ELEC4705 – Fall 2009

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LECTURE 20
Hetrojunction lasers and PhotoDetectors

Contents

20.1. Double Heterojunction Lasers

20.1.1. Problems with Homo-junction lasers

In previous lecture it was concluded that in homojunction semiconductor diode lasers there are a number of problems which result in very high current density to achieve lasing.

(a) Light is not confined to active region (lose power).

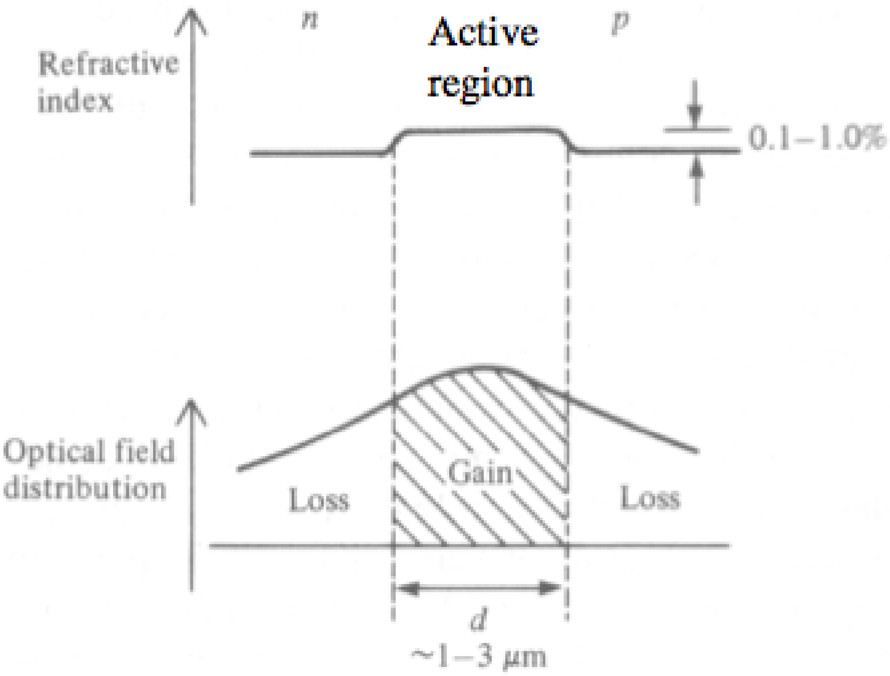
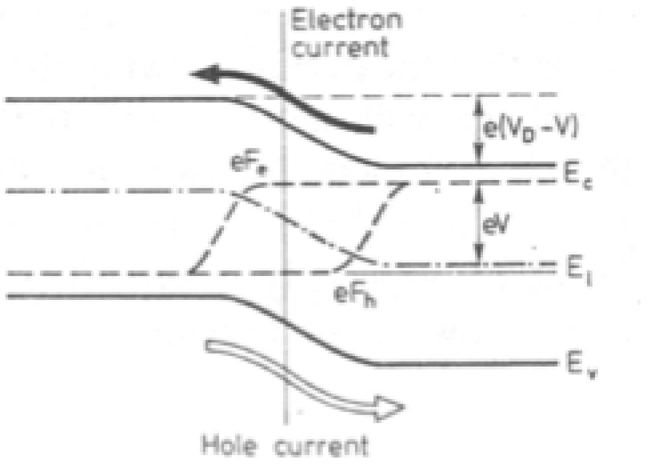


Figure 1. In this structure the additional carriers present in the active region increase its refractive index above that of the surrounding material, thereby forming a dielectric waveguide.

