

5. Describe the main heterostructure features exploited in electronic and optoelectronic applications

Heterostructure FET

1. Draw the equilibrium qualitative band diagram for an HEMT, pointing out the advantages with respect to a MESFET
2. Describe the channel sheet charge saturation effect in an HEMT, pointing out its consequence on the device electrical characteristic

Bipolar transistor

1. For an npn bipolar transistor, define and discuss all the current components crossing the emitter and collector junctions in forward operation. Define also the current amplifications α_F and β_F
2. Describe the physical causes of Early effect and discuss its impact on the static characteristics of an npn BJT, pointing out the consequences on the device doping levels
3. Define the base transit time and derive its relation with the other BJT parameters
4. Draw the equilibrium qualitative band diagram for a single heterostructure HBT, pointing out the advantages with respect to a homostructure BJT

Optoelectronic devices

1. Describe an optical communication system, analyzing the main optoelectronic components and their features
2. Describe optical fiber operation and their main applications
3. Discuss optical absorption and emission in a semiconductor, describing the advantages of using semiconductor alloys for optoelectronic applications
4. Describe a semiconductor LED, pointing out its main features
5. Describe the operating principle of a LASER diode
6. Describe the main photodetectors

BIPOLAR TRANSISTOR

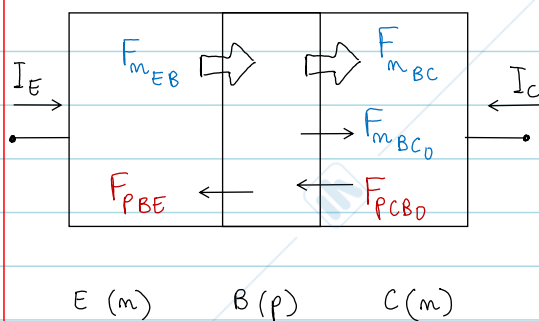
1 considering **mpn** transistor in **forward operations**

forward operation: **base-emitter junction forward** biased, $V_{BE} > 0$
base-collector junction reverse biased, $V_{BC} < 0$

making the assumption of **short base** in order that the injected electron flux is almost constant up to the BC junction

defining F_x as the flux per unit time of carriers x through the cross section of the device

$I = Q_x A J_x$ $x = m \Rightarrow I = -q A J_m$, $x = p \Rightarrow I = q A J_p$
 in order to simplify the relations, it's assumed $A = 1$



F_{mEB} flux of e from E to B

F_{pBE} flux of h from B to E

F_{mBC} flux of e from B to C coming from the EB injection

emitter current

$$I_E = -qF_{mEB} - qF_{pBE}$$

F_{mBC0} flux of e from **B to C** neglecting EB injection

collector current

$$I_C = qF_{mBC} + qF_{mBC0} + qF_{pCB0}$$

F_{pCB0} flux of h from **C to B** neglecting BE injection

where $qF_{mBC0} + qF_{pCB0} = I_{CB0}$ is the **reverse saturat. current** of the reverse biased BC junction

KCL \Rightarrow **base current** $\Rightarrow I_B = -I_E - I_C = qF_{mEB} + qF_{pBE} - qF_{mBC} - I_{CB0}$

ideal BJT $\Rightarrow I_E \approx -I_C$, $I_B \approx 0$ so it must be

$$F_{pBE} \approx 0$$

$$F_{mEB} \approx F_{mBC}$$

$I_{CB0} \approx 0$ which is granted as it is a reverse saturation current

figures of merit in forward operation

emitter injection efficiency $\gamma = \frac{F_{m_{EB}}}{F_{m_{EB}} + F_{p_{BE}}}$ ideal BST $\gamma \rightarrow 1$

base transport factor $b = \frac{F_{m_{BC}}}{F_{m_{EB}}}$, ideal BST $b \rightarrow 1$

substituting in the relations previously written for I_E, I_C

$$I_E = -q F_{m_{EB}} \frac{1}{\gamma} \Leftrightarrow F_{m_{EB}} = -\frac{\gamma I_E}{q}$$

