UNIT III

SEMICONDUCTOR PHOTON DETECTORS

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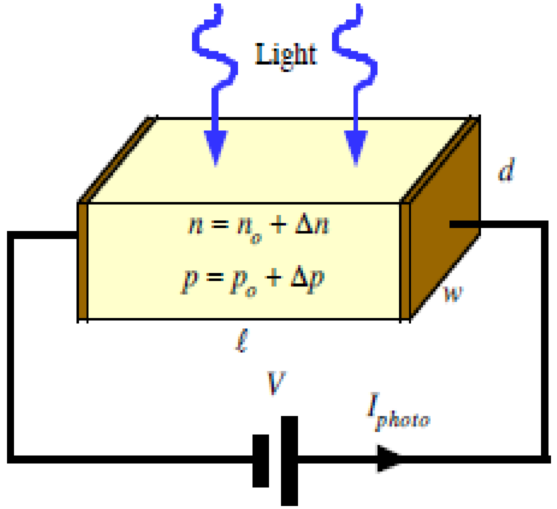
Principle of Photo Detection -The PIN Photodiode -Avalanche Photodiode- Principles- Structures-Responsivity - Efficiency , Hetero-junction Photodiodes-Schottky Junction Photo detectors -Metal-Semiconductor - Metal Photodiode- Phototransistors,

Array Detectors -Photoconductive detectors - Noise In Photo detectors- Charge Coupled Devices (CCD)

Principle of Photo Detection

- Optical detectors are used to convert variation in optical power into corresponding variation in electric current.
- The photodetector works on the principle of optical absorption. The main requirement of light detector is its fast response.

Photoelectric detectors relies on the photo electric effect and can be either external (*photoelectron emission*) or internal (*photoconductivity*).



Source : S. O. Kasap, "Optoelectronics and Photonics: Principles and Practices", Prentice Hall

Photodetector - Requirements

a) High sensitivity (responsivity) at the desired wavelength.

and low responsivity elsewhere

a) High fidelity. To reproduce the received signal waveform with fidelity (Example: for analog transmission the response of the photodetector must be linear with regard to the optical signal over a wide range).

b) Large electrical response to the received optical signal. The photodetector should produce a maximum electrical signal for a given amount of optical power.

d) Short response time. (pn-µsec, PIN/APD-nanosec)

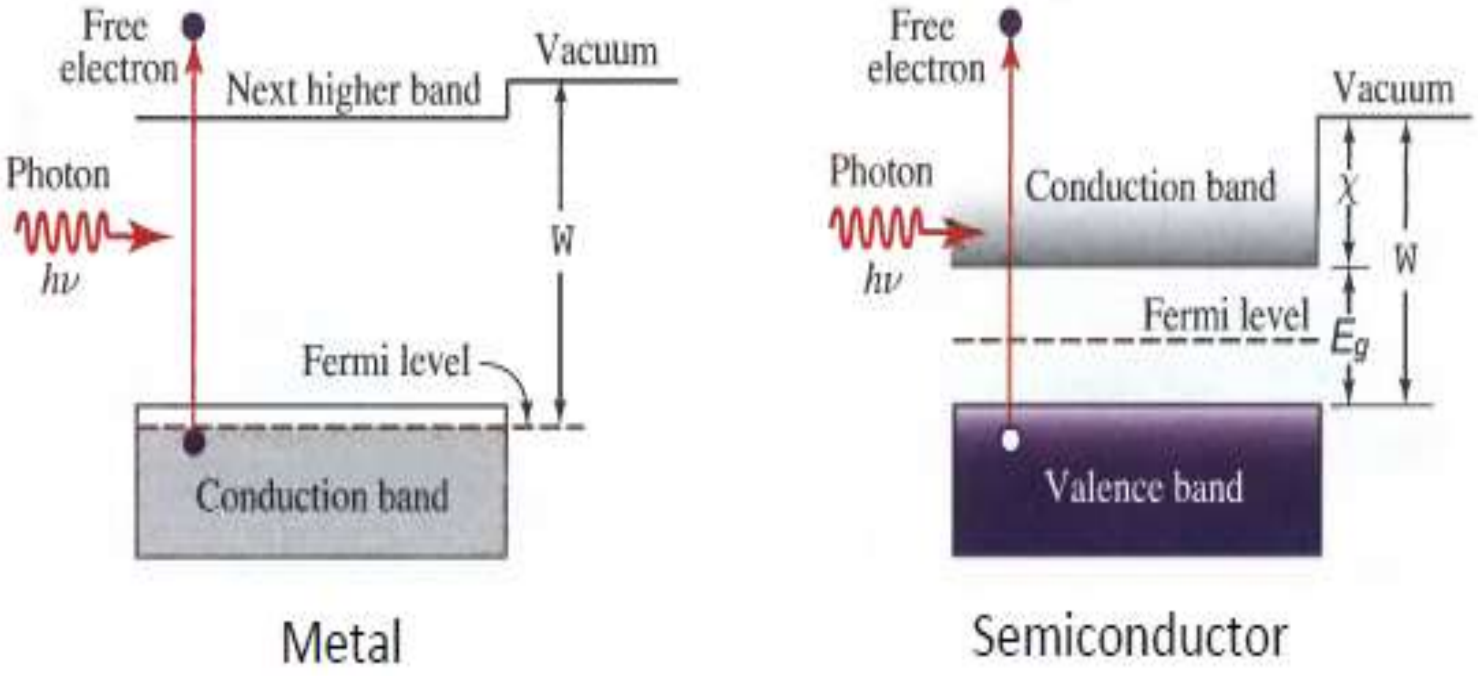
Principle of Photo Detection

Photodetectors

Photodetectors measure photon flux or optical power, i.e. convert light to an electric voltage or current.

There are two classes of detectors:

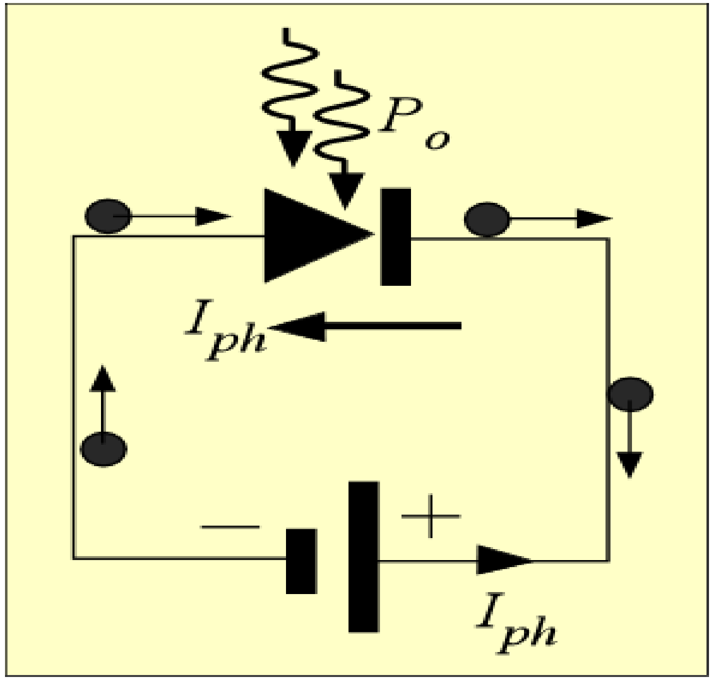
1. Photoelectric detectors
2. Thermal detectors (not discussed here)



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

Source : S. O. Kasap, "Optoelectronics and Photonics: Principles and Practices", Prentice Hall

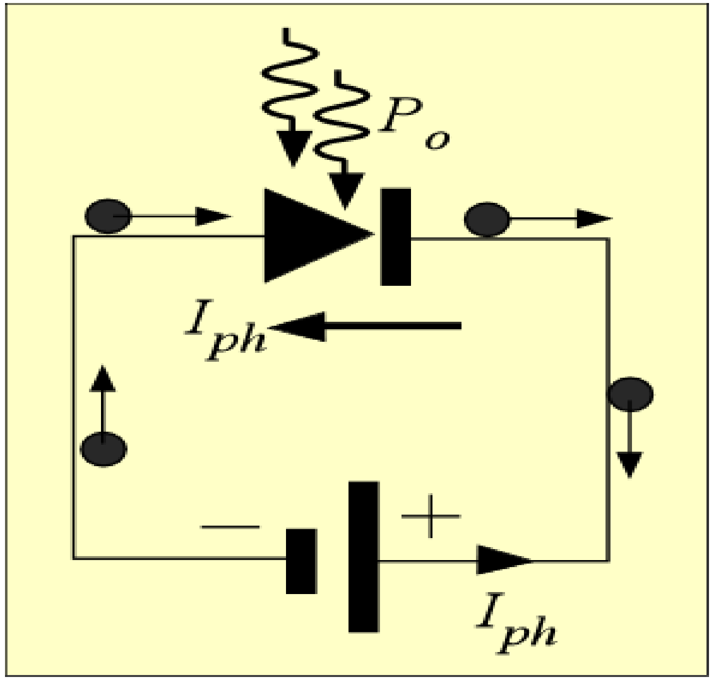
External quantum efficiency (QE) η_e of the detector



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

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

Source : S. O. Kasap, “Optoelectronics and Photonics: Principles and Practices”, Prentice Hall



Responsivity *R*

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

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

Source : S. O. Kasap, “Optoelectronics and Photonics: Principles and Practices”, Prentice Hall

Semiconductors

Band gap energy E_g at 300 K, cut-off wavelength λ_g and type of bandgap (D = Direct and I = Indirect) for some photodetector materials

Semiconductor	E_g (eV)	λ_g (eV)	Type
InP	1.35	0.91	D
$GaAs_{0.88}Sb_{0.12}$	1.15	1.08	D
Si	1.12	1.11	I
$In_{0.7}Ga_{0.3}As_{0.64}P_{0.36}$	0.89	1.4	D
$In_{0.53}Ga_{0.47}As$	0.75	1.65	D
Ge	0.66	1.87	I
InAs	0.35	3.5	D
InSb	0.18	7	D

Source : S. O. Kasap, “Optoelectronics and Photonics: Principles and Practices”, Prentice Hall

Photodetector - Requirements

- Minimum noise and reasonable cost
- Insensitive to temperature variations
- Stability.
- Small size
- Low bias voltage.
- High reliability
- Low cost
- Long operating life

Photodiodes

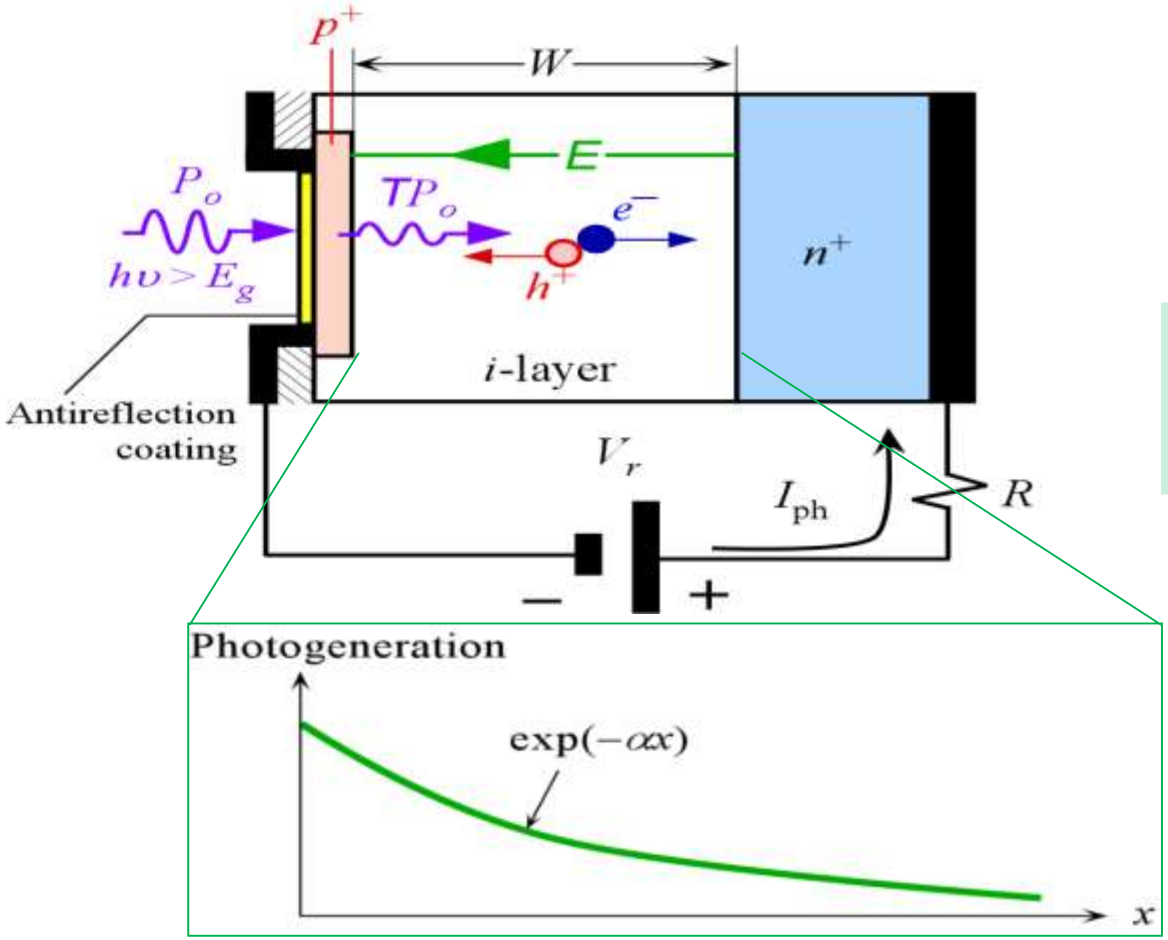
- Due to above requirements, only *photodiodes* are used as photo detectors in optical communication systems

- Positive-Intrinsic-Negative (*pin*) photodiode
  - No internal gain
- Avalanche Photo Diode (*APD*)
  - An internal gain of M due to self multiplication

- Photodiodes are *reverse biased* for normal operation

Internal Quantum Efficiency η_i

$$\eta_i = \text{Internal Quantum Efficiency} = \frac{\text{Number of EHP photogenerated}}{\text{Number of absorbed photons}}$$