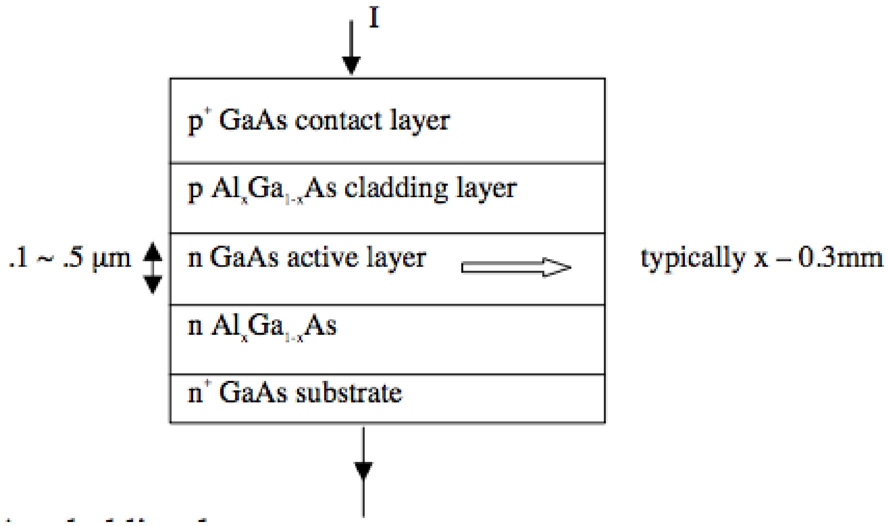
(b) Region of population inversion is not confined. This results in leakage current over the potential barrier.



20.1.2. Double Heterostructure (DH) Lasers

Heterojunction: A heterojunction is the junction formed at the contact between two semiconductors of different band gap energies.

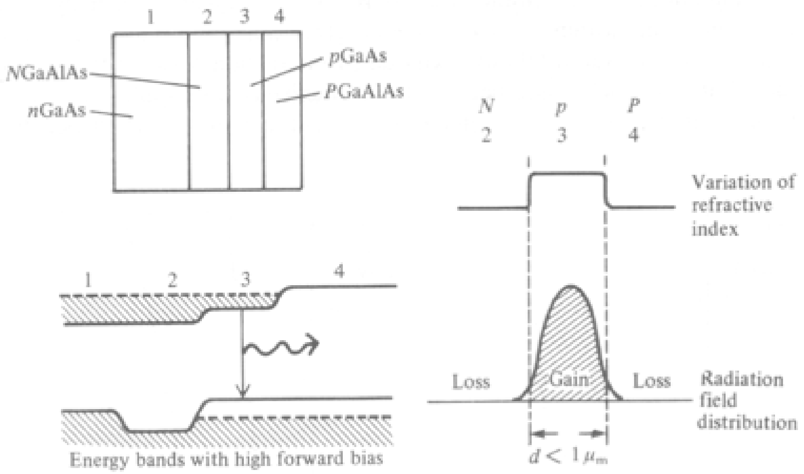
Typical modern semiconductor laser (more layers):



The *AlGaAs* cladding layers serve two purposes:

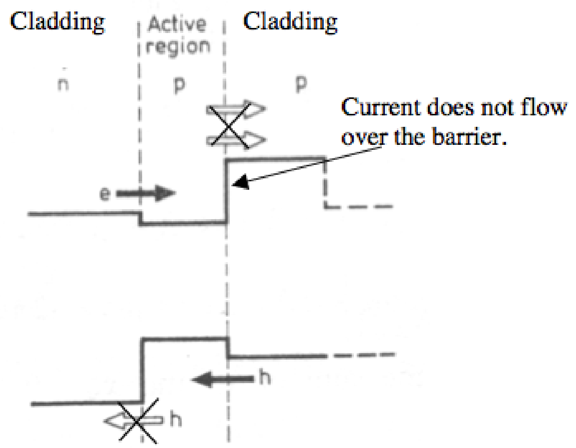
(a) Optical Confinement

As a general rule, the smaller the bandgap, the higher the refractive index. The active region with smaller bandgap has a higher refractive index compared with the cladding and this results in a better optical confinement. Because of the index difference, the active region in effect acts as a dielectric waveguide. The physical mechanism behind the confinement is total internal reflection as explained before.



(b) Free Carrier Confinement

Another feature of heterostructures is that the minority carriers cannot diffuse away from the active region because of the presence of the potential barrier. The injection currents of electrons and holes (black arrows) would be confined to the active region where they would recombine radiatively.



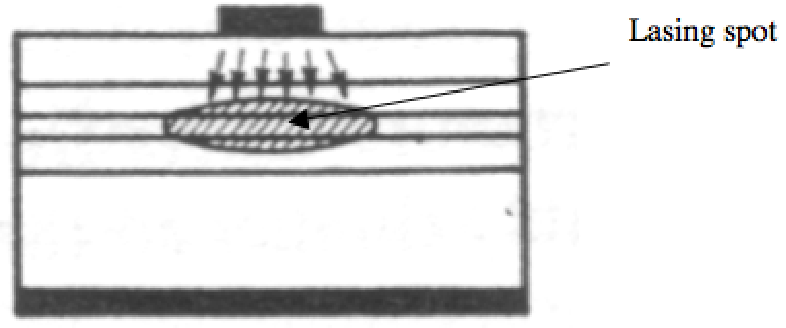
DH lasers have threshold current below 103A cm-2; continuous operation is possible (still need good heat sinking).

