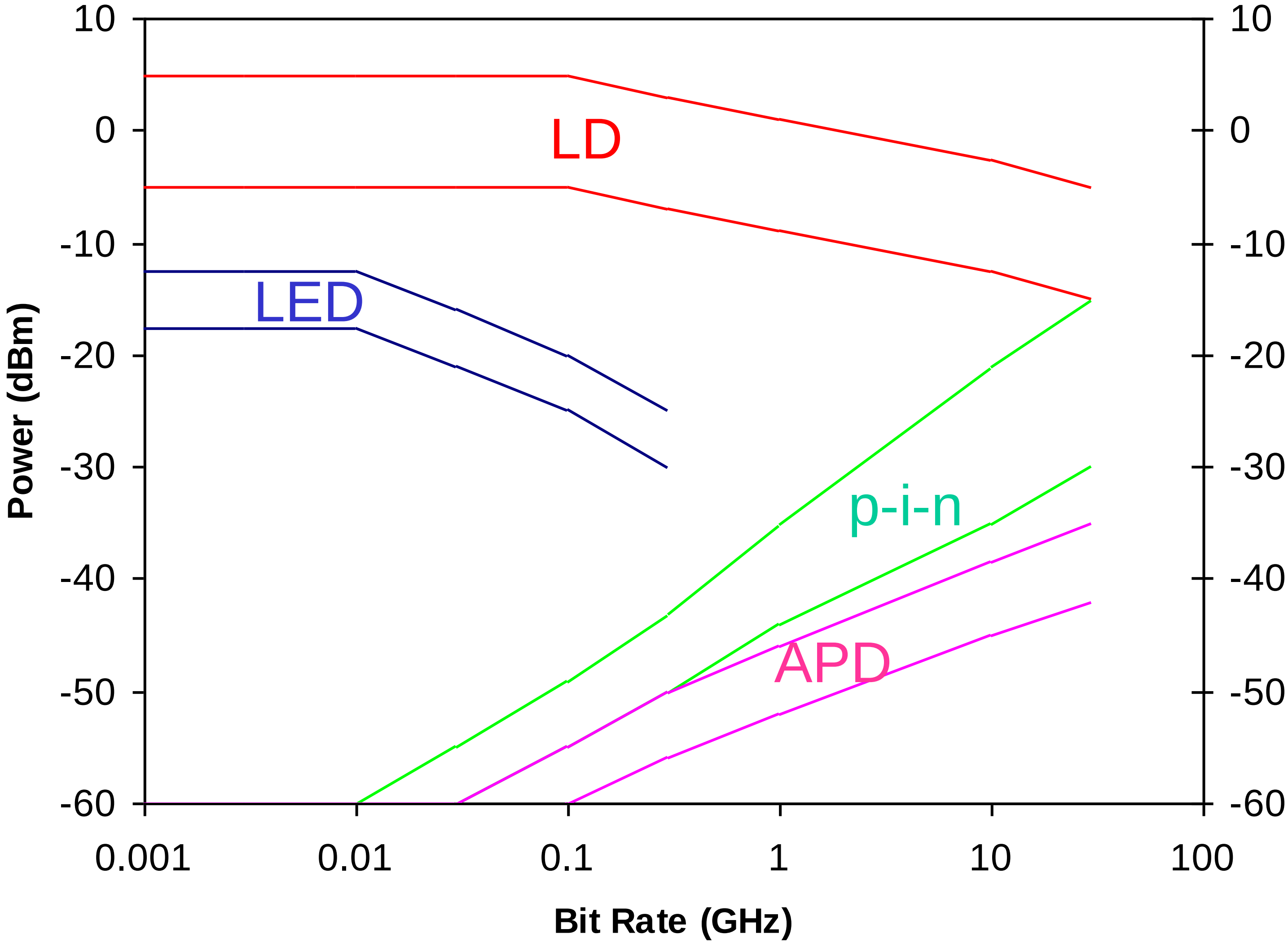
OPTICAL DEVICES

Launch Power / Receiver Power Curves
Spectral Linewidths of Devices
p-i-n diodes
Light Emitting Diodes (LED)
Fabry-Perot Laser Diodes
Single-mode Laser Diodes– Distributed Feedback (DFB) Laser
Photodiodes
Avalanche Photodiodes (APDs)

Launch And Receiver Powers Vs. Bit Rate



Linewidth of Transmitters

Dispersion is governed by linewidth – key parameter

Component	Linewidth
LED	~100nm
Fabry-Perot Laser	~ 1nm
DFB Laser (Distributed feed back)	~ 0.0001nm

Key Points

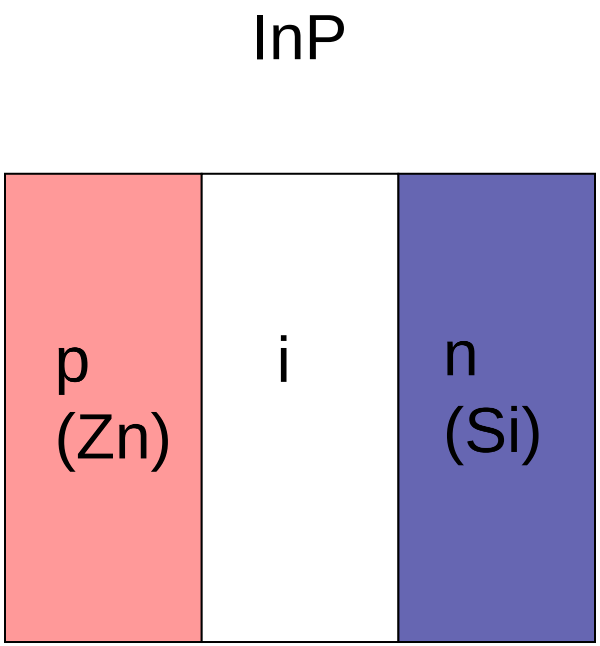
Laser diodes have higher launch powers than LEDs

