Optical Communications

Amplifiers & Light Detectors

Part7

Fiber Optic Communications

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Fourth Edition PRENTICE HALL

Amplifiers & Light Detectors

Amplifiers

In digital optical communication systems, a regenerator can be used in the path. In this case, the optical signal is converted to electrical, detected and retransmitted as optical again. This is expensive and noisy.

A regenerators have successfully used to extend fiber paths. For example 5000 km of cables with hundreds of regenerators.

All optical amplifiers are not bandwidth-limited but power limited.

The *traveling-wave laser* amplifier can be used without the mirrors. Or we can use Fabry-Perot laser with mirrors.

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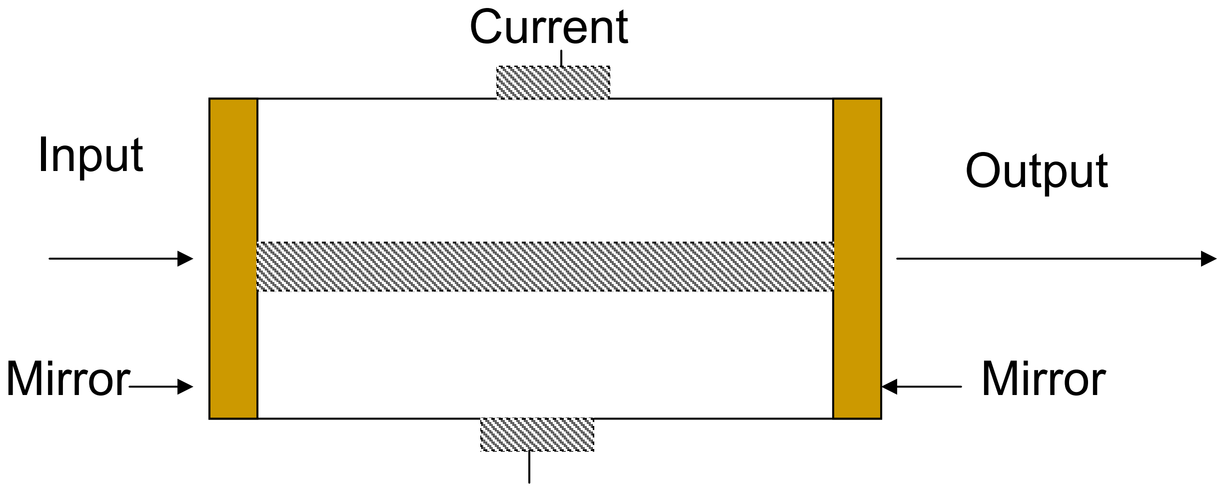
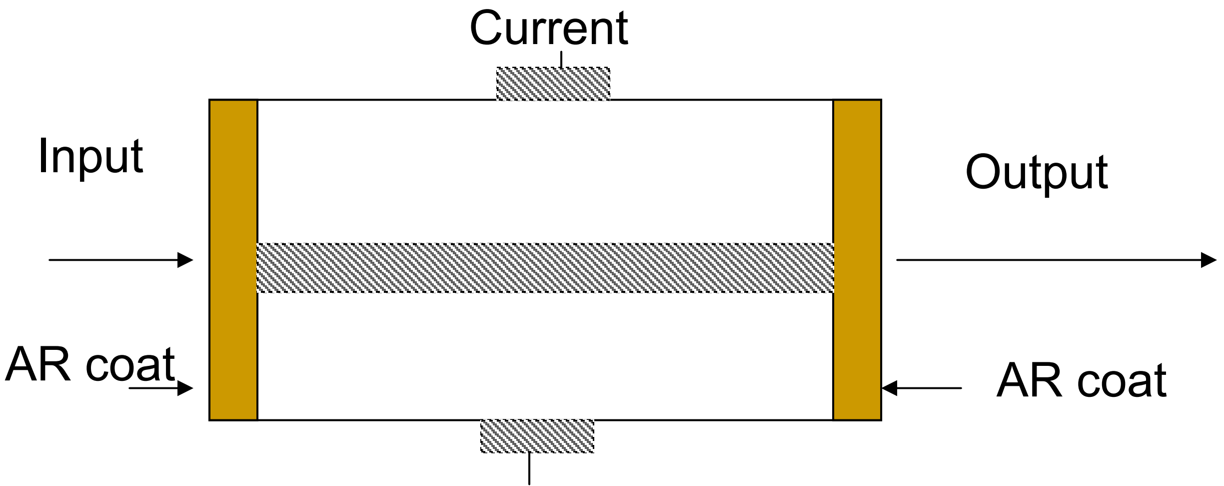


