Module 6

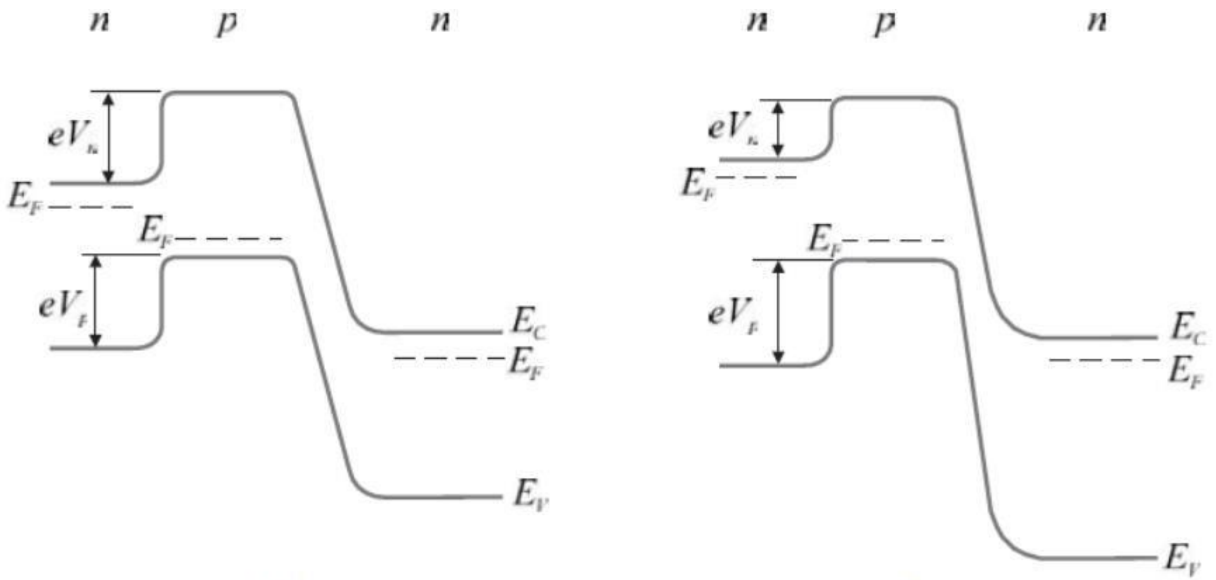
HETEROJUNCTION BIPOLAR TRANSISTORS(HBT)

- A desirable property for junction bipolar transistors is to have a high value of the amplification factor *β* up to the largest frequencies possible.

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$$

- In order to obtain a high *β*, both the current gain through the base, *α*, and the injection efficiency factor of the emitter, *γ* , should be as close as possible to unity.
- This condition requires the emitter region doping level to be much higher than that of the base region.
- However, there is a reduction in the energy gap of semiconductors when the doping level is very high which results in a notable reduction in carrier injection from the emitter region to the base region.
- Thus emitter could be fabricated by using a wide bandgap semiconductor.
- Bipolar transistors fabricated by using heterojuntions are called *heterostructure*

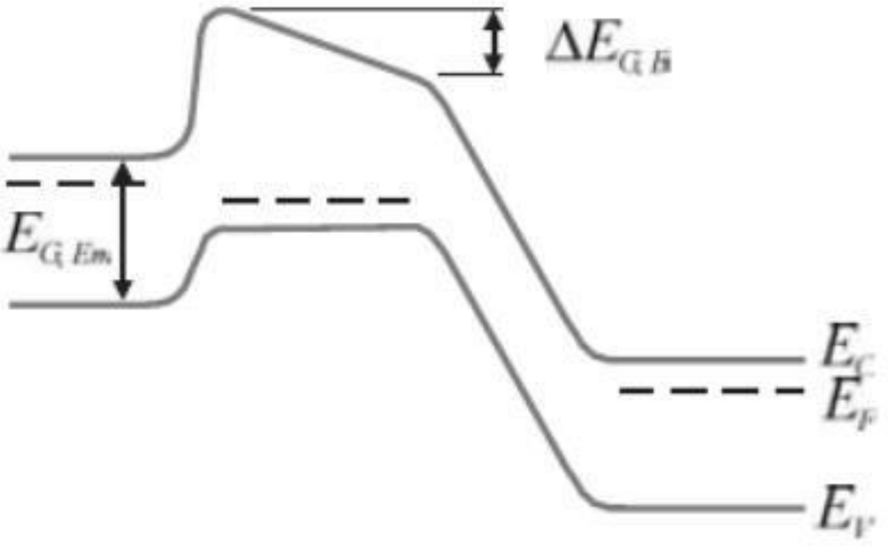
  bipolar transistors (HBT)