$$I_C = q b F_{m_{EB}} + I_{CB0} \Rightarrow I_C = -\gamma b I_E + I_{CB0} = -\alpha_F I_E + I_{CB0}$$

defining $\alpha_F = \gamma b$ common base current amplification in forward operation, $\alpha_F \leq 1$ ($=1$ ideal BST)

$$-I_E = \frac{I_C - I_{CB0}}{\alpha_F}$$

substituting into $I_B = -I_E - I_C = \frac{I_C - I_{CB0}}{\alpha_F} - I_C \Leftrightarrow$

$$\Leftrightarrow \alpha_F I_B = I_C - I_{CB0} - \alpha_F I_C = (1 - \alpha_F) I_C - I_{CB0} \Leftrightarrow$$

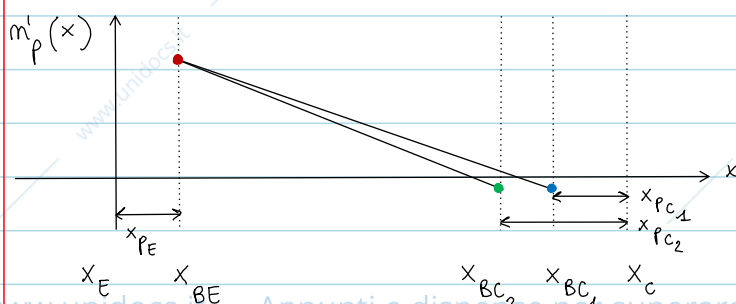
$$\Leftrightarrow I_C = \frac{\alpha_F}{(1 - \alpha_F)} I_B + \frac{I_{CB0}}{(1 - \alpha_F)}$$

defining $\beta_F = \frac{\alpha_F}{1 - \alpha_F}$ as the common emitter current amplification in forward operation since $\alpha_F \rightarrow 1 \Rightarrow \beta_F \gg 1$

2 Early effect

considering fixed V_{BE} and V_{CE} increasing from V_{CE1} to V_{CE2}

$$V_{BC1} = V_{BE} - V_{CE1}, \quad V_{BC2} = V_{BE} - V_{CE2} \Rightarrow V_{BC2} < V_{BC1}$$



from junction law applied to j. BE and j. BC

$$m'_p(x = x_{BE}) = \frac{m_i^2}{N_{AB}} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right)$$

$$m'_p(x = x_{BC_1}) = \frac{m_i^2}{N_{AB}} \left(e^{\frac{V_{BC_1}}{V_T}} - 1 \right) \approx -\frac{m_i^2}{N_{AB}} \text{ as } V_{BC_1} < 0$$

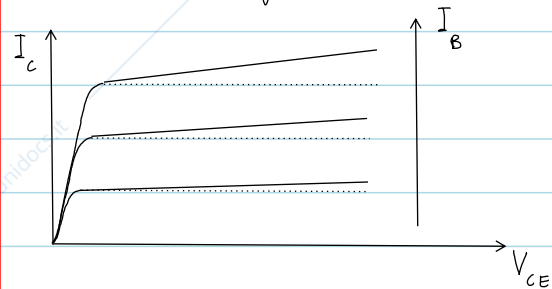
$$\text{also for } m'_p(x = x_{BC_2}) \approx -\frac{m_i^2}{N_{AB}}$$

as $|V_{BC}|$ increases the width of the depleted region of the BC junction increases $\Rightarrow x_{BC_2} < x_{BC_1}$

as it can be seen from the graph above

$\left| \frac{dm'_p}{dx} \right|_{V_{BC_2}} > \left| \frac{dm'_p}{dx} \right|_{V_{BC_1}}$ which implies that for $V_{BC} = V_{BC_2}$ the electron diffusion current increases so the I_c (I_E) current increases

as the depleted region of j. BC gets wider, the neutral region in the base gets smaller which decreases the recombination process in the base determining a reduction of I_B



in order to minimize the Early effect the depleted region at the BC junction should extend more in the collector and less in the base

as the global neutrality condition must hold

$$N_{AB} x_{p_c} = N_{D_c} x_{n_c}$$

if $N_{D_c} \ll N_{AB} \Rightarrow x_{n_c} \gg x_{p_c}$ so the collector's doping must be minimized