Fabry-Perot Laser



Traveling-wave amplifier

They are not practical and have several problems especially adding noise

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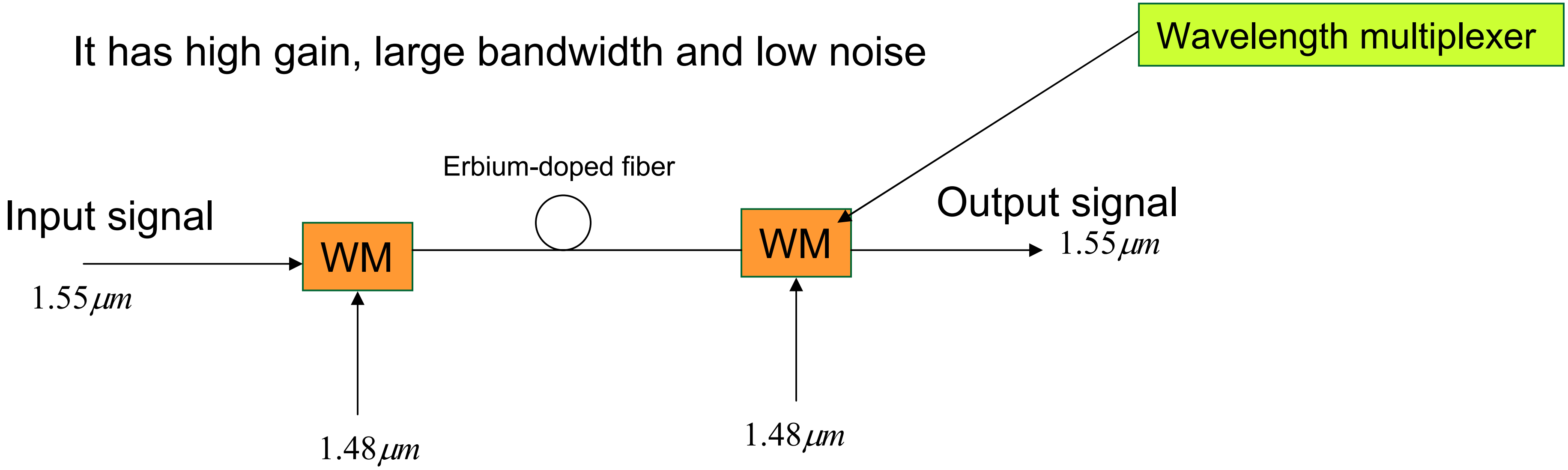
Erbium-doped fiber

It has high gain, large bandwidth and low noise



Wavelength multiplexer

Erbium-doped fiber

Input signal

$1.55\mu m$

WM

WM

Output signal

$1.55\mu m$

$1.48\mu m$

$1.48\mu m$

Laser diode
pump

Noise-figure

$$F = \frac{(S/N)_{in}}{(S/N)_{out}}$$

Light detectors

Principles of photo-detection:

1- external photoelectric effect in which electrons are feed from the surface of the metal by the energy absorbed from an incident stream of photons.

2- internal photoelectric effect in which a semiconductor junction devices in which free charge carriers (electrons and holes) are generated by absorption of incoming photons.

Detector properties are:

1- Responsivity

2- Spectral Response

3- Rise time

The **responsive** ρ is the ratio of the output current of the detector to its optic input current.

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$$\rho = \frac{i}{P}$$ Amperes per watt.

The **spectral response** refers to the curve of detector responsivity as a function of wavelength.

The responsivity at the specific wavelength emitted by the source must be used when designing the receiver.