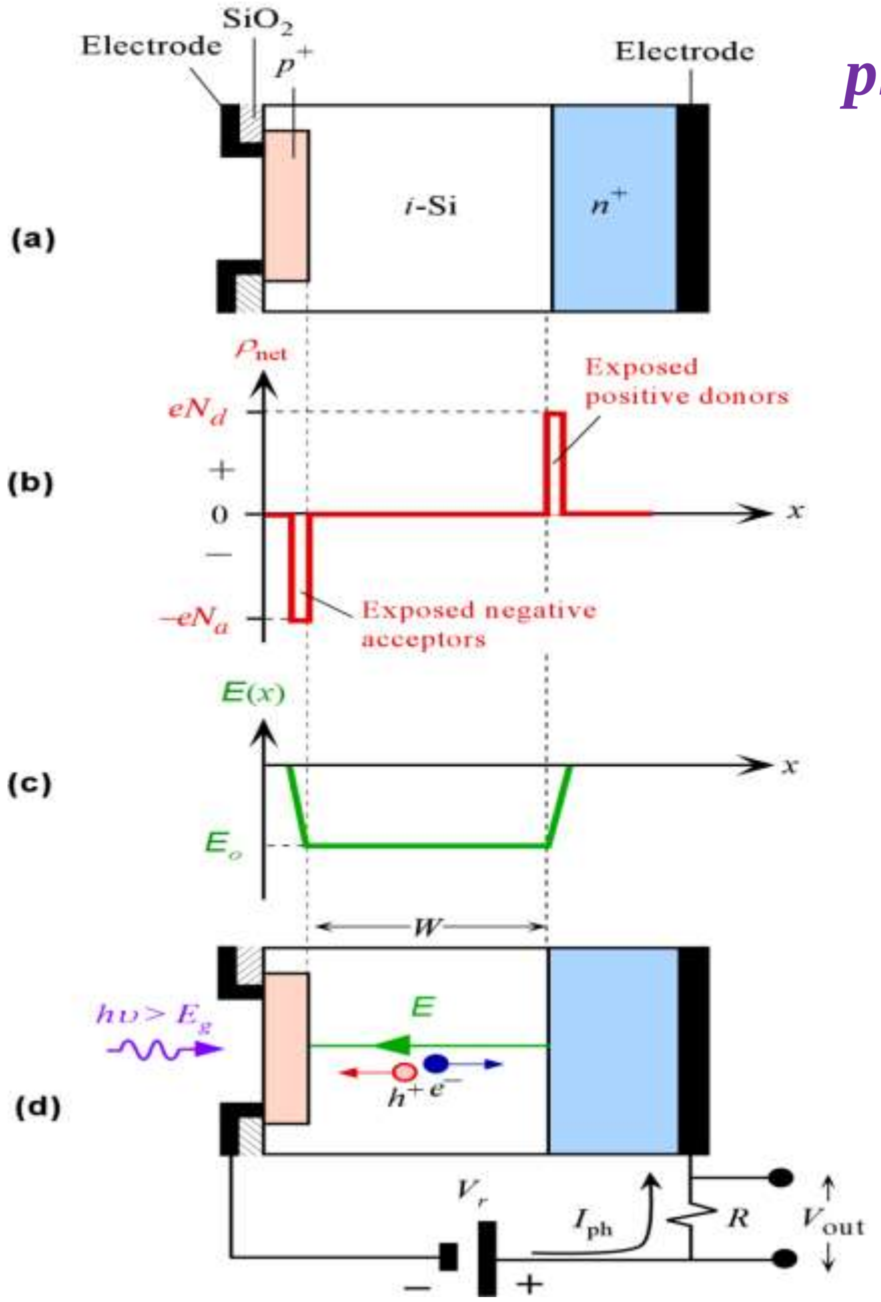
Assuming ℓ_p is very thin, and assuming $W >> L_h$

$$I_{ph} \approx \frac{e\eta_i T P_o(0)}{h\upsilon}[1 - \exp(-\alpha W)]$$

T = Transmission coefficient of AR coating

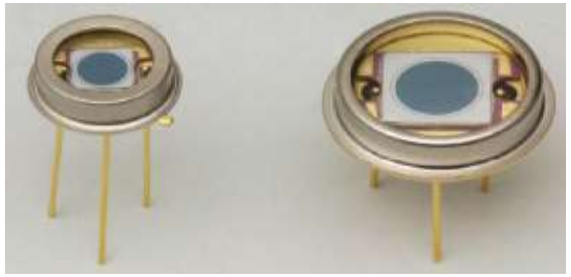
α = Absorption coefficient

Source : S. O. Kasap, "Optoelectronics and Photonics: Principles and Practices", Prentice Hall

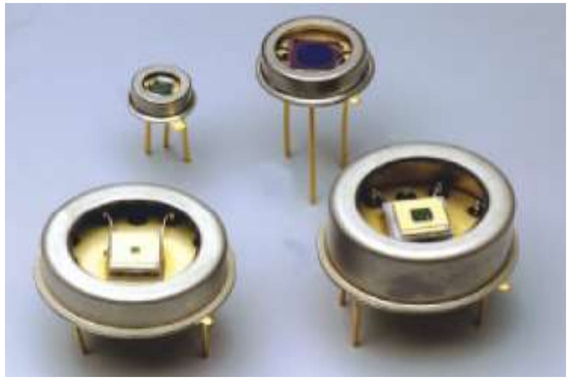


pin Photodiode

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.



Si pin



InGaAs pin

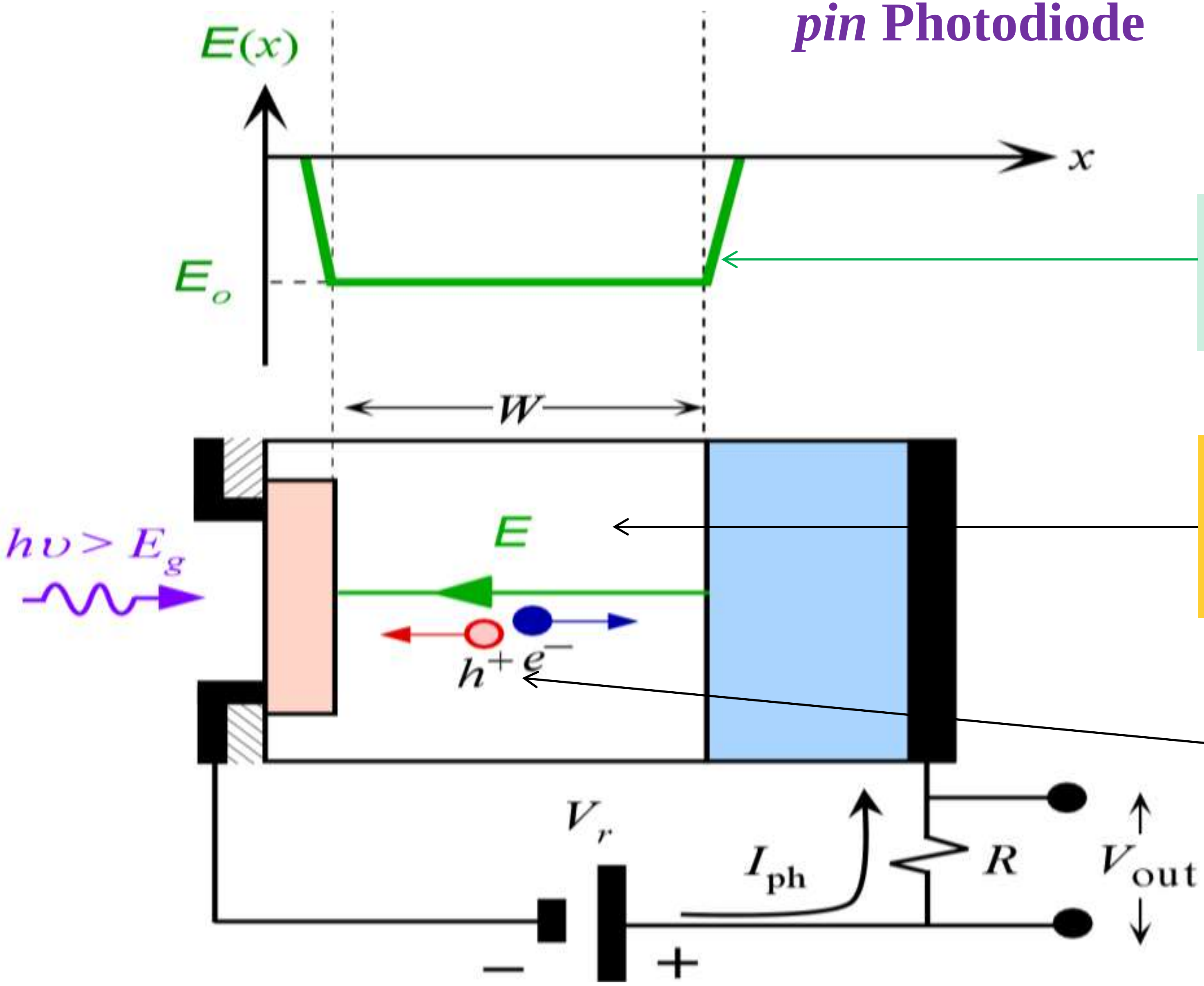
Courtesy of Hamamatsu

Source : S. O. Kasap, "Optoelectronics and Photonics: Principles and Practices", Prentice Hall

PIN Photo-Diode

- The PIN photodiode is structured with *p* and *n* regions separated by a lightly *n*-doped intrinsic (*i*) region.
- Incident photon with energy ≥ band-gap energy of the photodiode will generate free electron-hole pairs, known as *photo-carriers*.
- The high electric field present in the depletion region causes the carriers to separate and be collected across the reverse-biased junction.
- This gives rise to a *photo-current* flow in an external circuit, with one electron flowing for every carrier pair generated.
- In the absence of light, PIN photodiodes behave electrically just like an ordinary rectifier diode. If forward biased, they conduct large amount of current.

pin Photodiode



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

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

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

Source : S. O. Kasap, “Optoelectronics and Photonics: Principles and Practices”, Prentice Hall

PIN Photo-Diode

Operating Modes:

PIN detectors can be operated in two modes

1. **Photovoltaic Mode**
2. **Photoconductive Mode**

1. Photovoltaic Mode:

- No bias is applied to the detector.
- In this case, the detector works very slow and output is approximately logarithmic to the input light level.
- Real world fiber optic receivers never use the photovoltaic mode.

2. Photoconductive Mode:

- The detector is reversed biased.
- The output in this case is a current that is very linear with the input light power.
- The intrinsic region somewhat improves the sensitivity of the device. It does not provide internal gain. The combination of different semiconductors operating at different wavelengths allow the selection of material capable of responding to the desired operating wavelength.

PIN Photodiode

Diffusion Length:

- As the charge carriers flow through the material, some electron-hole pairs will recombine and disappear.
- On the average, the charge carriers move a *diffusion length* L_n or L_p for electrons and holes, respectively.

Carrier Life time:

- The time it takes for an electron or hole to recombine is known as the *carrier lifetime* and is represented by τ_n and τ_p, respectively.
- The lifetimes and the diffusion lengths are related by

$$\boldsymbol{L_n = (D_n\tau_n)^{1/2}} \qquad \text{and} \qquad \boldsymbol{L_p = (D_p\tau_p)^{1/2}}$$

where D_n and D_p are the electron and hole diffusion coefficients, expressed in units of cm^2/sec.

The PIN Photo diode

Optical power absorbed

- Optical radiation is absorbed in the semiconductor material according to the exponential law

$$P(x) = P_o[1 - \exp(-\alpha_s(\lambda)x)]$$

- Here, $\alpha_s(\lambda)$ is the *absorption coefficient* at wavelength λ,

  P_o is the incident optical power level, and

  $P(x)$ is the optical power absorbed in a

  distance x.

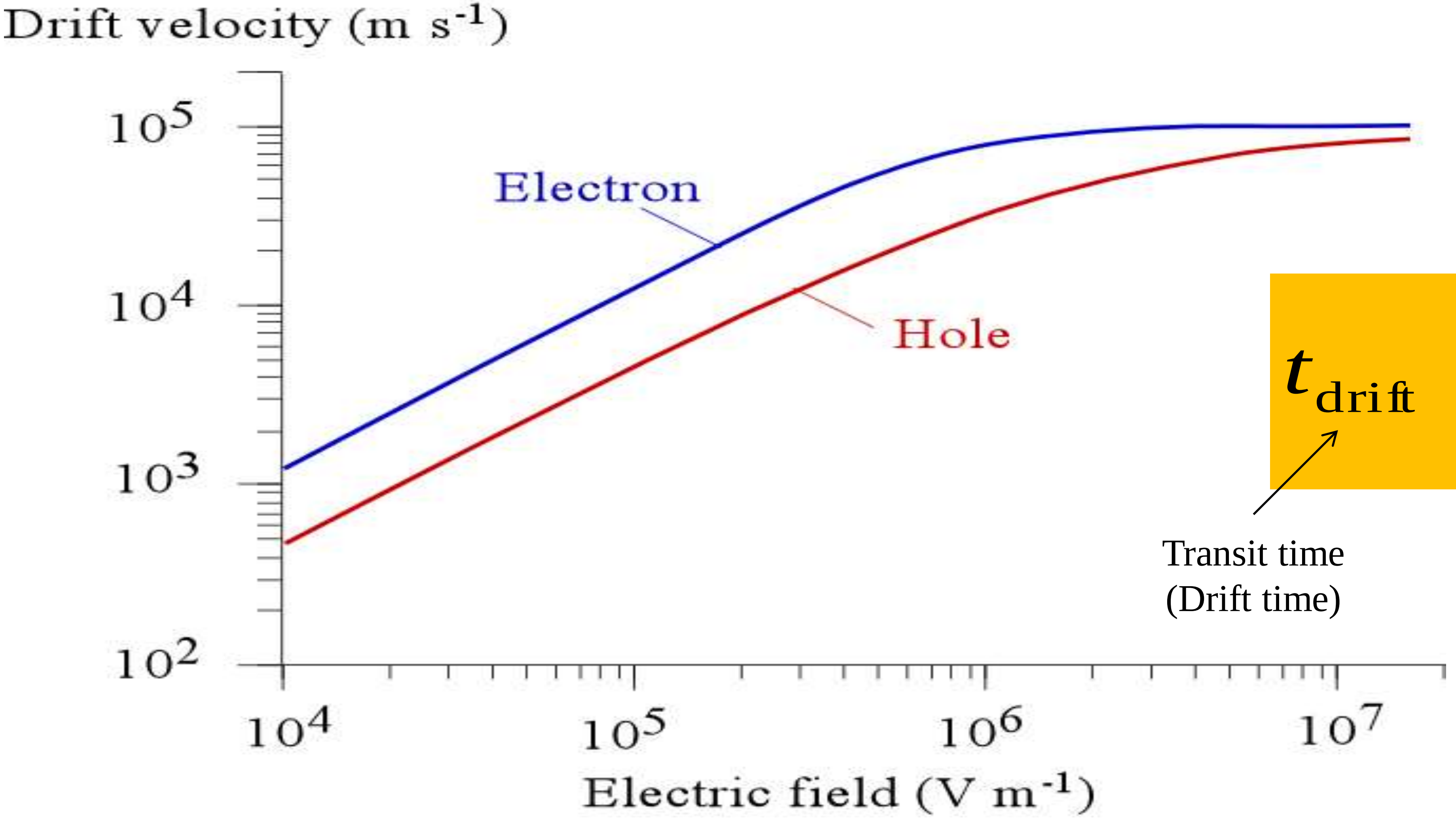
PIN Photo diode

- The optical absorption coefficient versus wavelength is shown in Fig. or several photodiode materials.
- The cutoff λ_c is determined by the band-gap energy E_g of the material:

$$\lambda_c(\mathrm{mm}) = hc/E_g = 1.24 \,/\, E_g(\mathrm{eV})$$

- The cutoff wavelength is about 1.06-µm for Si and 1.6-µm for Ge.
- For longer wavelengths, the photon energy is not sufficient to excite an electron from the valence to the conduction band.

pin Photodiode



Drift velocity vs. electric field for holes and electrons in Si.