- 3 the transit time τ_t is defined as the average time minority carriers injected from E into B require to cross the base neutral region and reach the BC junction

defining Q_B as the total base charge due to minority free carriers

due to transit time definition $\Rightarrow \frac{dQ_B}{dt} = -\frac{Q_B}{\tau_t}$

recombination phenomena $\Rightarrow \frac{dQ_B}{dt} = -\frac{Q_B}{\tau_{mB}}$

also implies a variation of Q_B

τ_{mB} lifetime of minority carriers due to gener. / recomb. effect

in forward operation, neglecting I_{CB0} and assuming $\gamma \approx 1$

$$|I_C| = \left| \frac{dQ_B}{dt} \right|_t = \frac{|Q_B|}{\tau_t} \quad |I_B| = \left| \frac{dQ_B}{dt} \right|_r = \frac{|Q_B|}{\tau_{mB}}$$

$$\beta_F = \left| \frac{I_C}{I_B} \right| = \frac{\tau_{mB}}{\tau_t}$$

since $\beta_F = \frac{\alpha_F}{1 - \alpha_F}$, $\alpha_F = \gamma b$ if $\gamma \approx 1 \Rightarrow \beta_F \approx \frac{b}{1 - b}$

$$\beta_F \Big|_{\gamma \approx 1} = \frac{1}{1 - b} = \frac{\tau_{mB}}{\tau} \Leftrightarrow b = \frac{\tau_{mB}}{\tau_t + \tau_{mB}}$$

- 4 For an homostucture BJT it can be demonstrated that in order to attain $\gamma \approx 1$ it must be $N_{DE} \gg 1$, so the emitter doping level should be N_{AB} much greater than the base doping level

high emitter doping level determines bandgap narrowing in the emitter (reduction of the bandgap in the emitter) this phenomena causes a reduction of β_F

$$\beta_F = \beta_{F0} \exp\left(-\frac{\Delta E_g}{k_B T}\right)$$

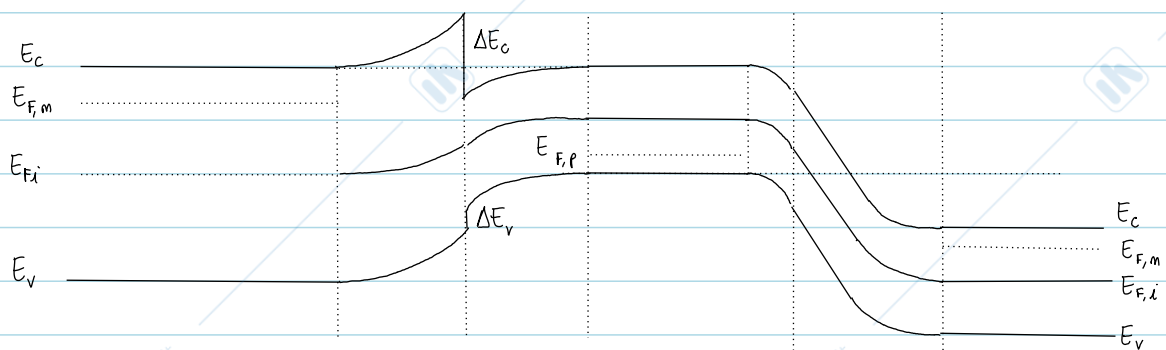
if we instead decrease the base doping level, the resistivity of the base neutral region increases. High value for the base parasitic resistance limits high freq. performance