The **rise time** t_r is the time for the detector output current to change from 10-90% of its final value when the optic input power variation is a step

The 3-dB bandwidth of the detector is

$$f_{3-dB} = \frac{0.35}{t_r}$$

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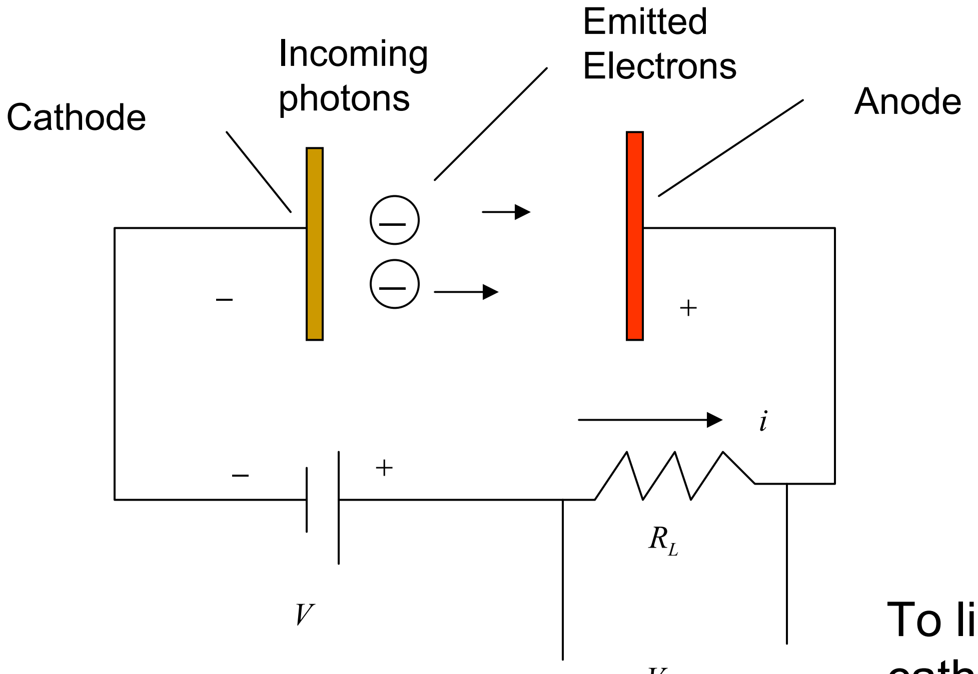
Vacuum Photodiode and Photomultiplier

They are used for testing of fiber components especially low levels of optic power.



Vacuum photodiode

-Bias voltage is applied to make anode positive and cathode negative

-Output voltage is zero.

-Incoming photons irradiate cathode, giving up their energies to electrons in metal.

-Electrons gain enough energy to escape from cathode and move toward the anode.

-Current flows through the circuit.

-When the electrons strike the anode, they combine with the positive charges and circuit current stops.

To liberate a single electron from the cathode requires a minimum amount of energy called work function.

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To liberate a single electron from the cathode requires a minimum amount of energy called **work function**.

$$hf \geq \phi$$

The lowest optic frequency that can be detected is

$$f = \frac{\phi}{h} \quad \text{or} \quad \lambda = \frac{hc}{\phi} = \frac{1.24}{\phi}$$

Not every photon whose energy is greater than the work function will liberate an electron. The **quantum efficiency** of emitter is:

$$\eta = \frac{N_e}{N_{ph}}$$

N_e → Number of emitted electrons

N_{ph} → Number of incident photons

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Number of photons per second striking the cathode is: $N_{ph} = \dfrac{P}{hf}$

Then the number of emitted electrons per second is $N_e = \dfrac{\eta P}{hf}$

The current is the charge per second

This is current that flows through the load resistor in the external circuit.

$$i = \frac{\eta e P}{hf} = \frac{\eta e \lambda P}{hc}$$

The responsivity is

$$\rho = \frac{i}{P} = \frac{\eta e}{hf} = \frac{\eta e \lambda}{hc}$$

The output voltage is $v = \dfrac{\eta e P R_L}{hf} = \rho P R_L$

The above equations are valid for semiconductor junction detectors.