Laser diodes have faster modulation rates than LEDs

Laser diodes have narrower spectral linewidths than LEDs

APDs are more sensitive than p-i-n diodes

p-i-n diodes – structure



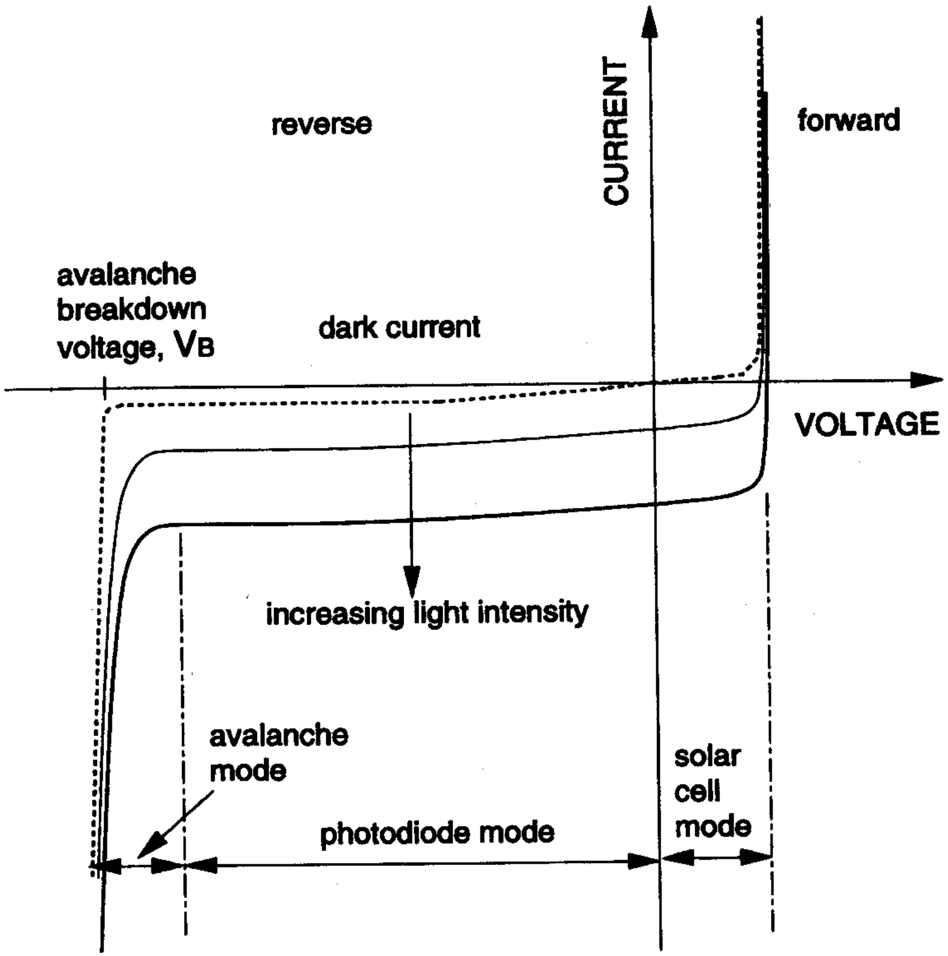
A semiconductor can be "doped" to give regions with excess holes or electrons

A p-i-n diode is a sandwich of such layers

Light Emission – Forward Bias

Light Detection – Reverse Bias

p-i-n diodes – operating characteristics



Light Emission – Forward Bias

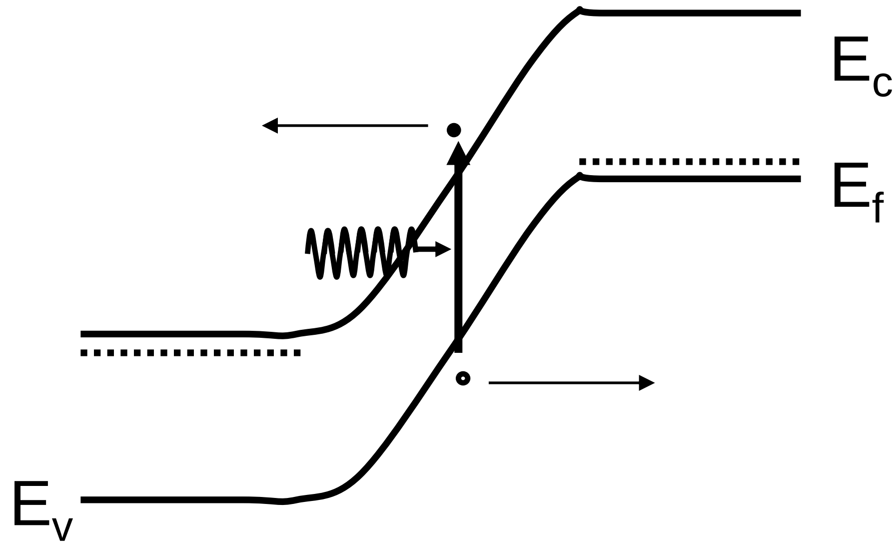
Light Detection – Reverse Bias

Too much forward bias – high current – high temperature – diode dies

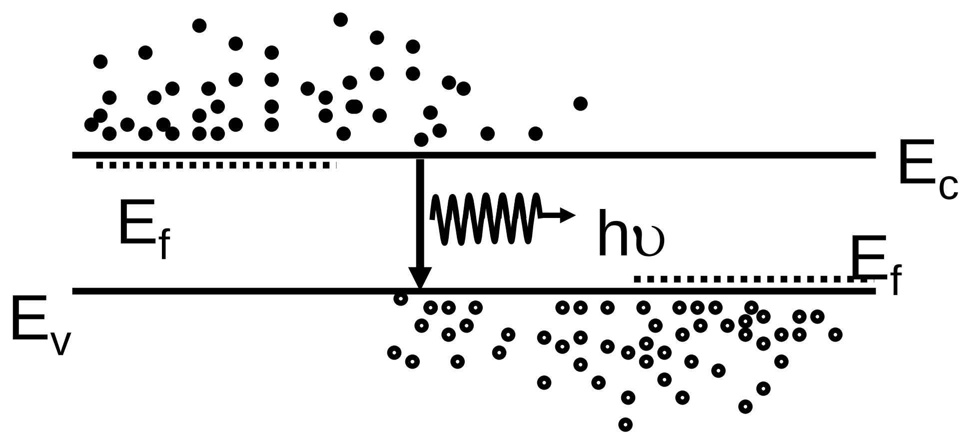
Too much reverse bias – get “avalanche” of current -– high temperature – diode dies

