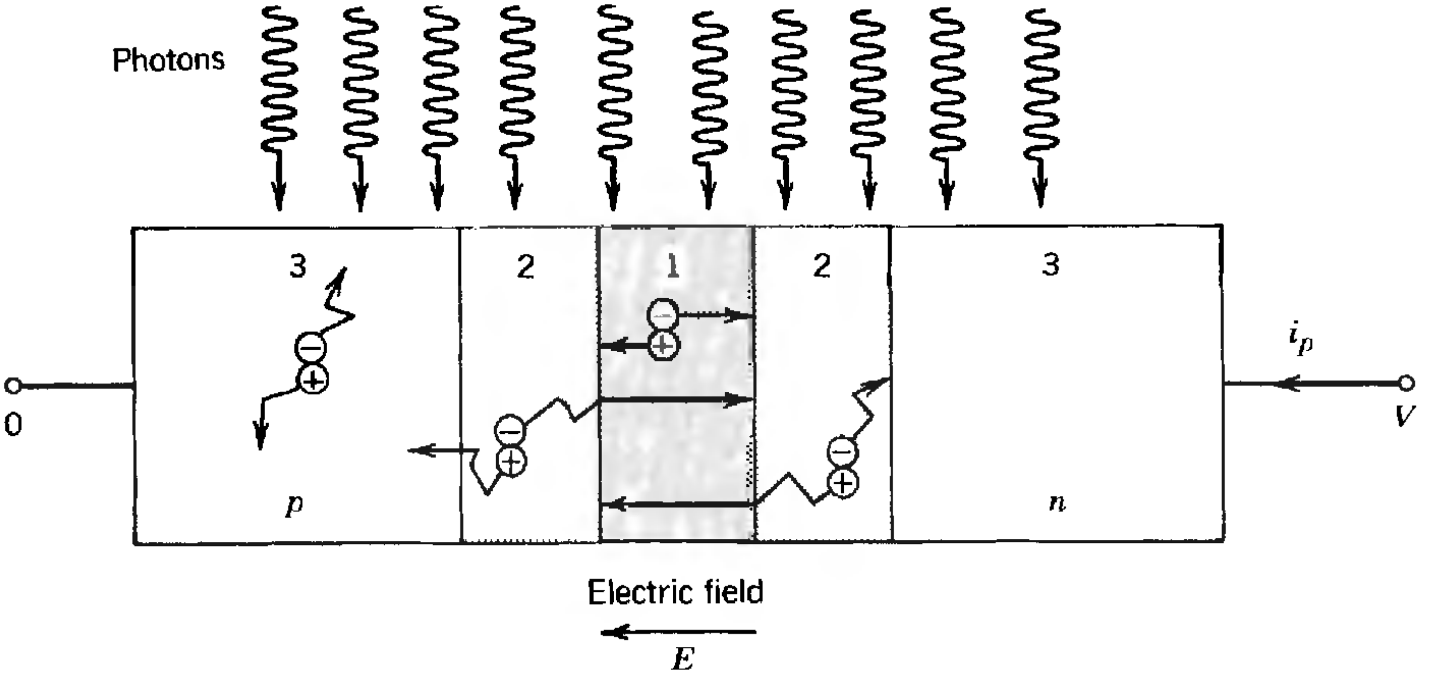

**Figure 17.3-1** Photons illuminating an idealized reverse-biased *p-n* photodiode detector. The drift and diffusion regions are indicated by 1 and 2, respectively.