20.1.3. Laser Geometries

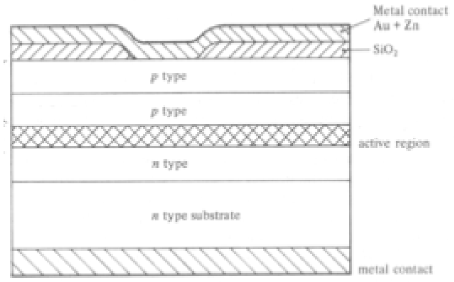
Stripe Generating Lasers

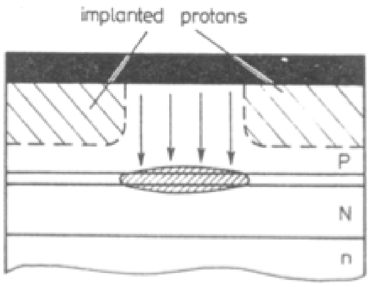
Further reductions in threshold current can be obtained by restricting the current along the junction plane into a narrow stripe which may only be a few microns wide.

Usually confine active region to a narrow stripe using geometry. By doing this, the radiation is emitted from a small area which simplifies the coupling of the radiation into optical fibers.



There are two possibilities for forming stripe by confining the current and therefore the optical generation.





- Lasing spot current largely confined to area under metal.
- Damage region on either side of metal stripe by intense proton bombardment makes material insulator

20.1.4. Controlling Output WaveLength

In simple DH laser with cleaved free mirrors, cavity length 300 m.

The two mirrors of the laser form resonant cavity and standing wave patterns are set up between the mirrors in exactly the same way that standing waves develop on a string.

The standing waves satisfy the condition $L = N/2$, where N is an integer. Each value of N defines an axial mode (or longitudinal) mode of the cavity. This can be used for further frequency selectivity. Due to thermal expansion, frequency shifts and other methods are required.

How can single frequency operation be achieved?

(a) Use shorter optical cavity not practical as it is difficult to handle very small chips.
(b) Use optical feed back in the device to eliminate other frequencies. Distributed Bragg Reflector (DBR) laser Add dimples into cladding layer to to reflect light.

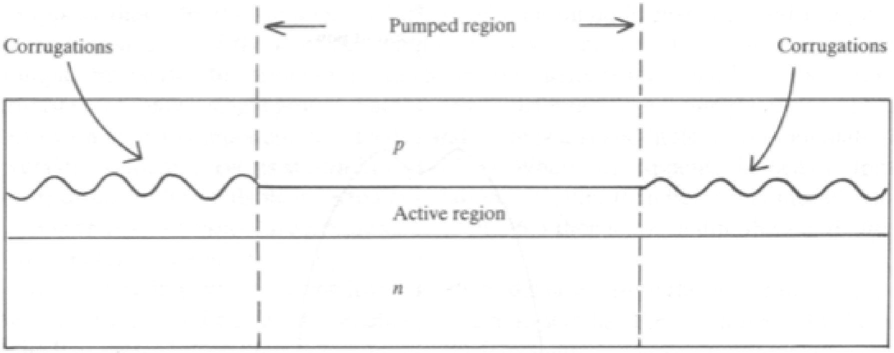
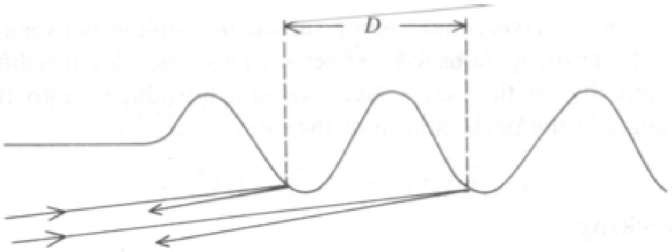


Figure 2. Distributed Bragg Reflector (DBR) laser

If dimple spacing $D = /2$ get constructive interference between beams reflected off each dimple and more precise control over output wavelength is possible (single mode operation).