p-i-n diodes

Reverse biased
p-n junction



Forward biased
p-n junction



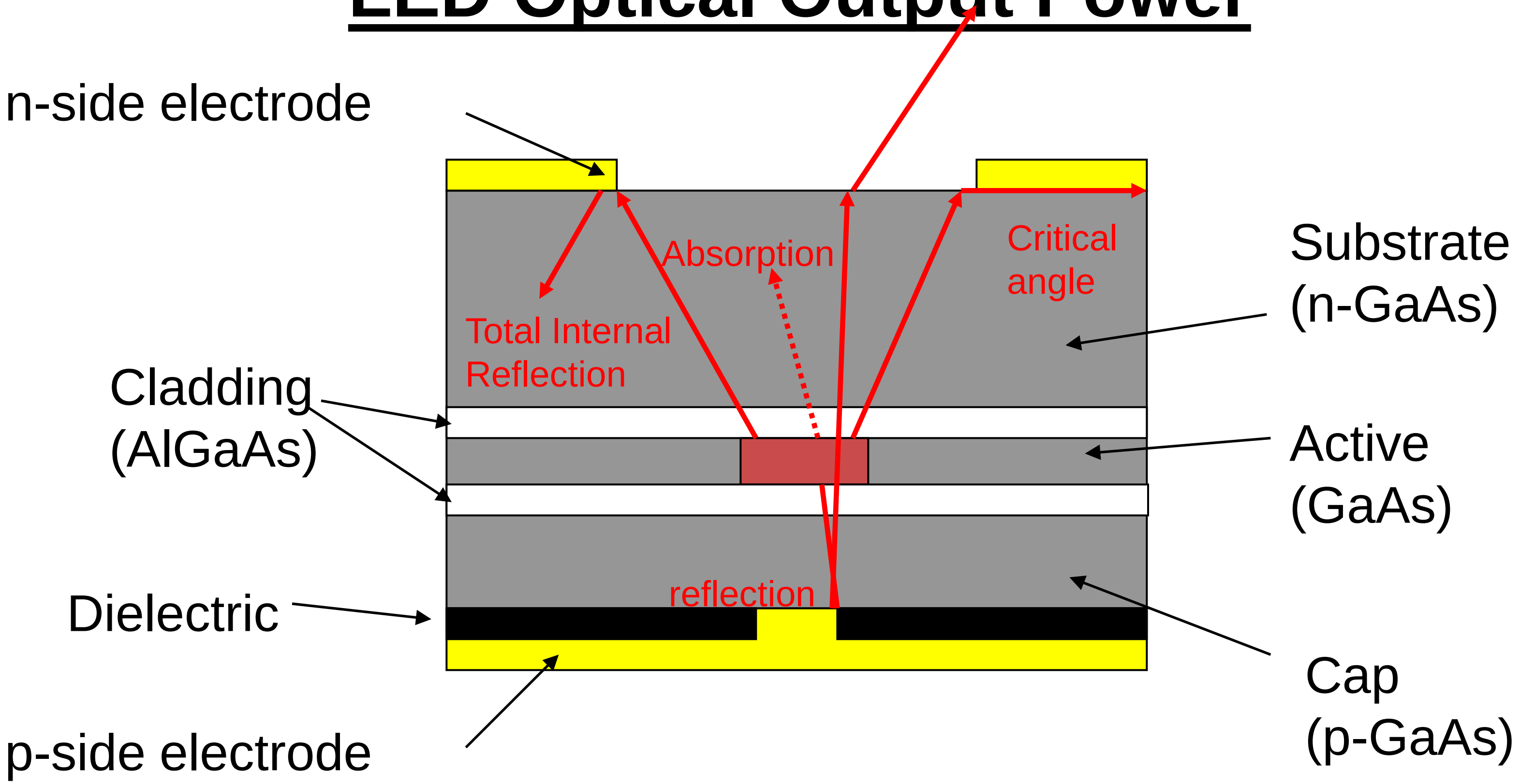
Spontaneous Emission

At low carrier densities within a diode

An electron and hole can recombine to give a photon

– light emitted in all directions
- Broad emission band ~100nm for semiconductors
– typical decay time ~ns

