PHOTODETECTORS

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Optical Spectrum

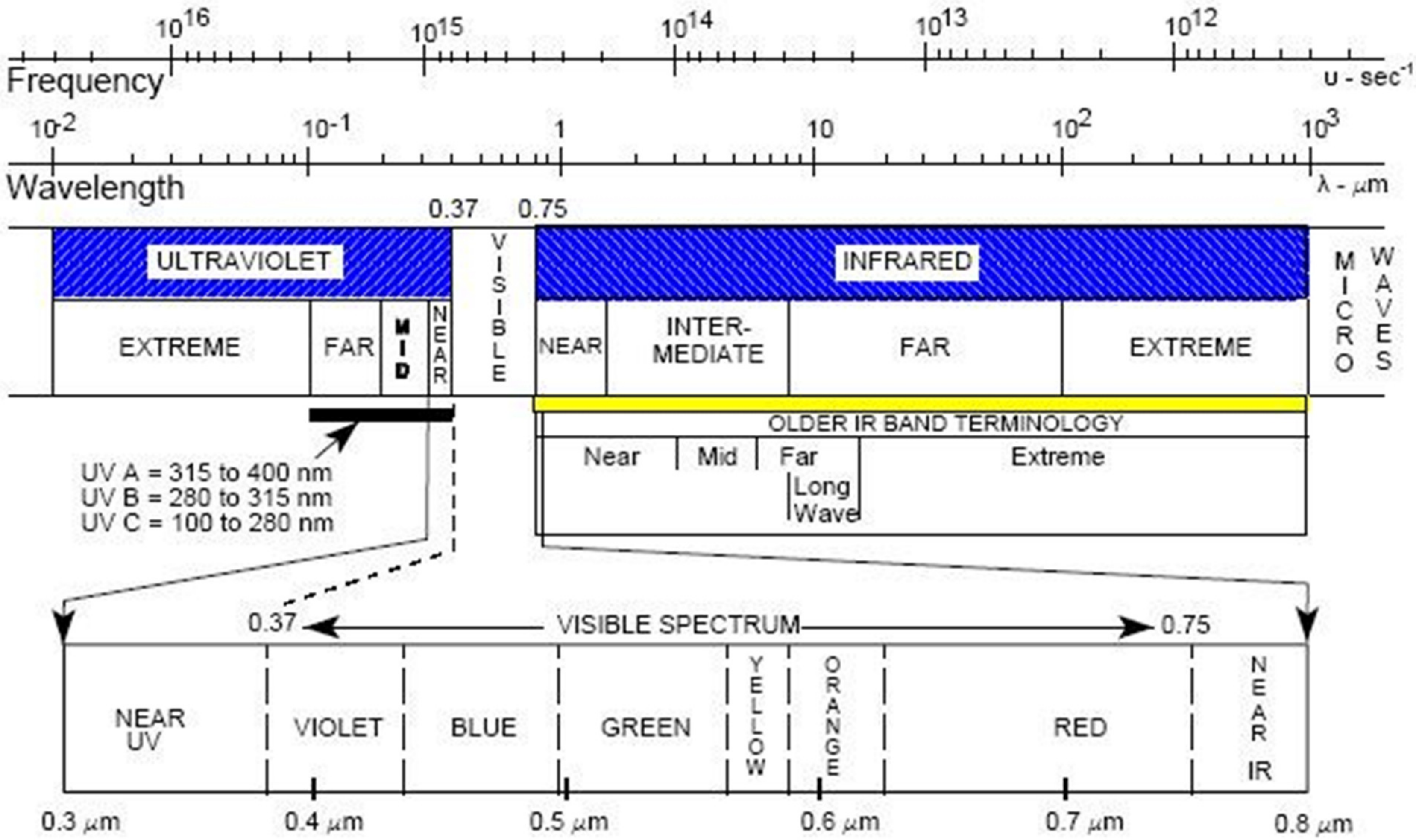
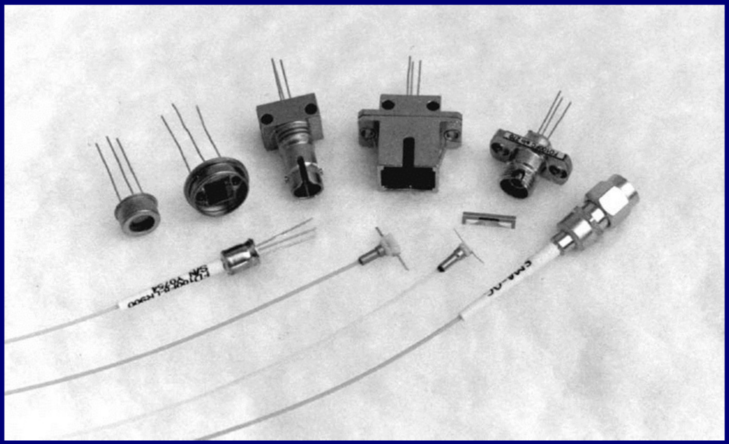
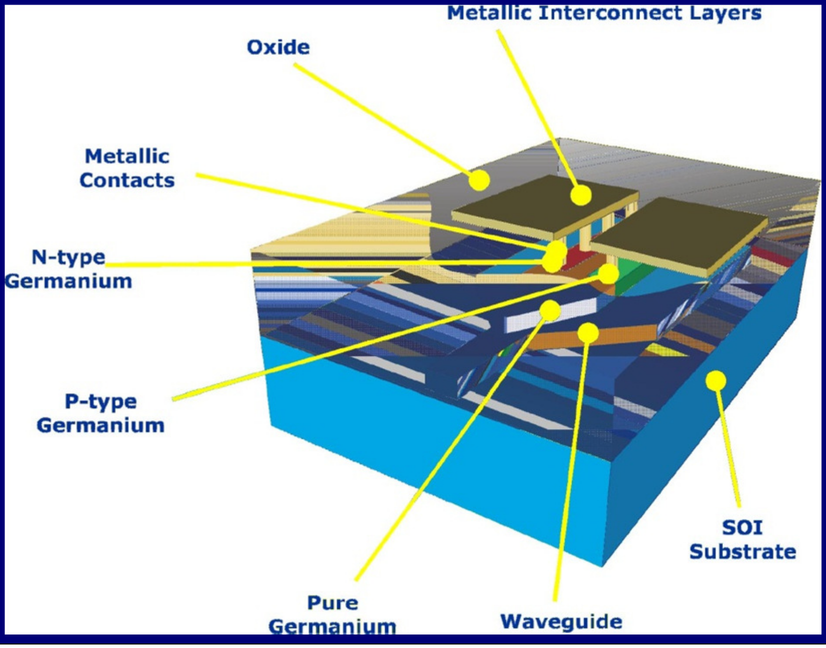


Figure 1. Optical Spectrum

What is a Photodetector?

- Converts light to electrical signal
  - Voltage
  - Current
- Response is proportional to the power in the beam





Classification of Photodetectors

- Semiconductor based – Photovoltaic/ Photoconductive
  - Photo generated EHP
  - bulk semiconductor - light dependent resistor
  - p-n junction, PIN
- Photoemissive - photoelectric effect based
  - incident photons free electrons
  - used in vacuum photodiodes, PMTs

More details

Photodiodes are semiconductor devices with a p–n junction or p–i–n structure (i = intrinsic material) (→ *p–i–n photodiodes*), where light is absorbed in a depletion region and generates a photocurrent. Such devices can be very compact, fast, highly linear, and exhibit a high quantum efficiency (i.e., generate nearly one electron per incident photon) and a high dynamic range, provided that they are operated in combination with suitable electronics. A particularly sensitive type is that of *avalanche photodiodes*, which are sometimes used even for photon counting.

- *Metal–semiconductor–metal (MSM) photodetectors* contain two Schottky contacts instead of a p–n junction. They are potentially faster than photodiodes, with bandwidths up to hundreds of gigahertz.
- *Phototransistors* are similar to photodiodes, but exploit internal amplification of the photocurrent. They are less frequently used than photodiodes.
- *Photoresistors* are also based on certain semiconductors, e.g. cadmium sulfide (CdS). They are cheaper than photodiodes, but they are fairly slow, are not very sensitive, and exhibit a strongly nonlinear response.

Source http://www.rp photonics.com/photodetectors.html

More Details …

- *Photomultipliers* are based on vacuum tubes. They can exhibit the combination of an extremely high sensitivity (even for photon counting) with a high speed. However, they are expensive, bulky, and need a high operating voltage.
- *Pyroelectric photodetectors* exploit a pyroelectric voltage pulse generated in a nonlinear crystal (e.g. LiTaO3) when heated by absorption of a light pulse on an absorbing coating on the crystal. They are often used for measurement of microjoule pulse energies from Q-switched lasers.
- *Thermal detectors* (powermeters) measure a temperature rise caused by the absorption of light. Such detectors can be very robust and be used for the measurement of very high laser powers, but exhibit a low sensitivity, moderate linearity, and relatively small dynamic range.

Source http://www.rp photonics.com/photodetectors.html

Important Properties of Photodetectors

Depending on the application, a photodetector has to fulfill various requirements:

- It must be sensitive in some given spectral region (range of optical wavelengths). In some cases, the responsivity should be constant or at least well defined within some wavelength range. It can also be important to have zero response in some other wavelength range; an example are *solar-blind detectors*, being sensitive only to short-wavelength ultraviolet light but not to sun light.
- The detector must be suitable for some range of optical powers. The maximum detected power can be limited e.g. by damage issues or by a nonlinear response, whereas the minimum power is normally determined by noise. The magnitude of the dynamic range (typically specified as the ratio of maximum and minimum detectable power, e.g. in decibels) is often most important. Some detectors (e.g. photodiodes) can exhibit high linearity over a dynamic range of more than 70 dB.
- In some cases, not only a high responsivity, but also a high quantum efficiency is important, as otherwise additional quantum noise is introduced. This applies e.g. to the detection of squeezed states of light, and also affects the photon detection probability of single-photon detectors.

Source http://www.rp photonics.com/photodetectors.html

Important Properties of Photodetectors …

- The active area of a detector can be important e.g. when working with strongly divergent beams from laser diodes. For light sources with very high and/or non-constant beam divergence, it is hardly possible to get all the light onto the active area. An integrating sphere may then be used (with appropriate calibration) for measuring the total power.
- The detection bandwidth may begin at 0 Hz or some finite frequency, and ends at some maximum frequency which may be limited by internal processes (e.g. the speed of electric carriers in a semiconductor material) or by the involved electronics (e.g. introducing some RC time constants). Some resonant detectors operate only in a narrow frequency range, and can be suitable e.g. for lock-in detection.
- Some detectors (such as pyroelectric detectors) are suitable only for detecting pulses, not for continuous-wave light.
- For detecting pulses (possibly on a few-photon level), the timing precision may be of interest. Some detectors have a certain “dead time” after the detection of a pulse, where they are not sensitive.

Source http://www.rp photonics.com/photodetectors.html

Important Properties of Photodetectors …

- Different types of detectors require more or less complex electronics. Penalties in terms of size and cost may result e.g. from the requirement of applying a high voltage or detecting extremely small voltages.
- Particularly some mid-infrared detectors need to be cooled to fairly low temperatures. This makes their use under various circumstances impractical.
- For some applications, one-dimensional or two-dimensional *photodetector arrays* are needed. For detector arrays, some different aspects come into play, such as cross-pixel interference and read-out techniques.
- Finally, the size, robustness and cost are essential for many applications.

Source http://www.rp photonics.com/photodetectors.html

Outline of the Rest of the Talk

- Quantum Efficiency
- Responsivity and Response Time
- Optical Generation Recombination
- Semiconductor Photodetectors
  - PHOTORESISTORS
  - PN DIODE
  - PIN DIODE
  - AVALANCHE PN DIODE
  - SUPPERLATTICE
- Noise in Photodetectors
- Summary of Photodetector Characteristics

Quantum Efficiency

Ratio of how many photoelectrons are produced for every photon incident on the photosensitive surface

$$\eta = (n_e/n_{ph}) \text{ x } 100\%$$

n_e is the rate of photoelectron generation
n_p is the incident photon rate

Values in the range 5 to 30% are typical
Quantum Efficiency

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

External QE is < 1, Improved by using reflecting surfaces

Internal QE = $\frac{\text{\# of EHP generated and collected}}{\text{\# of absorbed photons}}$

Responsivity & Response Time

Spectral Responsivity R / Radiant Sensitivity is a performance parameter

- The magnitude of the electrical signal output from a photodetector in response to a particular light power
- R = Photocurrent (A)/ Incident Optical power (W) = I_{ph}/P_o
- $R = \eta e/h\nu = \eta e\lambda/hc$
- R ~ 90-95% in the near IR have been achieved.