# Photo diodes are generally faster then photoconductors because the strong field in the depletion layer

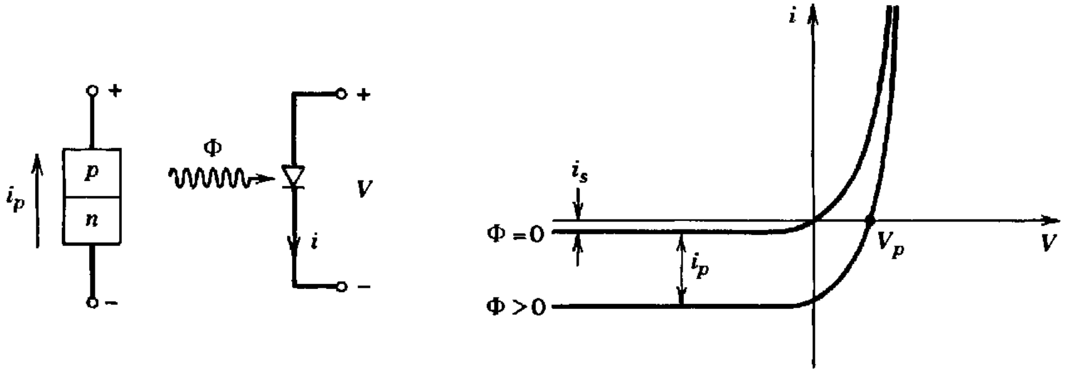

**Figure 17.3-2** Generic photodiode and its $i$–$V$ relation.

$$i = i_s\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right] - i_p,$$

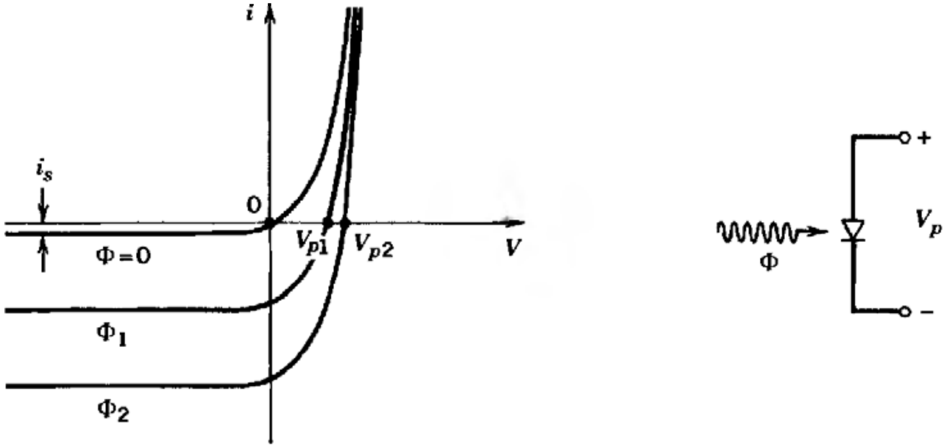

**Figure 17.3-3** Photovoltaic operation of a photodiode.

# Photodiodes are usually operated in the strongly reverse-biased mode

- A strong reverse bias creates a strong electric field which increases the drift velocity of the carriers- reducing transit time
- It increase the depletion layer- reducing the junction capacitance and improving the response time
- Increasing the depletion layer leads to a larger photosensitive area