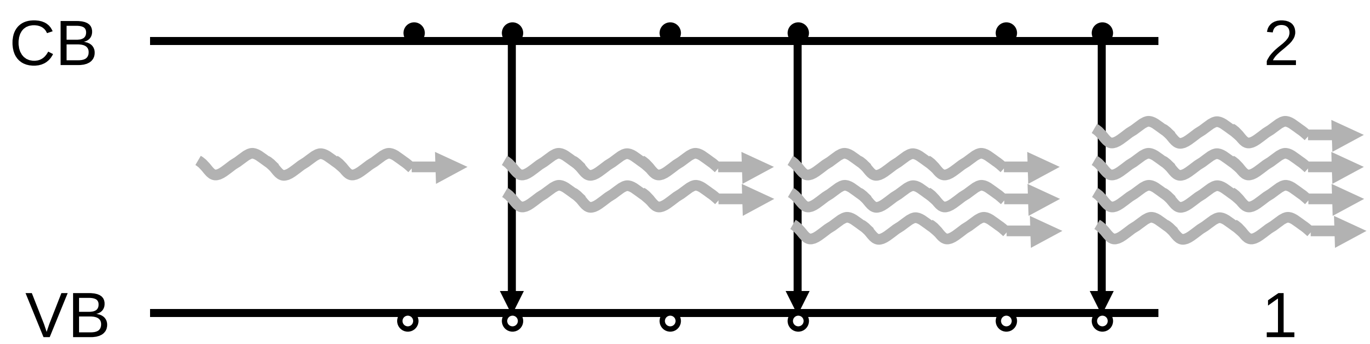
LED Optical Output Power



Typical external efficiencies of only ~1-3%

Surface and edge emitting types

Stimulated Emission

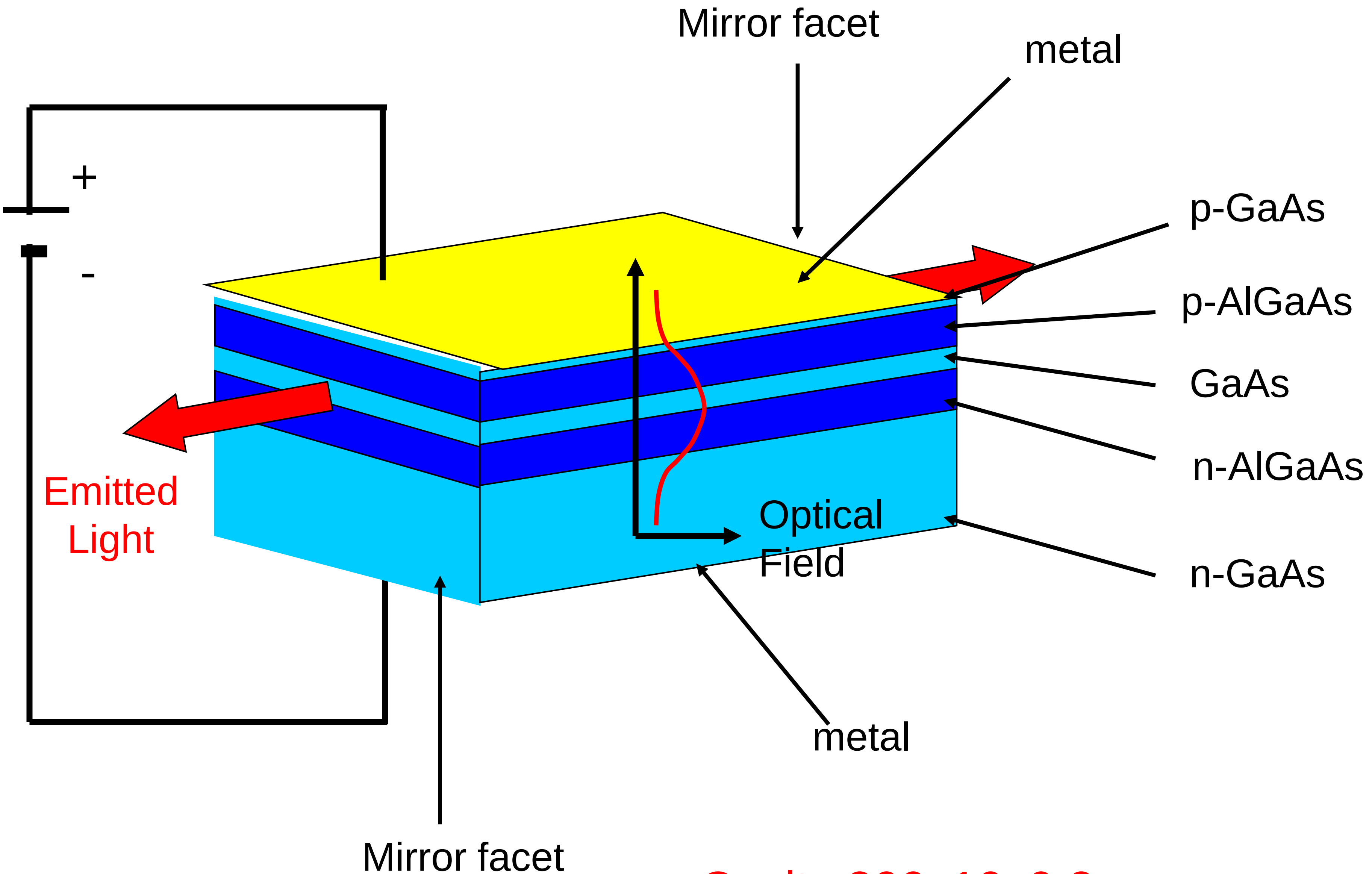


At high carrier densities within a diode

Recombination of electron and hole *stimulated* by another photon - can provide optical gain

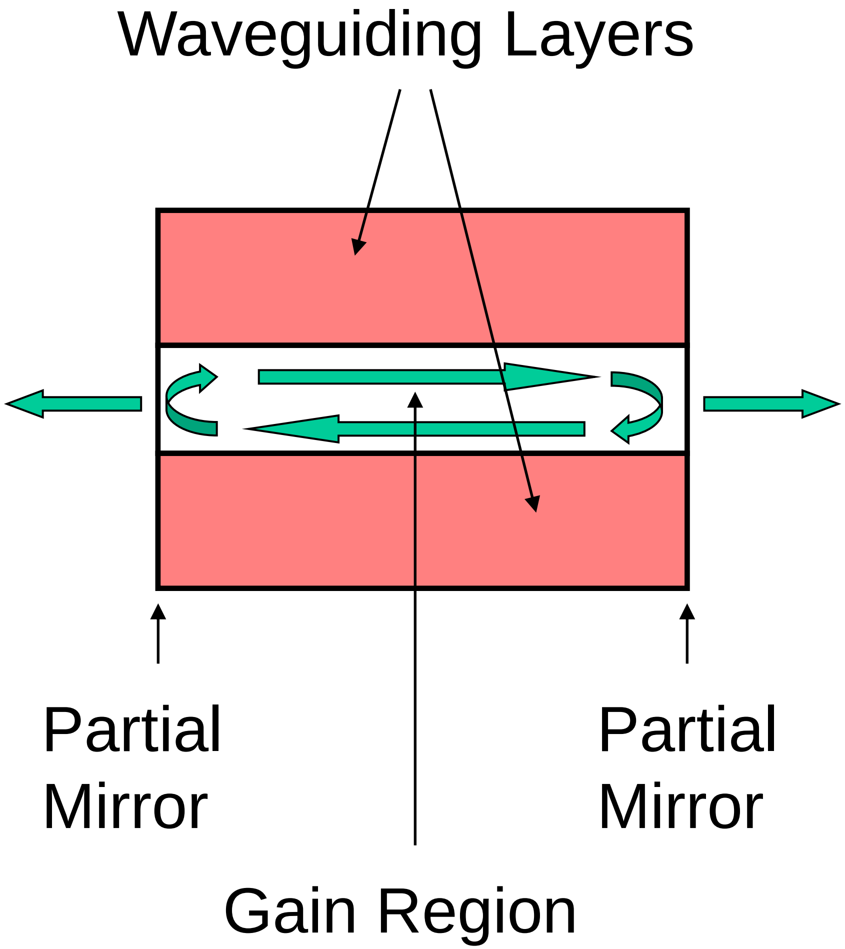
– new photon has same direction, wavelength, phase, as photon which stimulated the recombination
– typical decay time ~ps