Response Time

- A measure of how long it takes a detector to respond to a change in light power falling on it
- Measured with reference to a square input pulse
- Both rise and fall times are often quoted
- A good working rule is - choose a detector with rise time of ~1/10 of shortest pulse duration to be detected

Example

- **Calculate the responsivity of a photosensitive material with a quantum efficiency of 1% at 500 nm.**

Solution

Solution

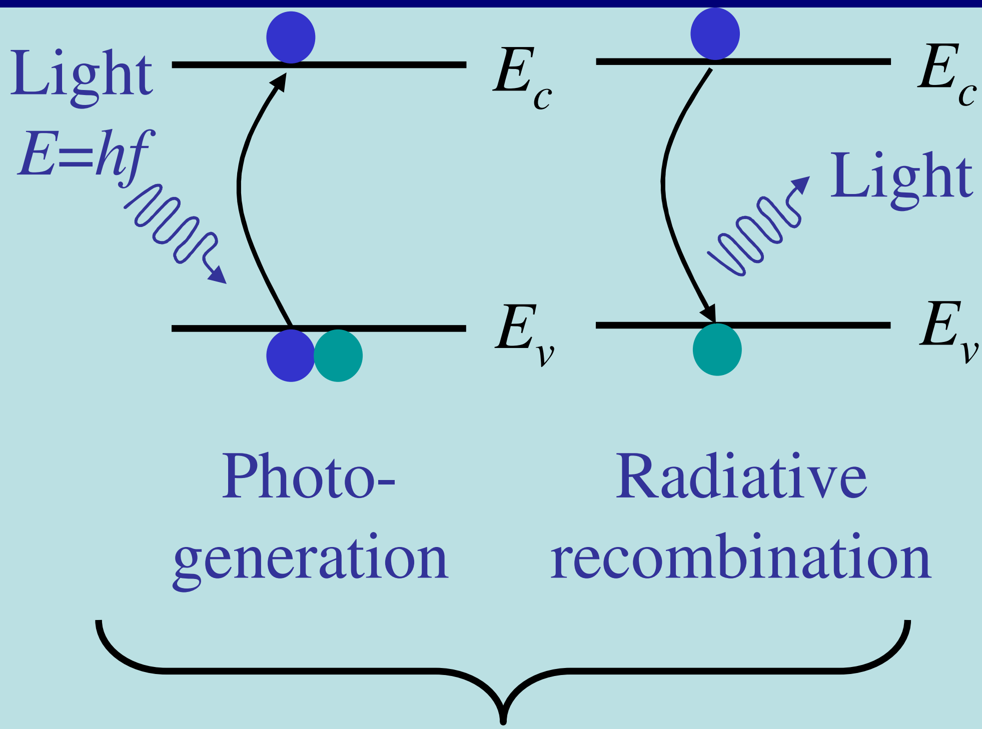
Responsivity is

$R = \eta\lambda e/hc$

$= 0.01 \times 500\times10^{-9}$ m $\times 1.6\times10^{-19}$ J/(6.63×10^{-34} J s $\times 3\times10^{8}$ m/s)

$= 4.0$ mA W^{-1}

Optical Generation-Recombination



Important for:

- narrow-gap semiconductors
- direct band-gap SCs used for fabricating LEDs for optical communications

Absorption Coefficient

$E_{incident\ Photon} > E_g$ $E_g = hc/\lambda_g$

Absorption coefficient is a material property and = α

Most of the photon absorption occurs over $1/\alpha = \delta$ the penetration depth

The Intensity of incident light varies as $I = I_o \exp(-\alpha x)$

In Direct Bandgap materials α increases sharply with decreasing λ

(do not require phonons to satisfy momentum conservation)

EHPs are near the surface outside the depletion region – rapid recombination due to surface defects

Materials for Photodiodes

Indirect Bandgap materials require phonon mediation

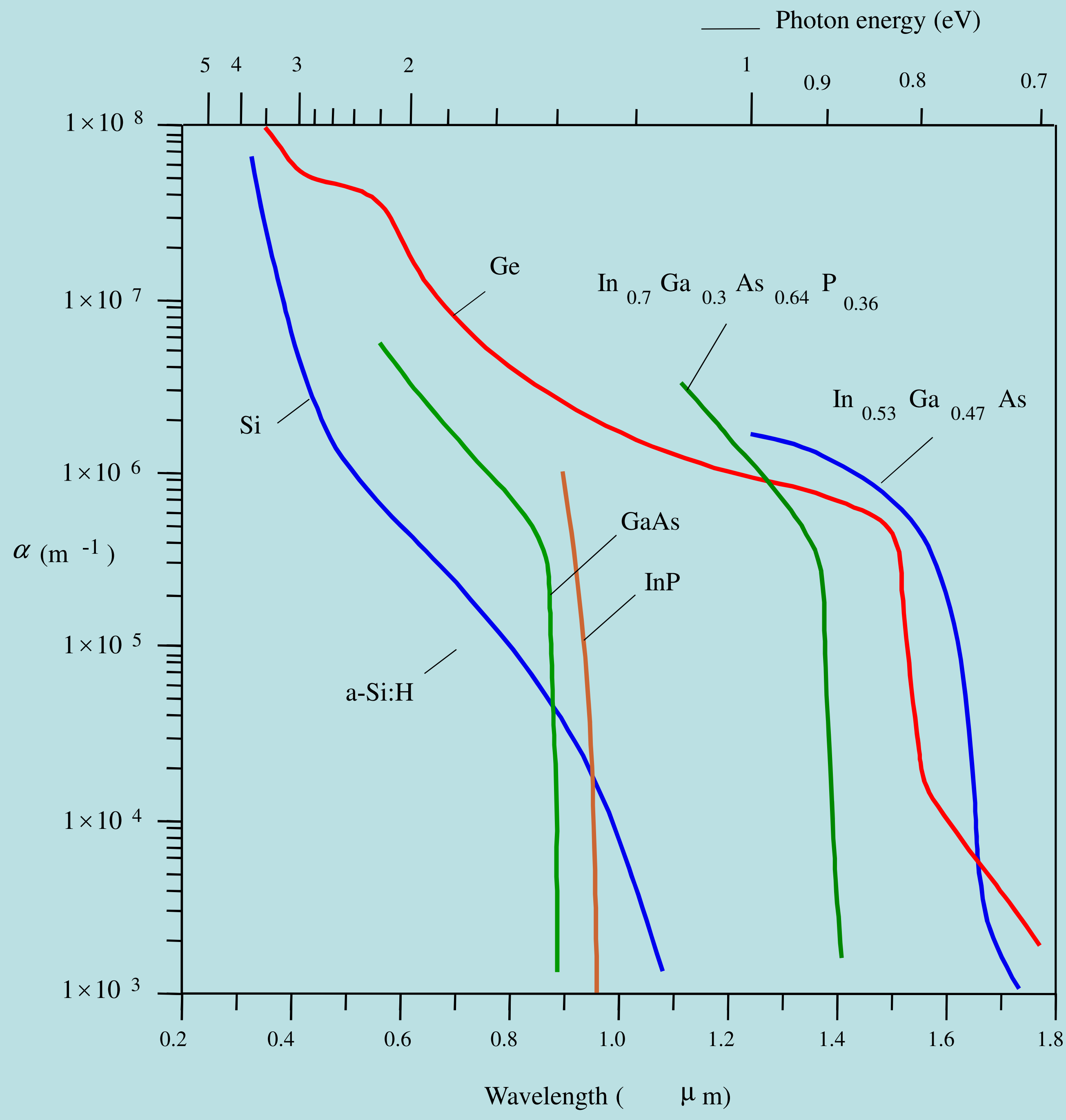
$\hbar k_{CB} - \hbar k_{vB} = \hbar K$ = phonon momentum

Probability of photon absorption is not as great as direct Band Gap materials

The absorption Energy is slightly off from the Band gap

α increases slowly for Si and Ge with decreasing λ

Only small number of EHPs can be produced



Photon energy (eV)
5
4
3
2
1
0.9
0.8
0.7
1 × 10 8
1 × 10 7
1 × 10 6
1 × 10 5
1 × 10 4
1 × 10 3
α (m -1)
Ge
In 0.7 Ga 0.3 As 0.64 P 0.36
In 0.53 Ga 0.47 As
Si
GaAs
InP
a-Si:H
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Wavelength (μ m)

Optical Generation-Recombination
- the Mathematics -

- # es/volume controls the probability of collision with a hole
  optical Recombination rate $r = Bnp$
  generation rate $g = Bp_o n_o = Bn_i^2$
- At equilibrium generation=recombination

- With incident light, generation rate $= g_{ph}$ = #EHPs created/vol/sec

$$g_{ph} = [\eta A\Gamma]/Ad = [\eta(I/h\nu)]/d = \eta I\lambda/hcd, \quad \Gamma = \text{photon flux}$$

$$\partial \Delta n / \partial t = -\Delta n/\tau + g_{ph}$$

τ=recombination time
Δn = excess photo electrons
$\Delta n = \tau g_{ph} = \tau\eta I\lambda/hcd$

$$\Delta\sigma = e\Delta n\mu_e + e\Delta p\mu_h = e\Delta n(\mu_e + \mu_h) = \{\tau\eta Ie\lambda/hcd\}(\mu_e + \mu_h)$$

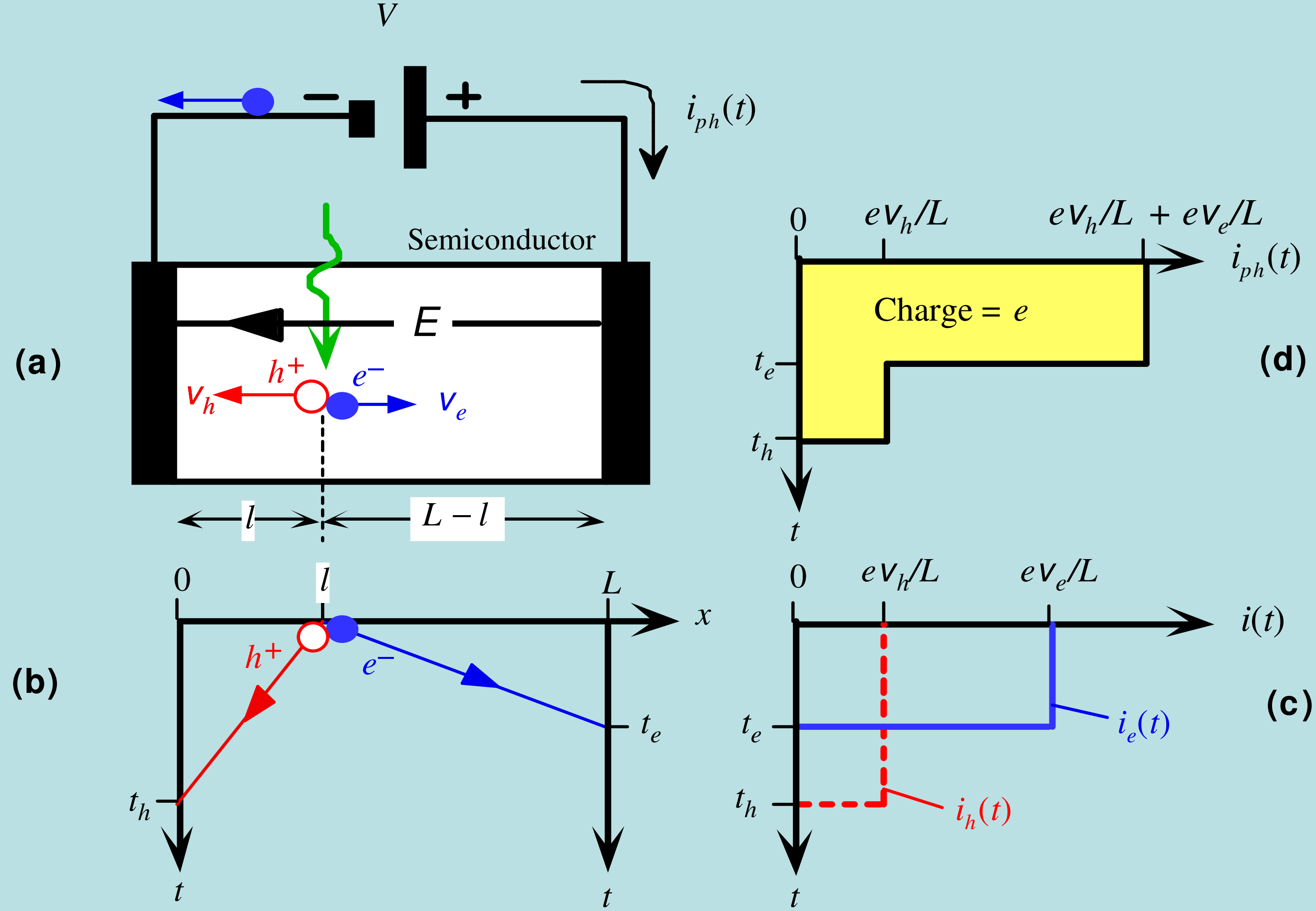
$J = \Delta\sigma E$, $I = JA$, Rate of flow = I/e

Semiconductor Photodetectors

PHOTORESISTORS

- $h\nu > E_g$ will promote an electron to the CB
- The increased number of electrons & holes available for conduction provide an increase in the conductivity
- A voltage in series with a load resistor is applied across semiconductor to pull electrons and holes to respective terminals
- Response times depend purely on the drift of the photon-generated carriers to their respective electrodes - relatively long ~ 50 ms
- Conductivity $\sigma = en\mu_e + ep\mu_h$, $\rho = 1/\sigma$
- Material CdS
- E_g = 2.42eV (green light)
- EHPs enhance current flow

  - IR detection possible with narrow band InSb or Cu/Hg doped Ge
  - Operation at 77K for $\lambda > 2\mu m$



(a) An EHP is photogenerated at $x = l$. The electron and the hole drift in opposite directions with drift velocities v_h and v_e. (b) The electron arrives at time $t_e = (L - l)/v_e$ and the hole arrives at time $t_h = l/v_h$. (c) As the electron and hole drift, each generates an external photocurrent shown as $i_e(t)$ and $i_h(t)$. (d) The total photocurrent is the sum of hole and electron photocurrents each lasting a duration t_h and t_e respectively.