(a) (b)

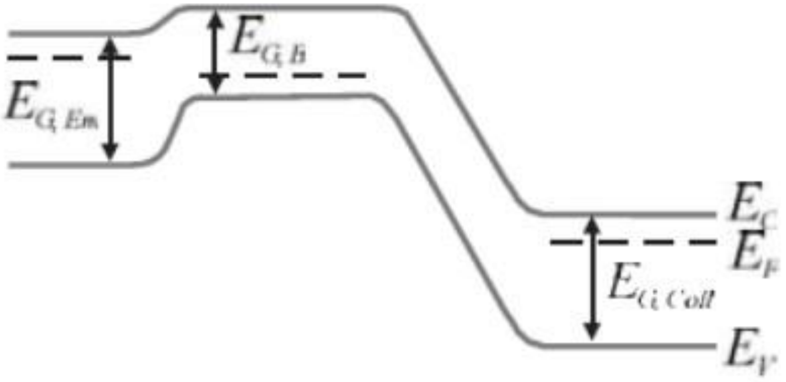
Band structure under polarization in the active region of: (a) homojunction bipolar transistor; (b) heterojunction bipolar transistor (HBT).

- Note that in second figure the band gap of the emitter is larger than that of the base region.
- Similarly, the barrier for the injection of electrons from the emitter to the base, *eV*n, is lower.
- The barrier height difference has an enormous influence on carrier injection through the emitter–base junction.
- The simultaneous reduction of the base resistance and the capacitance of the emitter–base junction are essential for the correct performance of HBTs at high frequencies.



(a) HBT with graded base region;

- Another interesting feature of heterostructures is the possibility to fabricate a graded base HBT.
- As a consequence, an internal electric field is created which accelerates electrons travelling through the base region, and therefore, allows HBTs to operate at even higher frequencies.



) double HBT, with wide bandgap emitter

- If the collector region is also fabricated from a wide bandgap semiconductor, the breakdown voltage of the base–collector junction can be notably increased.

- Due to the good behaviour of AlGaAs–GaAs heterojuntions, and to high values of the mobility, HBTs are usually fabricated from III-V semiconductors.
- In a typical HBT, the base length can be of about 50 nm and is heavily doped.
- These transistors can be used up to frequencies of approximately 100 GHz.
- The use of InGaAs–InAlAs and InGaAs–InP based heterostructures allows even higher operating frequencies (∼200 GHz) to be reached.
- An additional advantage of III-V semiconductor-based HBTs is the possibility of their integration of optoelectronic devices in the same chip.
- These *optoelectronic integrated circuits (OEIC)* usually include

semiconductor lasers.

- There are also research projects focused on the development of HBTs based on silicon technology, which make use of different silicon compounds as wide bandgap materials.

- One of these compounds is silicon carbide (SiC), whose bandgap is 2.2 eV.

- Another material widely employed is hydrogenated amorphous silicon, whose bandgap is 1.6 eV.

- The most promising of all silicon compounds for the fabrication of HBTs are SiGe-based alloys, from which heterojunctions can be formed.