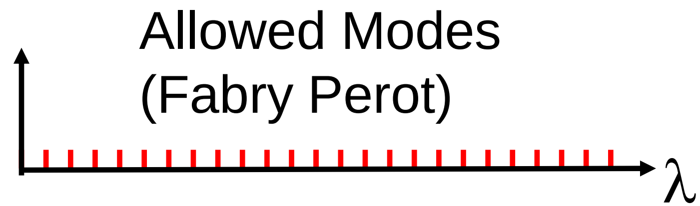
Heterostructure Laser

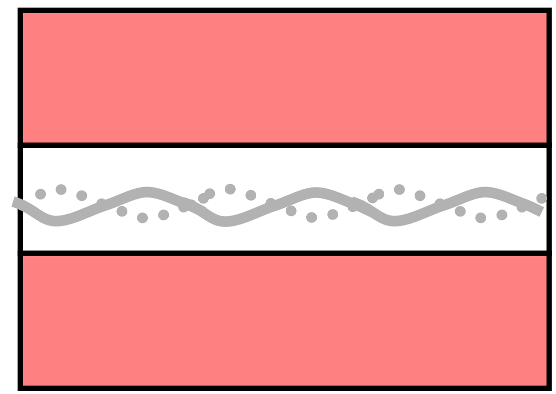


Cavity 300x10x0.2µm

Gain and Optical Feedback – LASER



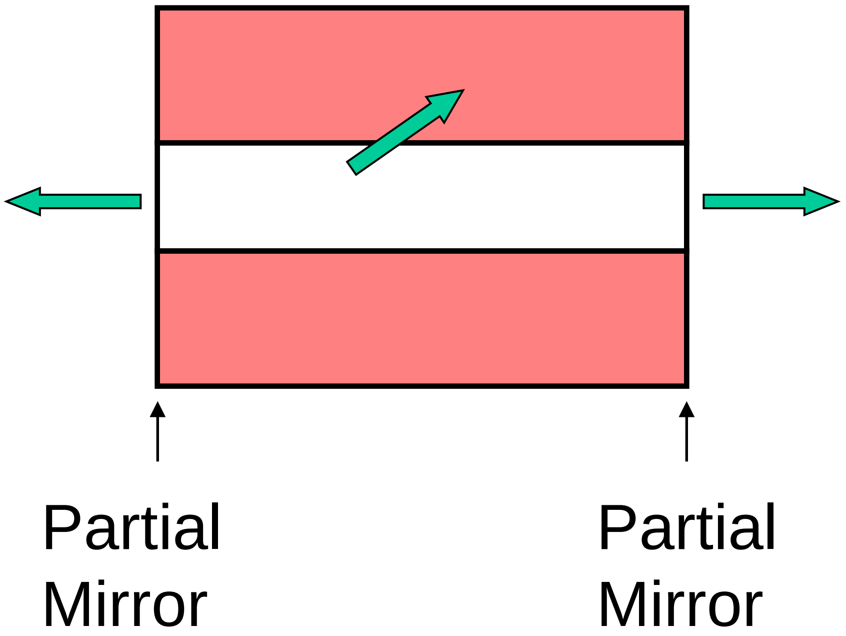




Standing Wave – gain effects cancelled for other wavelengths of light

Fabry Perot cavity length = nλ/2 for transmission

Losses and Lasing Threshold



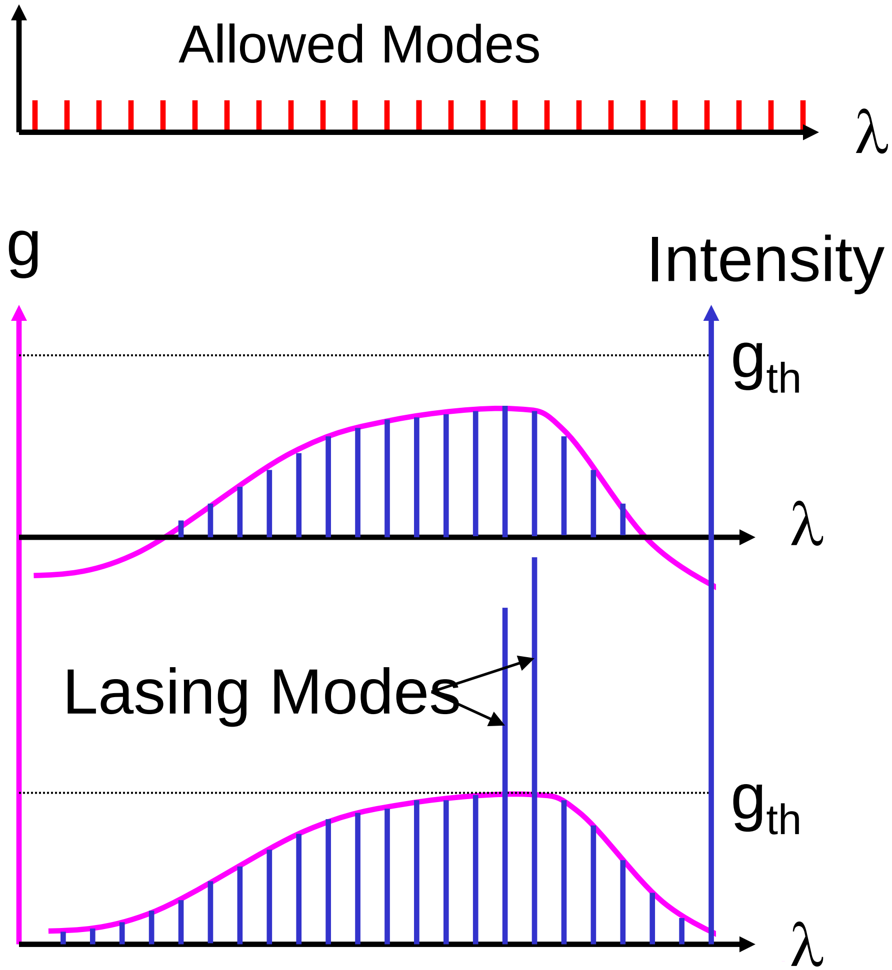
Light is lost from the cavity due to leakage through the partial mirrors

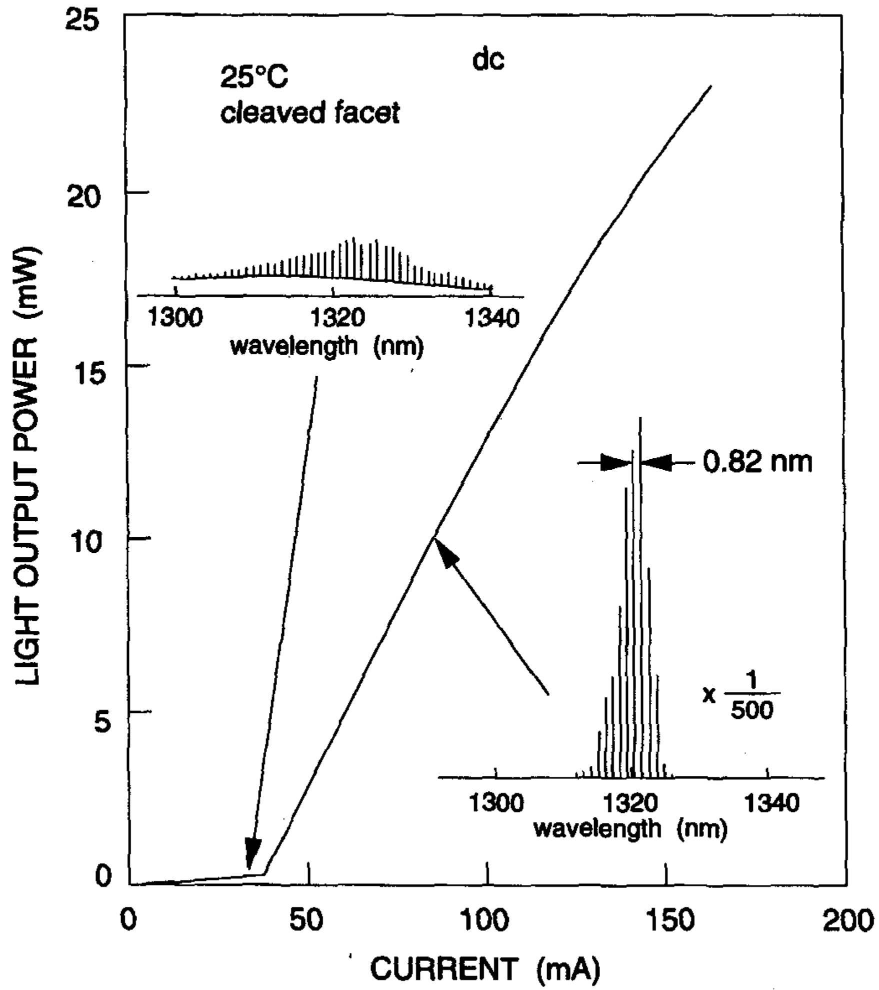
Also other internal losses – e.g scatting out of waveguide