Ramo's Theorem

$t_e = (L-l)/v_e$ and $t_h = (l)/v_h$

Work done by the electron = Energy supplied by the battery

$eEdx = VI_e(t)\, dt$

Using $E = V/(L-l)$, and $v_e = dx/dt$,

the photocurrent $I_e(t) = (e\, v_e)/(L-l)$, when $t < t_e$

$Q_{collected} = e$ = integral of electron current +hole current over dt

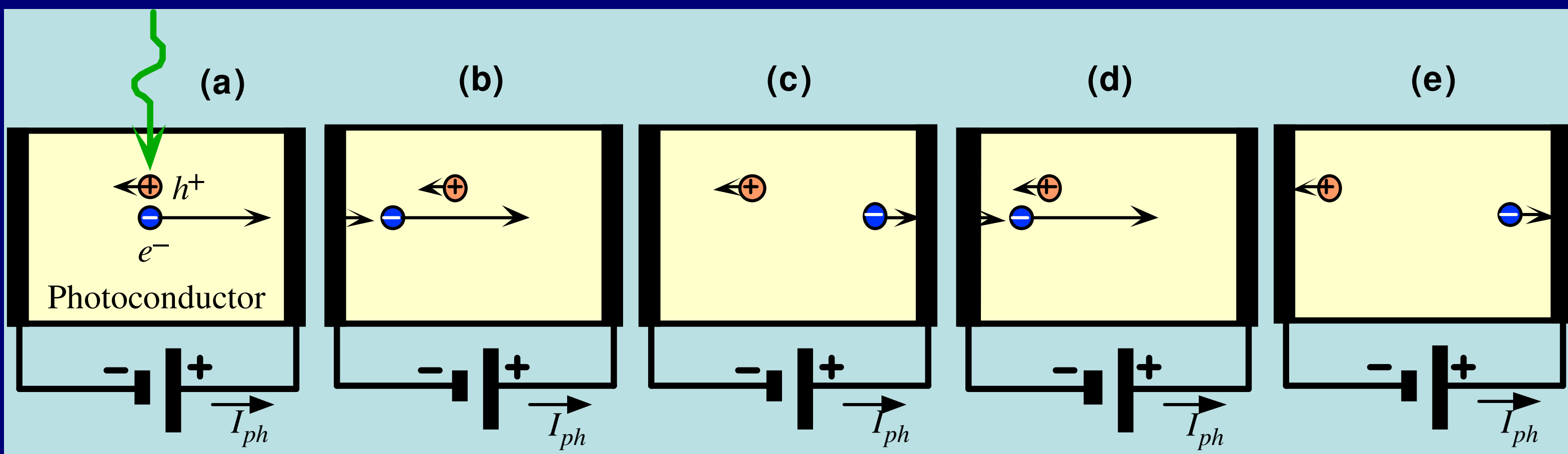
$Q = e((v_e t)/(L-l) + (v_h t)/(L)) = e$

Photoconductive detectors

External current is measured

$$\text{Gain} = \frac{\text{Rate of e flow in external circuit}}{\text{Rate of e generated by absorption}} = \frac{I_{ph}/e}{(\text{volume})\, g_{ph}} = \tau(\mu_e+\mu_h)(E/L)$$

Where g_{ph} is the photogeneration rate/unit volume/unit time



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 the photoconductor because, at any instant, the photoconductor must be neutral. Electrons drift faster which means as one leaves, another must enter.

Example

A CdS photoconductor has Eg = 2.42eV, $\tau = 10^{-3}$ seconds, the holes are trapped and the electron mobility =100cm^2/Vsec. The photocell is 1mm long and wide and 0.1mm thick with ohmic contacts. Assume each photon produces an electron and that they are uniformly distributed. The cell is irradiated with 1mW/cm^2 violet light at 409.6nm. Calculate

a. The long wavelength cutoff for absorption
b. The number of EHPs generated/second
c. The increase in the number of conduction electrons in the sample
d. The change in conductance of the sample
e. The photocurrent produced if 50V are applied to the sample.

THE JUNCTION PHOTODIODE

- Basic photodiode is a pn-diode with junction exposed to light
- Under equilibrium conditions a potential barrier, V_o, exists across the depleted areas on either side of the pn-junction
- No net current flows through the diode.
- Two distinct modes of operation are possible
  - photovoltaic mode - diode is operated with no applied voltage
  - photoconductive mode - with an applied reverse voltage

1. PHOTOVOLTAIC MODE

- **Diode is operated as open circuit**
- When illuminated the equilibrium is upset
- EHPs are generated in depletion region
- E across junction pulls electrons to the n-side and the holes to the p-side
- holes in p-type are increased as are electrons in n-type
- A photon induced current, i_{ph}, flows through the diode from the n side to the p side
- The energy barrier is reduced. More holes can cross from the p to n side and more electrons cross from n to p creating a forward current through the diode
- Diode is open circuit, the photon current must exactly balance the forward current
- No net current can flow
- The drop in energy barrier is seen as a forward voltage across the ends of the diode
- The photon induced voltage is measured → ***photovoltaic***

PHOTOVOLTAIC RESPONSE

forward current produced in pn junction for given applied potential

The forward current is balanced by the reverse photocurrent

$$i_f = i_{ph}$$

$$i_o[\exp(eV_{ph}/kT)-1] = i_{ph}$$

Assuming the exponential term to be much greater than unity

$$i_o[\exp(eV_{ph}/kT)] \approx i_{ph}$$

Thus external photovoltage, V_{ph}, across the ends of the diode is

$$V_{ph} = (kT/e)\ln(i_{ph}/i_o)$$

Characteristics of photovoltaic mode

The photon generated current is a linear function of light power

$$i_{ph} = \eta I \lambda q / hc$$

Voltage developed across the diode is logarithmic function of power

$$V_{ph} \propto \ln I$$

- output voltage is a non-linear function of incident light power
- EHPs are pulled to respective contacts under internal field
- speed of response depends on diode thickness ⇒ generally slow
- absence of a leakage current provides low noise

2. PHOTOCONDUCTIVE MODE

pn junction is operated under reverse potential bias

- positive terminal is connected to n-side and negative to p side
- Electrons in the n-side are pulled out of the depletion region and holes are pulled from the p side
- the depletion region widens
- The energy barrier increases by the applied potential
- The flow of majority carriers of any kind is halted and the only current that can flow is the reverse current, i_o due to thermally generated minority carriers

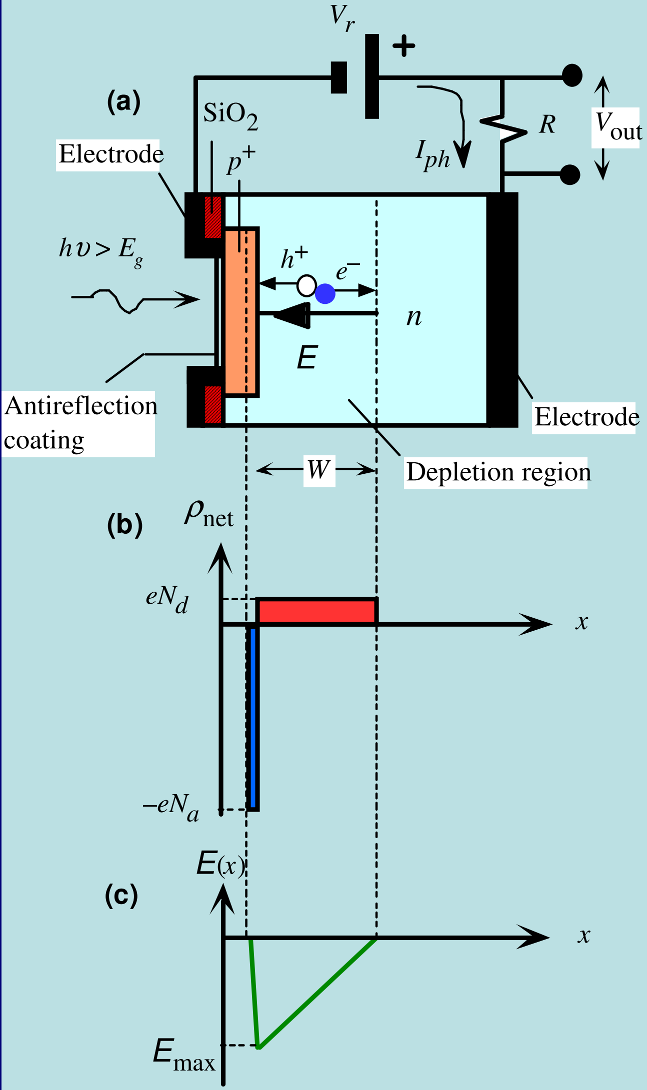
Under illumination, the photogenerated EHPs are again swept apart by the internal electric field across the junction

This constitutes a reverse photon current, i_{ph}, in the same direction as the thermally generated leakage current.

The benefits of the photoconductive mode

- the photon generated current constitutes the measured output signal and not the voltage drop across the diode
  - output signal is a linear function of the incident light power
- Photoconductive operation results in a higher response speed than photovoltaic because of the wide depletion layer and higher electric field transit time for charge carriers to reach their respective electrodes is reduced
- Main disadvantage of PC mode is increased noise due to ever present leakage current.

Photoconductive Detectors – details



(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.