# The p-i-n photodiode has number of advantages over the p-n diode, increasing the depletion layer

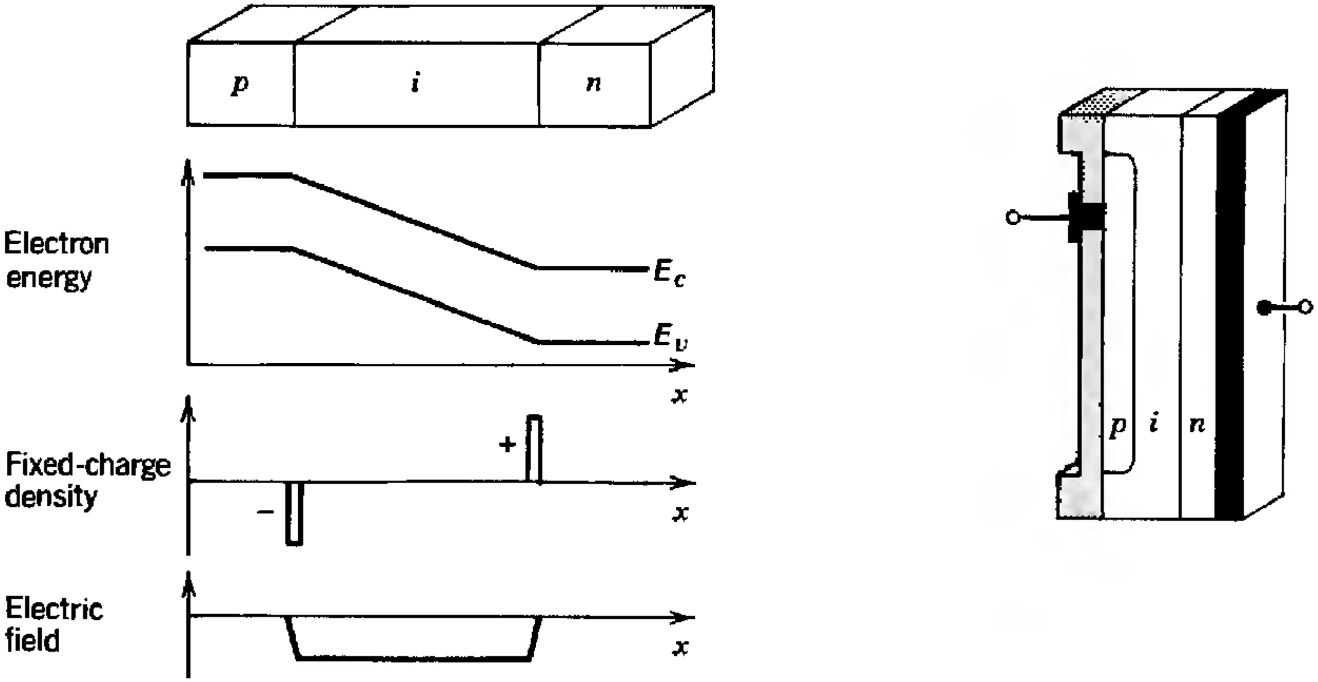

**Figure 17.3-6** The *p-i-n* photodiode structure, energy diagram, charge distribution, and electric field distribution. The device can be illuminated either perpendicularly or parallel to the junction.

**p-i-n diode:** response times in the tens of ps are available

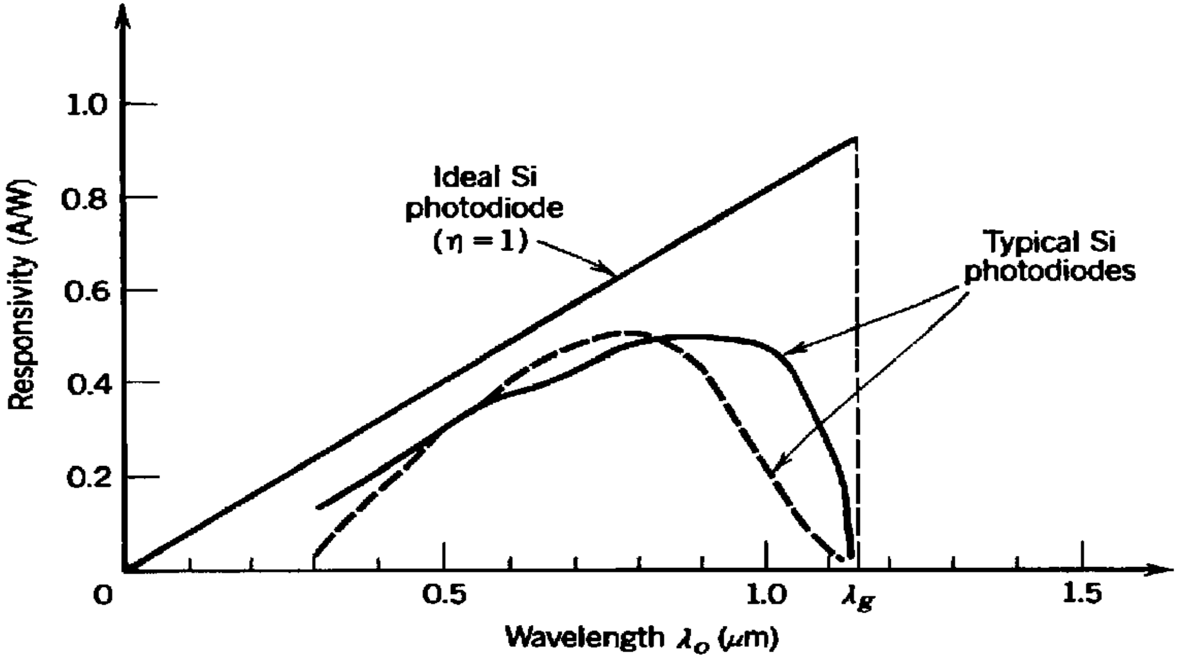

**Figure 17.3-7** Responsivity versus wavelength ($\mu$m) for ideal and commercially available silicon *p-i-n* photodiodes.