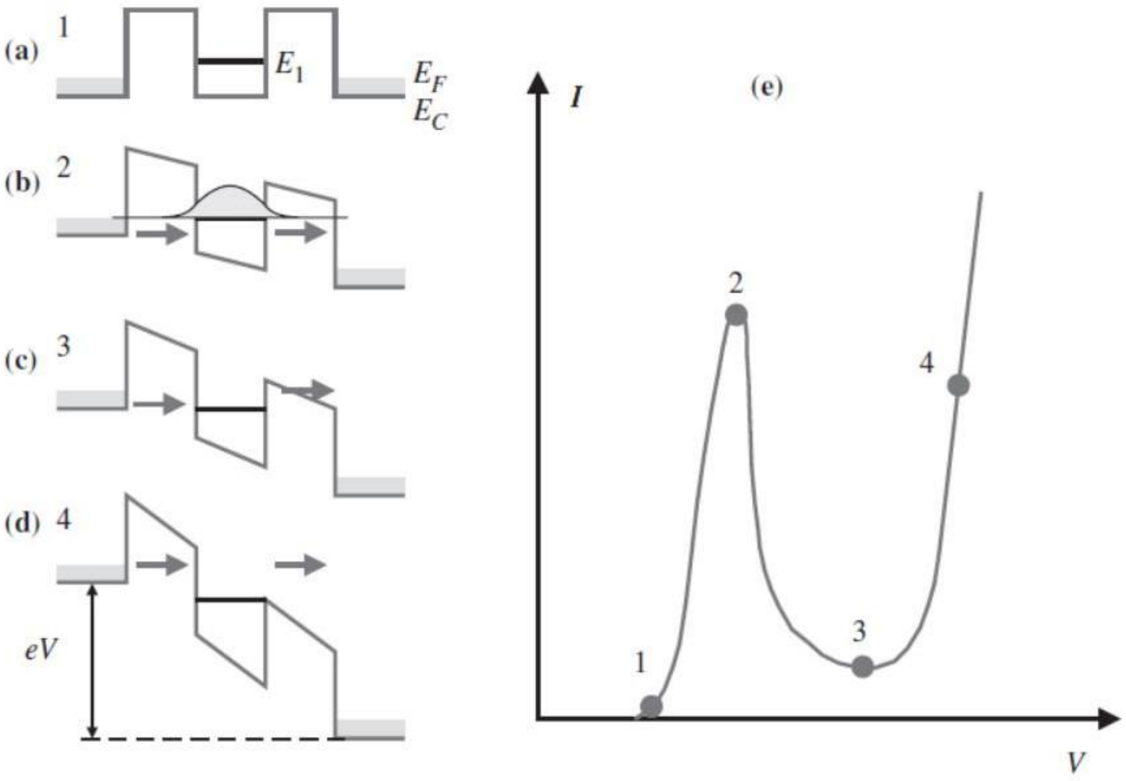
- Commercial HBTs have cut-off frequencies over 100 GHz, while research devices have reached values close to 400 GHz

- These HBTs have a higher power dissipation than MOSFETs, but can be operated at higher frequencies and with lower noise.

- All these improvements make the SiGe-based HBTs very promising devices.

RESONANT TUNNEL EFFECT

- Electrons in heterojunctions and in quantum wells can respond with very high mobility to applied electric fields.
- Here response to an electrical field perpendicular to the potential barriers at the interfaces will be considered.
- Under certain circumstances, electrons can tunnel through these potential barriers, constituting the so-called perpendicular transport.
- Tunnelling currents through heterostructures can show zones of *negative differential resistance (NDR)*, which arise when the current level decreases for increasing voltage.
- *Resonant tunnel effect (RTE)* takes place when the current travels through a structure formed by two thin barriers with a quantum well between them.



Schematic representation of the conduction band of a resonant tunnel diode: (a) with no voltage applied; (b), (c), and (d) for increasing applied voltages; (e) current–voltage characteristic.

- The thickness of the quantum well is supposed to be small enough (5–10 nm).
- The well region is made from lightly doped GaAs surrounded by higher gap AlGaAs.
- Let us suppose that an external voltage, *V*, is applied, starting from 0V.
- some electrons tunnel from the n+ GaAs conduction band through the potential barrier, thus resulting in increasing current for increasing voltage
- When the voltage increases, the electron energy in n+ GaAs increases until the value $2E1/e$ is reached, for which the energy of the electrons located in the neighbourhood of the Fermi level coincides with that of level *E*1 of the electrons in the well.
- In this case, resonance occurs and the coefficient of quantum transmission through the barriers rises very sharply.
- If the voltage is further increased the resonant energy level of the well is located below the cathode lead Fermi level and the current decreases (region 3), thus leading to the socalled negative differential resistance (NDR) region.

RESONANT TUNNELING DIODES (RTDs)

- used in microwave applications

- *RTDs* are based on *resonant tunnel effect (RTE)*.