Width of *i*-region
(Depletion region)

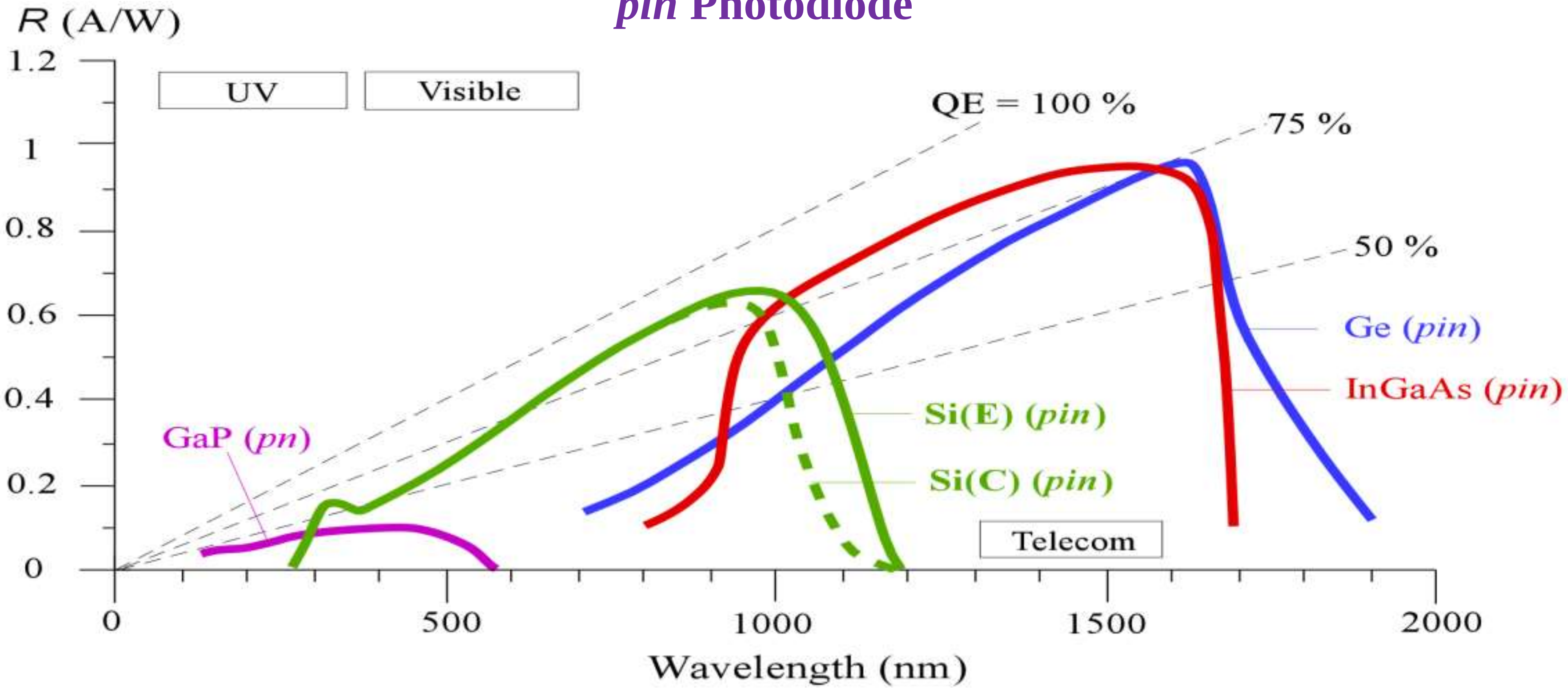
$$t_{drift} = \frac{W}{v_d}$$

Transit time
(Drift time)

Drift velocity

Source : S. O. Kasap, “Optoelectronics and Photonics: Principles and Practices”, Prentice Hall

pin Photodiode



The responsivity of Si, InGaAs and Ge *pin* type photodiodes. The *pn* junction GaP detector is used for UV detection. GaP (Thorlabs, FGAP71), Si(E), IR enhanced Si (Hamamatsu S11499), Si(C), conventional Si with UV enhancement, InGaAs (Hamamatsu, G8376), and Ge (Thorlabs, FDG03). The dashed lines represent the responsivity due to QE = 100 %, 75% and 50 %.

Source : S. O. Kasap, “Optoelectronics and Photonics: Principles and Practices”, Prentice Hall

EXAMPLE: Responsivity of a *pin* photodiode

A Si *pin* photodiode has an active light receiving area of diameter 0.4 mm. When radiation of wavelength 700 nm (red light) and intensity 0.1 mW cm^{-2} is incident, it generates a photocurrent of 56.6 nA. What is the responsivity and external QE of the photodiode at 700 nm?

Solution

The incident light intensity I = 0.1 mW cm^{-2} means that the incident power for conversion is

$P_o = AI = [\pi(0.02\text{ cm})^2](0.1\times10^{-3}\text{ W cm}^{-2}) = 1.26\times10^{-7}$ W or **0.126 μW**.

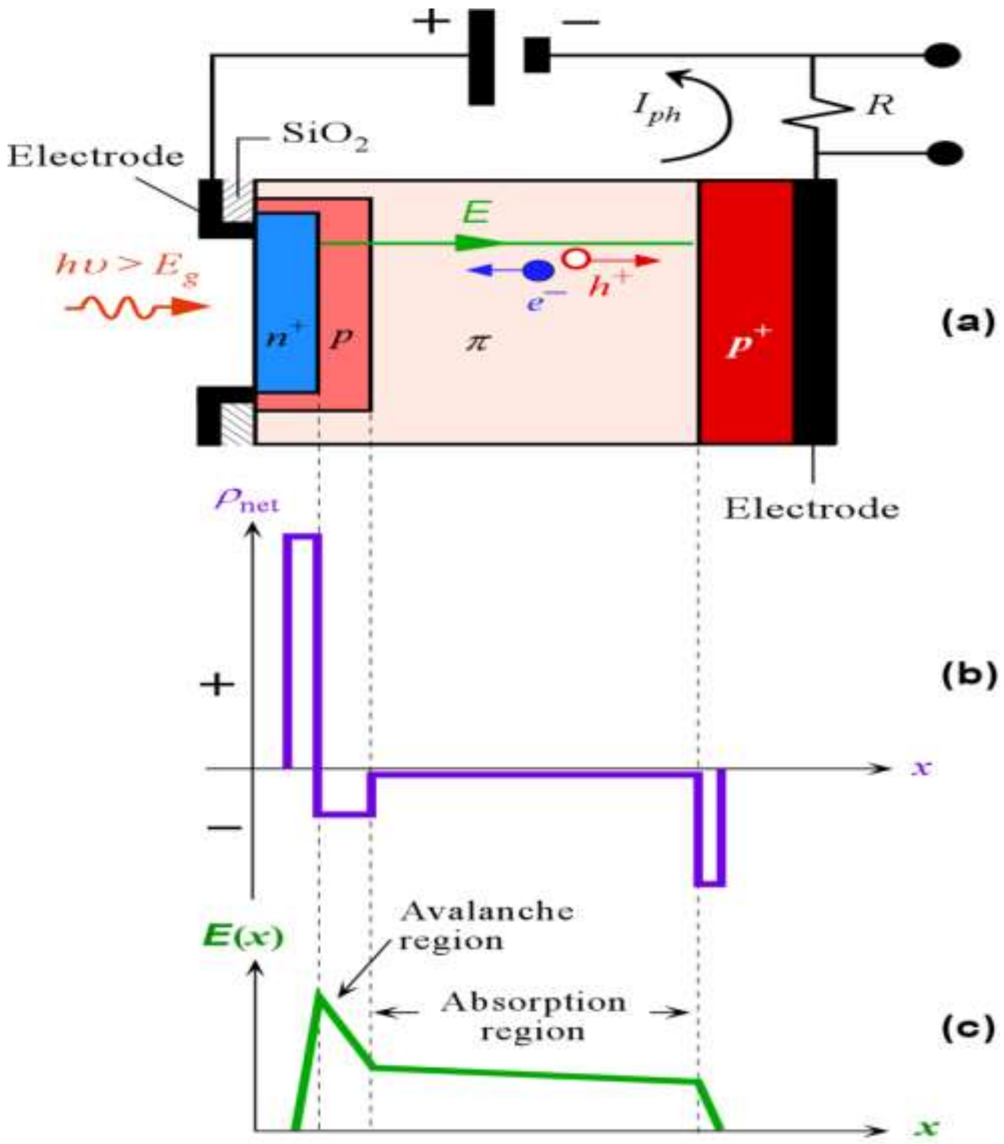
The responsivity is

$R = I_{ph}/P_o = (56.6\times10^{-9}\text{ A})/(1.26\times10^{-7}\text{ W}) = \mathbf{0.45\ A\ W^{-1}}$

The QE can be found from

$$\eta = R\frac{hc}{e\lambda} = (0.45\ \text{A W}^{-1})\frac{(6.62\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})}{(1.6\times10^{-19}\ \text{C})(700\times10^{-9}\ \text{m})} = 0.80 = \mathbf{80\ \%}$$

Avalanche Photodiode



(a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain.

(b) The net space charge density across the photodiode.

(c) The field across the diode and the identification of absorption and multiplication regions.

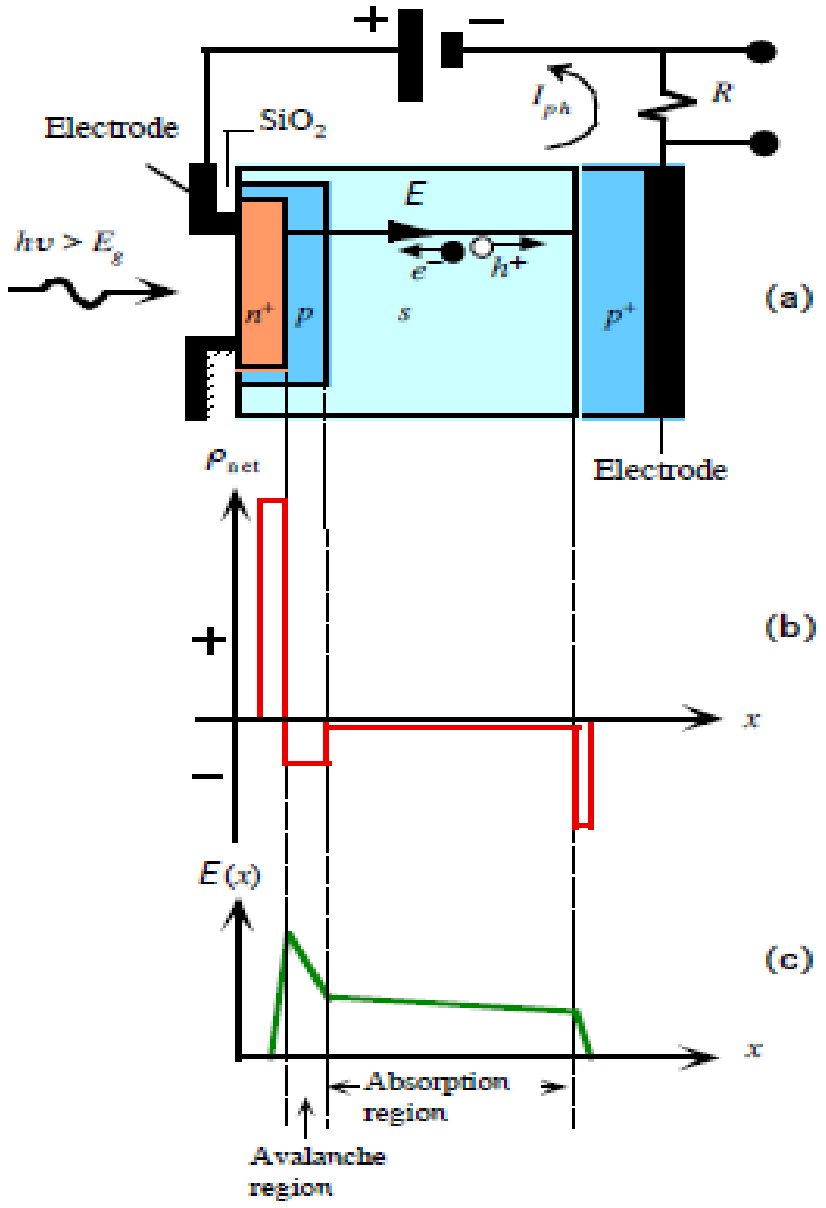
Source : S. O. Kasap, "Optoelectronics and Photonics: Principles and Practices", Prentice Hall

Avalanche photodiodes (APDs) are used widely in optical communications and for spectroscopy since they have high speed and internal gain.