To see this, we may consider two beams being reflected from different parts of the corrugations as shown in the figure. There will be constructive interference between the beams when 2D = m, where D is the wavelength of the corrugation.

Distributed Feed Back (DFB) laser is similar to DBR laser in principle, but dimpled grating extends across active layer causing optical feedback.

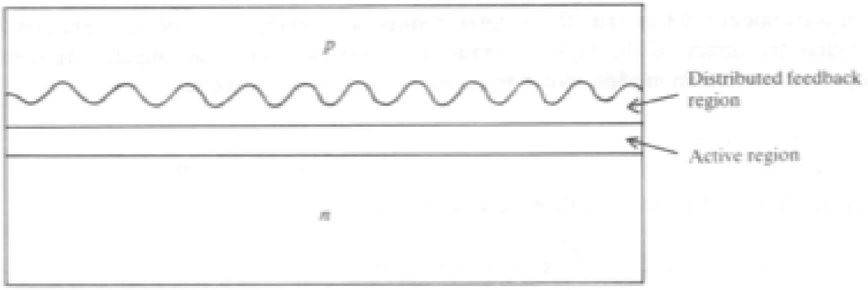


Figure 3. Distributed Bragg Reflector (DBR) laser

Long Wavelength optical communications

A silica fiber has minimum absorption at 1.5m, minimum dispersion at 1.3m, but not possible to use GaAs lasers or Si pin diode detectors at these wavelengths A preferred material is InxGa1-xAsyP1-y (Inx example of a quartenary) with appropriate choice of x and y, can lattice match to In P substrate.

- $In_{0.73}Ga_{0.27}As_{0.63}P_{0.37}$ $E_G = 0.95eV$ - ($\lambda = 1.5$ m)
- $In0.53Ga_{0.53}As$ $E_G = 0.73eV$ - ($\lambda = 1.3$m)

20.2. PhotoDetectors

To detect light, simply run a semiconductor laser backwards!

When a p-n junction is formed in a semiconductor material, a region depleted of mobile charge carriers is formed with a high internal electric field across it known as the depletion region. If an electron-hole pair is generated by photon absorption within this region, the internal field will cause the electron and hole to separate as shown in the following figure (figure 4).

$$J_{ph} = -e\eta\phi \tag{20.1}$$

where

ϕ: Photons per second

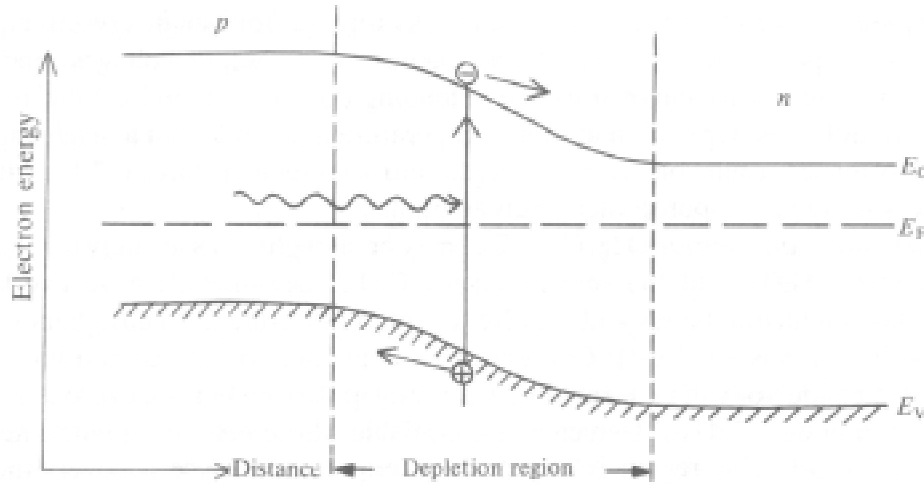


Figure 4. Energy Band Diagram, $J_{ph} = -e\eta\phi$

η: Quantum efficiency

$$\eta = \frac{photocarriers\ generated}{photons\ absorbed} \tag{20.2}$$

We may detect this charge separation in two ways, shown in figure 5

- If the device is left on open circuit, an externally measurable potential will appear between the p and n regions. This is known as the ***photovoltaic*** mode of operation.
- On the other hand, we may short circuit the device externally (usually operated under reverse bias) in which case an external current flows between the p and n regions. This is known as the ***photoconductive*** mode of operation.