- A figure of merit used for RTDs is the peak-to-valley current ratio (*PVCR*), of their *I–V* characteristic, given by the ratio between the maximum current (point 2) and the minimum current in the valley (point 3).

- The normal values of the figure of merit are about five for AlGaAs–GaAs structures at room temperature, values up to 10 can be reached in devices fabricated from strained InAs layers.

- It is observed that the maximum operation frequency increases as *C* decreases.

- The resonant tunnel diode is fabricated from relatively low-doped semiconductors, which results in wide depletion regions between the barriers and the collector region, and accordingly, small equivalent capacity.
- For this reason, RTDs can operate at frequencies up to several terahertz (THz).
- RTDs are the only purely electronic devices that can operate up to frequencies close to 1 THz.
- The power delivered from the RTDs to an external load is small and the output impedance is also relatively small.

- The output signal is usually of low power(lower than 0.3V)

- RTDs have been used to demonstrate circuits for numerous applications including static random access memories (SRAM), pulse generators, multivalued memory, multivalued and self latching logic analog to digital converters , oscillator elements , shift registers, low noise amplification etc.

Comparison of RTDs from different materials systems. J_p is the peak current density, *PVCR* the peak-to-valley current ratio, $\Delta I \Delta V$ the maximum available power (assuming 100% efficiency) in the NDR region; and R_D the negative resistance of the diode in the NDR region. Adapted from Paul, D.J. (2004) *Semicond. Sci. Technol.*, **19**, R75–R108.

Material	InGaAs	InAs	Si/SiGe	GaAs	Si Esaki
J_p (kAcm^{-2})	460	370	282	250	151
PVCR	4	3.2	2.4	1.8	2.0
$\Delta I \Delta V$	5.4	9.4	43.0	4.0	1.1
R_D (Ω)	1.5	14.0	12.5	31.8	79.5
Area (μm^2)	16	1	25	5	2.2

HOT ELECTRON TRANSISTORS

- When electrons are accelerated in high electric fields, they can acquire energies much higher than those corresponding to thermal equilibrium.

- when an external applied electric field accelerates electrons to very high velocities, the kinetic energy, and thus *T*e, can reach values which are much higher than those corresponding to the temperature of the crystal. In this case, the electrons are far from thermodynamic equilibrium, and receive the name of *hot electrons*.

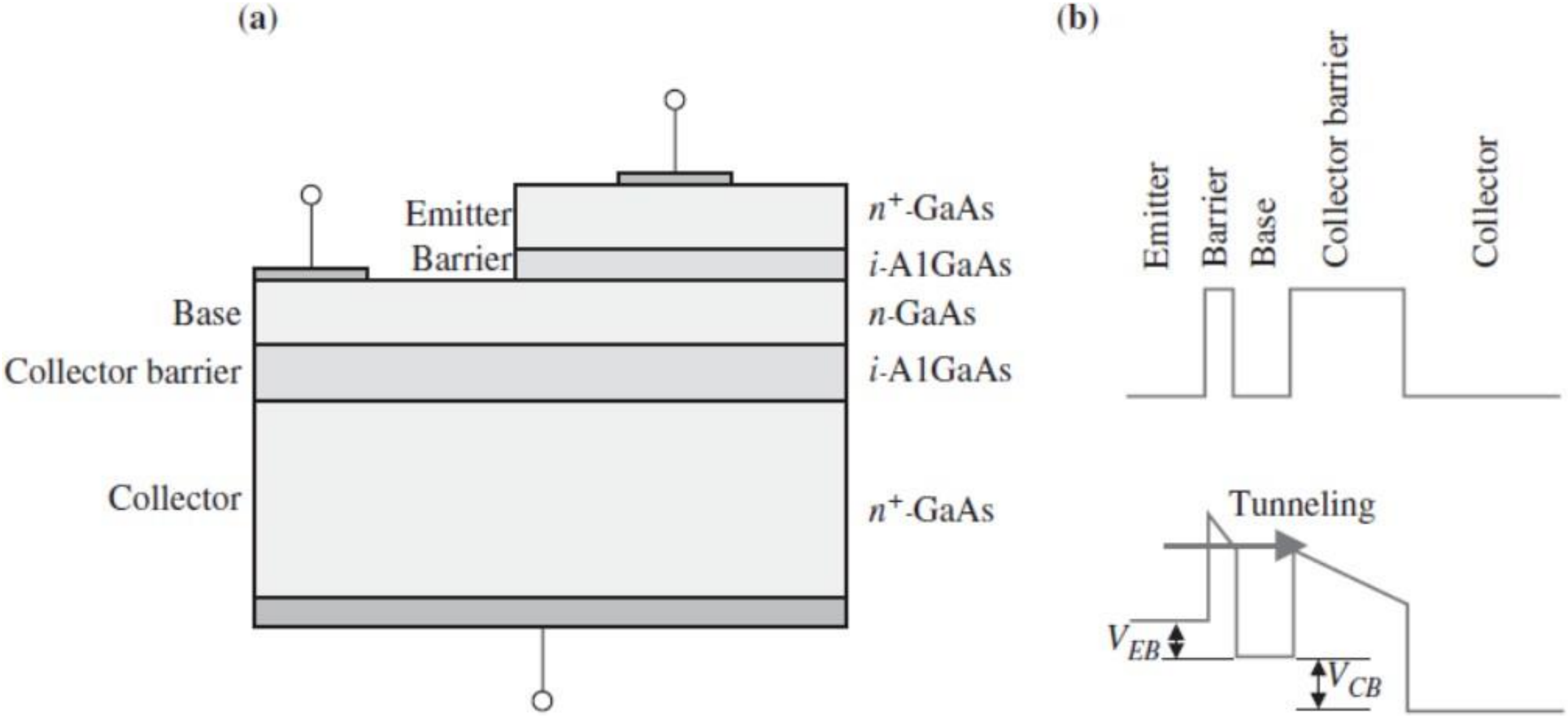
- **Heterojunctions between different gap semiconductors allow the generation of hot electrons, since the electrons will acquire a kinetic energy, given by the energy discontinuity in the conduction band V*E*c, when travelling from a wide bandgap semiconductor to one with smaller bandgap.**