## Heterostructure photodiodes is based on two different materials and it can minimize the optical absorption out side the depletion region

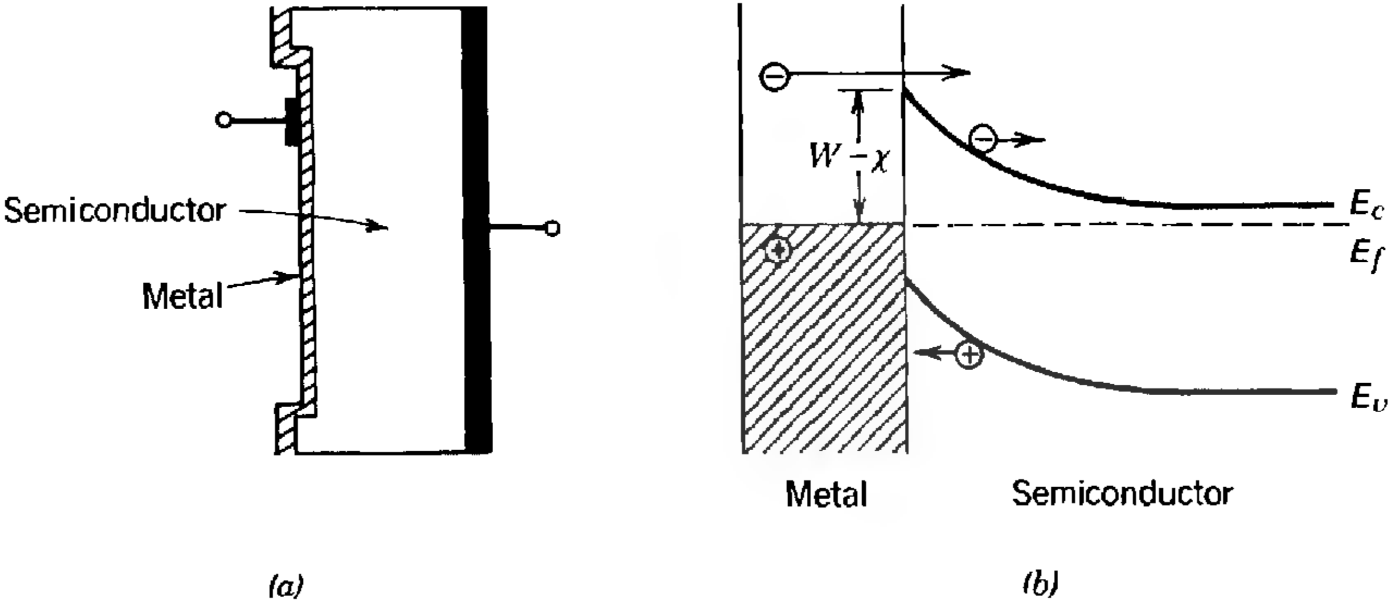

**Figure 17.3-8** (*a*) Structure and (*b*) energy-band diagram of a Schottky-barrier photodiode formed by depositing a metal on an *n*-type semiconductor. These photodetectors are responsive to photon energies greater than the Schottky barrier height, $h\nu > W - \chi$. Schottky photodiodes can be fabricated from many materials, such as Au on *n*-type Si (which operates in the visible) and platinum silicide (PtSi) on *p*-type Si (which operates over a range of wavelengths stretching from the near ultraviolet to the infrared).