The current-voltage characteristics of a p-n junction under various levels of illumination is shown in the figure 6. The dark characteristic (absence of light) is that of an ordinary p-n junction diode. Under increasing levels of illumination the curve is progressively shifted downwards. **The main drawback is the presence of a dark current which limits the ultimate sensitivity of the device.**

20.3. Structure

A simple pn photodiode is shown in figure 7. For high speed operation the depletion region must be kept thin to reduce the transit time of

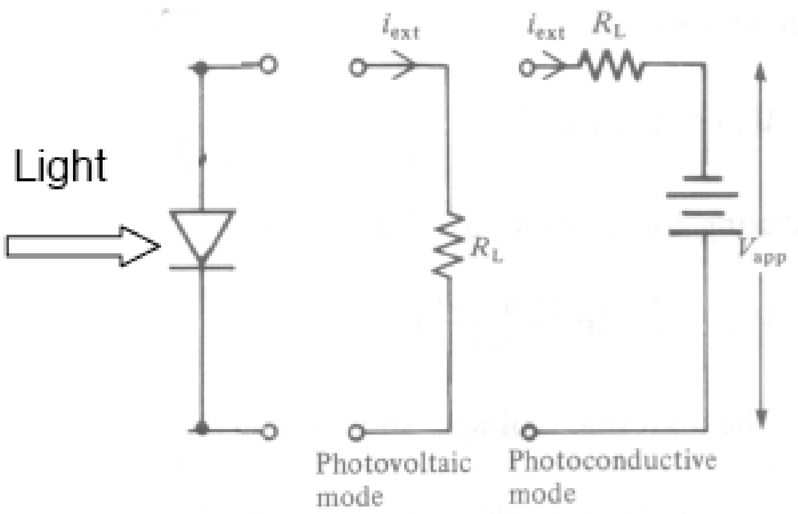


Figure 5. PhotoDetective modes

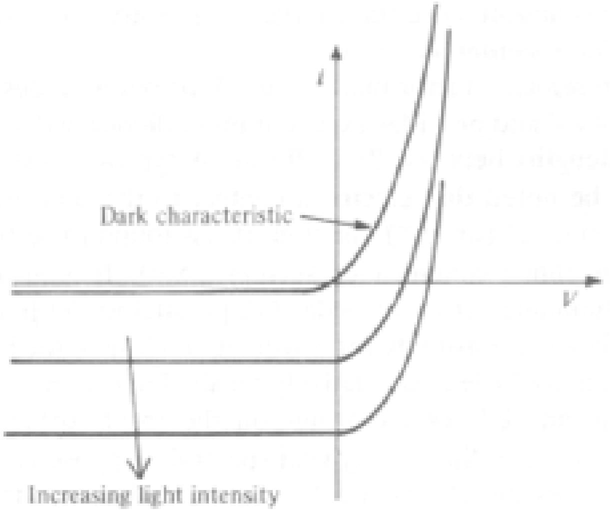


Figure 6. I-V curve

photocarriers. On the other hand, to increase the quantum efficiency, the depletion region must be sufficiently thick to allow a large fraction of the incident light to be absorbed. Thus there is a trade-off between the speed of response and quantum efficiency. The depletion width is given by equation 20.3.

$$W = \sqrt{\frac{2\varepsilon_s(V_{bi} - V)}{qN_A}} \tag{20.3}$$

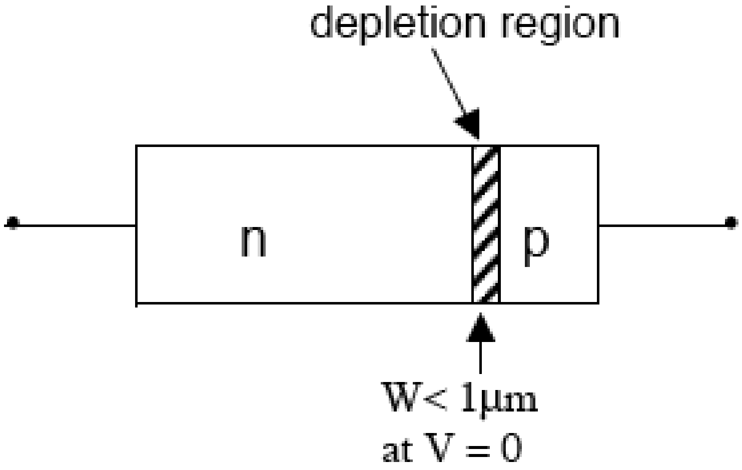


Figure 7. A simple PN diode structure

The depletion width is therefore a strong determinant of efficiency and speed of the device.