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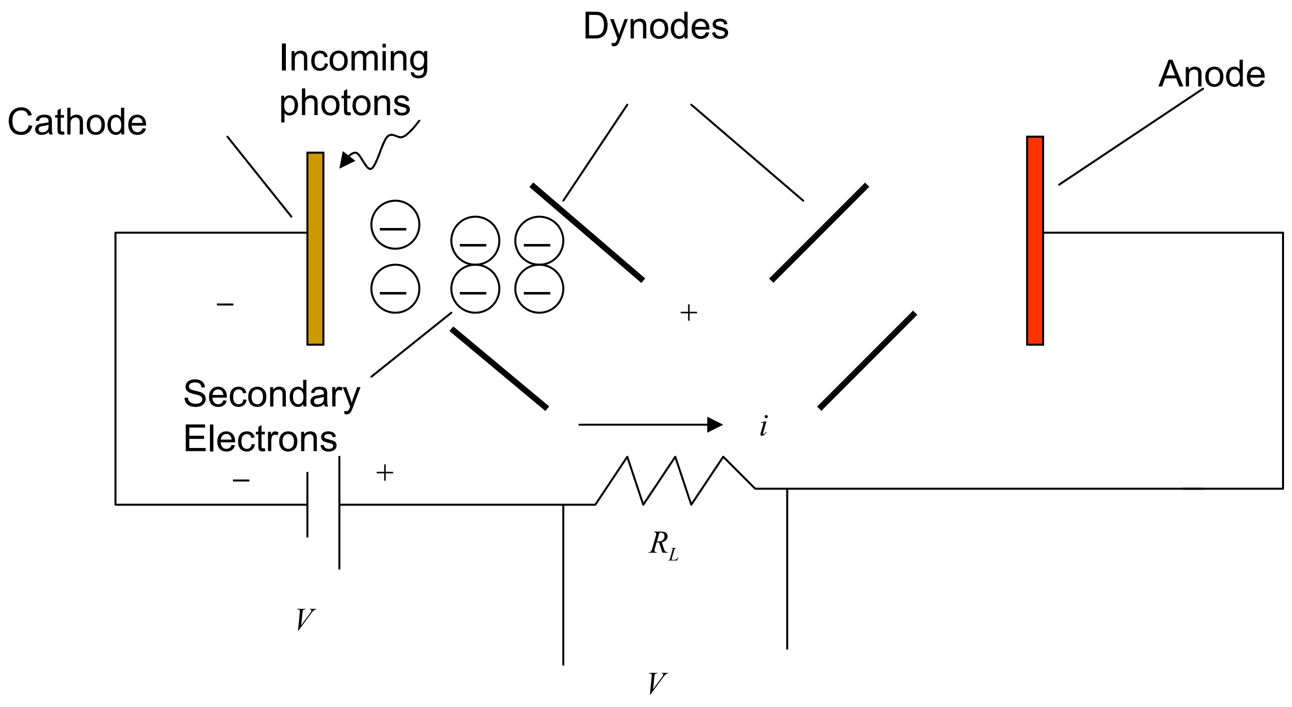
Photomultiplier

Photomultiplier tube PMT has much greater responsivity than does the photodiode because of an internal gain mechanism.



Photomultiplier

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The gain is

$$M = \delta^N$$

Where N is the number of dynodes and δ^N Is the number of electrons

- Electrons emitted from cathode are accelerated toward an electrode called dynode.
- The first dynode attracts electrons because it is placed at higher voltage than the cathode (100 V and more)
- the electrons hitting the dynode have high kinetic energies.
- They give up this energy, causing the release of electrons from the dynode. This process called secondary emission.
- An incident electron can liberate more than one secondary electron, thus amplifying the detected current.

$$i = \frac{M\eta eP}{hf}$$

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Photomultipliers are very fast and have rise time of a few tenths of nanoseconds. Their disadvantages include high cost, large size, high weight, and for power supply providing hundreds of volts.