When gain is equal to loss – system lases in a narrow wavelength range

Laser light is highly directional and efficiently produced

Lasing Spectrum - Function of Current





G_{th} = gain threshold

Transmitter Characteristics

LED
– spontaneous emission – low current densities

Laser
– high current densities – stimulated emission – optical feedback

Linewidth

LED	~100nm	(Spontaneous Emission)
FP Laser	~ 1nm	(Stimulated Emission + FP modes)
DFB Laser	~ 0.0001nm	(Stimulated Emission + Grating)

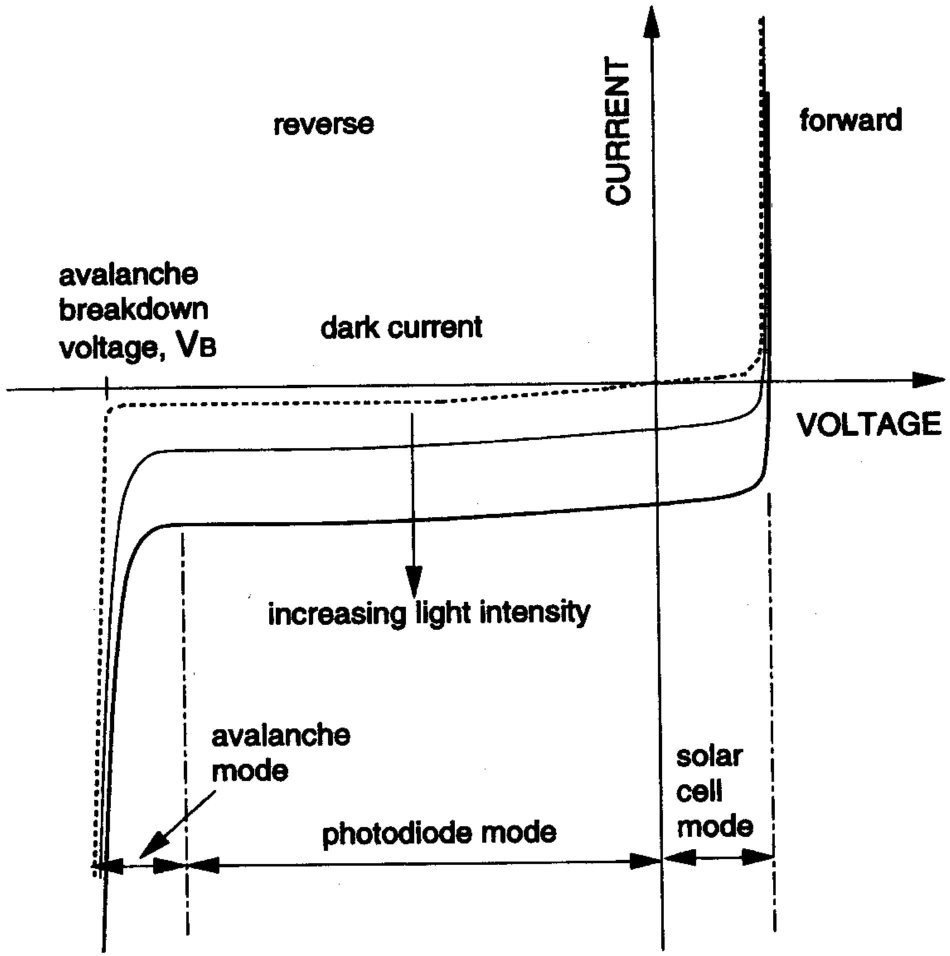
Launch Power

LED	low	(Spontaneous emission non directional)
Laser	high	(Stimulated emission directional)

Modulation Characteristics

LED	slow	(Spontaneous recombination ~ns)
LD	faster	(Stimulated recombination ~ps)

p-i-n photodiode



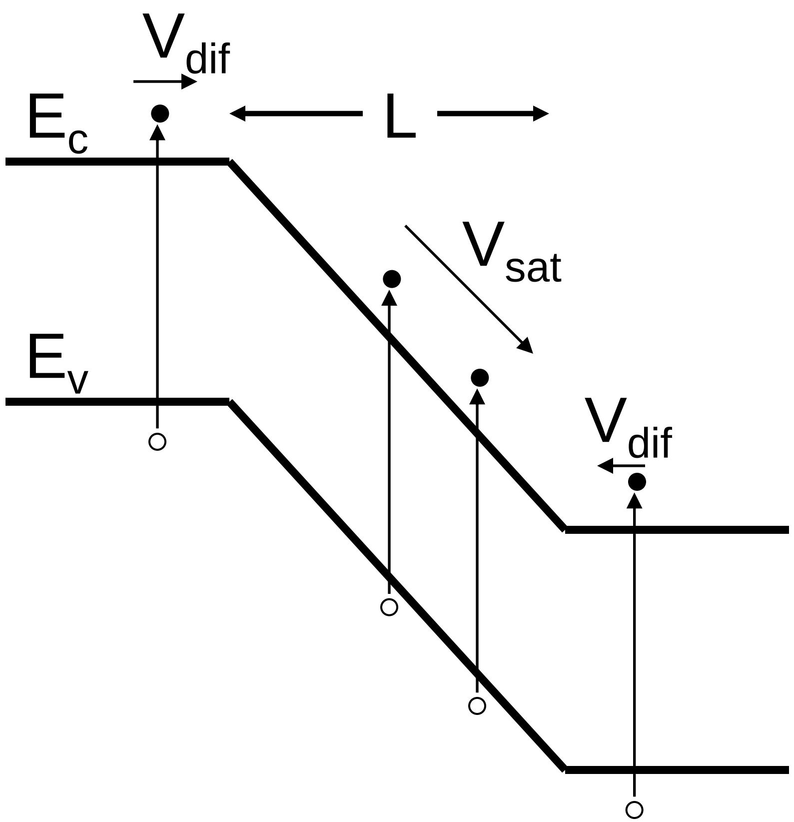
In reverse bias get large electric field across intrinsic region