$N_a >> N_d$

The depletion region extends in the n side

Reverse biasing: Junction voltage = $V_o + V_r$

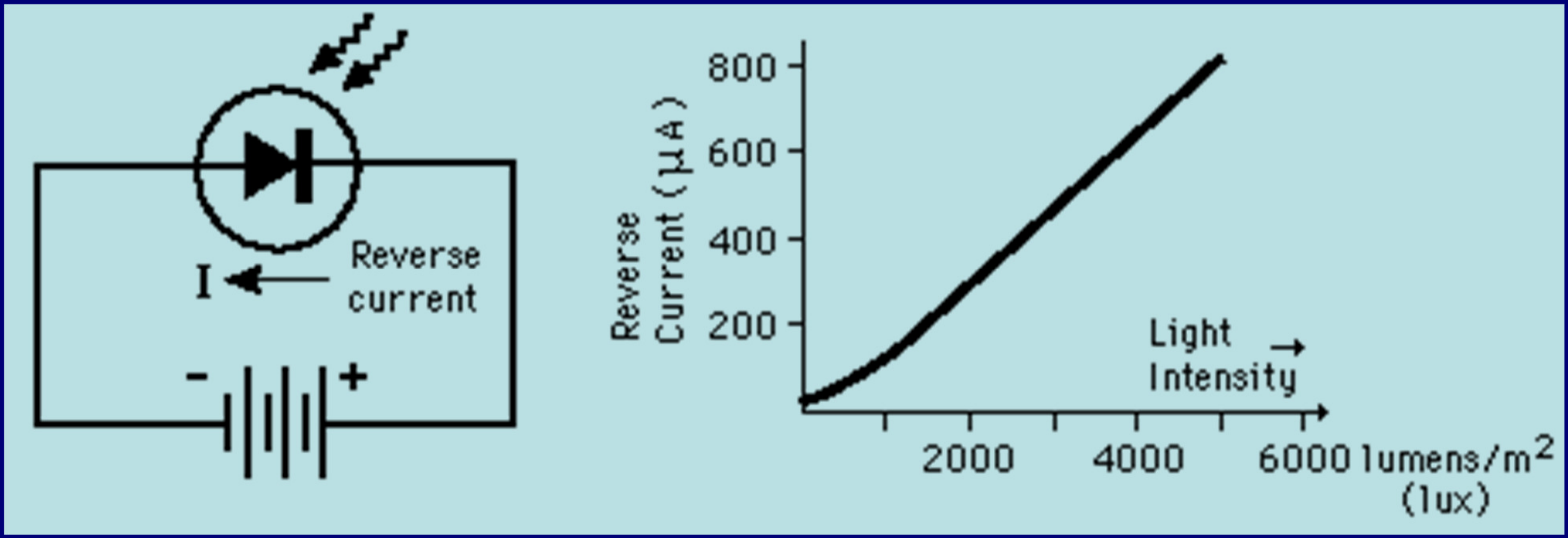
An EHP is created in the depletion region

The charges move towards the neutral regions

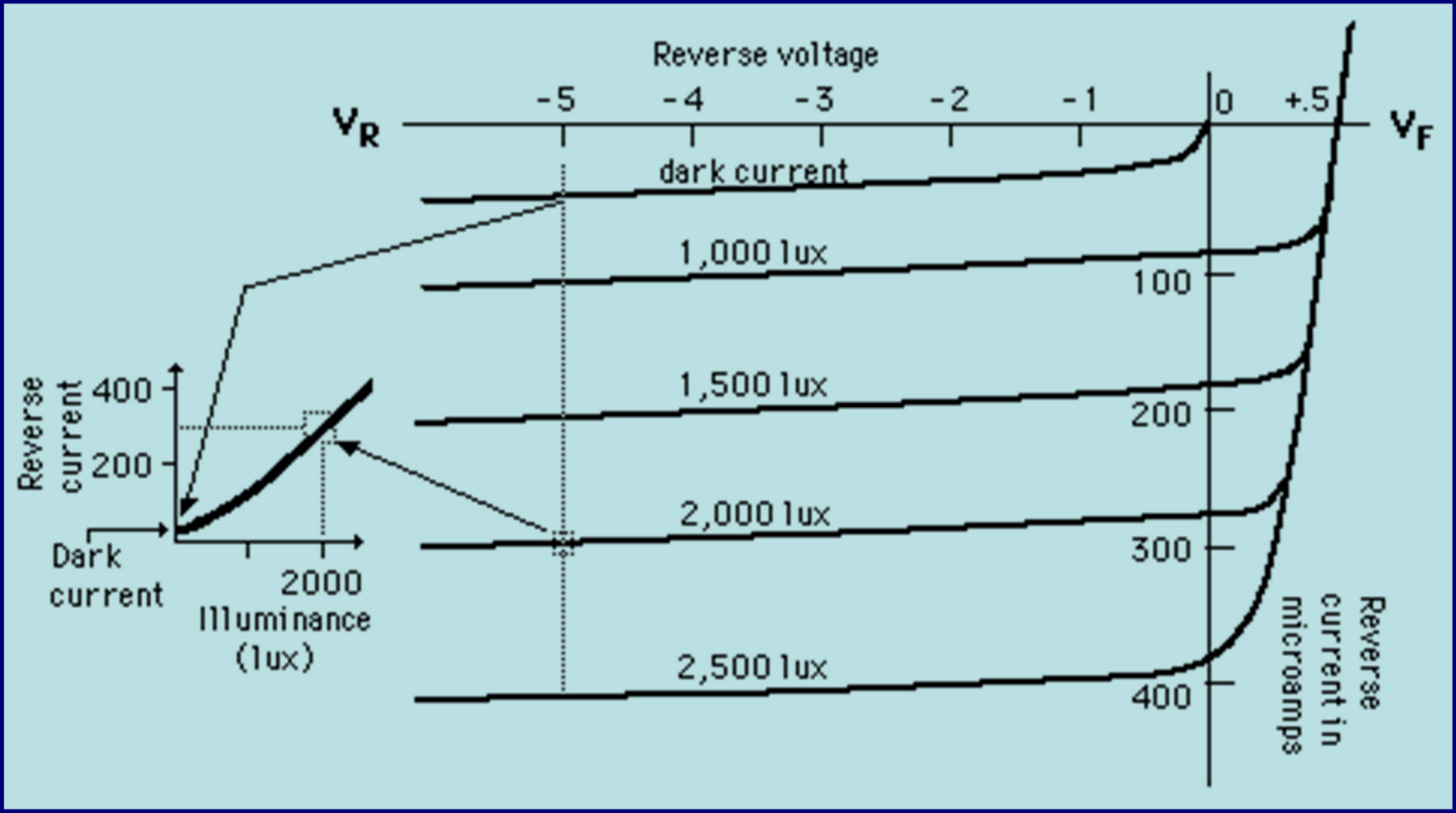
The Current lasts until the charges diffuse to the neutral region

$I_{ph} = eN$ (not 2eN)

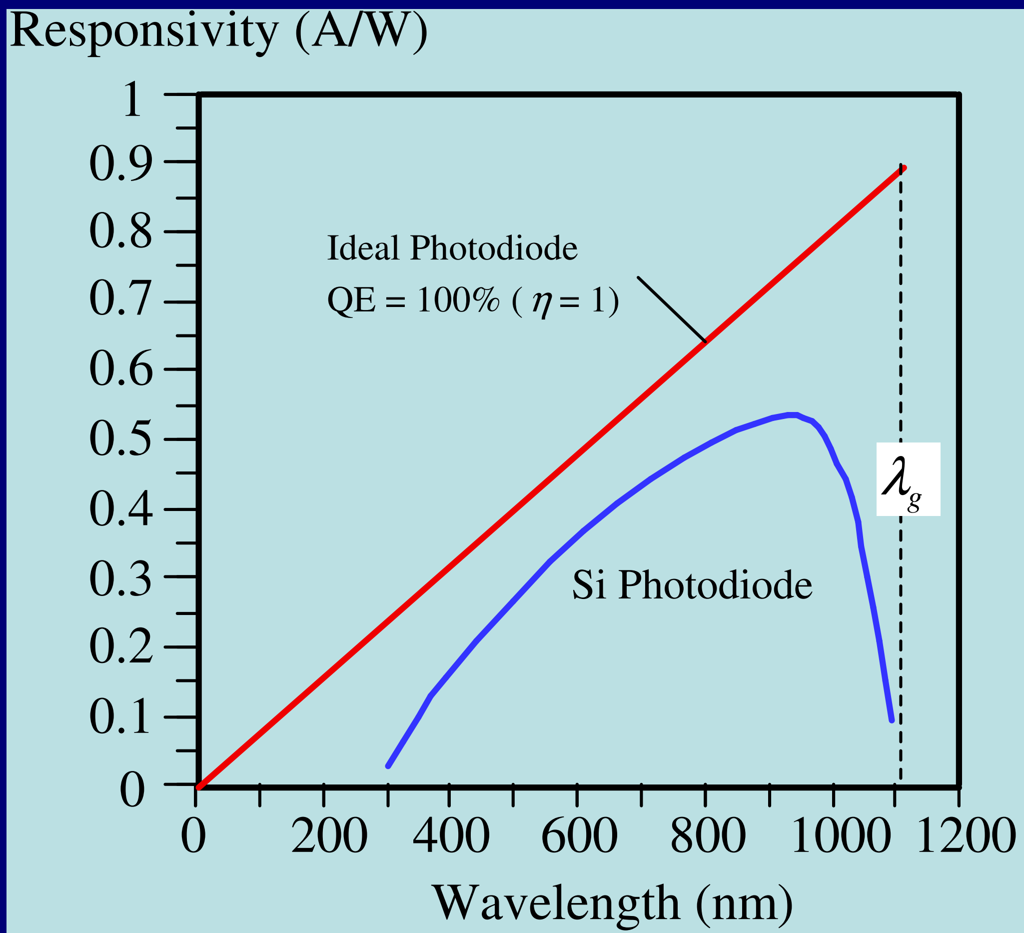
Photodiode I-P characteristics



Photodiode Characteristics



The reverse current through a photodiode varies linearly with iluminance once you are significantly above the dark current region.



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

Examples

a Determine the maximum value of the energy gap which a semiconductor, used as a photoconductor, can have if it is to be sensitive to yellow light (600 nm).

b A photodetector whose area is 5×10^{-2} cm^2 is irradiated with yellow light whose intensity is 2 mW cm^{-2}. Assuming that each photon generates one electron-hole pair, calculate the number of pairs generated per second.

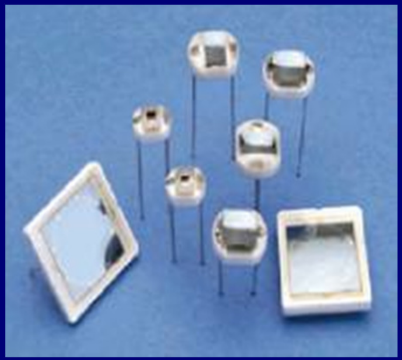
c From the known energy gap of the semiconductor GaAs (E_g = 1.42 eV), calculate the primary wavelength of photons emitted from this crystal as a result of electron-hole recombination. Is this wavelength in the visible?

d Will a silicon photodetector be sensitive to the radiation from a GaAs laser? Why?

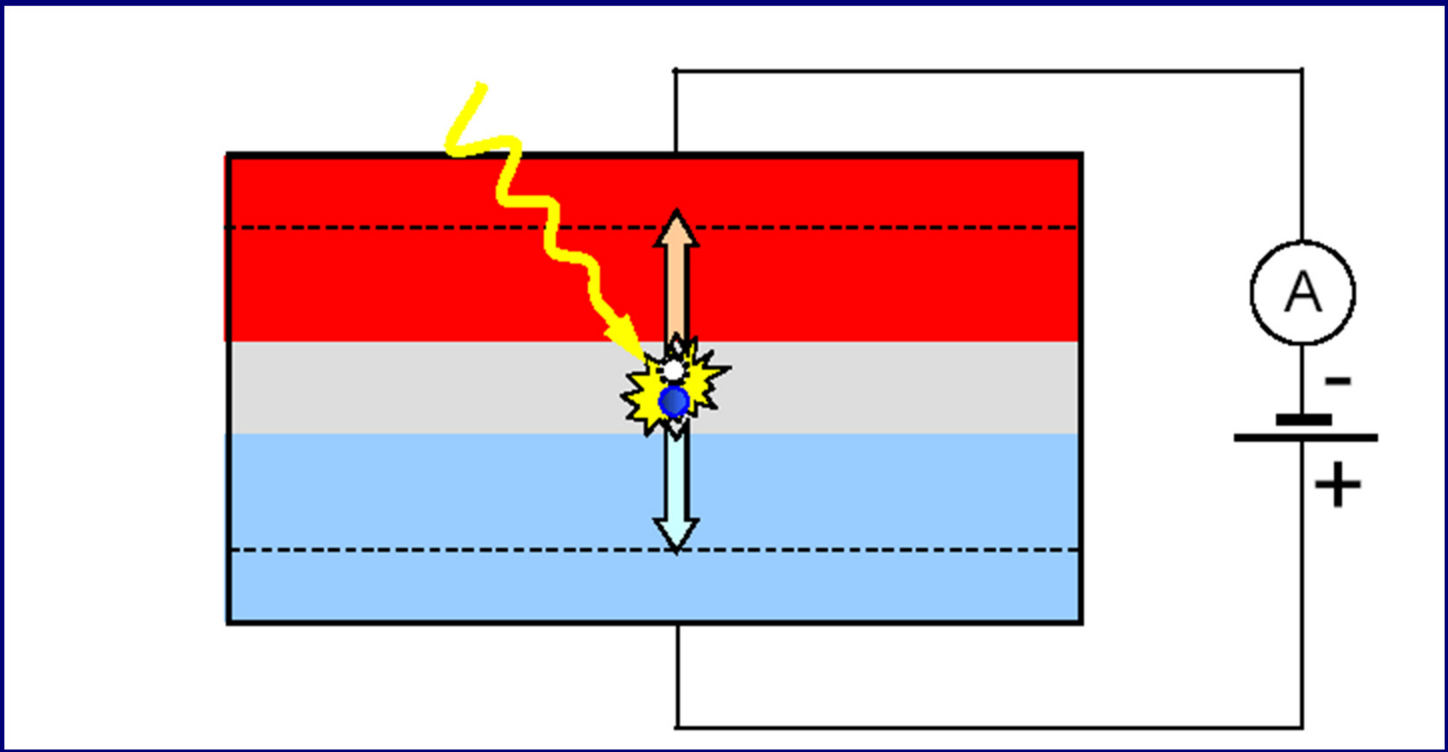
THE PIN PHOTODIODE

- PN junction photodiode has drawbacks
  - Reverse current breakdown
  - Capacitance is too large to allow detection at high modulation frequencies
  - Depletion width is a few microns – penetration depth is greater and EHPs are in the n region
  - Diffusion based device
  - QE is low at long wavelengths