# **Array detectors:** containing a large number of photodetectors and can form many spatial points

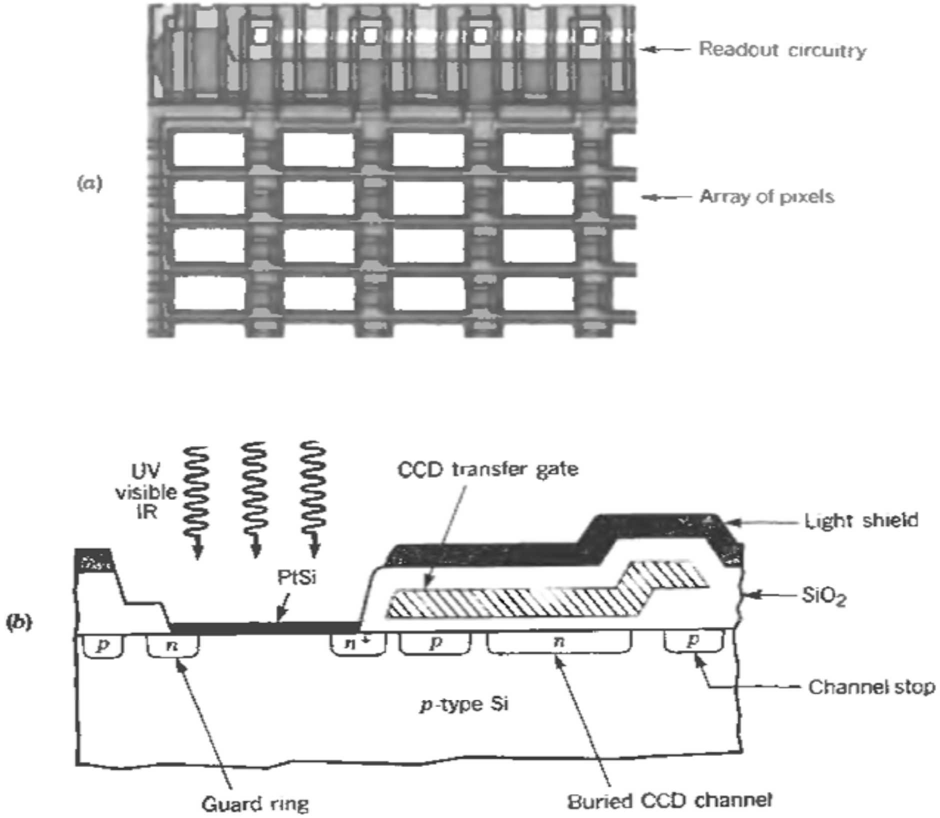

**Figure 17.3-10** (*a*) Corner of an array of 160 × 244 PtSi/Si Schottky-barrier photodiodes. Each pixel is 40 $\mu$m × 80 $\mu$m in size. Portions of the readout circuitry are visible. (Courtesy of W. F. Kosonocky.) (*b*) Cross section of a single pixel in the CCD array. The light shield prevents the generation of photocarriers in the CCD transfer gate and buried channel. The guard ring minimizes dark-current spikes and the channel stop confines the signal charge in the lateral direction. (Adapted from B.-Y. Tsaur, C. K. Chen, and J. P. Mattia, PtSi Schottky-Barrier Focal Plane Arrays for Multispectral Imaging in Ultraviolet, Visible and Infrared Spectral Bands, *IEEE Electron Device Letters*, vol. 11, pp. 162–164, 1990, copyright © IEEE.)

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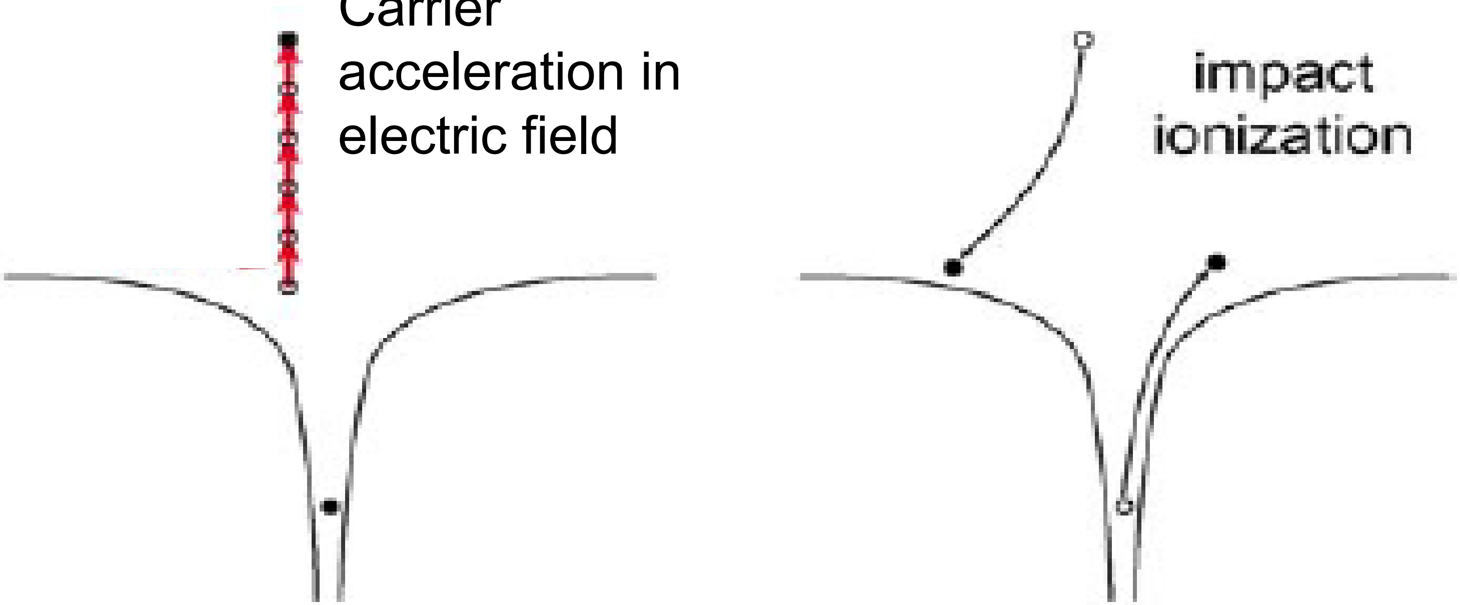
# carrier is accelerated in strong electric field and when they acquiring enough energy they excite new carrier