- The above effect is called *electron injection by heterojunction*.

- AlGaAs–GaAs heterojunction, the value of V*E*c, ranges from 0.2 to 0.3 eV

- One way of selecting the most energetic electrons in a given distribution consists of making them cross a potential barrier.

- Evidently, if the barrier is not very thin, only the most energetic electrons will have enough energy to overcome the barrier.



Hot electron transistor: (a) structure of the device; (b) energy band diagram (for the conduction band) under positive voltage applied to the collector. After [2].

- Figure shows the typical structure of a hot electron transistor, consisting of a n+ GaAs emitter, a very thin (∼50 Å) AlGaAs barrier, the GaAs base region (∼1000 Å), another thick AlGaAs barrier of about 3000 Å, and the n+ GaAs collector.

- When a positive voltage is applied to the collector, the injection of hot electrons coming from the emitter takes place by tunnelling through the thin AlGaAs barrier, since the base is positively biased with respect to the emitter.

- It must be noted that the barrier's energy lavel can be modulated by varying the voltage difference between emitter and base, *V*BE.

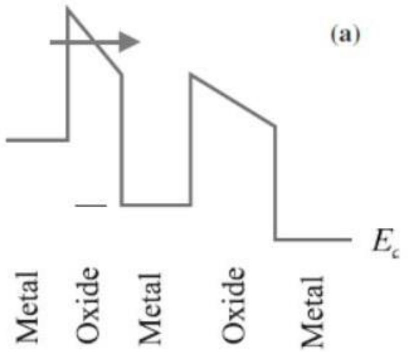
- The velocity of the injected electrons is much higher than in other type of transistors.

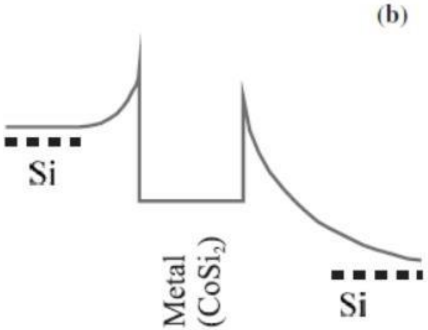
- The base transit time when the transistor is polarized can be of the order of tens of femtoseconds, but that associated to the crossing of the collector barrier is relatively higher.

- Nowadays, there are several efforts to reduce this time, although the collector barrier cannot be reduced as desired since leakage currents have to be prevented.