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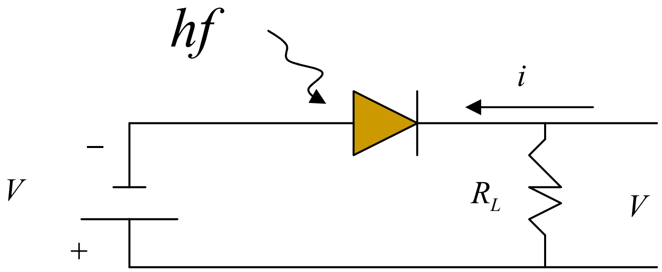
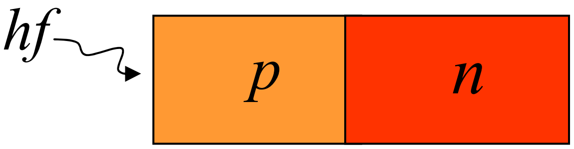
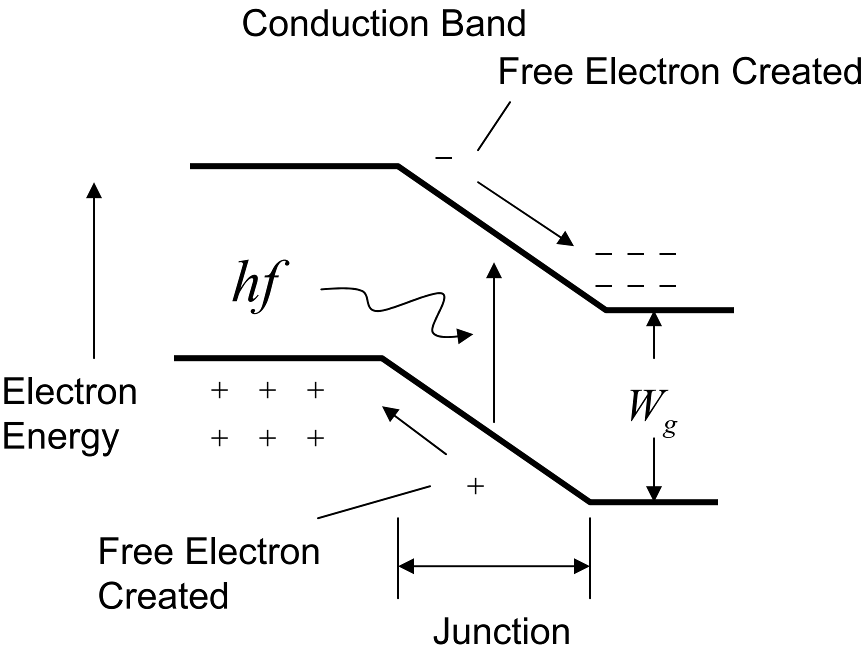
Semiconductor Photodiode

Semiconductor junction photodiodes are small, light, sensitive, fast and can operate with just a few bias volts.







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- The simple pn photodiode illustrates the basic detection mechanism of a junction detector .
- When reverse biased, the potential energy barrier between the p and n junction increases.
- Free electrons and free holes cannot climb the barrier, so no current flow.
- The junction refers to the region where the barrier exists.
- If there is no free charges in the junction, it is called the depletion region.
- When an incident photon being absorbed in the junction after passing through the p layer, the absorbed energy raises a bound electron across the bandgap from the valence to the conduction band. The electron is free to move.
- A free hole is left in the valence band at the position vacated by electron.
- The electron will travel down the barrier and the hole will travel up the barrier.
- These moving charges cause current flow through the external circuit.