There are several APD design depending on application. Here we consider a **reach-through APD:**

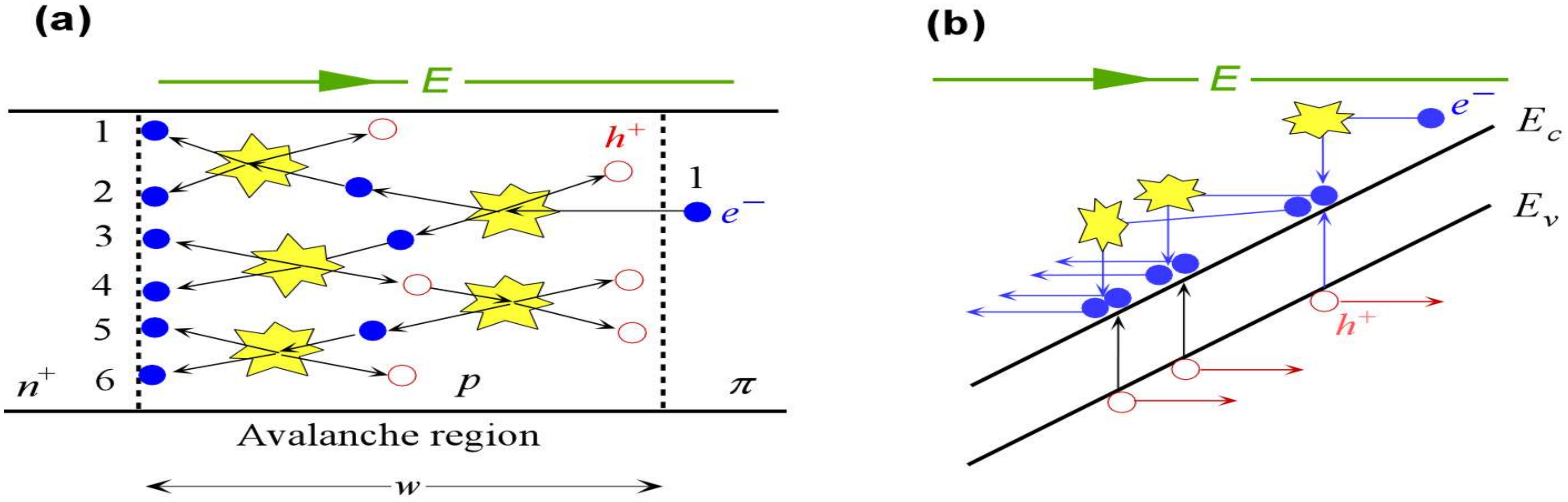
- The n+ side is thin and illuminated directly by the light incident
- Three p-type layers are buried within the the substrate. A thin p-layer is fabricated under the n+ region. The middle layer is lightly doped (almost intrinsic). A final p+ region is located at the counter electrode.

- The diode is reversed biased to increase fields within the depletion region where absorption occurs.



Source : S. O. Kasap, "Optoelectronics and Photonics: Principles and Practices", Prentice Hall

Avalanche Photodiode



(a) A pictorial view of impact ionization processes releasing EHPs and the resulting avalanche multiplication. (b) Impact of an energetic conduction electron with crystal vibrations transfers the electron's kinetic energy to a valence electron and thereby excites it to the conduction band

Avalanche Photodiode

- When a p-n junction diode is applied with high reverse bias, breakdown can occur by two separate mechanisms.

1. Direct ionization of the lattice atoms → Zener breakdown
2. **High voltage carriers causing Impact Ionization of the lattice atoms → Avalanche breakdown.**

APDs uses the avalanche breakdown phenomenon for its operation. The APD has its internal gain which increases its responsivity.

Avalanche Photodiode

Impact Ionization:

The photo generated carriers traverse a region where a very high electric field is present. These carriers can gain enough energy under high electric field and excite new electron-hole pairs. This phenomenon is called Impact Ionization

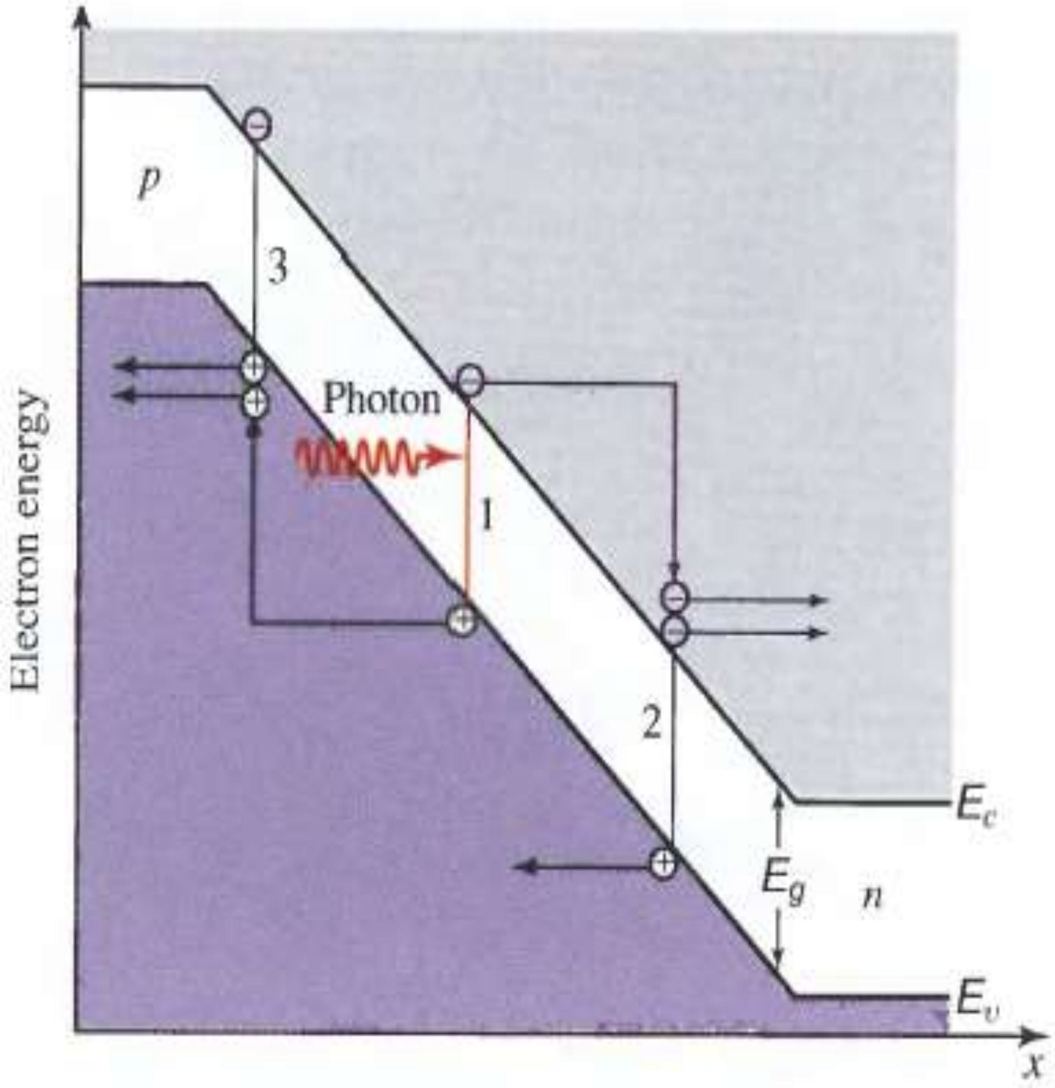
Avalanche Effect:

During Ionization new generated carriers also accelerated by high electric field and gain enough energy to cause further impact ionization. This phenomenon is called avalanche effect.

Operates by converting each detected photon to a cascade of moving carrier pairs. This is achieved by using a **strongly reverse-biased photodiode**. The large electric field then induces **impact ionization**.

ionization coefficients α_e and α_h

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



The multiplication of carriers in the avalanche region depends on the probability of impact ionization, which depends strongly on the field in this region and hence on the reverse bias V_r. The overall or effective **avalanche multiplication factor** M, also known as the **gain**, of an APD is defined as[11]

$$M = \frac{\text{Multiplied photocurrent}}{\text{Primary unmultiplied photocurent}} = \frac{I_{ph}}{I_{pho}} \tag{5.6.1}$$

where I_{ph} is the APD photocurrent that has been multiplied and I_{pho} is the **primary or unmultiplied photocurrent**, the photocurrent that is measured in the absence of multiplication, for example, under a small reverse bias V_r. The multiplication M is a strong function of the reverse bias, as shown in Figure 5.14 (c), and also the temperature. The multiplication M can be approximately described by an empirical relationship of the form[12]

$$M = \frac{1}{1 - \left(\frac{V_r}{V_{\text{br}}}\right)^m} \tag{5.6.2}$$

where 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. For Si APDs M values can be as high as 1000 or more, but for many commercial Ge and InGaAs APDs M values are typically around 10–20. The multiplication M defined in Eq. (5.6.1) is also

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

$$R = \eta_e \frac{e\lambda}{hc} = (0.6)\frac{(1.6 \times 10^{-19}\ \text{C})(1550 \times 10^{-9}\ \text{m})}{(6.626 \times 10^{-34}\ \text{J s})(3 \times 10^{8}\ \text{m s}^{-1})} = 0.75\ \text{A W}^{-1}$$

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

$$I_{pho} = RP_o = (0.75\ \text{A W}^{-1})(20 \times 10^{-9}\ \text{W}) = 1.5 \times 10^{-8}\ \text{A} \quad \text{or} \quad 15\ \text{nA}$$

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

$$I_{ph} = MI_{pho} = (12)(1.5 \times 10^{-8}\ \text{A}) = 1.80 \times 10^{-7}\ \text{A} \quad \text{or} \quad 180\ \text{nA}$$

The responsivity at $M = 12$ is

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

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

$$R = \eta_e \frac{e\lambda}{hc} = (0.70)\frac{(1.6 \times 10^{-19}\ \text{C})(830 \times 10^{-9}\ \text{m})}{(6.626 \times 10^{-34}\ \text{J s})(3 \times 10^{8}\ \text{m s}^{-1})} = 0.47\ \text{A W}^{-1}$$

The unmultiplied primary photocurrent from the definition of R is

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

The multiplied photocurrent is

$$I_{ph} = MI_{pho} = (100)(4.67\ \text{nA}) = 470\ \text{nA} \quad \text{or} \quad 0.47\ \mu\text{A}$$

Advantages and Disadvantages of APD

Advantages:

- Excellent linearity over optical power range from nano watts to several microwatts.
- Better sensitivity (5 to 15 dB)
- Wide range of gain variation
- APD offers internal gain
- Better Signal to Noise ratio

Disadvantages:

- Due to complex structure, fabrication is difficult
- APD and supporting circuitry is more expensive
- Random nature of gain mechanism contributes additional noise
- High voltage (50 to 400 V) and temperature compensation is needed for stabilization
- Internal gain of APD is temperature dependent.

Comparison of PIN and APD

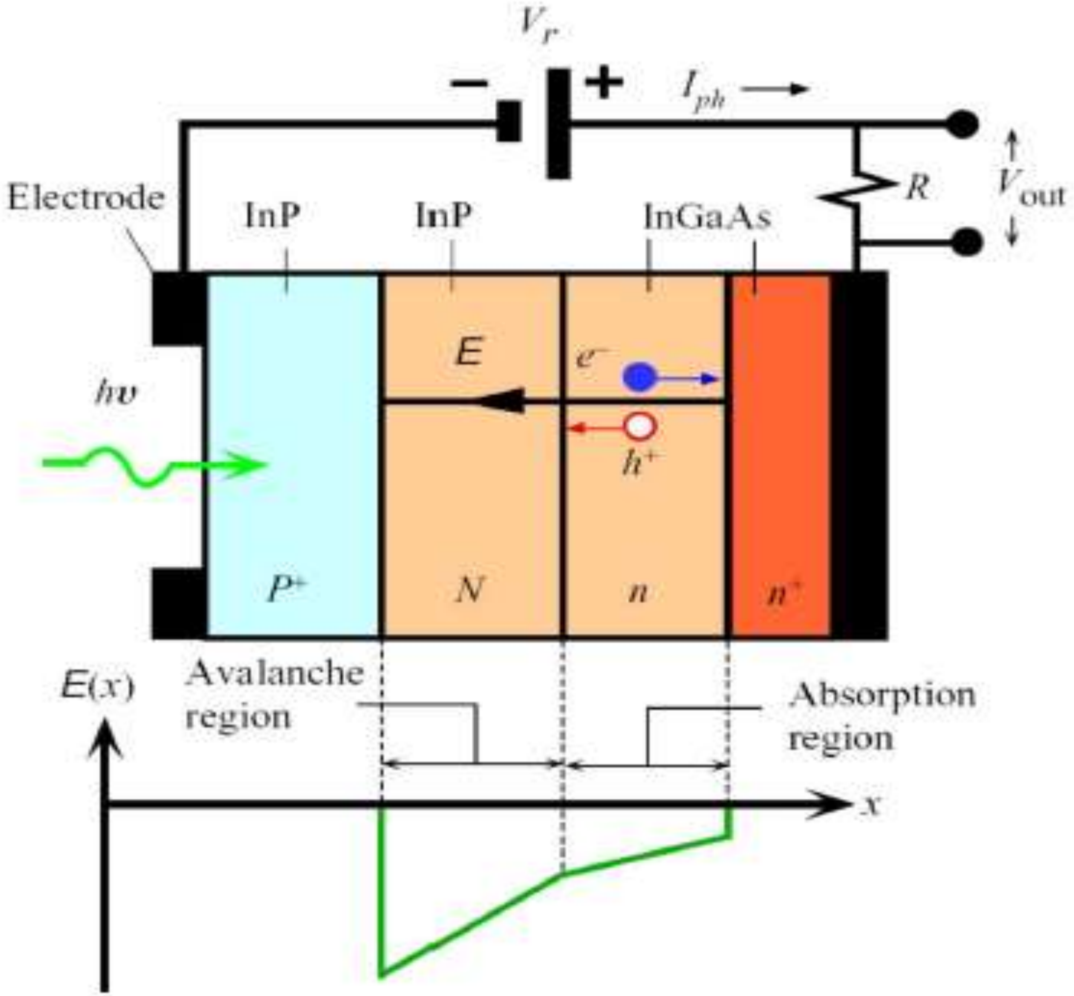
S. No	Parameters	PIN	APD
1	Sensitivity	Less sensitive (0-12 dB)	More sensitive (5-15 dB)
2	Biasing	Low reverse biased voltage (5 to 10 V)	High reverse biased voltage (20 – 400 volts)
3	Wavelength region	300 -1100 nm	400 – 1000 nm
4	Gain	No Internal gain	Internal gain
5	S/N Ratio	Poor	Better
6	Detector Circuit	Simple	More complex
7	Conversion efficiency	0.5 to 1.0 A/W	0.5 to 100 A/W
8	Cost	Cheaper	More Expensive
9	Support circuitry required	None	High voltage and temperature compensation

Responsivity gives transfer characteristics of detector i.e. photo current per unit incident optical power.