Carrier acceleration in electric field

# Avalanche photodiode operates by converting each detected photon into a cascade of moving carrier pairs

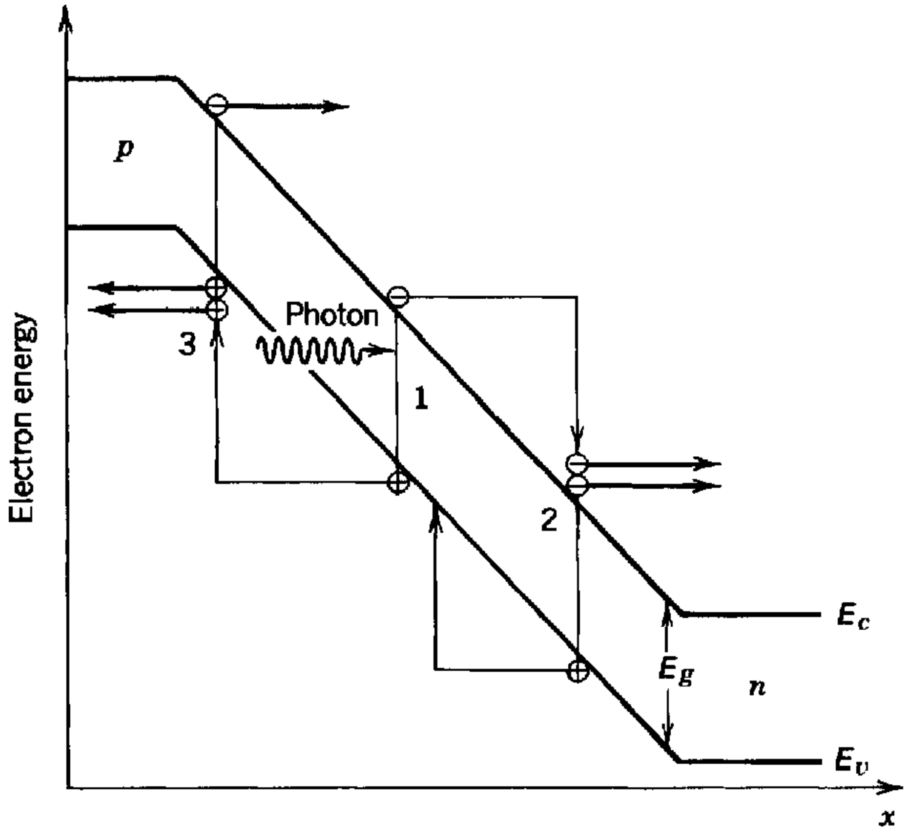


**Figure 17.4-1** Schematic representation of the multiplication process in an APD.

$$k = \frac{\alpha_h}{\alpha_e}.$$

The abilities of electrons and holes to impact ionize are characterized by the ionization coefficients