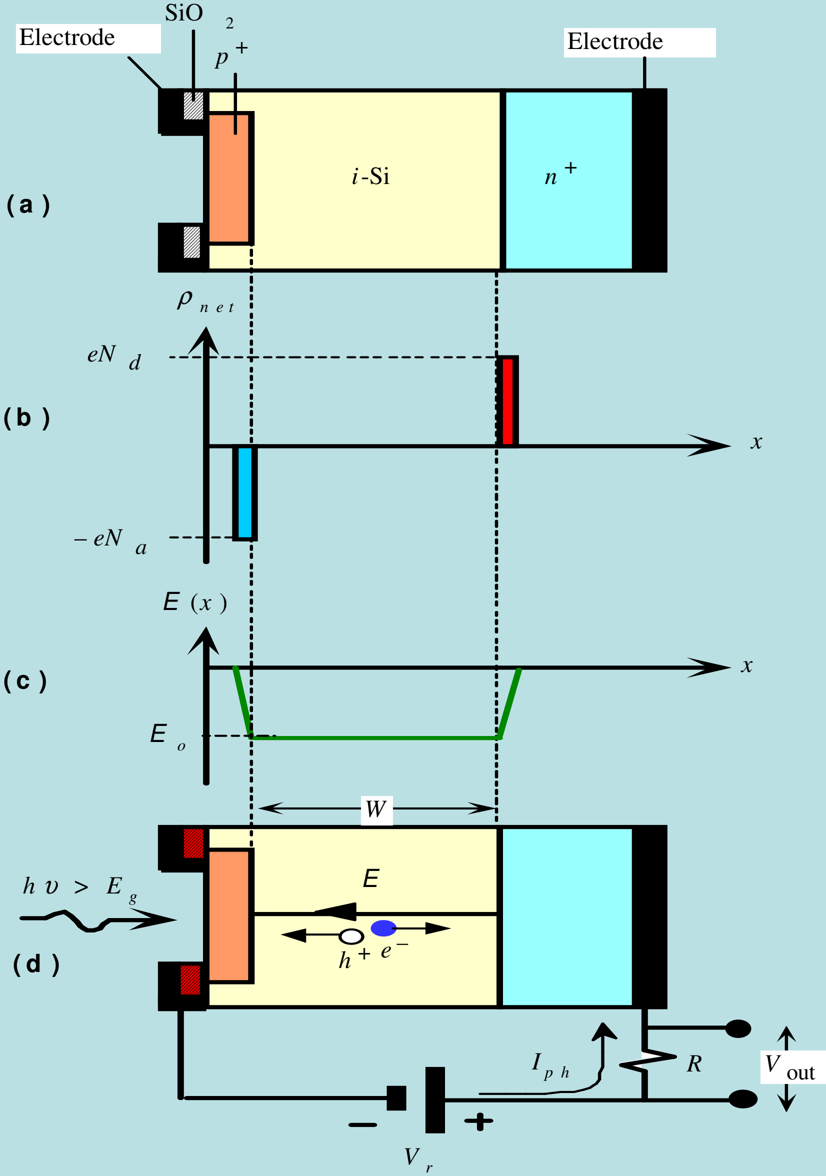
- Pin design – p^+ – intrinsic – n^+
  - Width of Intrinsic layer = W
  - W can be tailored to enhance efficiency
  - Field in the intrinsic region is uniform unlike pn junction
  - Field prevents further diffusion of charge carriers, lower noise



Pin Photodiode



P-I-N photodetector have an increased detection volume compared to simple P-N junction photodetectors



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 in photodetection is reverse biased.

Large I layer

Depletion Region extends

PIN photodiode

Uniform E field

Absorption over W
Transit Time affected

PIN Diode Characteristics

Capacitance $C = \varepsilon_o \varepsilon_r A/W$, no V dependence ~pF

RC time constant with 50 ohm load ~ 50ps

With a Reverse Bias

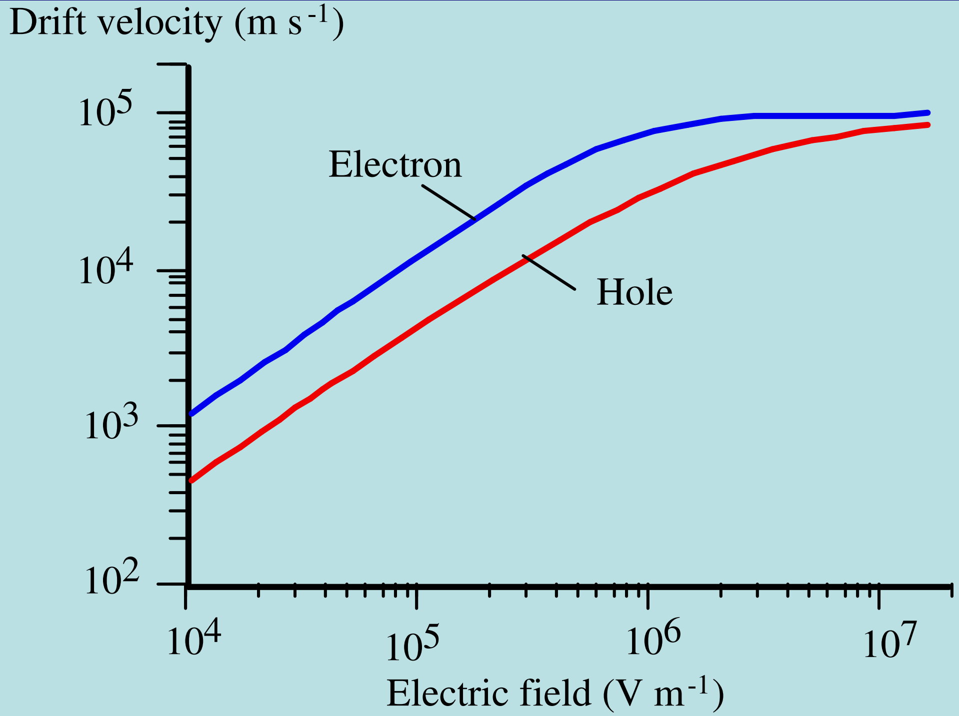
$E = E_o + V_r/W \sim V_r/W$ since it is large comparatively

Photon absorption ***is in the intrinsic region.*** EHPs migrate and generate a Photo-Current that is detected by measuring the voltage across the Load Resistor

Response time depends on transit time across W

A larger W yields more EHPs but slower response

$T_{drift} = W/v_d$



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

Silicon

At $E = 10^6$ V m^{-1},

$v_d \sim 10^5$ m s^{-1}.

If $W = 10$ μm,

then $t_{drift} \sim 0.1$ ns.

$t_{drift} > RC$

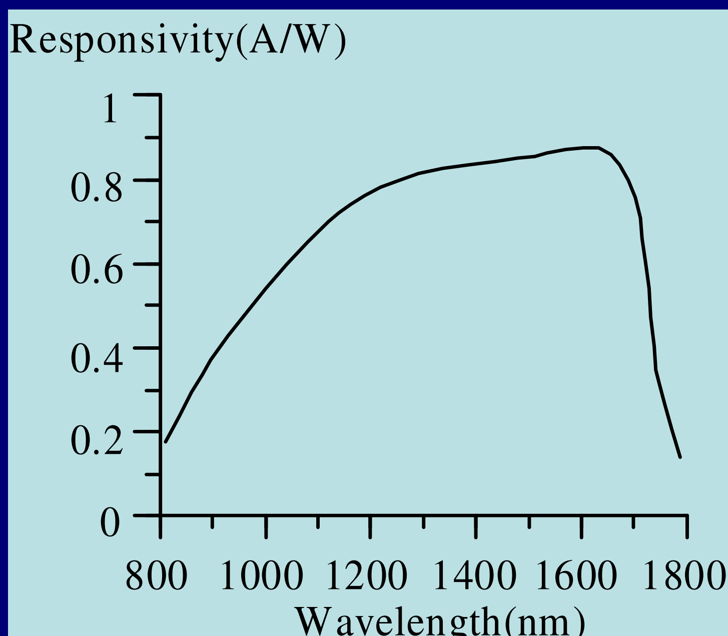
The speed of pin diodes is limited by the transit time of photogenerated carriers across the intrinsic layer. If we reduce the width of the i-Si layer, the quantity of absorbed photons and thus the responsivity will also be reduced.

Example

Consider a commercial InGaAs *pin* photodiode whose responsivity is shown in Figure. Its dark current is 5 nA.

a What optical power at a wavelength of 1.55 μm would give a photocurrent that is twice the dark current? What is the QE of the photodetector at 1.55 μm?

b What would be the photocurrent if the incident power in **a** was at 1.3 μm? What is the QE at 1.3 μm operation?



The responsivity of an InGaAs *pin* photodiode

Solution

Solution

a At $\lambda = 1.55´10^{-6}$ m, from the responsivity vs. wavelength curve we have $R \approx 0.87$ A/W. From the definition of responsivity, we have $P_o = I_{ph}/R = 2I_{\text{dark}}/R = (2X5X10^{-9}\text{ A})/(0.87\text{ A W}^{-1}) = 1.15´10^{-8}$ W or **11.5 nW**.

From the definitions of quantum efficiency (QE) η and responsivity we have

$$\eta = \frac{hcR}{e\lambda} = \frac{(6.62\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})(0.87\ \text{A W}^{-1})}{(1.6\times10^{-19}\ \text{C})(1.55\times10^{-6}\ \text{m})}$$

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

$\therefore$ $\approx$ **0.70 (70%)**

b At $\lambda = 1.3X10^{-6}$ m, from the responsivity vs. wavelength curve we have $R = 0.82$ A/W. Since P_o is the same and 11.5 nW as in **a**,

$$I_{ph} = R\,P_o = (0.82\text{ A W}^{-1})(1.15X10^{-8}\text{ W}) = 9.43´10^{-9}\text{ A}$$ or **9.43 nA**.

The QE at $\lambda = 1.3$ µm is

$$\eta = \frac{hcR}{e\lambda} = \frac{(6.62\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})(0.82\ \text{A W}^{-1})}{(1.6\times10^{-19}\ \text{C})(1.3\times10^{-6}\ \text{m})}$$