Typical responsivities of PIN photodiodes are

- Silicon PIN photodiode at 900 nm → 0.65 A/W
- Germanium PIN photodiode at 1300 nm → 0.45 A/W
- InGaAs PIN photodiode at 1300 nm → 0.9 A/W

Heterojunction Photodiodes
Separate Absorption and Multiplication APDs



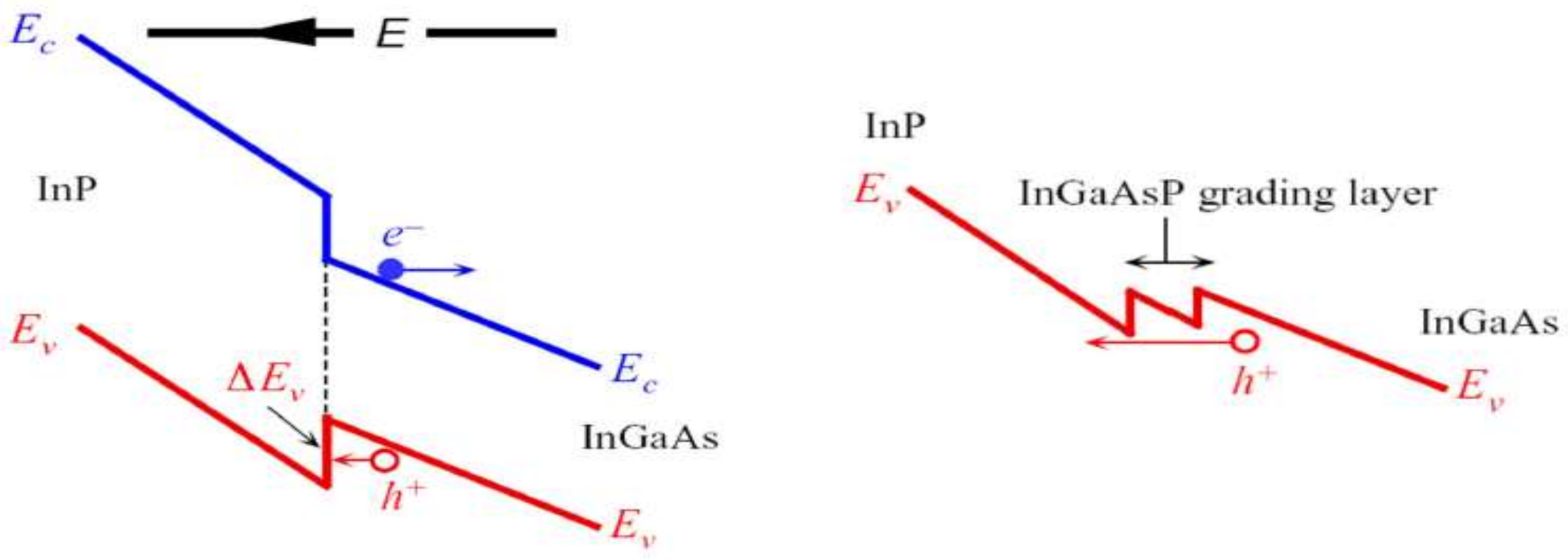
III-V compound semiconductor APDs for use at the wavelengths of 1.3 μm and 1.5 μm.

Photon energy is smaller than the bandgap energy of InP. Photon absorption occurs in the n-InGaAs layer. The avalanche region is in the N-InP layer. Photon absorption and multiplication are separated.

Multiplication is initiated by holes.

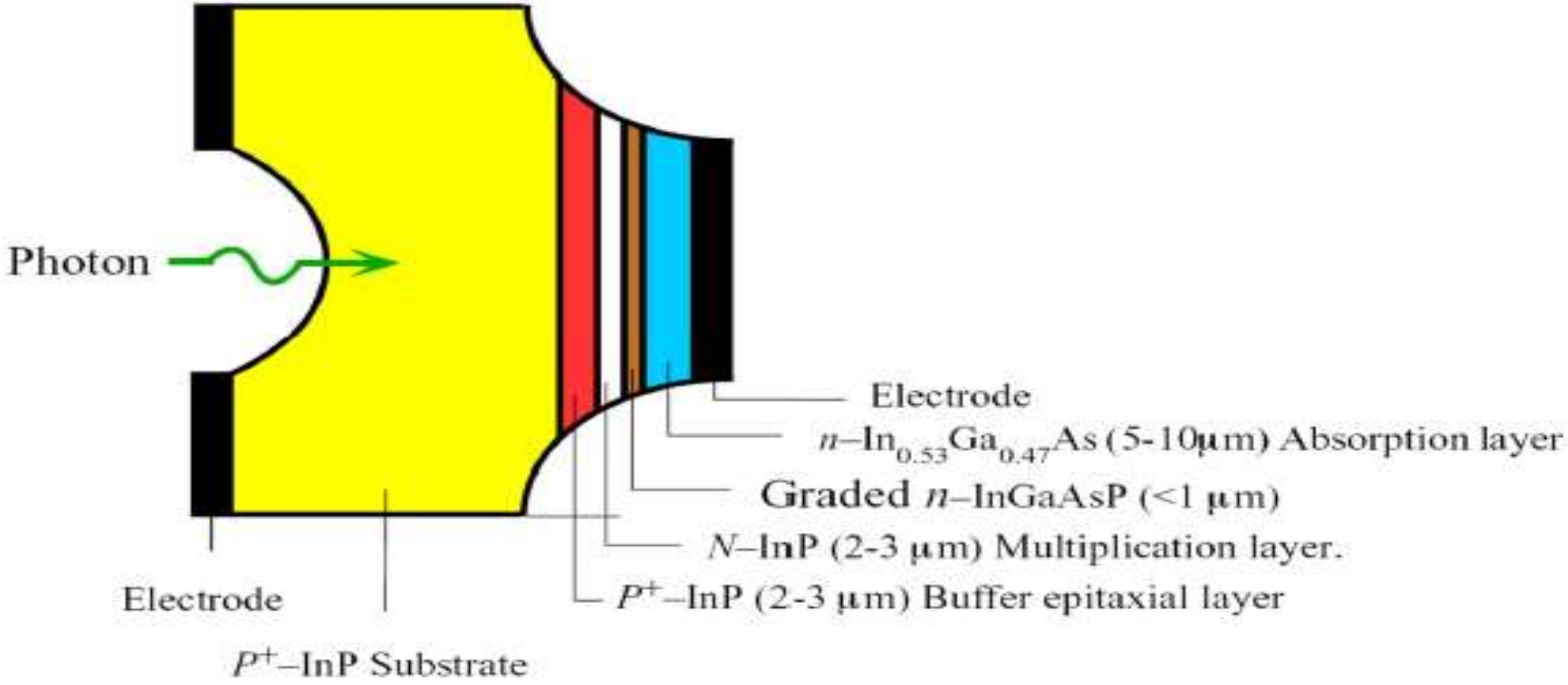
Source : S. O. Kasap, "Optoelectronics and Photonics: Principles and Practices", Prentice Hall

Heterojunction Photodiodes
Separate Absorption and Multiplication APDs



Source : S. O. Kasap, “Optoelectronics and Photonics: Principles and Practices”, Prentice Hall

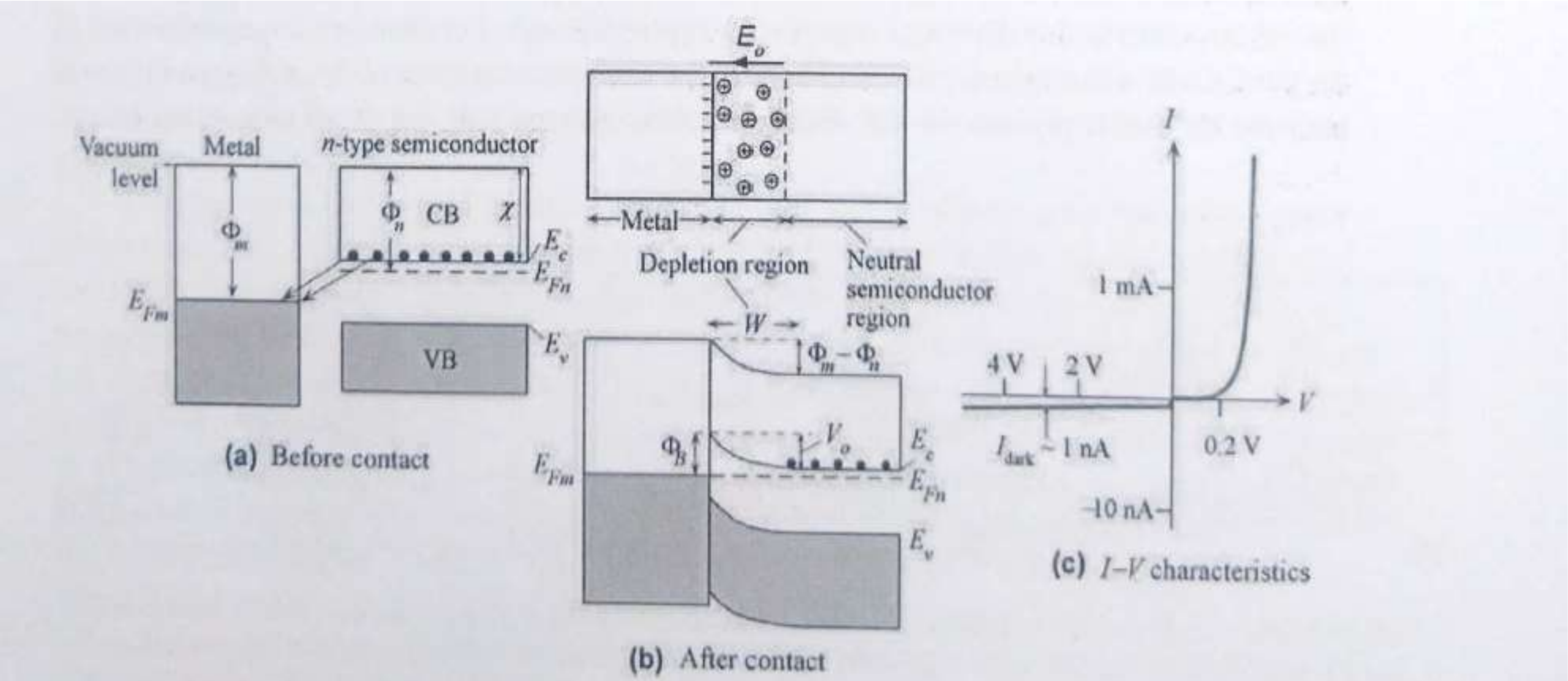
Heterojunction Photodiodes
Separate Absorption and Multiplication APDs



Graded InGaAsP with an intermediate bandgap breaks ΔE_v and makes it easier for holes to pass to the InP layer.

Source : S. O. Kasap, "Optoelectronics and Photonics: Principles and Practices", Prentice Hall

SCHOTTKY JUNCTION PHOTODETECTOR



(a) Before contact

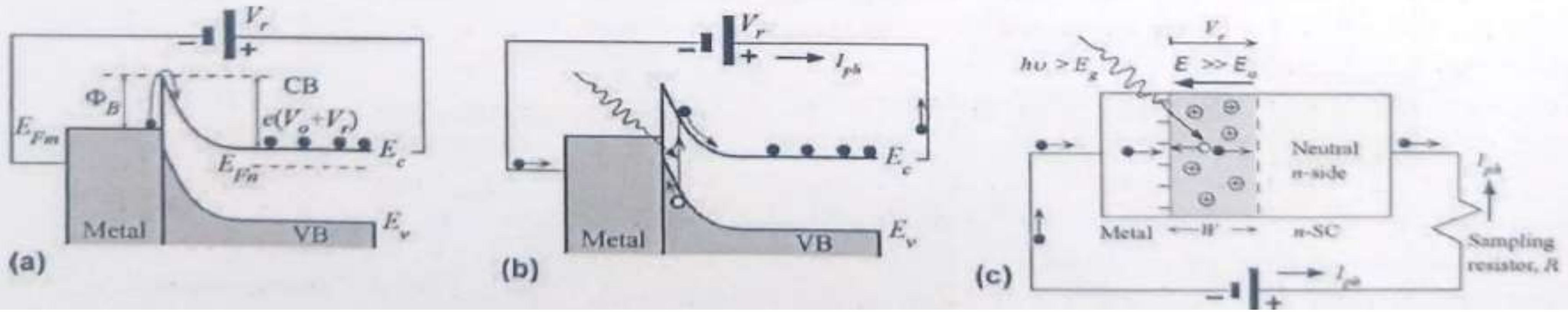
(b) After contact

(c) I–V characteristics

Source : S. O. Kasap, "Optoelectronics and Photonics: Principles and Practices", Prentice Hall

The I–V characteristic of the Schottky junction is shown in Figure 5.22 (c), and is very similar to the pn junction.[16] As apparent from Figure 5.22 (b), the barrier against electron injection from the n-SC to the metal is eV_o. The barrier against electron injection from the metal into the n-SC is Φ_B. In equilibrium, these two injection rates (they depend exponentially on the barrier heights) are small and just balance each other. Under forward bias, with the positive terminal connected to the metal and negative to the n-SC, the applied voltage V drops across the SCL, which reduces the built-in voltage to $V_o - V$. The barrier Φ_B remains unaltered. Since the injection rate depends on the Boltzmann factor $\exp\left[-e(V_o - V)/k_BT\right]$, there is an increase in this rate by a factor of $\exp(eV/k_BT)$, which leads to a very large rate of injection from the n-SC to the metal. The forward current is therefore large and depends exponentially on V.

Under reverse bias V_r, as shown in Figure 5.23 (a), V_o increases to $V_o + V_r$. The electron injection rate from n-SC to the metal vanishes and the current is dominated by the small rate of injection from the metal to n-SC over Φ_B and depends on $\exp(-\Phi_B/k_BT)$. The reverse current in the dark I_d depends on the nature of the metal to semiconductor contact (Φ_B) and the device area. It is smaller for wider bandgap semiconductors; some values are shown in Table 5.4 where I_d ranges from a few femtoamps to microamps per mm^2 of device area.