By introducing an intrinsic layer of material in between the junction a p-i-n diode is created. The depletion region thickness (the intrinsic layer) can be tailored to optimize the quantum efficiency and frequency response. We have a nominally intrinsic "i" layer, but in practice very lightly doped fully depleted region is formed. Photogenerated carriers are swept out of depletion region by high ε field and ideally, carriers move at $\sim V_{sat}$.

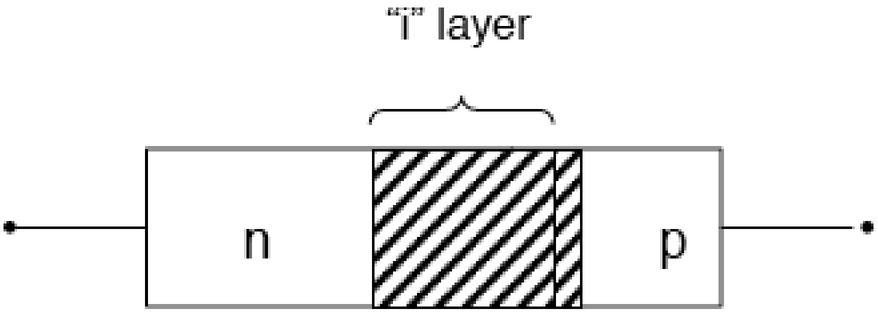


Figure 8. A PIN structure

20.4. Avalanche detectors

Useful internal amplification is achieved in the avalanche photodiode. In this device, a basic p-n structure is operated under very high (close to breakdown $\sim\ 100V$) reverse bias. In the very intense Electric field carriers can gain enough energy to enable other carriers to be excited across the energy gap by impact excitation. This results in an avalanche of carrier multiplication. **Thus, one photon produces many electrons/holes and lots of current (high sensitivity).** Figure 9 illustrates the principle of operation of an avalanche photodiode. An electron having reached the point A has sufficient energy above the conduction band bottom to enable it to excite an electron from the valence band into the conduction band (CD). In doing so, it falls from A to B.

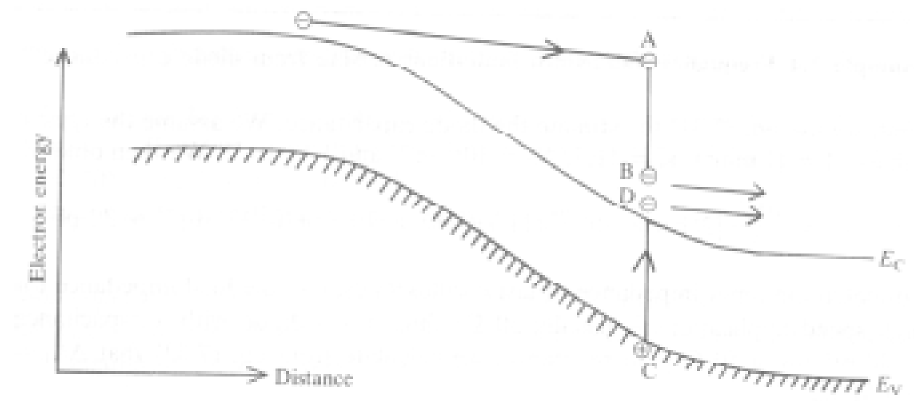


Figure 9. Avalanche

20.5. Photodetector materials

- Silicon:
    - band gap energy $= 1.1\,eV$, sensitive for $\lambda < 1100\,nm$
    - indirect gap
    - cheap, mature technology
- Germanium:
    - band gap energy $= 0.7\,eV$, works in telecommunications range
    - direct gap for $\lambda < 1550\,nm$
    - difficult material

- GaAs:
  - band gap energy $= 1.5\,eV$, sensitive for $\lambda < 860\,nm$
  - direct gap
- InGaAsP:
  - band gap energy $= 0.7\,eV$, works in telecommunications range
  - direct gap