Get electron and hole drift at saturation velocity (V_{sat}) ~10^5m/s

Additional signal generated by the photodiode is "dark current" (i.e. not due to background light)

Main origins – leakage currents due to
- crystal defects – need to grow high perfection crystals
- surface states – careful in fabrication – passivate surfaces

Carrier Collection Time



Minority carriers in doped regions may diffuse into intrinsic region (slow) – minimise diffusion in two ways – thin doped region and use of different materials

Carriers generated in intrinsic region

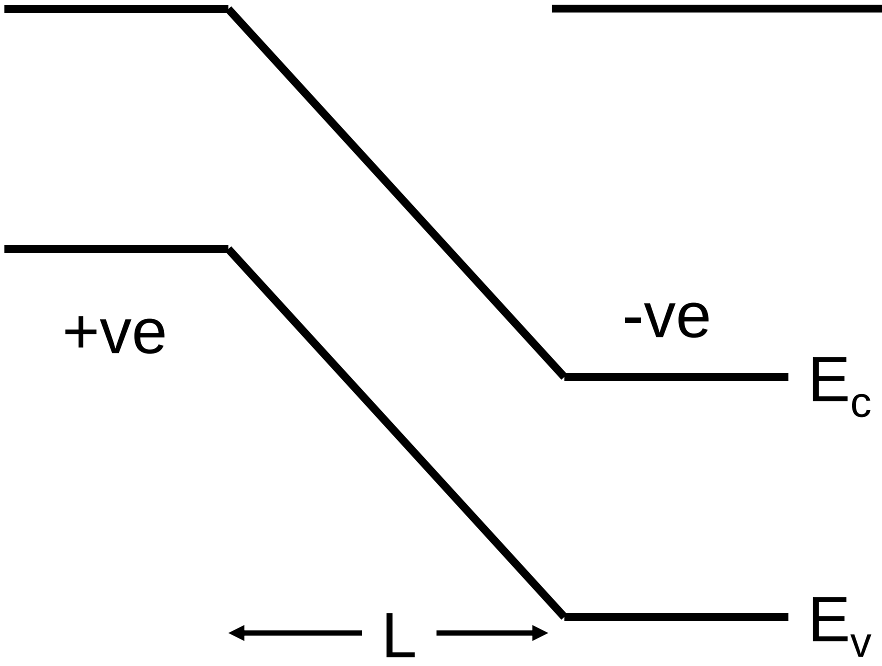
Carrier Collection Time for carriers across reverse biased diode

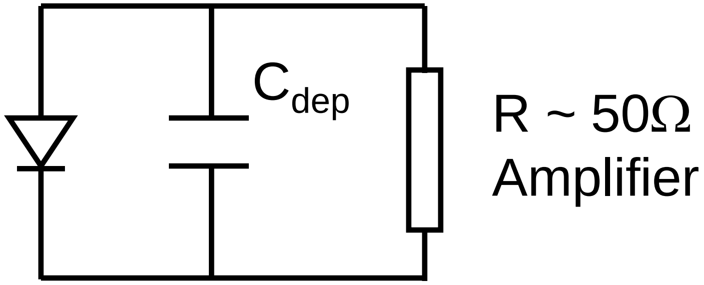
$t_c = L/V_{sat}$

V_{sat} ~10^5m/s L ~microns

Gives ~GHz operation

RC time constant





Need to consider junction capacitance

Have +ve and negative charge separated by a distance L

C ~$\varepsilon\varepsilon_0$A/L

For fast photodiodes need

Small area A,
trade off effects of varying L –
Absorption, Capacitance,
Carrier capture time

Response Time Example

InGaAs (ε= 12) photodiode 10um thick i-region
optical window 200um diameter
Saturation velocity = 10^5 m/s
Driving a preamplifier of 50 impedance

Transit time = L/v = $10 \times 10^{-6} / 10^5 = 1 \times 10^{-10}$ s = 0.1ns

$C = \varepsilon\varepsilon_0 A/L = 12 \times 8.85 \times 10^{-12} \times \pi \times (100 \times 10^{-6})^2 / 10 \times 10^{-6}$