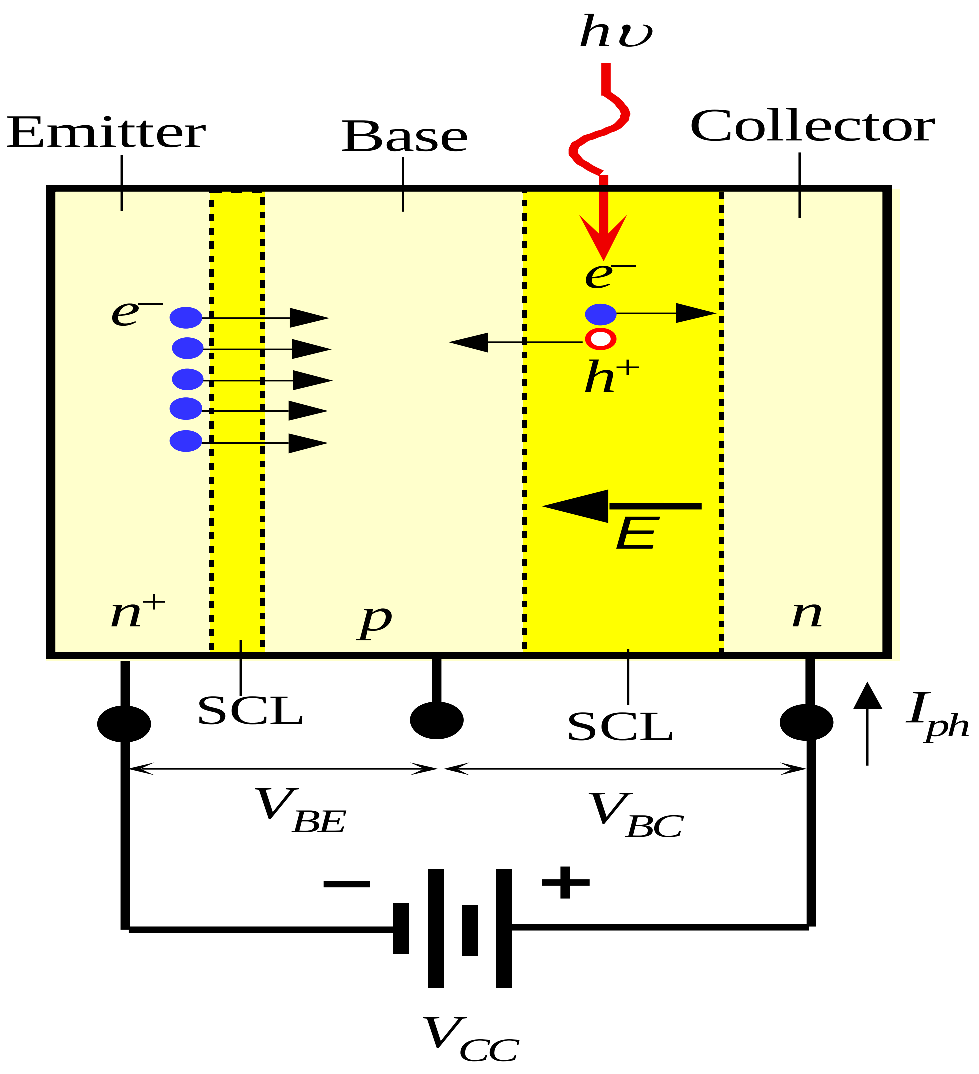


As a photodiode, the Schottky junction (SJ) is reverse biased so that the field in the depletion region is large. If we illuminate the depletion region of the SJ with photons of energy greater than E_g the photogeneration will take place within the SCL, where there is a strong field. The electrons and holes will roll down their respective energy hills as shown in Figure 5.23 (b), that is, they drift in this depletion region as in Figure 5.23 (c). For photon energies less than E_g the device can still respond, providing that the $h\upsilon$ can excite an electron from E_{Fm} in the metal over the PE barrier Φ_B into the CB, from where the electron will roll down toward the neutral

Phototransistor

- Phototransistor is a bipolar junction transistor (BJT) that operates as a photo detector with a photocurrent gain.
- In ideal device, only the **space charge layers** (SCL), contain an electric field.
- The base terminal is normally open and there is a voltage applied between the collector and emitter terminals just as in the normal operation of a common emitter BJT.

Phototransistor



The principle of operation of the photodiode. SCL is the space charge layer or the depletion region. The primary photocurrent acts as a base current and gives rise to a large photocurrent in the emitter-collector circuit.

Principle of Phototransistor

- An incident photon is absorbed in the SCL between the **base and collector** to generate an EHP.
  - The field *E* in the SCL separates the EHP and drifts them in opposite direction
  - This is the primary photocurrent and constitutes a base current even the base terminal is open circuit
- When the drifting electron reaches the collector, it becomes collected by the battery.
- When the hole enters the neutral base region, it can be neutralized by injecting a large number of electrons into the base.
  - It effectively "forces" a large number of electrons to be injected from the emitter.

Principle of Phototransistor

- Typically, the electron recombination time in the base is very long compared with the time it takes for electrons to diffuse across the base
  - This means that only **a small fraction of electrons** injected from the emitter can recombine with holes in the base
- Thus, the **emitter has to inject a large number of electrons** to neutralize this extra hole in the base
- These electrons (except one) diffuse across the base and reach the collector and thereby constitute an **amplified photocurrent**

Emitter current

- Alternatively, the photogeneration of EHPs in the collector SCL decreases the resistance of this region
    - which decreases the voltage $\boldsymbol{V_{BC}}$ across the base collector junction
- Consequently, the base-emitter voltage V_{BE} must increase because of $V_{BE}+V_{BC} = V_{CC}$
- This increase in V_{BE} acts as if it were a forward bias across the **base-emitter junction** and injects electrons into the base due to the transistor action,
    - That is the emitter current $I_E \propto \exp\left(eV_{BE}/kT\right)$.

Current gain

- Since the photon generated primary photocurrent I_{pho} is amplified as if it were a base current (I_B), the photocurrent flowing in the external circuit is

  $$I_{ph} \approx b\, I_{pho}$$

  where b is the current gain (or h_{FE}) of the transistor

- The phototransistor construction is such that incident radiation is absorbed in the base-collector junction SCL.

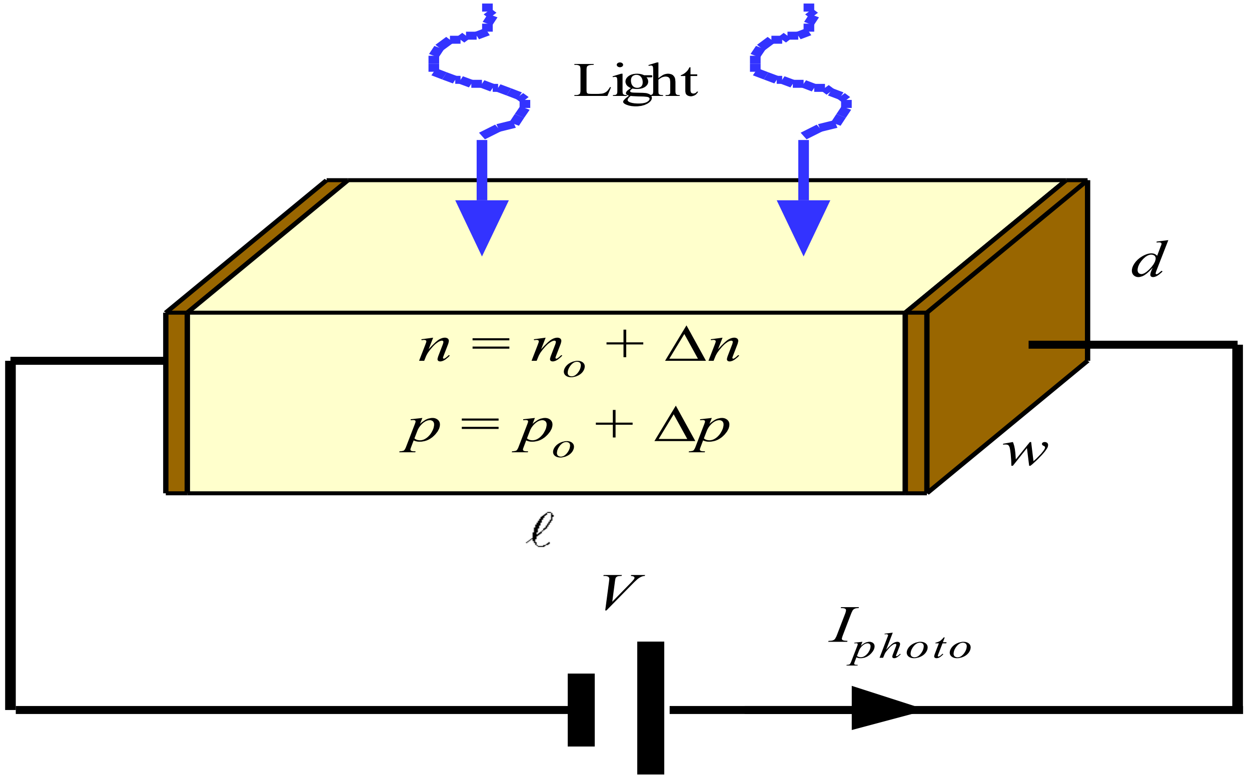
Photoconductive detectors

- The **photoconductive detectors** have the simple structure
  - Two electrodes are attached to a semiconductor that has the desired **absorption coefficient** and **quantum efficiency** over the wavelength of interest.
- Incident photons become absorbed in the semiconductor and photogenerate EHPs.
  - The result is an **increase in the conductivity** of the semiconductor and hence an **increase in the external current** which constitutes the photocurrent I_{ph}.

Photoconductive Gain

- The **actual response** of the detector
  - depends whether the contacts to the semiconductor are ohmic or blocking (For example Schottky junctions that do not inject carriers)
  - depends on the nature of carrier recombination kinetics
- We will consider a photoconductor with **ohmic contacts**
  - The contacts **do not limit the current flow**
- With ohmic contacts, the photoconductor exhibits **photoconductive gain**
  - The external photocurrent is due to more than one electron flow per absorbed photon.

Photoconductive detectors

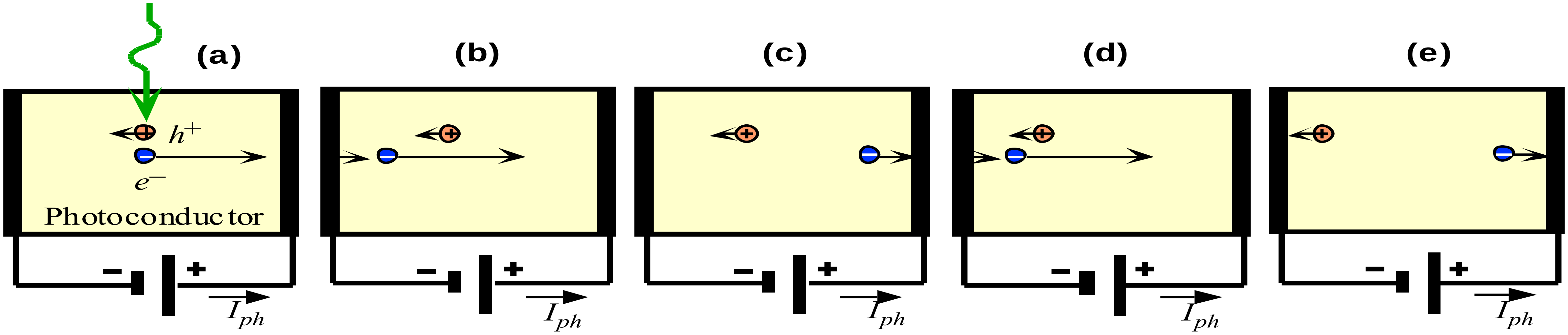


A semiconductor slab of length ℓ, width w and depth d is illuminated with light of wavelength λ.

Principle of photoconductive detectors

- The absorbed photon photogenerates an EHP, which drift in opposite directions.
  - The electrons drifts much faster than the hole and therefore leaves the sample quickly
- The sample must be neutral, which means another electron must enter the sample from the negative electrode
  - This new electron also drifts across quickly to leave the sample while the hole is still drifting slowly in the sample
- Thus another electron must enter the sample to maintain neutrality, and so on, until either the hole reaches the negative electrode or recombines with one of these electrons entering the sample.

Principle of photoconductive detectors

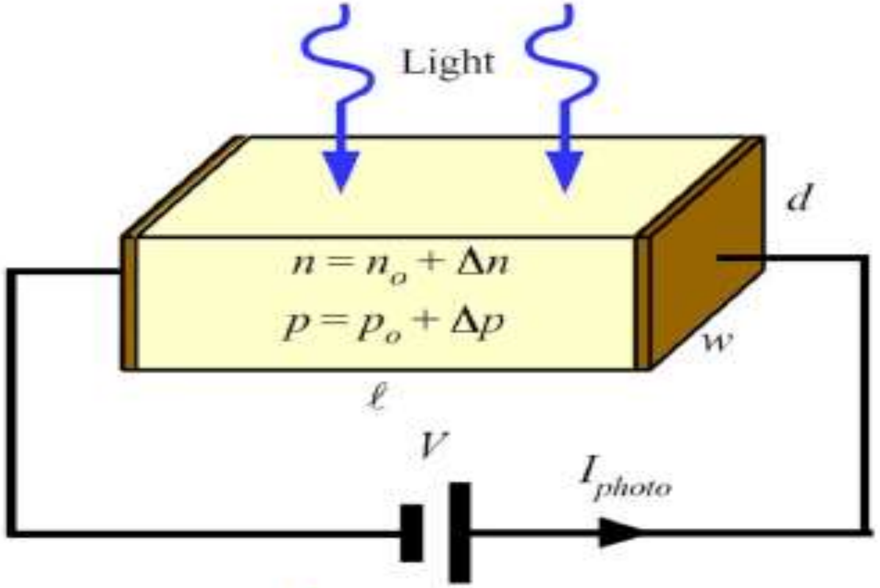


A photoconductor with ohmic contacts (contacts not limiting carrier entry) can exhibit gain. As the slow hole drifts through the photoconductors, many fast electrons enter and drift through th photoconductor because, at any instant, the photoconductor must be neutral. Electrons drift fast which means as one leaves, another must enter.