- Much effort is currently being developed to progressively reduce the dimensions of HET devices, so that the electron transit time is as short as possible.

- to overcome transit time problems, it was proposed to substitute the semiconductor at the base by a material that behaves as a metal, is non-contaminant, and does not show electromigration effects. The resulting device is called *metal base transistor (MBT)*.





- The two most common MBTs structures are represented in figure
- For the base region of MBTs, materials such as cobalt silicide (CoSi2) is used; this silicide shows a conductivity almos as high as that of metals and is chemically compatible with silicon technology.
- shows the band structure of a device consisting of a metal-oxide-metal-oxide-metal heterostructure, under forward bias between the emitter–base and base–collector electrodes.
- In this case, electrons are injected by tunnelling through a thin barrier into the emitter junction.
- Second figure shows an even simpler MBT, formed by Si–CoSi2–Si.
- CoSi2 is chosen as material for the base region due to the good lattice matching properties with silicon that results i high quality interfaces
- In these transistors, hot electrons behave as ballistic electrons they practically do not suffer scattering since their me free path is larger than the thickness of the base region.
- the most significant of MBT is that they are unipolar devices and can operate at higher

  frequencies.

RESONANT TUNNELLING TRANSISTOR

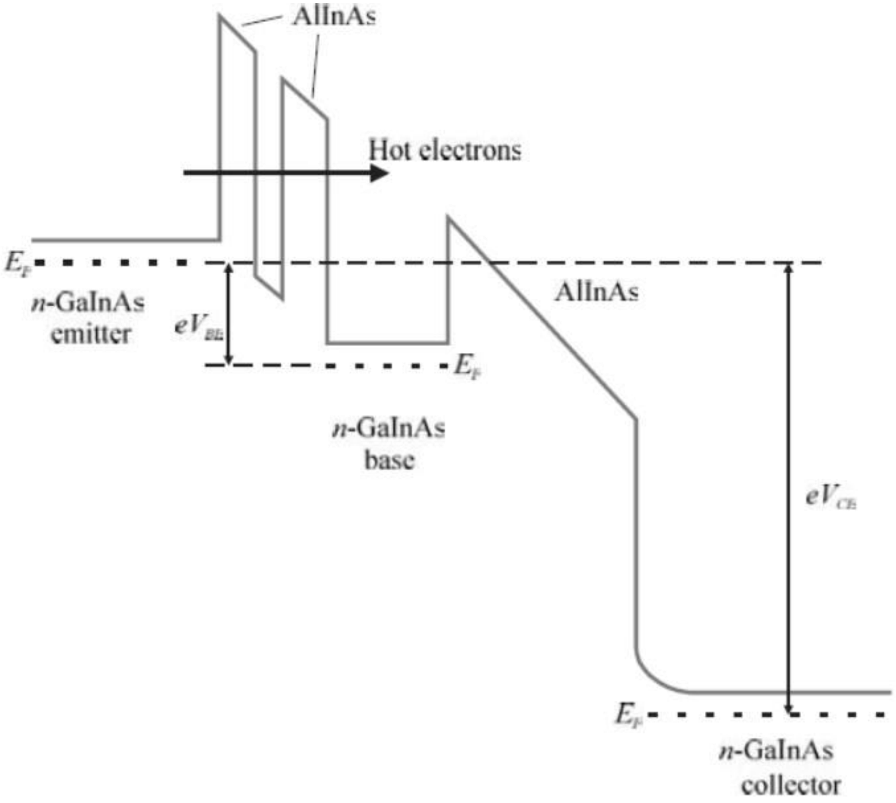
- Diodes based on the resonant tunnel effect (RTE) can be incorporated into standard bipolar transistors, field effect transistors or into hot electron transistors.