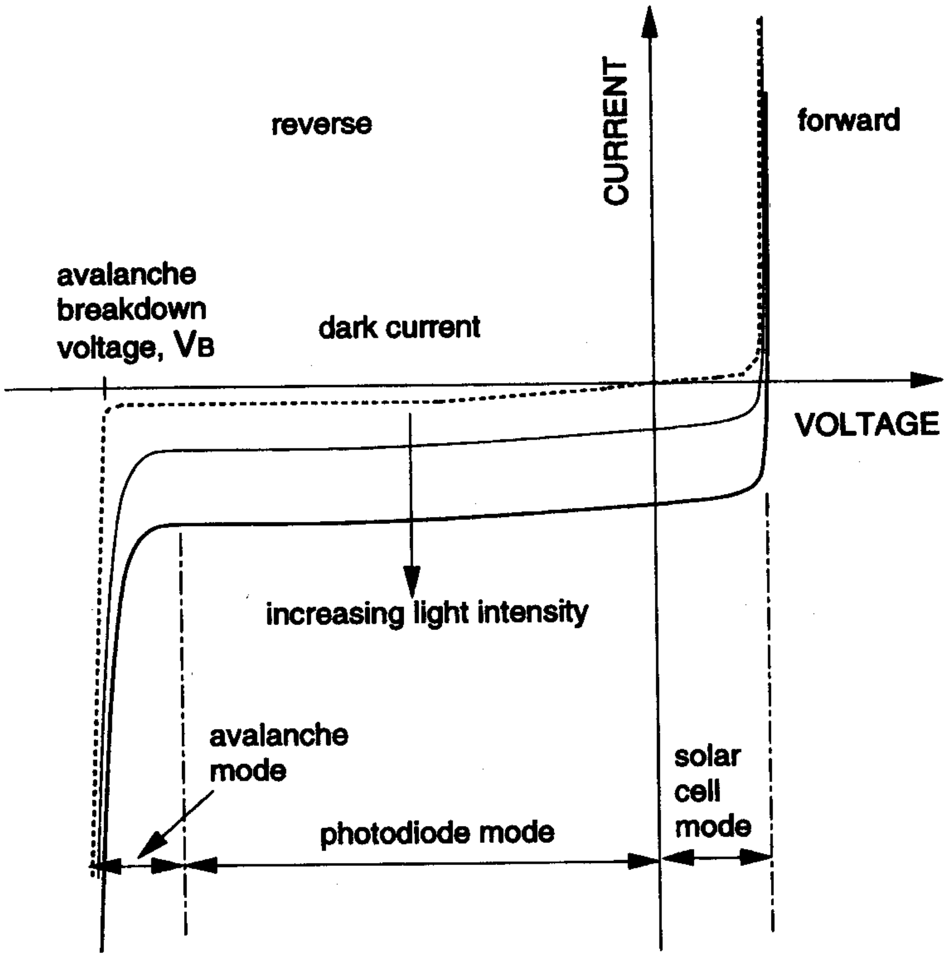
C = 0.33pF

RC = 0.017ns = τ

Response of photodiode is limited by carrier capture to 0.1ns = 10GHz

The detector broadens the pulse by τ so that pulses become indistinguishable when $\tau = 1/2B$, hence bit rate limited to $B = 1/(2\tau)$

Avalanche photodiode

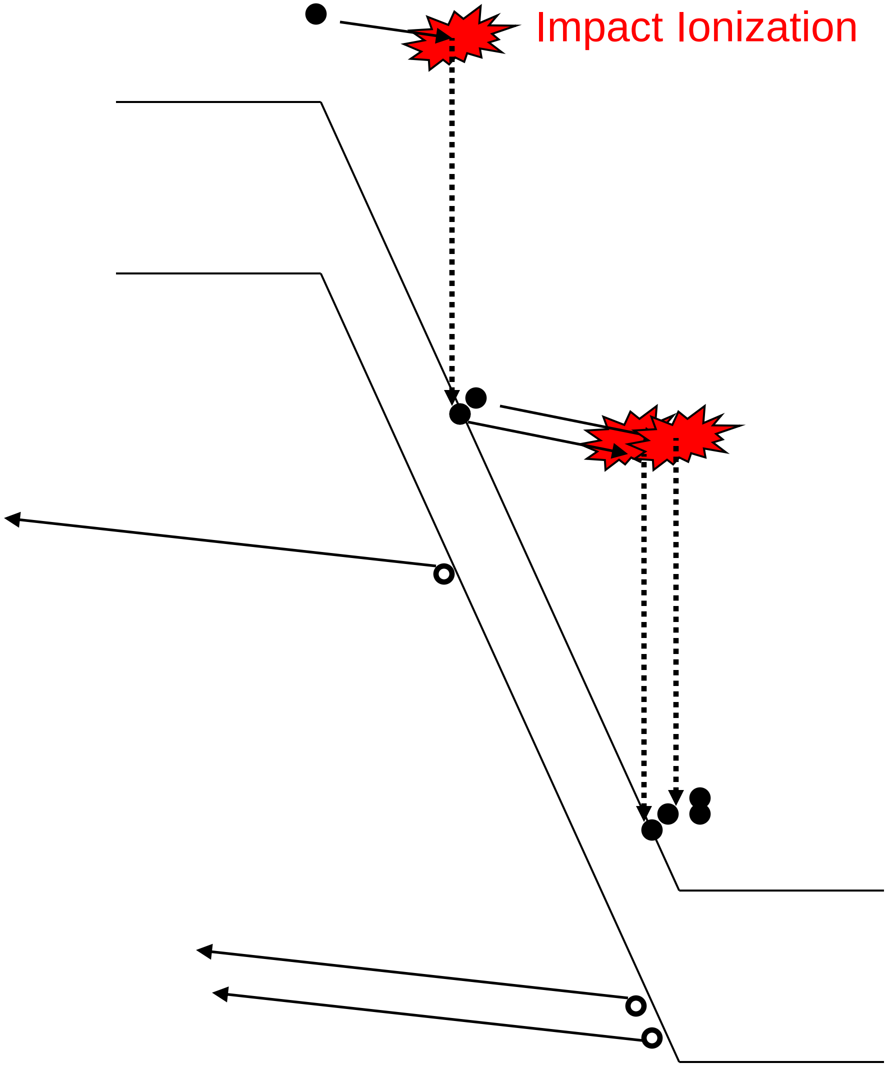


Operate in avalanche mode

Carriers gain enough energy to impact ionize additional carriers giving internal gain

Internal Gain makes more sensitive receiver – lower receiver power required

Multiplication and Avalanche Breakdown



For a p-i-n diode under high reverse bias an electron can rapidly gain a large kinetic energy which can be given up to produce another free electron (and hole)

This process can “run away” and cause an avalanche of current which if left unchecked may destroy the device

If controlled this produces a multiplication of the photocurrent – internal gain

Summary

Diodes

The key semiconductor device is the diode consisting of p and n doped regions separated by an undoped (intrinsic/depletion) region.   This undoped region will be designed to form a transmitter or receiver structure.

For transmitters the diode is operated in forward bias, where large currents can flow allowing electrons and holes to recombine, creating photons

For receivers the diode is operated in reverse bias where an incident photon creates an electron and hole which are separated by the electric field (preventing re-emission of light) and give rise to a (photo)current.

Summary (2)

Transmitters

Important factors for Transmitters are launch power, modulation rate, and spectral linewidth

LEDs have lower launch powers and modulation rates compared to laser diodes – because LEDs operate via spontaneous emission (long carrier lifetimes, any direction for emission), while lasers operate via stimulated emission (short carrier lifetimes,directional emission)

LEDs exhibit an emission spectrum which is broad ~100nm. One reason for this broad emission is thermal broadening. Laser diodes operate using optical feedback under conditions of high optical gain. The spectral width of the emission is determined by the form of the optical feedback.

For laser diodes the choice of the optical feedback mechanism can alter the spectral width – e.g. Fabry-Perot etalon or grating

Summary (3)

Receivers

Important factors for receivers are sensitivity and noise which will dictate the power required at the receiver to achieve a given bit-error rate.

Furthermore, the time response of the receiver is of importance. This is limited by the transit of carriers across the intrinsic region and the saturation velocity, and by the RC time constant. These two factors have competing requirements on the intrinsic region width - requiring small and large values for fast response times, respectively.

Internal gain can be achieved within a p-i-n diode if it is operated at high reverse biases. The multiplication of carriers in this region may be controlled giving ~10dB internal gain, significantly reducing the minimum receiver power.