# The multiplication region should be thin to minimize the possibility of uncontrolled avalanche

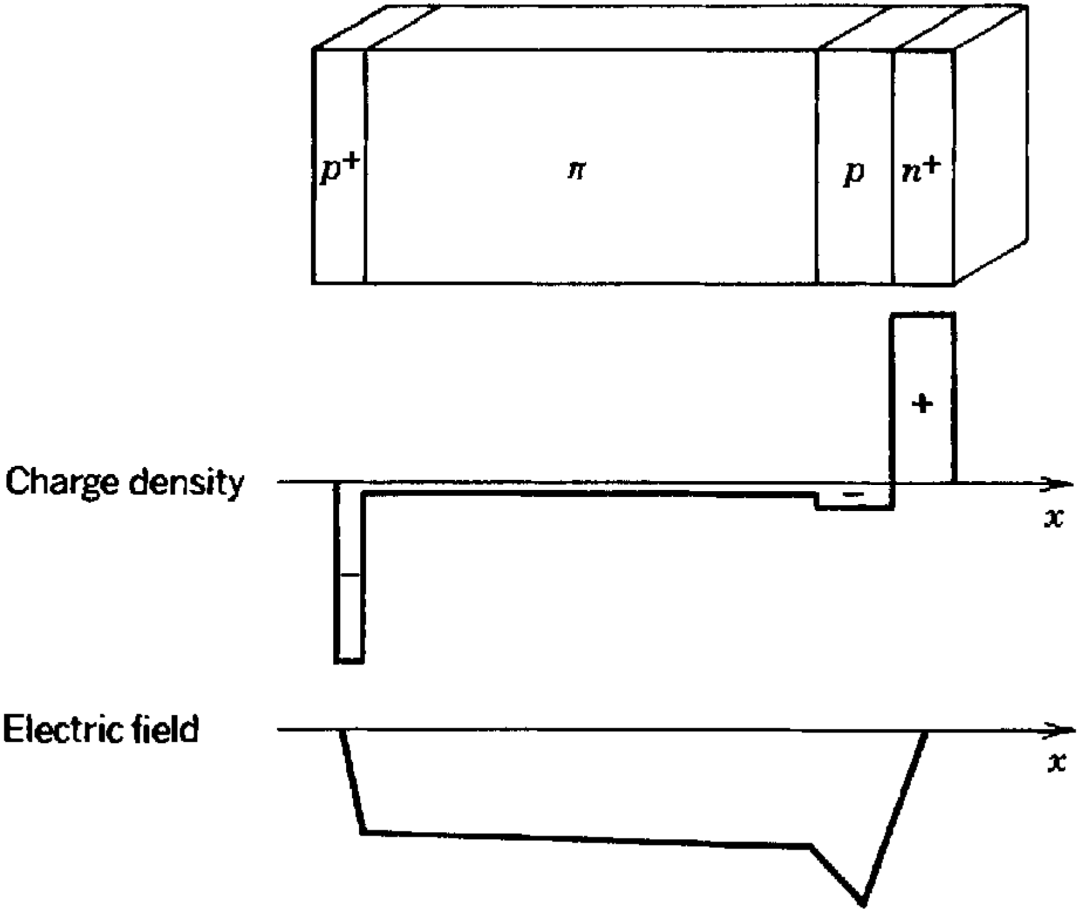


**Figure 17.4-2** Reach-through $p^+$-$\pi$-$p$-$n^+$ APD structure.

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## The device generates a random electric current

- **Photon noise:** random arrive of photons
- **Photo electron noise:** photon fails to generate pair in probability of 1-η
- **Gain noise:** the amplification process is mostly random.
- **Receiver circuit noise:** from components in the electrical circuit