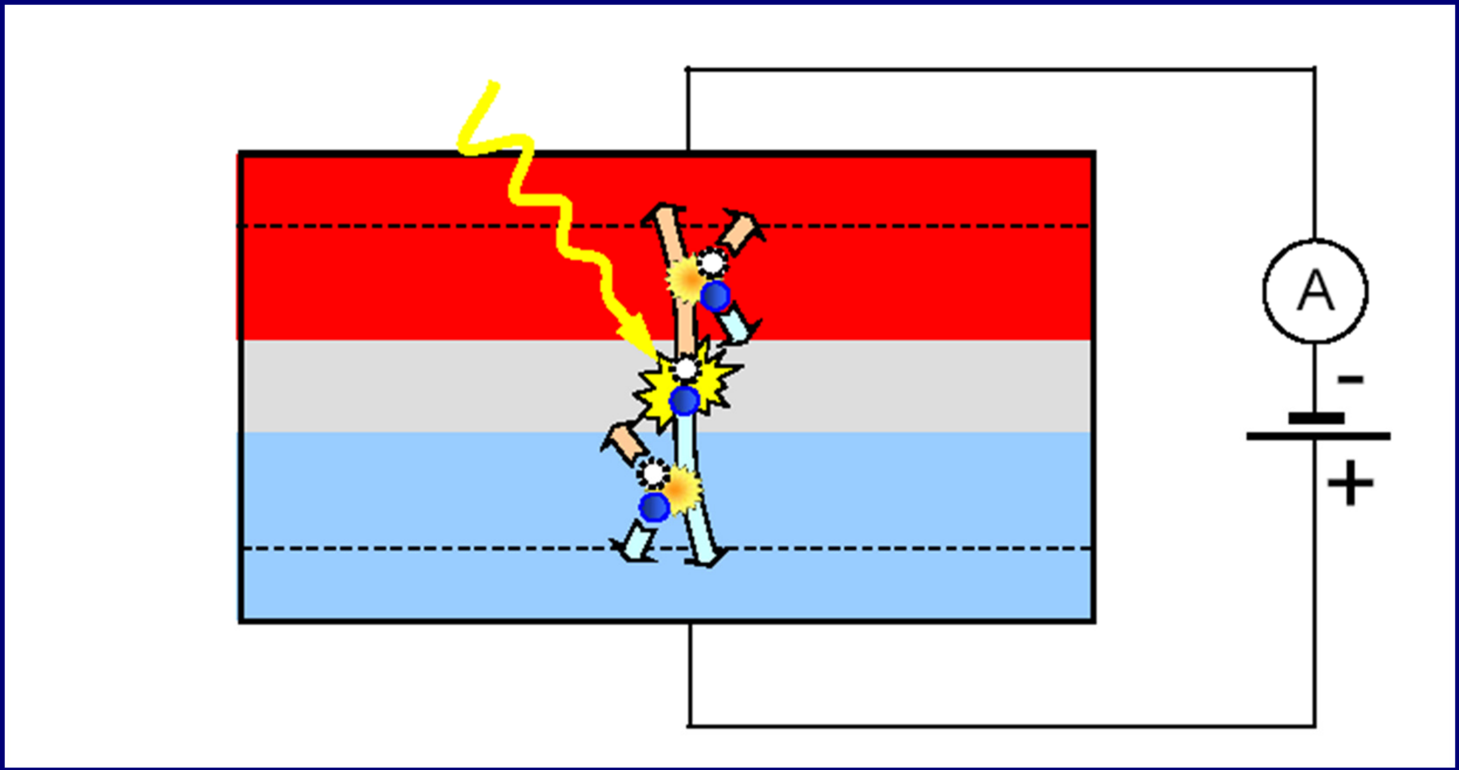
$\approx$ **0.78 (78%)**

THE AVALANCHE PHOTODIODE

- The common device, in the past, that provided gain was the photomultiplier tube (PMT).
- The PMT has a number of practical limitations:
  – It is a bulky vacuum tube;
  – it generates heat; and compared to a photodiode,
  – it offers limited linearity, a narrow spectral response range, and a low QE (< 25%).
- APD are designed to provide an internal current
- Gain is achieved by impact ionization
- In the avalanche photodiode, a large (up to 2kV) external bias accelerates photoelectrons so that each primary electron ultimately results in thousands of electrons at the electrode.
- Advanced APD structure

  1. Heterostructure APD
  2. Multiquantum –well (MQW) APD

The APD



An avalanche photodiode is driven in reverse mode, close to junction breakdown: the internal field is then so large than accelerated charge carriers have enough energy to generate new electron-hole pairs (avalanche effect)

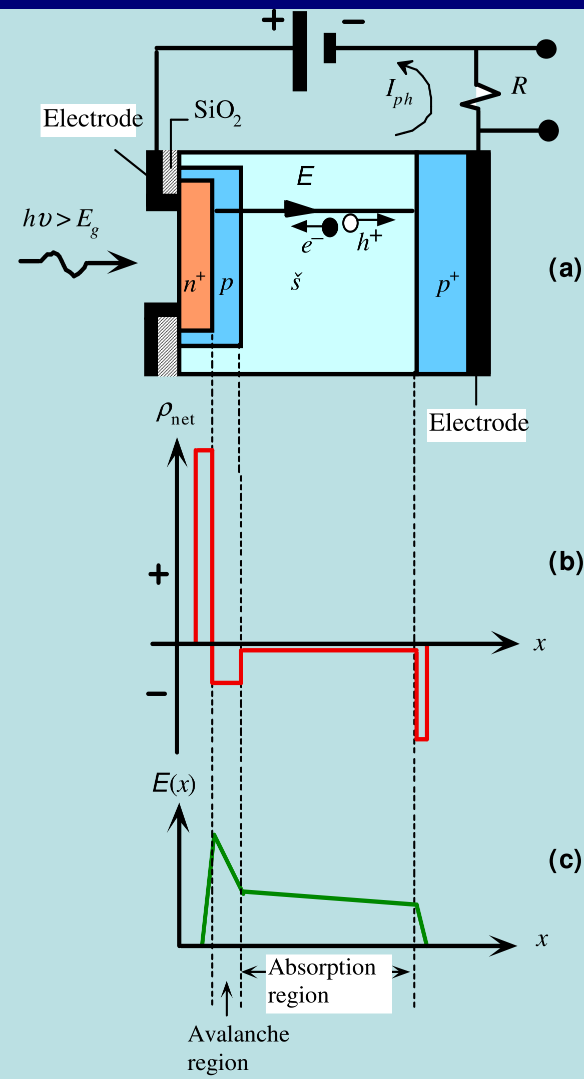
The Avalanche Diode

Lightly doped π-layer (almost intrinsic).

Under a sufficient reverse bias, the depletion region in the p-layer widens to reach-through to the π-layer (**reach-through APD**).

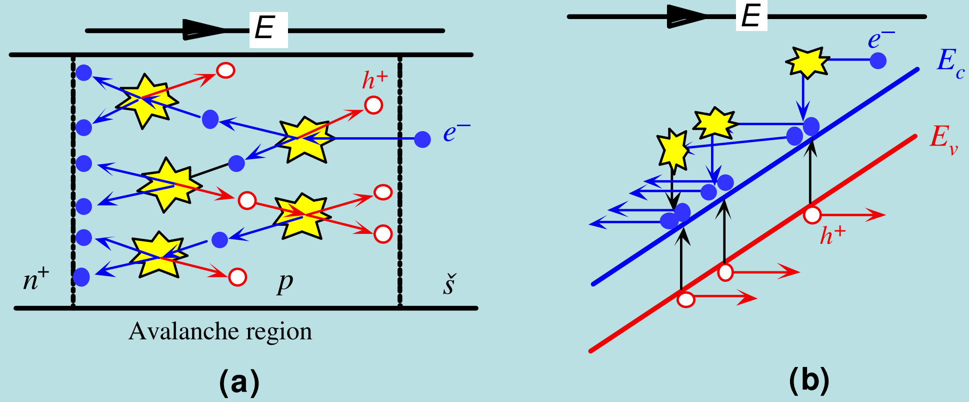
Photogeneration occurs mainly in the π-layer.

The electric field is maximal at the n^+p junction.



(a) A schematic illustration of the structure of an avalanche photodiode (APD) bia
for avalanche gain. (b) The net space charge density across the photodiode. (c) Th
field across the diode and the identification of absorption and multiplication regio

The Avalanche Process



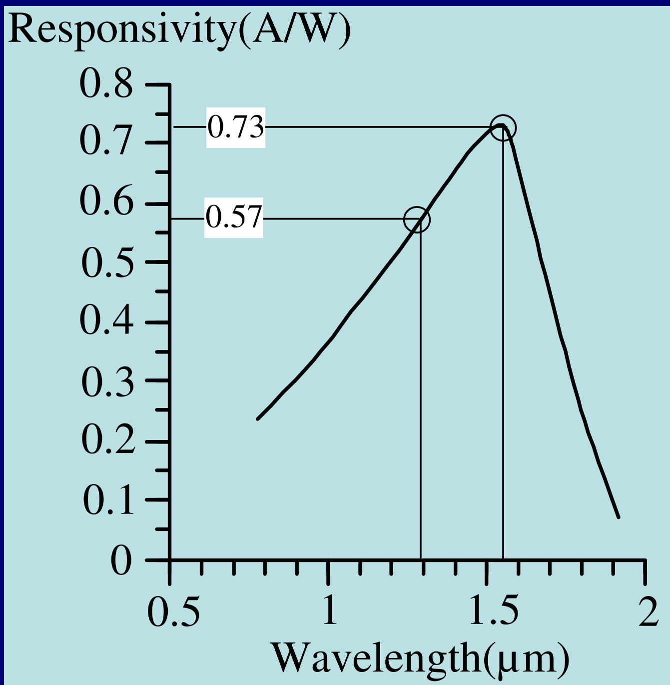
(a) A pictorial view of impact ionization processes releasing EHPs and the resulting avalanche multiplication. (b) Impact of an energetic conduction electron with crystal vibrations transfers the electron's kinetic energy to a valence electron and thereby excites it to the conduction band.

The drift electrons acquire sufficient energy in the p-layer to **impact-ionize** some silicon covalent bonds and release EHPs.

The generated EHPs can further gain sufficient kinetic energy to cause impact ionization and release more EHPs, leading to an **avalanche of impact ionization processes**.
A large number of EHPs can thus be generated from a single electron entering the player.
In silicon electrons have higher impact ionization efficiency.

Example

Consider a commercial Ge *pn* junction photodiode which has the responsivity shown in Figure. Its photosensitive area is 0.01 cm^2 (diameter of 113 μm) It is used under a reverse bias of 10 V when the dark current is 0.5 μA. What is the light intensity at 1300 nm and at 1.55 μm that gives a photocurrent equal to the dark current? What is the QE at the peak responsivity?



The responsivity of a commercial Ge *pn* junction photodiode

Solution

Given, photocurrent $I_{ph} = I_d = 0.5\ \mu\text{A} = 0.5\times10^{-6}$ A and area, $A = 1\times10^{-6}\ \text{m}^2$, the incident optical power,

At $\lambda = 1550$ nm,

$$P_o = I_{ph}/R = (0.5\times10^{-6}\ \text{A})/(0.73\ \text{A W}^{-1}) = 6.85\times10^{-7}\ \text{W}$$

Light intensity, $I_o = P_0/A = (6.85\times10^{-7}\ \text{W})/(1\times10^{-6}\ \text{m}^2) =$ **0.685 W m^{-2}** or **0.0685 mW cm^{-2}**.

At $\lambda = 1300$ nm,

$$P_o = I_{ph}/R = (0.5\times10^{-6}\ \text{A})/(0.57\ \text{A W}^{-1}) = 8.77\times10^{-7}\ \text{W}$$

Light intensity, $I_o = P_0/A = (8.77\times10^{-7}\ \text{W})/(1\times10^{-6}\ \text{m}^2) =$ **0.877 W m^{-2}** or **0.0877 mW cm^{-2}**.

QE at peak responsivity corresponds to $\lambda = 1550$ nm and $R = 0.73$, thus

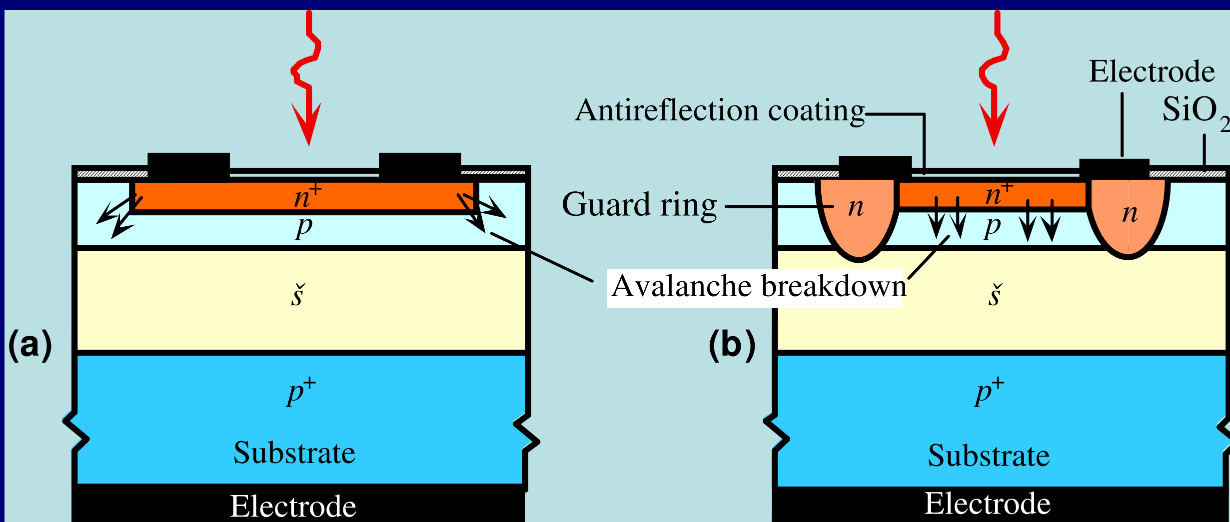
$$\text{Quantum efficiency, } \eta = \frac{hcR}{e\lambda} = \frac{(6.626\times10^{-34}\ \text{Js})\times(3\times10^{8}\ \text{ms}^{-1})\times(0.73\ \text{A/W})}{(1.60218\times10^{-19}\ \text{C})\times(1.55\times10^{-6}\ \text{m})} = \mathbf{0.584\ or\ 58.4\%}$$

Structure of an APD

Avalanche multiplication factor $M = \dfrac{\text{Multiplied photocurrent}}{\text{Primary unmultiplied photocurrent}}$

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

V_{br}: avalanche breakdown voltage.
n: characteristic index.
M is a strong function of both reverse bias voltage and temperature.
$M \sim 100$ (Si APD), $M \sim 10$ (Ge APDs).