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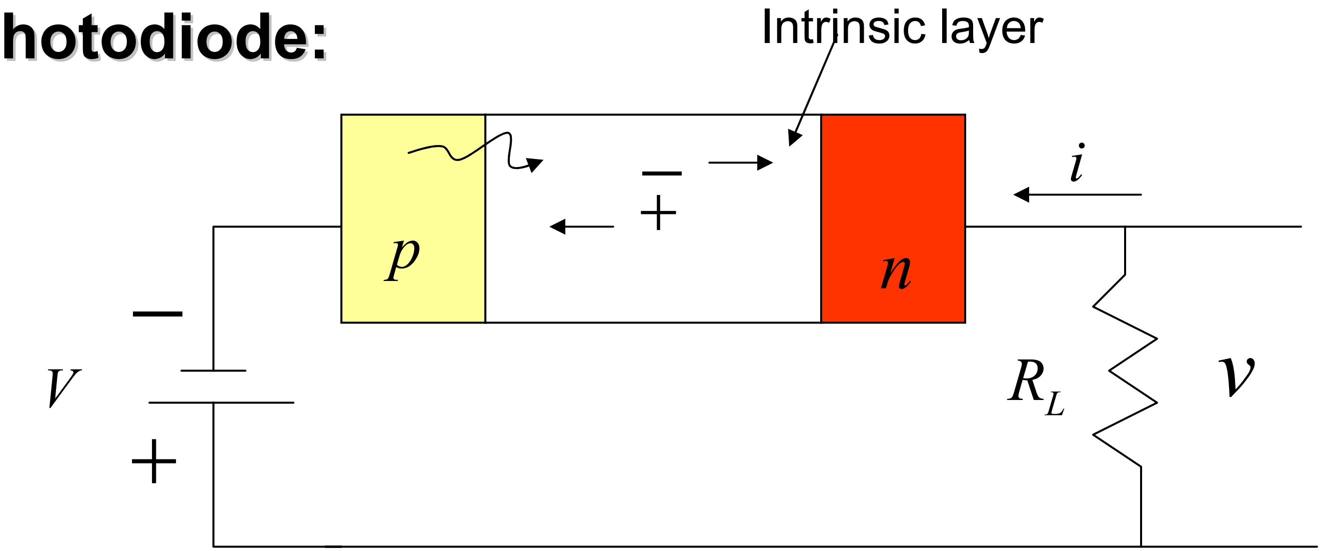
A semiconductor junction used as a light source and as a light detector. For emission, the diode is forward biased. For detection the diode is reverse biased.

PIN Photodiode:



PIN photodiodes are the most common detectors in fiber systems. The intrinsic layer has no free charges , so it has a high resistance. This improves the efficiency and the speed relative to the pn photodiode.

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Cutoff wavelength:

To create an electron-hole pair, an incoming photon must have enough energy to raise an electron across the bandgap. This requirement, leads to a cutoff wavelength. $hf \geq W_g$

$$\text{Micrometers} \longrightarrow \lambda = \frac{1.24}{W_g} \longleftarrow \text{Electron volts}$$

Example: compute the cutoff wavelength for silicon and germanium PIN diodes. Their bandgap energies are 1.1 eV and 0.7 eV respectively.

Solution:

For silicon $\lambda = \frac{1.24}{1.1} = 1.27\,\mu m$

For germanium $\lambda = \frac{1.24}{0.67} = 1.85\,\mu m$

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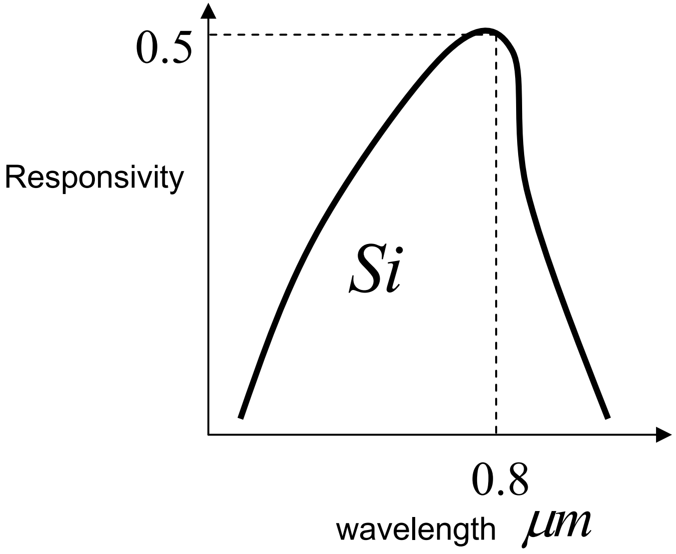
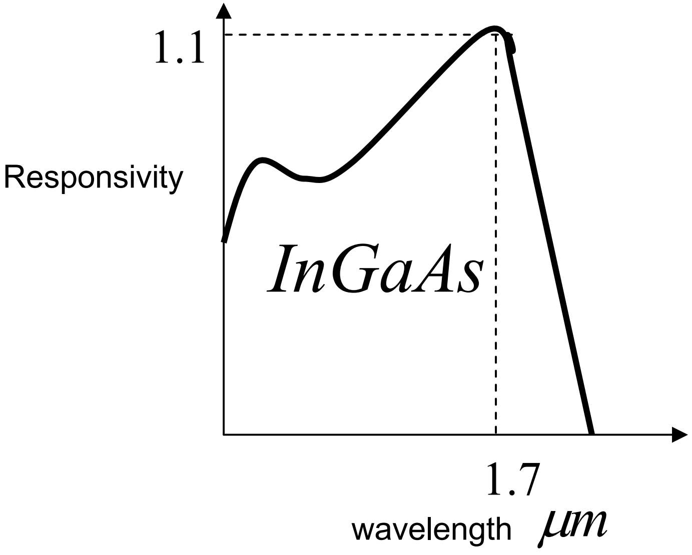
Material	Wavelength range μm	Wavelength of peak response μm	Peak responsivity (A/W)
Silicon	0.3-1.1	0.8	0.5
Germanium	0.5-1.8	1.55	0.7
InGaAs	1.0-1.7	1.7	1.1





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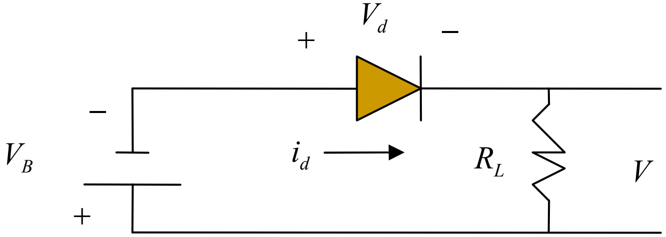
Even when there is no optic power presents, a small reverse current flows through a reversed-biased diode. This current is called dark current.

Example: estimate the minimum detectable power for a PIN diode whose responsivity is 0.5 A/W and whose dark current is 1 nA

Solution: $P = \frac{I_D}{\rho} = \frac{1nA}{0.5} = 2nW$



$$V_B + \upsilon_d + i_d R_L = 0$$

The output voltage is $\upsilon = \rho P R_L$

The maximum current correspond to a maximum input power $P_{\max} = \frac{V_B}{\rho R_L}$

There is a linear relationship between voltage and optic power $\frac{\upsilon}{P} = \rho R_L$

Speed of Response:

The rise time of PIN photodiode is limited by the junction capacitance C_d , formed by the semiconducting p and n layers.

$$t_r = 2.19 R_L C_d$$

The corresponding 3-dB bandwidth is

$$f_{3-dB} = \frac{1}{2\pi R_L C_d}$$

Example:

A PIN photodiode has a capacitance 5 pF and rise time of 2 ns. Compute its 3-dB bandwidth and largest load resistor that can be used without increasing the rise time.

Solution: $f_{3-dB} = \frac{0.35}{2\times 10^{-9}} = 175 MHz$

The rise time should be less than ¼ of the transit time

$2.19 R_L C_d \le 0.5 ns$ Then $R_L \le 46\Omega$

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Transit time is the time takes for free charges to traverse the depletion layer.

How to choose load resistor

Defining equation	**Conclusion**
$\upsilon = \rho P R_L$	R_L large for high-output voltages
$P_{\max} = \dfrac{V_B}{\rho R_L}$	R_L small for large dynamic range
$f_{3-dB} = \dfrac{1}{2\pi R_L C_d}$	R_L small for large bandwidth
$i_{NT}^2 = 4kT\Delta f / R_L$	R_L large to reduce the thermal-noise effect.

i_{NT}^2	Mean square value of the thermal-noise current
T	Absolute temperature
Δf	Receiver bandwidth
k	Boltzmann constant

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Avalanche photodiode

Is a semiconductor junction detector that has internal gain which increases its responsivity over pn or PIN devices.