Exploiting a heterostructure bip. trans., in which the emitter has a wider bandgap than the base, solve these limitations. The band discontinuity ΔE_v acts as a energy barrier for holes in the base, thus confining them in the base and minimizing the flow of holes from the base to the emitter. As a consequence, it's possible to obtain large values of γ_F without requiring to have a large doping ratio $\frac{N_{DE}}{N_{AB}}$. Furthermore, the doping level of the base

can be increased reducing the base parasitic resistance thus improving high freq. performance

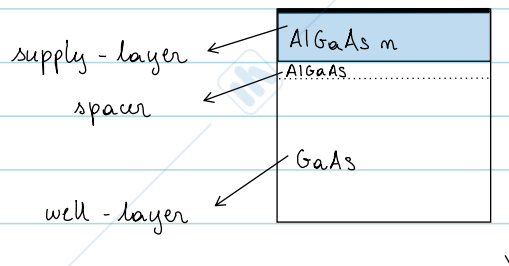
The band discontinuity ΔE_c permits only to high energy electrons to be injected into the base, causing a reduction of the transit time τ_t

as $\frac{1}{\tau_t}$ represents the maximum angular freq. that the device is able to follow, reducing τ_t improves freq. perf.
 $b \approx 1 - \frac{\tau_t}{\tau_{mB}}$ reducing τ_t permits to have b closer to 1



HETEROSTRUCT. FET

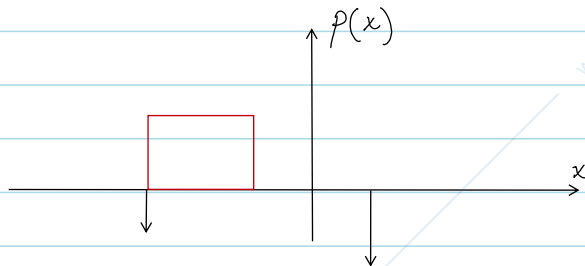
1 Assuming the following structure for an HEMT device (only structure under gate represented)



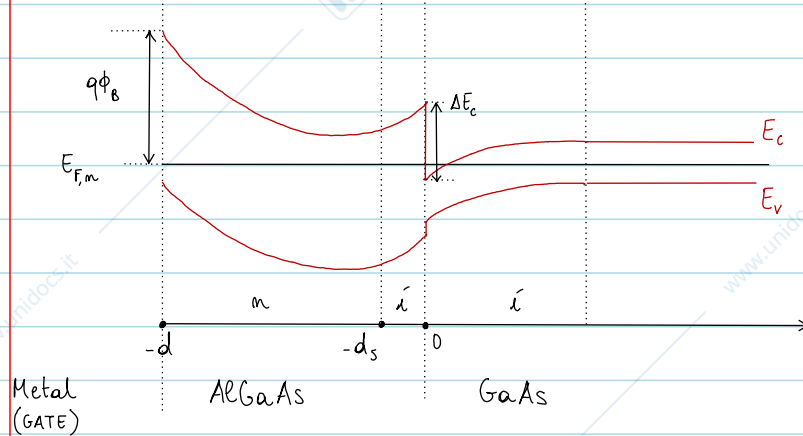
assuming $q\phi_n > q\phi_{\text{GaAs}} > q\phi_{\text{AlGaAs}}$

and from the fact that for correct operation the supply layer

must be completely depleted (in order to avoid spurious channels) a charge distribution could be represented as



from which a qualitative band diagram could be derived



the layer above the channel (AlGaAs, n doped) can be made thinner increasing the channel capacitance while, thanks to the conduction band discontinuity ΔE_c , maintaining a low value of $V_{th,0}$ meaning that an HEMT is able to carry more current for the same value of gate bias.