- Such transistors are called *resonant tunneling transistors (RTT)*

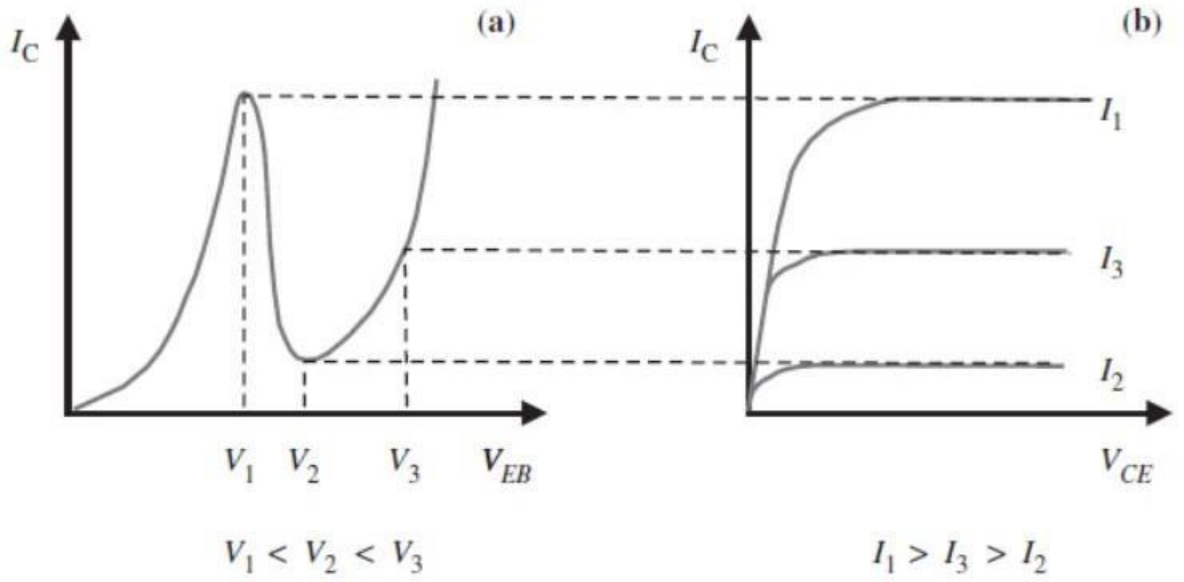
- Let us first consider a bipolar transistor in which a RTD is added to the emitter junction.

- Since the emitter to base polarization voltage, *V*EB, controls the tunneling resonant current.

- The collector current will show the typical RTD dependence.



.. Schematic energy band representation of a resonant tunnelling hot electron transistor biased in the active region.



Qualitative dependence of the collector current of a resonant tunnelling transistor as a function of: (a) base–emitter voltage; (b) collector–emitter voltage.

- The output *I*–*V* characteristics present alternate regions of positive and negative transconductance that can be controlled by the voltage *V*EB.

- Energy diagram of hot electron resonant tunnelling transistor biased in the active region is shown previously.

- Between the emitter and base regions of this transistor there exists a resonant tunnelling heterostructure, capable of injecting a large current when the electron resonant condition is reached.

- The position of the resonant level related to the emitter, is controlled by the voltage level applied to the base region, V_{BE}.

- This voltage can be increased until the resonant condition is reached.

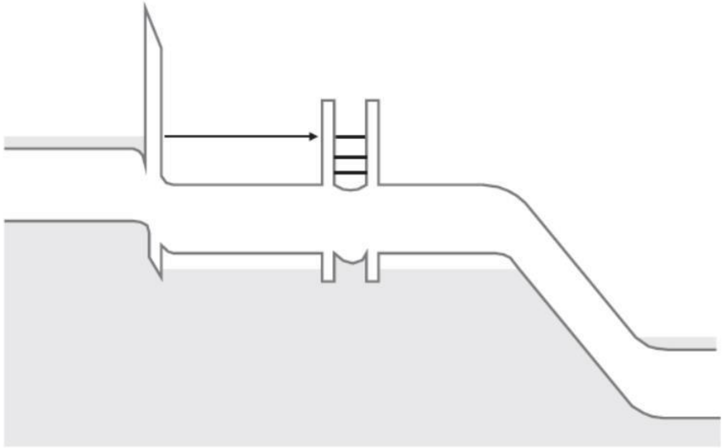
- A maximum in the output current, I_C, is then produced.

- If V_{BE} is further increased, the current starts to diminish until a minimum value at V_2 is reached, similar to the description of the *I*–*V* characteristic of RTE.

- output characteristics of this transistor also show regions of negative differential resistance.

- The resonant tunnel structure injects electrons in a very narrow energy range

- Resonant tunnelling diodes can also be incorporated in a different manner to bipolar transistors.