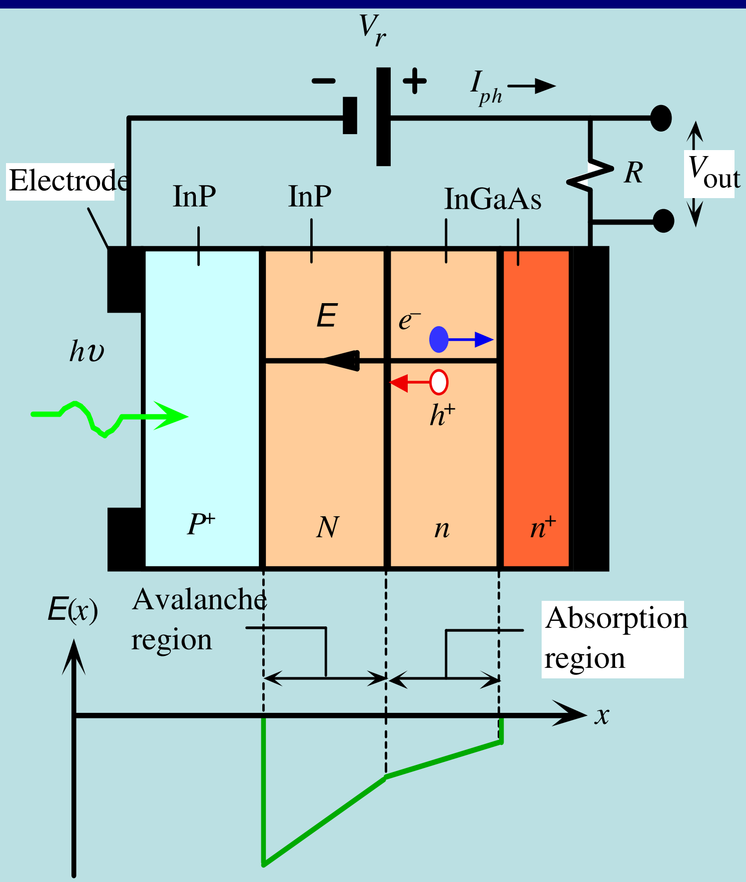


(a) A Si APD structure without a guard ring. (b) A schematic illustration of the structure of a more practical Si APD

Avalanche Diode

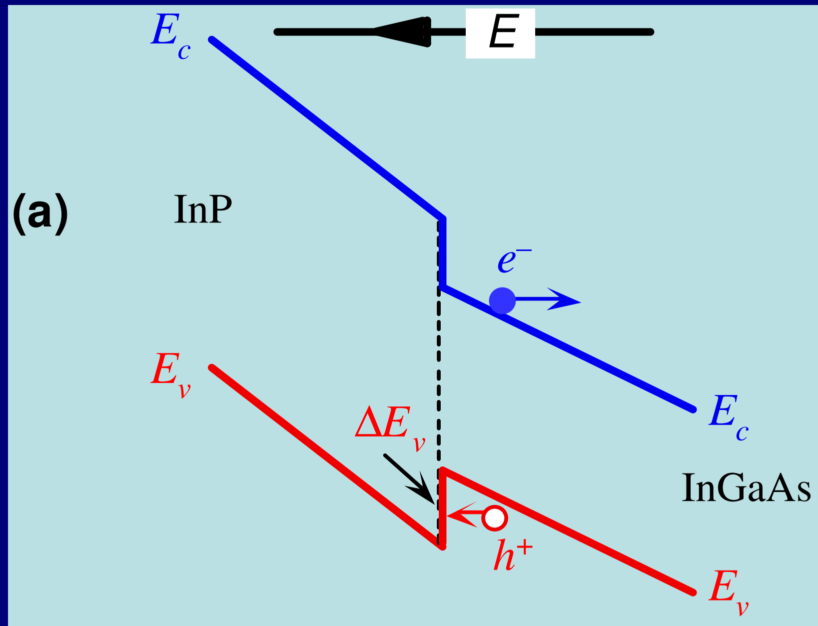
- Speed depends on
  - time to cross the absorption region
  - Time to build up the avalanche process
  - Holes to transit through the absorption region
- Signal is gained at the cost of speed

Separate Absorption and Multiplication (SAM) APD

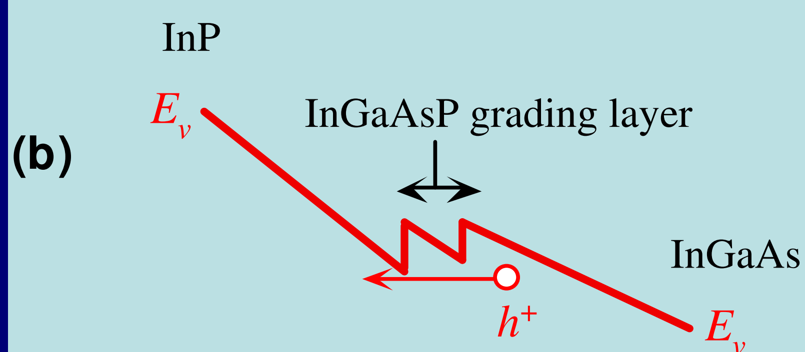


Simplified schematic diagram of a separate absorption and multiplic (SAM) APD using a heterostructure based on InGaAs-InP. *P* and *N* refer to *p* and *n* -type wider-bandgap semiconductor.

- III-V 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.



(a) Energy band diagram for a SAM heterojunction APD where there is a valence band step ΔE_v from InGaAs to InP that slows hole entry into the InP layer.



(b) An interposing grading layer (InGaAsP) with an intermediate bandgap breaks ΔE_v and makes it easier for the hole to pass to the InP layer

Typical Characteristics of Different PDs

TABLE 5.2 Typical characteristics of some *pn* junction, pin and APD type photodetectors based on Si, Ge and InGaAs. t_r is the rise time of the photocurrent from 10% to 90% of its final value when an optical step excitation is applied with photodetector under normal operating conditions (under reverse bias). I_{dark} is typical dark current at normal operating conditions for photosensitive area less than 1 mm^2.

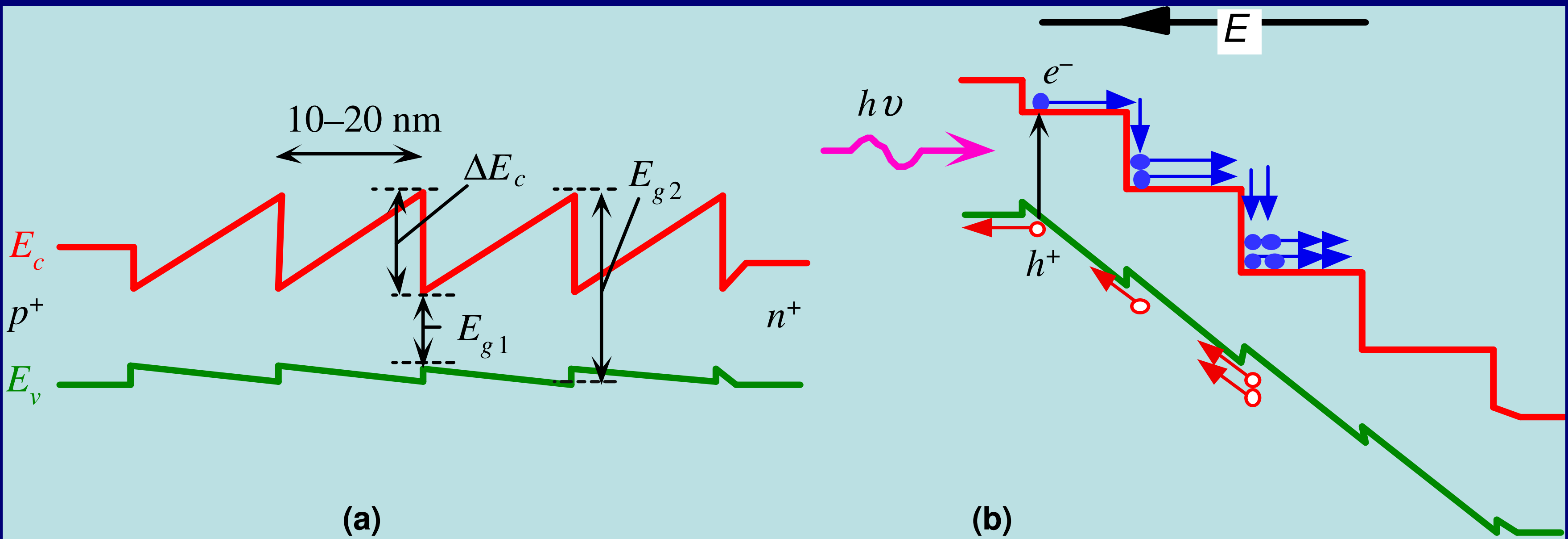
Photodiode	λ_{range} nm	λ_{peak} nm	R at λ_{peak} A/W	Gain	t_r (ns)	I_{dark}
Si *pn* junction	200–1100	600–900	0.5–0.6	<1	0.5	0.01–0.1 nA
Si *pin*	300–1100	800–900	0.5–0.6	<1	0.03–0.05	0.01–0.1 nA
Si APD	400–1100	830–900	40–130	10–100	0.1	1–10 nA
Ge *pn* junction	700–1800	1500–1600	0.4–0.7	<1	0.05	0.1–1 μA
Ge APD	700–1700	1500–1600	4–14	10–20	0.1	1–10 μA
InGaAs-InP *pin*	800–1700	1500–1600	0.7–0.9	<1	0.03–0.1	0.1–10 nA
InGaAs-InP APD	800–1700	1500–1600	7–18	10–20	0.07–0.1	10–100 nA

SUPERLATTICE STRUCTURES

- Statistical variations in avalanche multiplication causes noise
- Reduce excess noise by using only one type carrier for impact ionization
- MQW Superlattice : many alternating layers of different Eg
- Only e can be multiplied, does not need high E-field

Heterostructure PD : Superlattice APD

Staircase superlattice APDs in which the bandgap is graded within each layer are designed to achieve single carrier multiplication in order to reduce the inherent excess avalanche noise

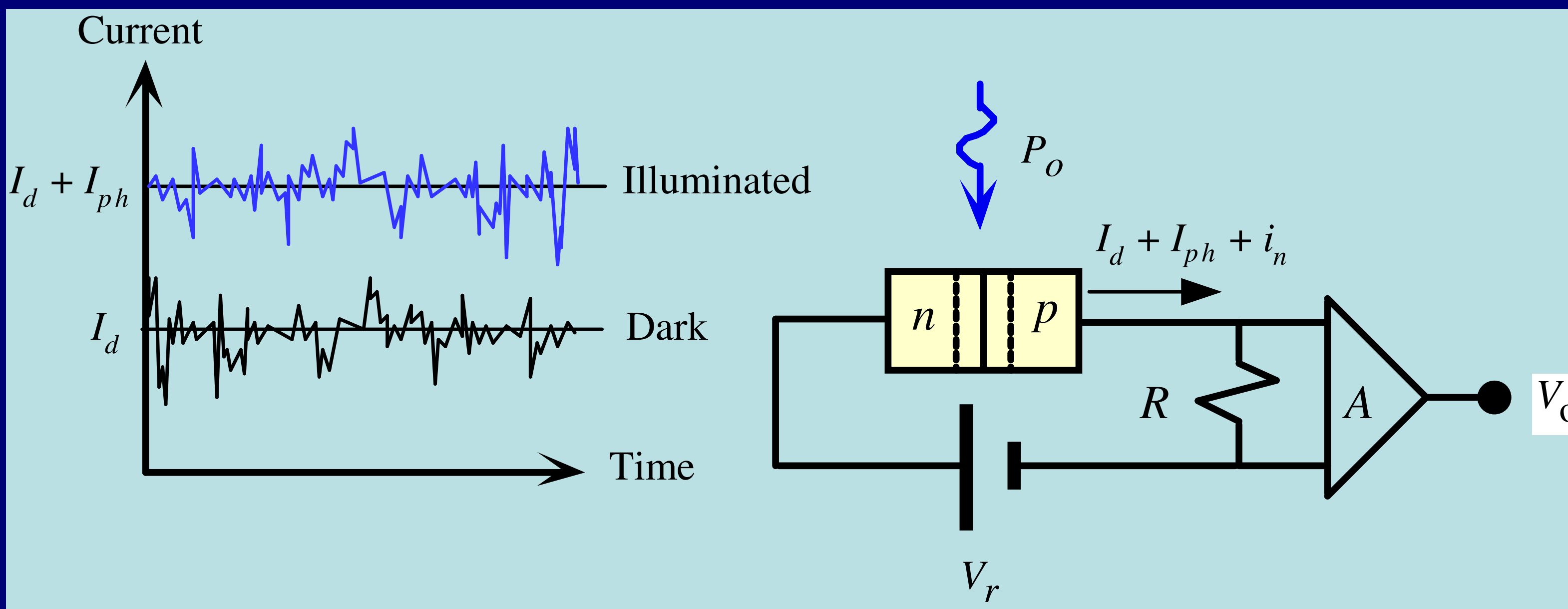


Energy band diagram of a staircase superlattice APD (a) No bias. (b) With an applied bias.