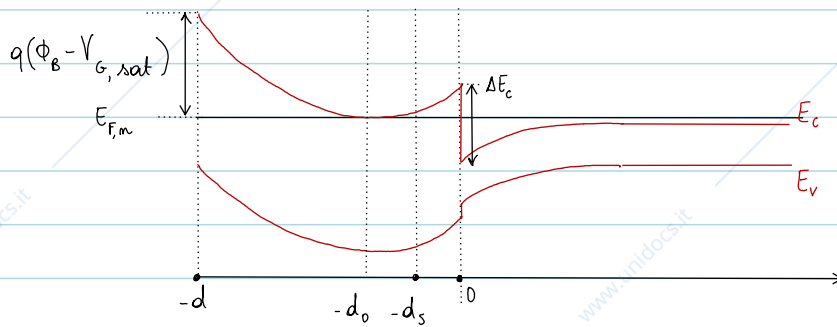
the most important advantage is that in HEMT devices the conduction channel is spatially confined in the quantum well resulting in a behaviour very close to the ideal one (for MESFET the analysis must be made very complex in order to model the real behaviour of the device).

2

the charge control law for HEMT device

$$-qm_s = -C_{ch}(V_G - V_{th,0}) \text{ from which } m_s = \frac{C_{ch}}{q}(V_G - V_{th,0})$$

as V_G is increased the conduction band lowers such that $E_c(-d_0) = E_{F,m}$ for a value of $V_G = V_{G,sat}$



$d_0 \triangleq x; \min\{E_c\}$
in the supply layer

as the concentration of e^- in the supply layer according to Boltzmann relation $n(x) = N_c \exp\left(-\frac{E_c - E_{F,m}}{k_B T}\right)$ so for $x = d_0$

and $V_G = V_{G,sat} \Rightarrow n(d_0) = N_c$ so in the supply layer the channel of the parasitic HESFET is created.

Increasing V_G increases the population in this parasitic ch. without making m_s grow, shielding the e^- in the main ch.

$$\text{imposing } \left. \frac{dE_c}{dx} \right|_{x=-d_0} = 0 \Leftrightarrow d_0 = d_s + \frac{\epsilon_w}{qN_D} \epsilon_{s_0,sat}$$

by imposing $E_c(-d_0) = E_{F,m}$ and recalling $E_{F,m} - E_c(0^+) = q\alpha m_{s,sat}$

$$m_{s,sat} = -(d_s + \Delta d)N_D + \sqrt{(d_s + \Delta d)^2 N_D^2 + 2 \frac{N_D \epsilon_{sup} \Delta E_c}{q^2}}$$

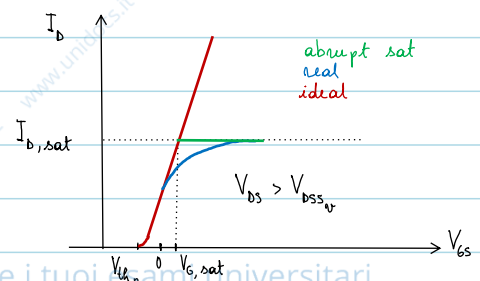
substituting $m_{s,sat}$ in the charge control law of HEMT

$$V_{G,sat} = V_{th,0} + \frac{qm_{s,sat}}{C_{ch}}$$

so in order to operate correctly the HEMT transistor $\Rightarrow V_{th,0} < V_G < V_{G,sat}$

this behaviour results in a maximum current that the device is able to carry

$$I_{D,sat} = W \alpha v_{m,sat} q m_{s,sat}$$



OPTOEL. DEVICE

1 An optical comm. sys. similarly to all other comm. sys is characterized by a transmitter, a communication channel and a receiver. An optical fiber which spatially confine the optical signal is used in order to realize the communication channel. Although optical fibers are characterized by a very low attenuation of the signal, which makes optical fibers optimal for long distance communications, repeaters (optical amplification stages) are used for extreme long distances. An example of optoelectronic devices used as optical amplification stage are Erbium Doped Fiber Amplifiers.