A photo is absorbed in the depletion region , creating a free electron and a free hole.

The large electrical forces in the depletion region cause these charges to accelerate, gaining kinetic energy to create additional electron-hole pairs.

One accelerating charge can generate several new secondary charges.

The secondary charges can create more electron-hole pairs.

The accelerating forces must be strong to impart high kinetic energies. This achieved with large reverse bias (hundreds of volts.

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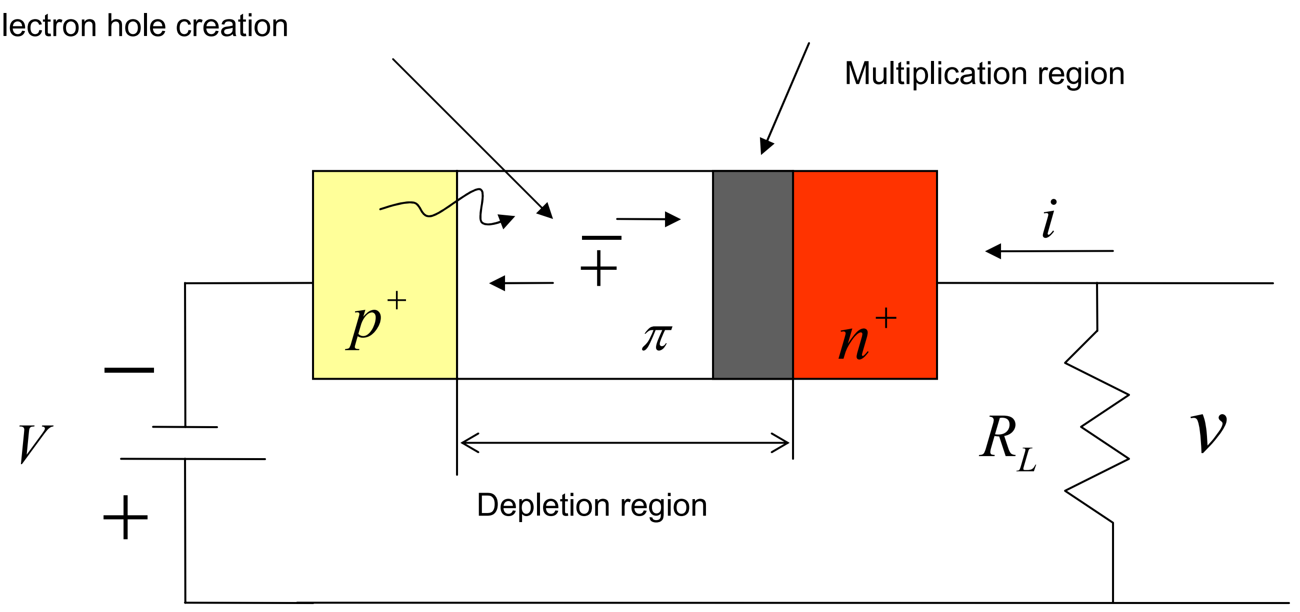
Electron hole creation

Multiplication region

Depletion region

The current generated by APD is

$$i = \frac{M\eta eP}{hf} = \frac{M\eta e\lambda P}{hc}$$

The responsivity of APD is

$$\rho = \frac{i}{P} = \frac{M\eta e}{hf} = \frac{M\eta e\lambda}{hc}$$

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APDs have excellent linearity over optic power levels (nanowatt to several microwatts)

With high optical power, APD is needed.

The gain of an APD is temperature dependent, generally decreasing as the temperature rises.

Material	Structure	Rise time (ns)	Wavelength (nm)	Responsivity (A/W)	Dark current (nA)	Gain
Silicon	PIN	0.5	300-1100	0.5	1	1
Germanium	PIN	0.1	500-1800	0.7	200	1
InGaAs	PIN	0.3	900-1700	0.6	10	1
Silicon	APD	0.5	400-1000	75	15	150
Germanium	APD	1	1000-1600	35	700	50
InGaAs	APD	0.25	1000-1700	12	100	20