Gain

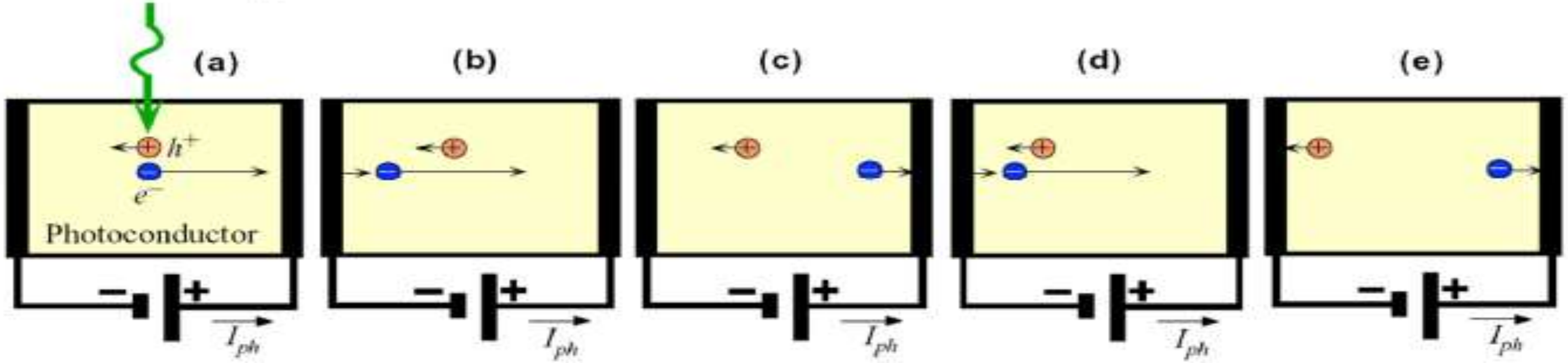
- The external photocurrent therefore corresponds to the flow of many electrons per absorbed photon, which represents a **gain**.
- The gain depends on the drift time of the carriers and their recombination lifetime

Photoconductive Detectors and Photoconductive Gain

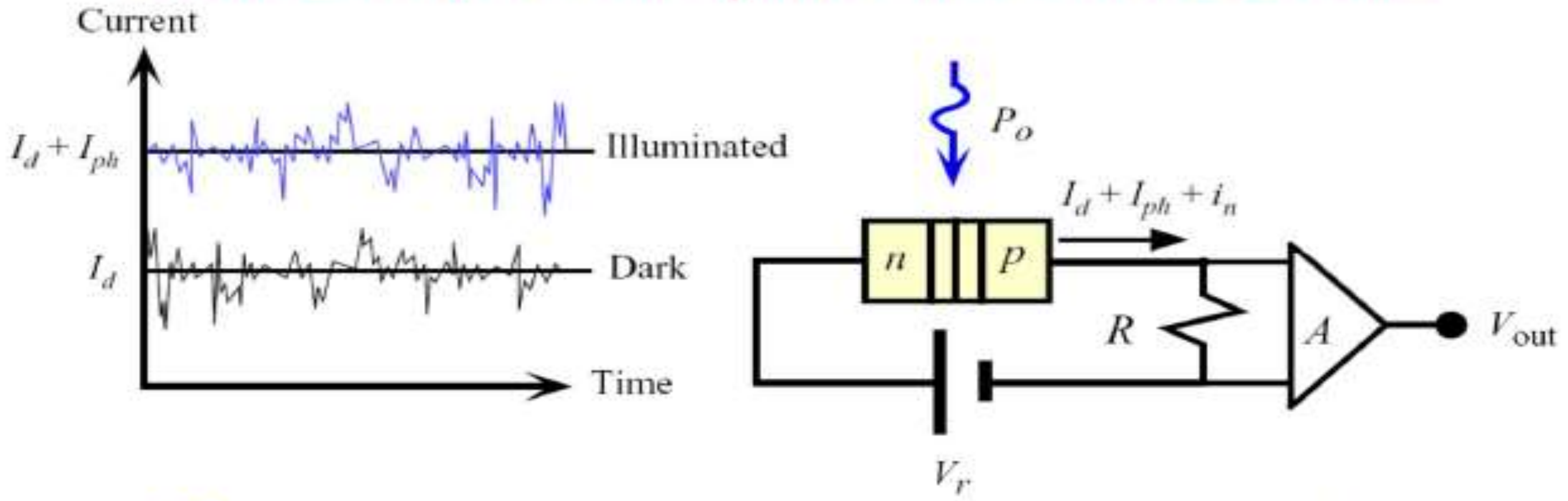


We consider a photoconductor with **ohmic contacts**, which do not limit the current flow.

Assume, for example, that electrons drift faster than holes. If an electron leaves the sample quickly, another electron must enter the sample to maintain **neutrality**. The external photocurrent therefore corresponds to the flow of many electrons per absorbed photon, which represents a **gain**.



Noise in pn and pin Photodetectors



Dark current I_d: It is due to thermal generation of electron-hole pairs (EHPs) in the depletion layer.

Shot noise: It is due to the fact that the electrical conduction is by discrete charges. There is a statistical distribution in the transit times of the carriers across the photodiode. Carriers are collected as discrete amounts of charge that arrive at random times. The root mean square (rms) value of the fluctuations in the dark current is

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

B is the frequency bandwidth.

Noise in pn and pin Photodetectors

Quantum noise: The photodetection process involves the interaction of discrete photons with valence electrons. The quantum nature of photons gives rise to a statistical randomness in the EHP photogeneration process, and thus the photocurrent will always exhibit fluctuations about its mean value.

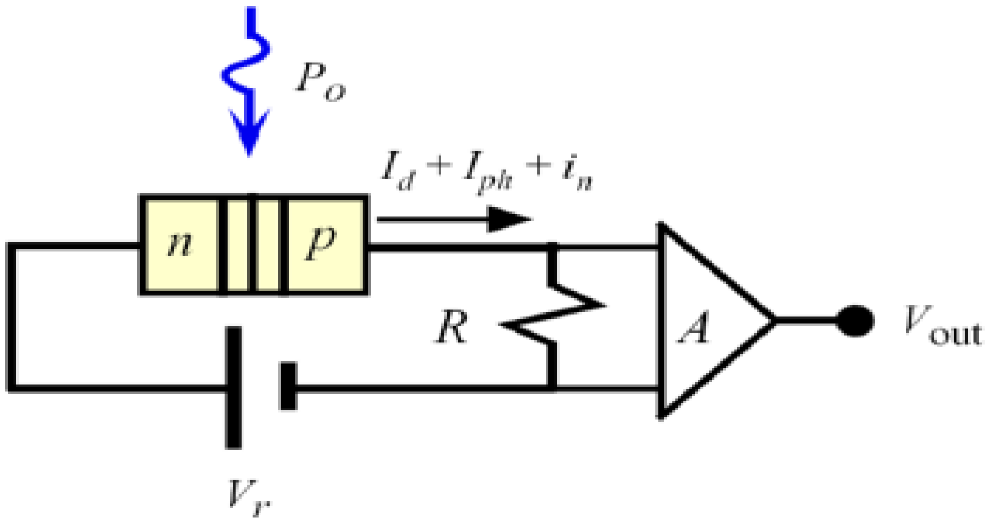
$$i_{\text{n-quantum}} = \left[2eI_{\text{ph}}B\right]^{1/2}$$

The total noise will be

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

$$i_{\text{n}} = \left[2e\left(I_{\text{d}} + I_{\text{ph}}\right)B\right]^{1/2}$$

There will be a sampling resistor for measuring the current and an amplifier. The total noise should also include the thermal noise in the resistor and the noise in the input stage of the amplifier.



Noise in pn and pin Photodetectors

In photodetector (receiver) design, we are often interested in the **signal to noise ratio**, SNR or *S*/*N*.

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

$$= \frac{I_{ph}^{2} R}{i_n^{2} R + \text{Resistor Noise Power} + \text{Amplifier Noise Power}}$$

The **noise equivalent power** (NEP) is another important property of a photodetector that is frequently quoted. NEP is the optical power required to generate a photocurrent signal (I_{ph}) that is equal to the total noise current (i_n) in the photodetector at a given wavelength and within a bandwidth of 1 Hz. The detectivity D is the reciprocal of NEP, $D = 1/\mathrm{NEP}$.

Noise in pn and pin Photodetectors

From the definition of the responsivity, we have

$$I_{ph} = RP_o$$

Suppose that the photogenerated current I_{ph} is equal to the noise current i_n when the incident optical power P_o is P_1. Then,

$$RP_1 = \left[2e\left(I_d + I_{ph}\right)B\right]^{1/2}$$

According to the definition of NEP, we have

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

Noise in APDs

In APDs, both photogenerated and thermally generated carriers entering the avalanche zone are multiplied. The shot noise associated with these carriers are also multiplied. If I_{d0} and I_{ph0} are un-multiplied dark current and photocurrent, respectively, then the shot noise current as an rms value is

$$i_{n-APD} = M\left[2e\left(I_{d0} + I_{ph0}\right)B\right]^{1/2} = \left[2e\left(I_{d0} + I_{ph0}\right)M^2 B\right]^{1/2}$$

APDs exhibit excess **avalanche noise**. This excess noise is due to the randomness of the impact ionization process. Some carriers travel far and some travel short distances within the avalanche zone. In addition, the impact ionization does not occur uniformly over the multiplication region but is more frequent in the highest field zone. The multiplication factor fluctuates about a mean value.

$$i_{n-APD} = \left[2e\left(I_{d0} + I_{ph0}\right)M^2 FB\right]^{1/2}$$

F is called the **excess noise factor**. It depends on the multiplication factor and the impact ionization probabilities.

A Si *pin* photodiode has a quoted NEP of 1×10^{-13} W Hz$^{-1/2}$. What is the optical signal power it needs for a signal to noise ratio (SNR) of 1 if the bandwidth of operation is 1 GHz?

Solution

By definition, NEP is that optical power per square root of bandwidth which generates a photocurrent equal to the noise current in the detector.

$$\mathrm{NEP} = P_1/B^{1/2}$$

Thus,

$$P_1 = \mathrm{NEP}B^{1/2} = (10^{-13}\ \mathrm{W\ Hz^{-1/2}})(10^9\ \mathrm{Hz})^{1/2} = 3.16 \times 10^{-9}\ \mathrm{W} \quad \text{or} \quad 3.16\ \mathrm{nW}$$

Consider an InGaAs APD with $x \approx 0.7$ which is biased to operate at $M = 10$. The unmultiplied dark current is 10 nA and bandwidth is 700 MHz.

(a) What is the APD noise current per square root of bandwidth?
(b) What is the APD noise current for a bandwidth of 700 MHz?
(c) If the responsivity (at $M = 1$) is 0.8 A W^{-1} what is the minimum optical power for a SNR of 10?

(a) In the absence of any photocurrent, the noise in the APD comes from the dark current. If the unmultiplied dark current is I_{do} then using $F = M^x$ in Eq. (5.12.11), the noise current (rms) is

$$i_{n\text{-dark}} = \left[2eI_{do}M^{2+x}B\right]^{1/2} \tag{5.12.12}$$

Thus,

$$\frac{i_{n\text{-dark}}}{\sqrt{B}} = \sqrt{2eI_{do}M^{2+x}} = \sqrt{2(1.6 \times 10^{-19}\,\text{C})(10 \times 10^{-9}\,\text{A})(10)^{2+0.7}}$$

$$= 1.27 \times 10^{-12}\,\text{A Hz}^{-1/2} \quad \text{or} \quad 1.27\,\text{pA Hz}^{-1/2}$$

(b) In a bandwidth B of 700 MHz, the noise current is

$$i_{n\text{-dark}} = (700 \times 10^6\,\text{Hz})^{1/2}(1.27\,\text{pA Hz}^{-1/2}) = 3.35 \times 10^{-8}\,\text{A} \quad \text{or} \quad 33.5\,\text{nA}$$

(c) The SNR with a primary photocurrent I_{pho} in the APD is

$$\text{SNR} = \frac{\text{Signal power}}{\text{Noise power}} = \frac{M^2 I_{pho}^2}{\left[2e(I_{do} + I_{pho})M^{2+x}B\right]} \tag{5.12.13}$$

SNR APD

Rearranging to obtain I_{pho} we get

$$(M^2)I_{pho}^2 - \left[2eM^{2+x}B(\text{SNR})\right]I_{pho} - \left[2eM^{2+x}B(\text{SNR})I_{do}\right] = 0$$

This is a quadratic equation in I_{pho} with defined coefficients since M, x, B, I_{do}, and SNR are given. ılving this quadratic with a SNR = 10 for I_{pho} we find

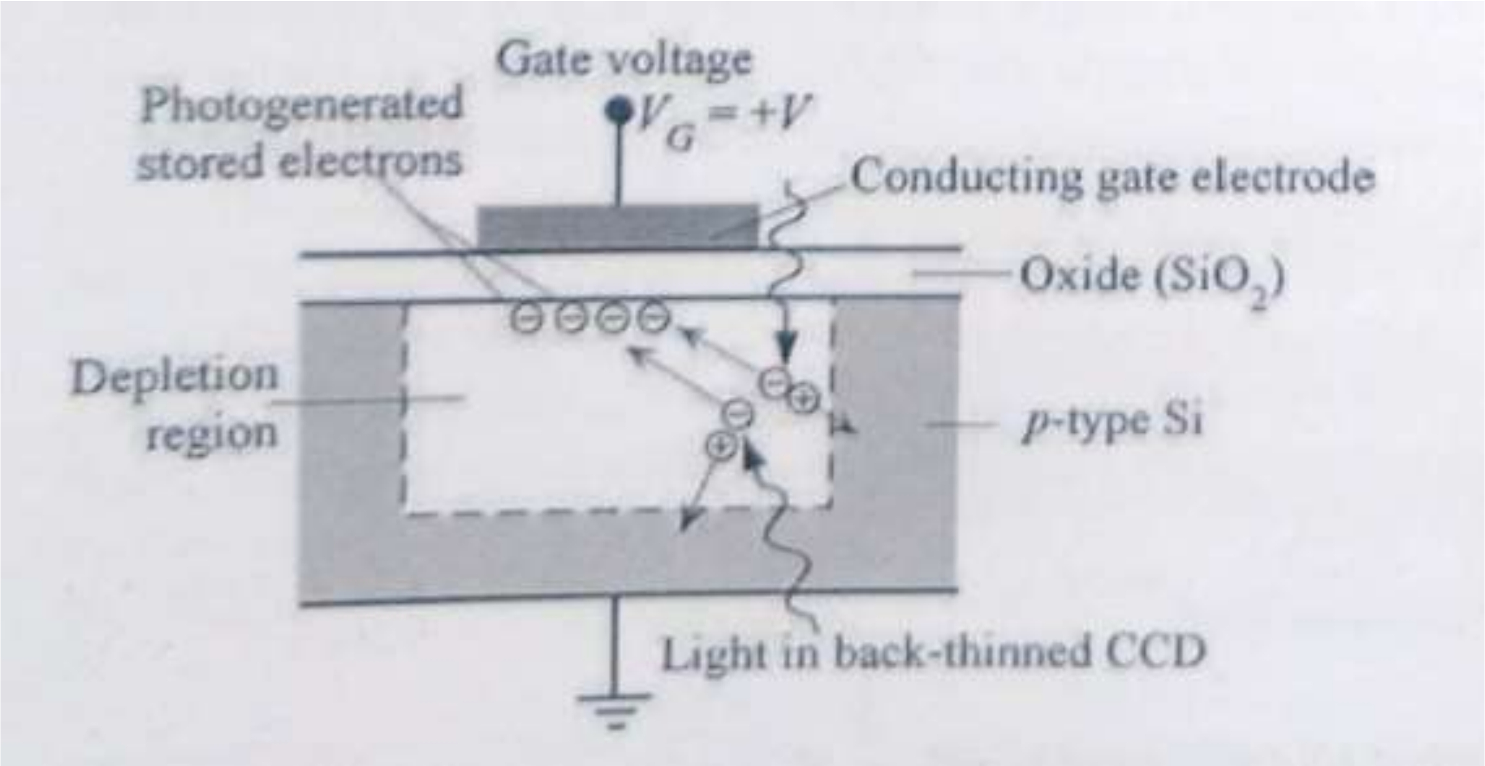
$$I_{pho} \approx 1.76 \times 10^{-8}\,\text{A} \quad \text{or} \quad 17.6\,\text{nA}$$