The transmitter is made up of the electrical signal source, an optical source (LED, LASER) and a modulator which is responsible to transfer the information from the electrical domain to the optical domain. Two type of modulation are possible:

internal \rightarrow current driving the light source is directly modulated by the signal \Rightarrow baud \approx 20 GHz

external \rightarrow optical carrier from the source modulated by ext. devices \Rightarrow baud \approx 100 GHz

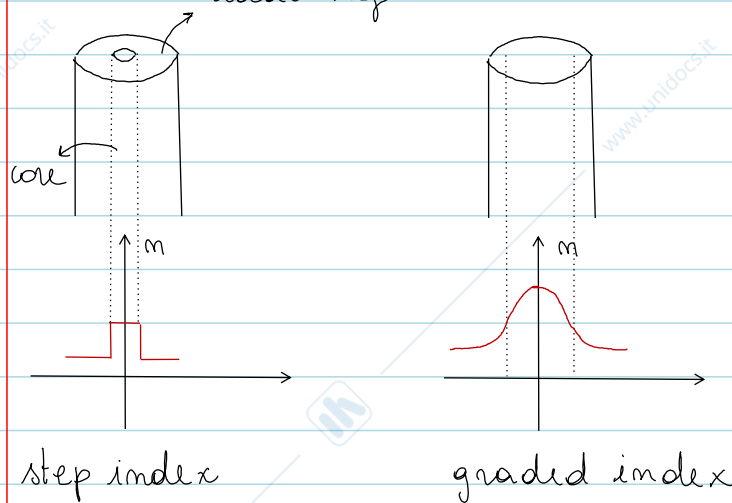
receivers must convert the upcoming optical signal into an electrical signal. The optical power is absorbed and converted into electrical power, by absorbing incoming photons and converting them into free carriers.

The main parameters of an optical receiver are:

sensitivity: min optical power required to detect signal
mod. bandwidth: detect signals with high bit-rate

2 Optical fibers are circular dielectric waveguides. In dielectric waveguides the spatial confinement of the electro-m. wave is obtained with perfect insulators. In this type of guided propagation, the field is confined into materials with high refractive index following the total reflection effect.

Optical fibers are usually made of SiO_2 , appropriately doped in order to change refractive index



The behaviour of step index optical fibers could be studied applying geometrical optics if the diameter of the core is much smaller to the wavelength of the optical signal. If this requirement is not met it is necessary to solve Maxwell equations.

Advantages of optical fibers:

low attenuation (minimum in III window $\Rightarrow 1.55 \mu\text{m}$ of the order of 0.2 dB/Km)

3

The emission of a photon in a sc. corresponds to the recombination of an e^-/h couple. The recomb. process provides energy to the semicond. energy linked to the energy bandgap E_g of the material $\Rightarrow E_g = hf$ which links the emission freq. of the photon to the bandgap of the material.

The absorption of a photon instead corresponds to the fact that the energy of the photon is used to generate an e^-/h pair. The absorption of the photon can only take place if the photon energy $hf > E_g$ bandgap of material.

The optical generation/recomb. are more favourable in direct bandgap compound semicond.

Direct bandgap sc are characterized by the fact that the minimum value of the cond. band and the max. value of the valence band occurs for the same value of the wave vector.

As photons as zero mass they don't carry any momentum. Defining free carrier momentum as $p = \hbar \cdot \bar{k}$, \bar{k} wave vector.

As during recomb/gen. process energy and momentum must be conserved, by exploiting direct bandgap as E_c and E_v are characterized by the same value of \bar{k} , the electron and hole have the same momentum and so no momentum exchange is required in order to guarantee momentum conservation.

Generally direct bandgap sc are used to realize efficient and high quality light source LASER

Absorption of photons correspond to a generation of e^-/h process with generation rate G_{op}

As the optical power is absorbed following

$$P_{op}(x) = P_{op}(0) e^{-\alpha x}$$

as the variation of the absorbed optical power
 $dP_{op} = P_{op}(x+dx) - P_{op}(x)$ as $dx \rightarrow 0 \Rightarrow dP_{op} \approx -\alpha P_{op}(x) dx$

each absorbed photon having energy hf generates an e/h pair so G_{op} is the number of e/h generated per unit time/volume

$$\Rightarrow G_{op}(x) = -\frac{\alpha P_{op}(x)}{hf} = -\frac{\alpha P_{op}(x)}{h\nu} = \alpha \phi_0(x) \quad \begin{array}{l} \alpha, \text{ abs coeff} \\ \phi_0(x), \text{ photon flux} \end{array}$$