Noise in Photodetectors

Noise in pn & pin Photodetectors

- Thermal generation of EHP (dark current) → fluctuation (shot noise)
- Statistical distribution in the transit time of carriers
- Photocurrent signal must be greater than shot noise dark current $I_{n\text{-}dark} = [2eI_dB]^{1/2}$



In *pn* junction and *pin* devices the main source of noise is shot noise due to the dark current and photocurrent.

Noise in pn & pin Photodetectors

Quantum noise (photon noise) : quantum nature of the photon gives rise to a statistical randomness in the EHP generation process

$$I_{n\text{-}quantum} = [2eI_dB]^{1/2}$$

Generally the dark current shot noise and quantum noise are the main sources of noise in pn & pin PD

Total shot noise: $I_n = [2e(I_d+I_{ph})B]^{1/2}$

SNR : $\dfrac{\text{signal power}}{\text{noise power}} = (I_{ph}^2/I_n^2)$

Noise equivalent power (NEP) :

Optical signal power per sqrt of frequency bandwidth required to generate a photocurrent signal that is equal to total noise current

Therefore SNR=1at NEP = $P_1/B^{1/2}$ = (1/R) $[2e(I_d+I_{ph})]^{1/2}$

R is the responsivity and RP = I

Detectivity D =1/NEP

Avalanche noise in APD

- In the signal multiplication process, shot noise is also multiplied

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

- APDs exhibit excess avalanche noise : randomness of the impact ionization process

- Excess noise factor F : function of M & IO probability

$$I_n = [2eM^2 F(I_d+I_{ph})B]^{1/2}$$

Thermionic Emission Current

The Thermionic Emission Current is the current obtained with no radiation incident

It depends on T, area and work function

$i_T = \alpha A T^2 \exp(-e w_o / k_B T)$

α is a constant = 1.2 X 10^{-6} $A/m^2/K^2$ for metals

Reduced by lowering T

The rms variation is given by an equation similar to Shot noise

Shot Noise and Responsivity

The magnitude of thermal current fluctuations with frequencies between f and Δf is

$\Delta I_s = (2Ie\Delta f)^{1/2}$

Where I is the total external current (dark +external)

If R = Responsivity

The minimum detectable signal is

$P_{min} = (2i_T e\Delta f)^{1/2}/R$

Example

Determine the minimum signal power detectable if the cathode area is 1000mm^2, the material has a work function of 1.25eV and the cathode Temperature is 300K. Assume the bandwidth is 1 Hz.

Solution

$I_T = 2 \times 10^{-14}$ A

R = 0.1A/W

$P_{min} = 8 \times 10^{-16}$W

Summary

Detector Characteristics

Figures of Merit- Responsivity, Efficiency

- Responsivity – I_{ph}/P_o, A/W, tells you spectral range, Allows one to determine how much signal will be available for a particular application, no info about noise.

- Quantum efficiency – η - expresses the effectiveness of the incident radiant energy for producing electrical current in a circuit.

Detector speed - response to changes in light intensity

- Rise time is time taken for the photocurrent to reach 63.2% of steady state value
- Fall time is time taken by the photocurrent to drop to 36.8% of the steady state value
- For pulsed cases, Rise time is time difference between the points at which the detector has reached 10% of its peak output and the point at which it has reached 90% of its peak response
- The fall (decay) time is defined as the time between the 90% point and the 10% point on the trailing edge of the pulse waveform.
- a source whose rise time is less than 10% of the rise time of the detector being tested should be used
- limitations introduced by the electrical cables and by the display device, for example, the oscilloscope or recorder

Photodiode Speed

– For photodetectors,
  - the transit time of photogenerated charge carriers within the detector material and
  - from the inherent capacitance and resistance associated with the device.
  - It is also affected by the value of the load resistance that is used with the detector.
  - There is a tradeoff in the selection of a load resistance between speed of response and high sensitivity.

Linearity

- Photodetectors are characterized by a response that is linear with incident intensity over a broad range, perhaps many orders of magnitude. P_{out} vs. P_{in} is linear
- Noise will determine the lowest level of incident light that is detectable.
- The upper limit is determined by the maximum current that the detector can handle without becoming saturated.
- Saturation is a condition in which there is no further increase in detector response as the input light is increased.
- Linearity = maximum percentage deviation from a straight line over a range of input light levels.

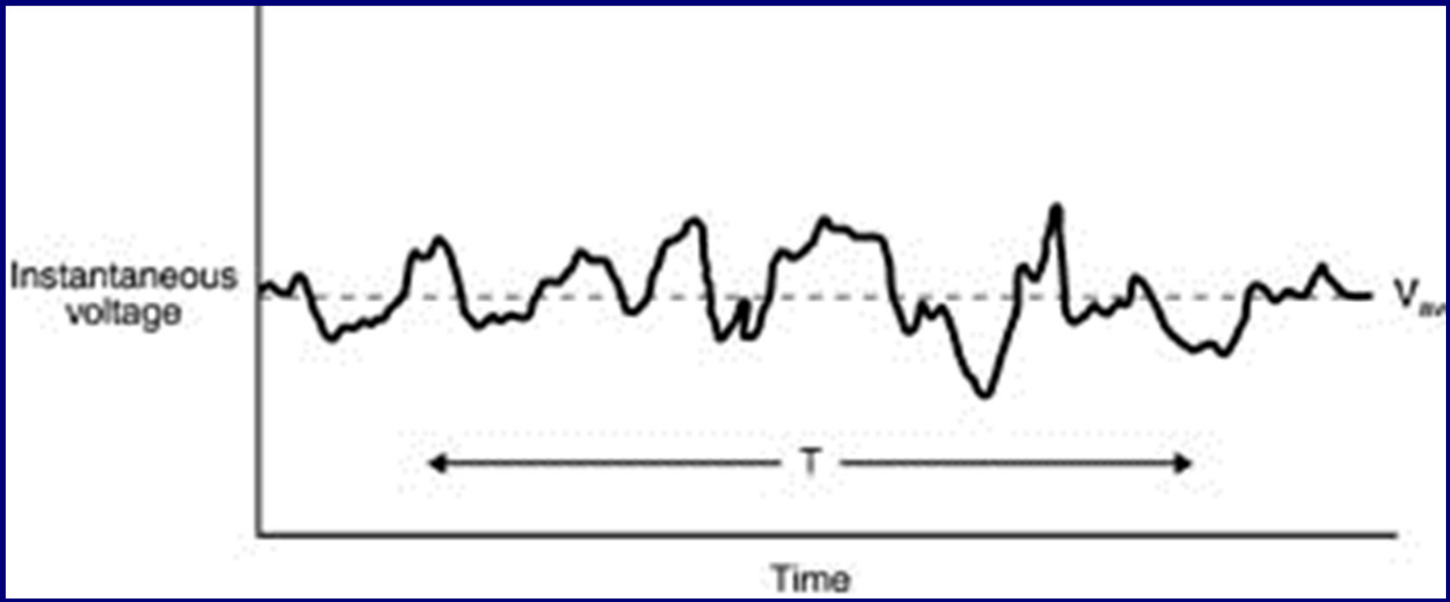
Eg: The maximum deviation from a straight line could be 5% over the range of input light from 10^{-12} W/cm^2 to 10^{-4} W cm^2.

Then the linearity is 5% over eight orders of magnitude in the input.

Noise in Detectors

- Noise is any undesired signal which masks the signal
- Noise is generated externally or internally - fluctuations in V & I due to various statistical processes in the device.
- External noise involves those disturbances that appear in the detection system because of actions outside the system. Eg: pickup of hum induced by 60-Hz electrical power lines and static caused by electrical storms.
- Internal noise includes all noise generated within the detection system itself.
- Cannot be described as a time varying function like I or V – erratic, therefore random
- A simple average is meaningless because the average is zero.
- Describe using an average of the squares of the deviations around V_{av}, with the average taken over a period of time T much longer than the period of the fluctuations.

Noise



Shot Noise

- fluctuations in the stream of electrons in a vacuum tube.
- The arrival of electrons at the anode (like the noise of a hail of shot striking a target)
- In semiconductors, the major source of noise is due to random variations in the rate at which charge carriers are generated and recombined.
- Reverse Biased pn junctions exhibit a dark current I_d which fluctuates because electrical current is by discrete charges which have a distribution in transit times
- Rms value of the fluctuations = Shot noise current

$$I_{n\text{-}dark} = [2eI_dB]^{1/2}$$

B = frequency bandwidth of the detector

- The shot noise may be minimized by keeping any DC component to the current small, especially the dark current, and by keeping the bandwidth of the amplification system small.

Photon/Quantum Noise

- Quantum Noise
  - Detection by interaction of discrete photons with valence electrons
  - Random fluctuation in rate of arrival of photons (background noise)
  - Randomness in EHP generation process

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

- Total Noise

$$I^2_n = I^2_{n\text{-quantum}} + I^2_{n\text{-dark}}$$

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

- The background noise increases with the field of view of the detector and with the temperature of the background.
- Reduce the field of view of the detector so as to view only the source of interest and if possible keep the T of the background cool.

Noise in Photodetectors

- Thermal Noise – Random V fluctuations due to motion of conduction electrons
- Signal to Noise Ratio SNR or S/N = Signal Power/Noise Power
  - For photodetectors $S/N = I^2_{ph}/ I^2_d$
- Noise Equivalent Power (NEP) = Optical Signal Power needed to generate a photocurrent = Noise current at a given wavelength and for a 1Hz bandwidth.
- Detectivity = 1/NEP
- For a responsivity R and incident optical power P_o , $I_{ph} = RP_0$
- For a power $P_0 = P_1$ the noise current

$$I_{ph} = RP_1 = I_n = [2e(I_d + I_{ph})B]^{1/2}$$
$$NEP = P_1/(B)^{1/2} = 1/R\ [2e(I_d + I_{ph})]^{1/2}$$

Johnson Noise

- Thermal fluctuations in conducting materials.
- It results from the random motion of electrons in a conductor.
- The electrons are in constant motion, colliding with each other and with the atoms of the material.
- Each motion of an electron between collisions represents a tiny current.
- The sum of all these currents taken over a long period of time is zero, but their random fluctuations over short intervals constitute Johnson noise.
- $V^2 = 4k_BTRB$, R = Resistance, B = Bandwidth, T = Temperature
- Reduce this type of noise by
  - cooling the system, especially the load resistor.
  - reducing the value of the load resistance, although this is done at the price of reducing the available signal.
  - keeping the bandwidth of the amplification small; one Hz is a commonly employed value.

Example

A photomultiplier has a load R of 1000ohms at 300K and a bandwidth of 1kHz. Calculate the Johnson noise.

If the dark current is 10^{-14} Amps, what is the shot noise current?

If the gain is 107 and if we ignore any multiplication noise contribution, what is the voltage appearing across the load resistor?

Solution

Johnson noise = 4.1×10^{-9}V

$\Delta i_s = 1.8 \times 10^{-15}$ A

V = 1.8×10^{-5}V

1/f or Box Noise

- The term 1/f noise is used to describe a number of types of noise that are present when the modulation frequency *f* is low.
- Also called excess noise because it exceeds shot noise at frequencies below a few hundred Hertz.
- In photodiodes, the boxcar noise, suddenly appears and then disappears in small boxes of noise observed over a period of time.
- The mechanisms that produce 1/f noise are not understood and there is no mathematical expression to define 1/f noise. The noise power is inversely proportional to *f*, the modulation frequency. This dependence of the noise power leads to the name for this type of noise.
- To reduce 1/f noise, a photodetector should be operated at a reasonably high frequency, often taken as 1000 Hz.
- To reduce Johnson noise and shot noise, the amplification bandwidth should be small (perhaps 1 Hz),
- Measurements of the spectral detectivity are often expressed as D*(l ,1000,1).

Allowable Light Levels

- The manufacturer specifies a maximum allowable continuous light level.
- Light levels in excess of this maximum may cause saturation, hysteresis effects, and irreversible damage to the detector.
- If the light occurs in the form of a very short pulse, it may be possible to exceed the continuous rating by some factor (perhaps as much as 10 times) without damage or noticeable changes in linearity.