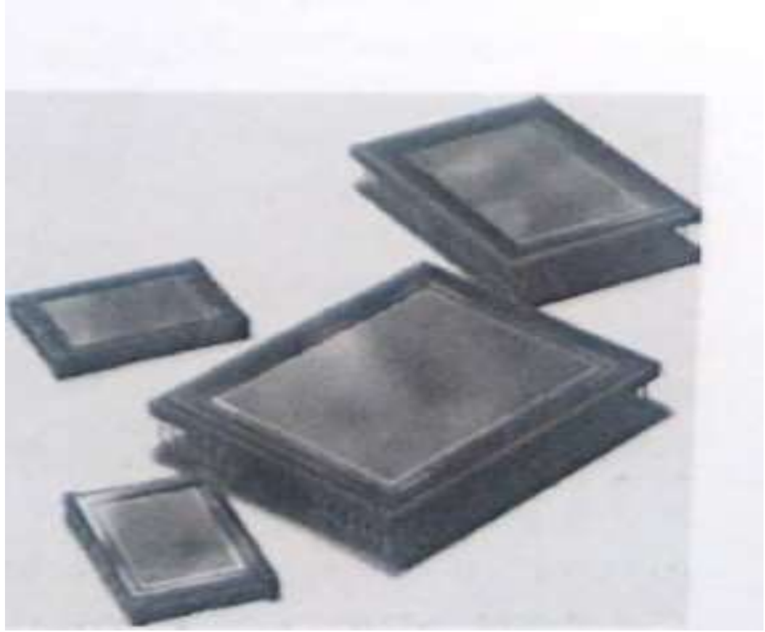
While it may seem odd that I_{pho} is less than the dark noise current (33.5 nA) itself, the ac- ıl photocurrent I_{ph} is 176 nA, since it is multiplied by M. Further, the total noise current $_{\text{APD}} = \left[2e(I_{do} + I_{pho})M^{2+x}B\right]^{1/2}$ is 55.7 nA, so that one can easily check that SNR $= I_{ph}^2/i_{n\text{-APD}}^2$ is leed 10.

By the definition of responsivity, $R = I_{pho}/P_o$, we find

$$P_o = I_{pho}/R = (1.76 \times 10^{-8}\,\text{A})/(0.8\,\text{A W}^{-1}) = 2.2 \times 10^{-8}\,\text{W} \quad \text{or} \quad 22\,\text{nW}$$

Charge Coupled devices - CCD



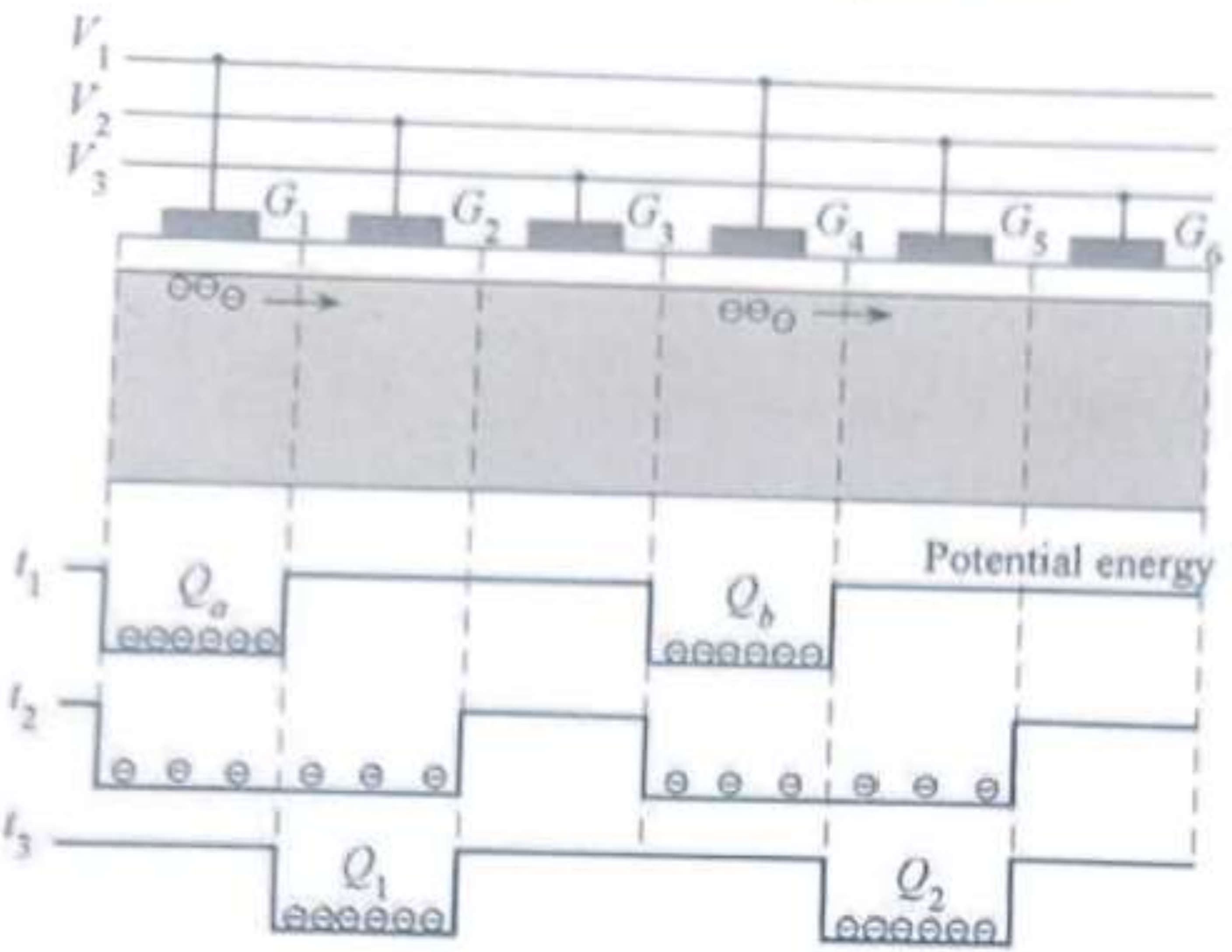


One element of a CCD imaging sensor,

Source : S. O. Kasap, “Optoelectronics and Photonics: Principles and Practices”, Prentice Hall

Charge-coupled devices (CCDs) are commonly used as image sensors in professional and consumer television cameras and camcorders, and as image sensors in digital still cameras. However, the term CCD in general does not imply an image sensor but a chip that is able to store and transfer signals in the form of charge. The CCD chip is an integrated circuit made from crystalline silicon and has a large number of pixels (each is a detector element); for example, a 2.5 cm × 2.5 cm CCD chip may have 1024 × 1024 or 2048 × 2048 pixels on its surface. The basic pixel structure is a MOS (metal-oxide-semiconductor) or a MIS (metal-insulator-semiconductor) device as shown in Figure 5.37. Notice that the structure is based on a *p*-type Si, an oxide layer, and a metal electrode, which is usually transparent. There is a depletion region inside the *p*-type semiconductor. The EHPs are generated inside the depletion region by illumination either from the top surface or from the backside as shown in Figure 5.37. In back-thinned CCD, light enters the depletion region not from the gate side but from the "substrate" side, which has been thinned to allow the light to pass through.

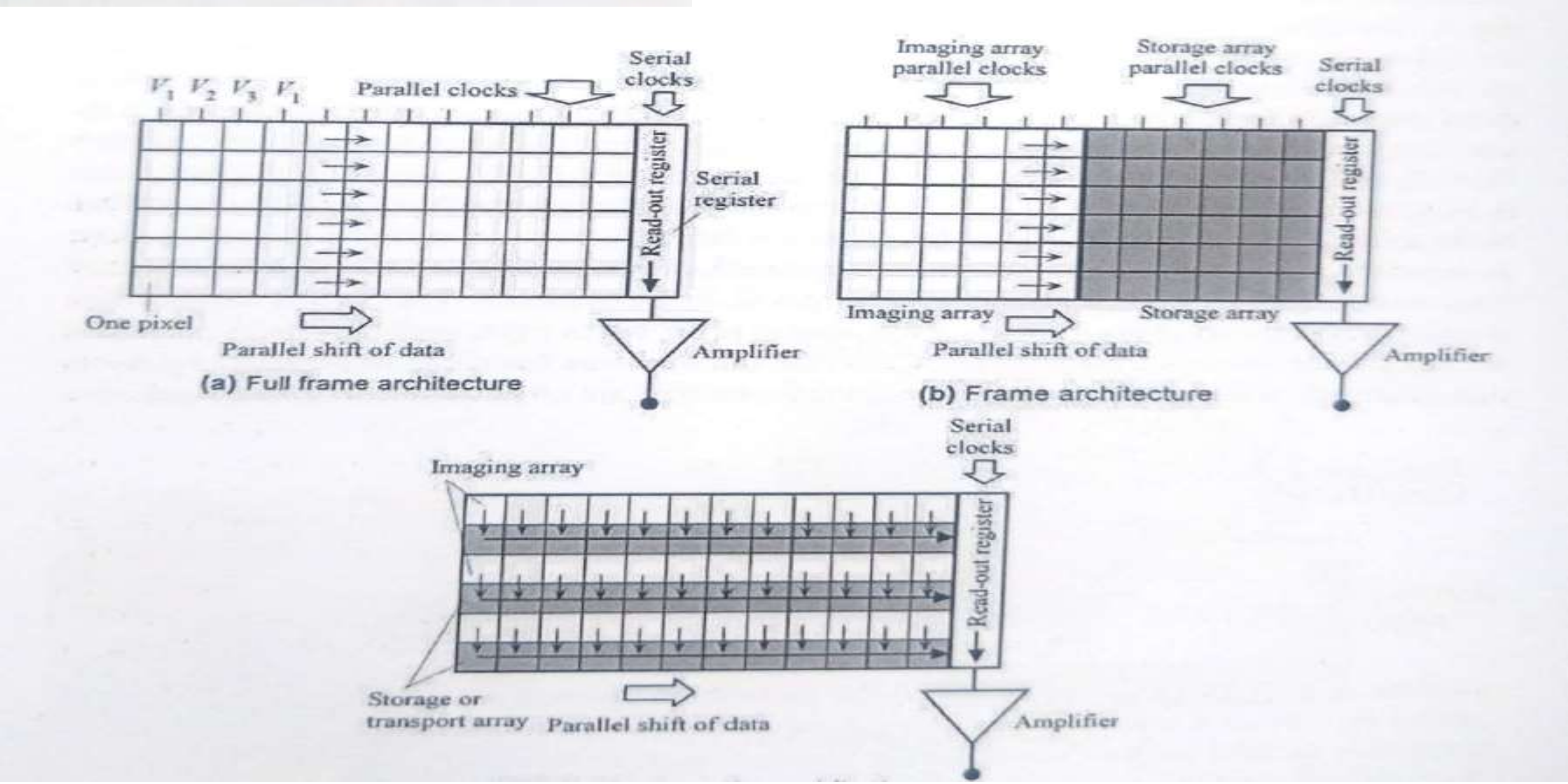
When a positive voltage $+V$ is applied to the gate V_G in Figure 5.37 ($V_G = +V$), the photogenerated electrons in the depletion region are collected in a layer near the interface as shown in Figure 5.37. (With no gate voltage, photogenerated electrons and holes disappear by recombination.) These electrons are trapped inside a potential energy well, introduced by $+V$ on the gate. Their total charge is proportional to the total light exposure. This charge constitutes the electrical signal. The objective is to read all these charges stored at the illuminated pixels.



Time	V_1	V_2	V_3
t_1	$+V$	0	0
t_2	$+V$	$+V$	0
t_3	0	$+V$	0

Source : S. O. Kasap, “Optoelectronics and Photonics: Principles and Practices”, Prentice Hall

Interline transfer architecture



Source : S. O. Kasap, “Optoelectronics and Photonics: Principles and Practices”, Prentice Hall

In a **three-phase CCD** read-out, there are three line voltages V_1, V_2, V_3 to which the gates are connected in an alternating fashion: G_1 to V_1, G_2 to V_2, and G_3 to V_3, G_4 to V_1 again and so on as shown in Figure 5.38. V_1, V_2, and V_3 are appropriately clocked to shift the charges from pixel to pixel to a register located at the end of the chip. If initially (time $t = t_1$) $V_1 = +V$ and $V_2 = V_3 = 0$, then photogenerated charges will be stored under G_1, G_4, *etc.* as Q_a, Q_b, *etc.* Later ($t = t_2$) we can make $V_1 = +V$, $V_2 = +V$, and $V_3 = 0$. The charge Q_a is shared between the wells under G_1 and G_2. Even later ($t = t_3$), we can bring V_1 down to zero, the charge Q_a must go into the available potential well, which is under G_2. Thus, by toggling gate voltages, Q_a has been shifted from G_1 to G_2, and similarly Q_b from G_4 to G_5 and so on. The charges are therefore clocked progressively along the gates, from pixel to pixel, left to right, until they reach the end of the array where there is a register. The CCD read-out therefore functions like a *shift register* in that clock pulses shift the information along the chain; they are often termed *CCD shift registers*.

References

1. S.O. Kasap, “**Optoelectronics & Photonics: Principles & Practices**”, 2nd edition, Pearson Education, 2013.