- 4 LED light emitting diode are pn junction. In depleted region of a pn junction carriers recombination prevails in forward bias. The material is chosen in such a way that optical generation is the dominant phenomenon in the depleted region among the recombination phenomena, so that the injected carriers from the neutral regions into the depleted region are converted into photons. In order to guarantee the max. efficiency in this conversion process a heterostructure is exploited in order to create a quantum well in the depleted region. By spatially confining the carriers injected into the depleted region the ratio between the optical power and the injected current is improved.

Spontaneous emission is dominant in LED resulting in a low spectral purity of the emitted photons $\Delta\lambda \approx 1\mu\text{m}$ that in freq. domain corresponds to $\Delta f = 6\text{ THz}$

The emitted optical power $P_{op} = hf \frac{I}{q} \approx E_g \frac{I}{q}$, $I \triangleq$ diode current
 in reality an efficiency coeff must be included as not every e/h recombines and generates photons (also reflected and/or reabsorbed)

Exploiting direct modulation, bandwidth $B = \frac{1}{2\pi\tau_r}$ where τ_r is the radiative lifetime which decreases as I increases. $\max\{B\} \approx 200\text{ MHz}$ which is a quite low value \Rightarrow LED are characterized by a quite slow response.

5

In LASERS stimulated emission is dominant. In stimulated emission the photons generated are coherent (same physical property) to the photons already present into the structure, resulting in a much better spectral purity of the optical signal created. As stimulated emission probability is proportional to the density of photons in the region where photons are created. The spatial confinement of the electromagnetic wave is obtained by a resonating cavity tuned to a frequency f_0 which creates a positive feedback that increases the photons generated by stimulated emission. So by increasing the total current injected into the system, by means of the resonant cavity stimulated emission prevails on spontaneous emission. This phenomenon is characterized by a threshold value of the current for which stimulated emission starts to become dominant on spontaneous emission.

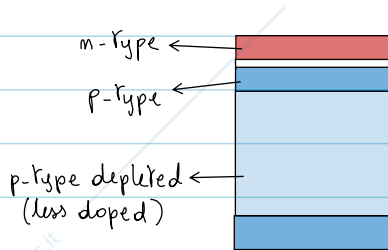
5

Photodetectors are capable to absorb photons and provide a current directly proportional to the incident optical power
 Photo-conductors: uniform material where as photons are absorbed the free carrier concentration is changed thus changing the material electrical conductivity. The material should be as intrinsic as possible in order to obtain the best sensitivity (as in general for this type of sensors sensitivity is low)

Photodiodes: reverse bias pn junction - The current is nominally negligible (reverse sat. current) and by generating free carriers in the depleted region causes an increase of the reverse sat. current. The result is a device with better sensitivity as photo-conductors.

By enlarging the volume of the depleted region in which carriers are generated, performance improves: this concept is exploited in pin photodiodes.

avalanche photodetectors



reverse bias large enough to bring the E in the depl. region of pn junction close to the breakdown value of the structure

photon absorbed in p-depleted region \Rightarrow e/h couple. The e is carried towards to pn junction where it could create more carriers because of impact ionization. Large variations of $I_s \Rightarrow$ better sensitivity.

Metastable device (more noise as amplification occurs)

the most important limitation of these devices is caused by the low minority carrier lifetime
 main parameter to be optimized: responsivity, efficiency in converting the incident optical power into an electrical signal (current)

$$R = \frac{I}{P_{op}} = \frac{q}{hf} \frac{e/h}{\frac{\text{photons}}{t}} = \frac{q \cdot e/h}{hf \text{ phot.}} = \eta \frac{q}{hf}$$

↑ quantum efficiency