# SNR- signal to noise ratio of the photoelectron is lower then that of the incident photons

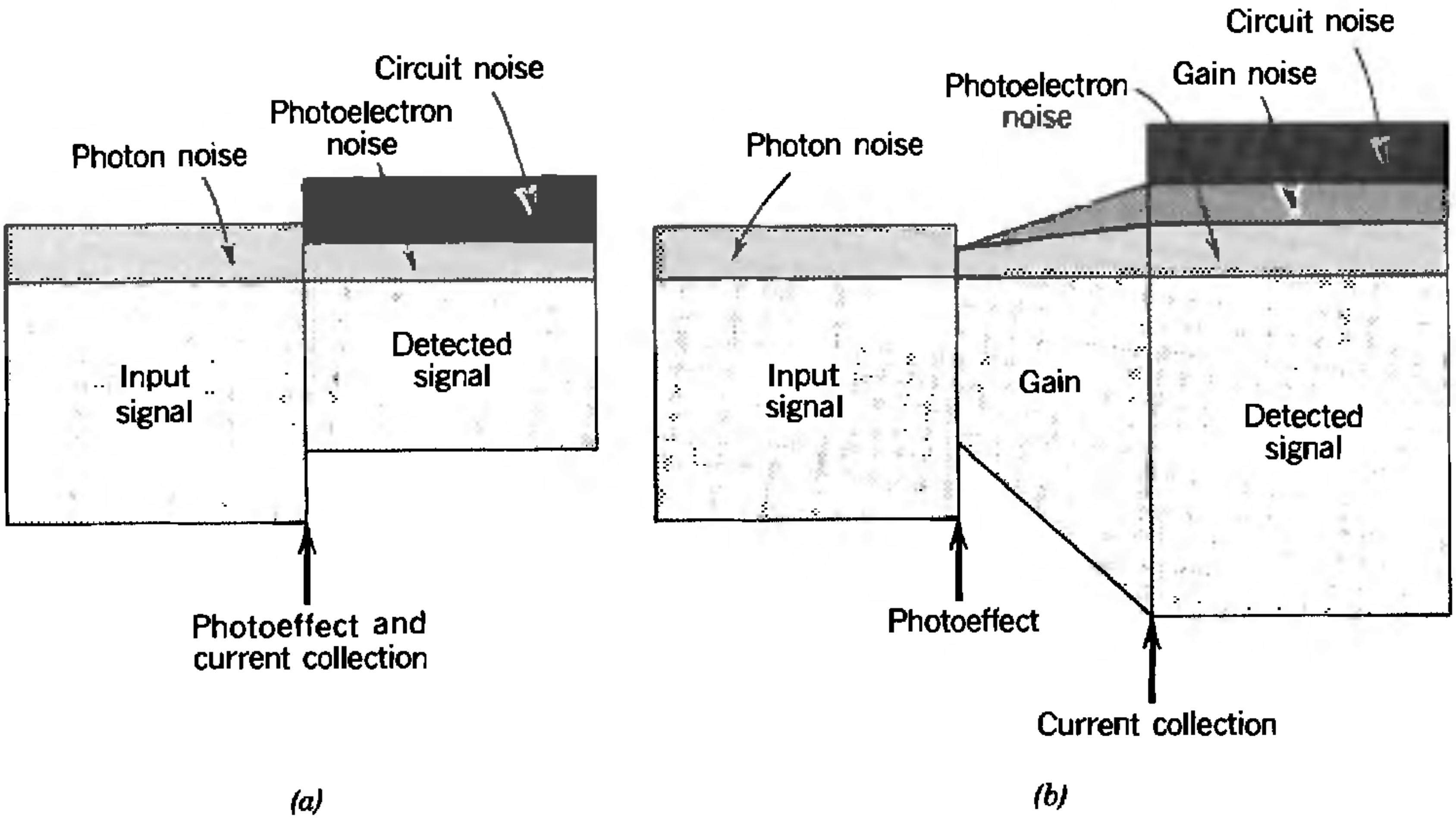

**Figure 17.5-1** Signal and various noise sources for (*a*) a photodetector without gain (e.g., a *p-i-n* photodiode) and (*b*) a photodetector with gain (e.g., an APD).

## An optical receiver can be characterized by three performance measures

- **SNR**=(mean)$^2$/variance ($SNR_i=\underline{i}^2/\sigma_i^2$)
- **Minimum detectable signal-** the mean signal that yield SNR=1
- **Receiver sensetivity-** the mean signal when $SNR=SNR_0$

# There are few other sources of noise

- Background noise
- Dark current noise
- Leakage current?

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# Advantages and disadvantages in the PMT device (vacuum photomultiplier tube)

- Good detectors for the vary low light levels
- They can achieved high temporal resolution of 10-100ps using microchannel plate (PMT) type
- They are relatively bulky and fragile and easily damaged by excess light or voltage
- Limited dynamic range
- Relatively low quantum efficiency
- Require a high voltage supply

# Advantages and disadvantages in the APD device

- Compact, robust, monolithic
- Tend to be more prone to noise than PMT's
- Requiring high voltage
- Very sensitive to temperature and excess bias
- Problem in SPC (single photon counting) mode- phenomenon of after pulsing is a by product in this device

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# Quantum dots is a nanometer sized semiconductor region within another material of larger band gap

- Electrons in a quantum dot are confined, they have no kinetic energy and they occupy spectrally sharp energy levels
- They tends to trap electrons due their lower conduction band energy then their surrounding
- Each quantum dot has a finite capacity for electrons
- Trapped electrons experience interaction with the dot and with the surrounding
- In a quantum dot single photon detector the negative charge trapped within the dots limit the current flowing in a nearby thin sensing layer

**Photon-induced release of electron from a dot produced a detectable change in the current through the sensing layer.**

# Self organized grows can be easily incorporated into a device structures

- pictures

# Quantum dots semiconductor- sensitive robust and cheap

- High detection efficiency
- The short gate transistor device should show a sub-nanosecond response
- Low noise

# Several improvement research in photo detectors type APD's

- Infrared photon counting using sum-frequency generation and Si APD
- Improving photon counting with InGaAs APD
- SSPD- superconducting single photon detectors

# SSPD- superconducting single photon detectors

- The incident photon heats the electronic population in the wire and produces a transition from the super conducting to the normal state

picture

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