. Schematic representation of a resonant tunnelling transistor (RTT) with a quantum well in the base region. After [4].

- Figure shows a AlGaAs–GaAs bipolar transistor to which a RTD has been added to the base terminal.

- It consist of a quantum well between the two potential barriers in the RTD.

- The existence of several energy levels in the quantum well has been considered.

- There are several new applications of RTTs, mainly in the field of digital electronics.

- These devices allow the implementation of logic gates with a smaller number of transistors than usually needed

- A full adder circuit can be fabricated from just one resonant tunnel bipolar transistor and two standard ones, while the same conventional adding circuit needs about 40 transistors.

SINGLE ELECTRON TRANSISTOR

- The concept of *single electron transistor (SET)* is based on the behaviour of 0D nanometric structures, such as quantum dots, in which electrons are distributed in discrete energy levels.

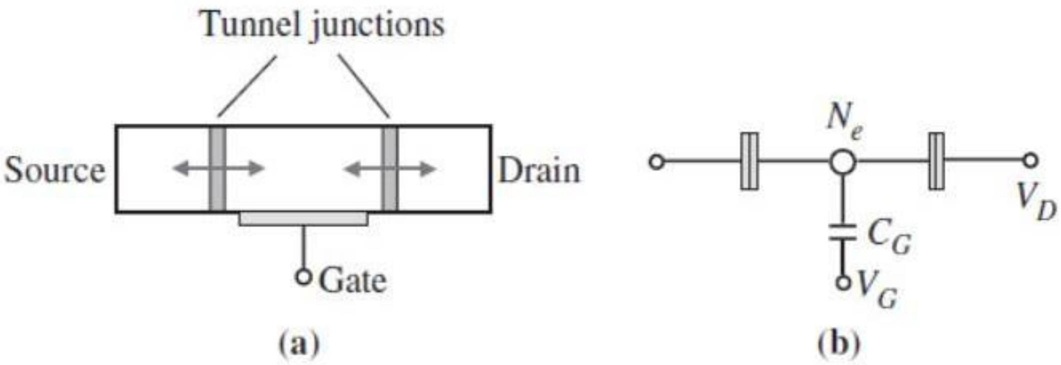
- One of the most interesting properties of these structures is called *Coulomb blockade effect.*

- When the tiny conducting material is extremely small, the electrostatic potential significantly increases even when only one electron is added to it.

- For the correct operation of SETs two conditions have to be met.

- First, the change in electric energy when an electron enters or leaves the quantum dot, i.e. the charging energy, has to be much larger than kT.

- Secondly, the resistance RT of the tunnel junction must be large enough compared to the quantum resistance RQ = h/e2



- Figure (a) shows the schematic representation of a SET and Figure (b) is its equivalent circuit as a three-terminal device.

- The quantum dot, is connected to the source and drain by two tunnel barriers.

- The number of electrons in the Coulomb island can be controlled by the external voltage, *V*G

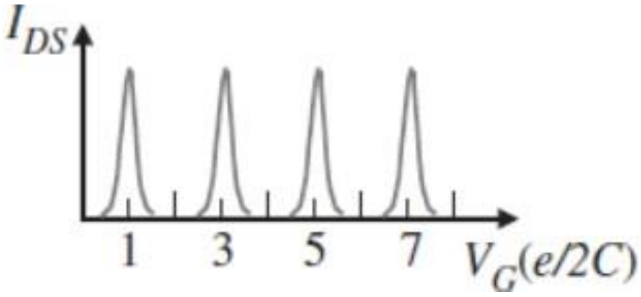
- In order to fabricate transistors based on the Coulomb blockade effect, three terminals are needed.

- One of these terminals can be used as a gate to control the current flow through the quantum dot.

- Therefore, the SET basically consists of a quantum dot connected to the source and drain electrodes through tunnel junctions.

- The gate electrode is coupled to the quantum dot by an insulating material, in such a way that the electrons cannot tunnel through the barrier.

- Since the source or drain current flow is controlled by the gate, the described three-terminal device operates as a transistor.
- the quantum dot playing the role of the channel region in MOSFETs.



- The current–voltage characteristics of the SET can be determined by applying a continuously sweeping voltage, *V*G, to the gate electrode.

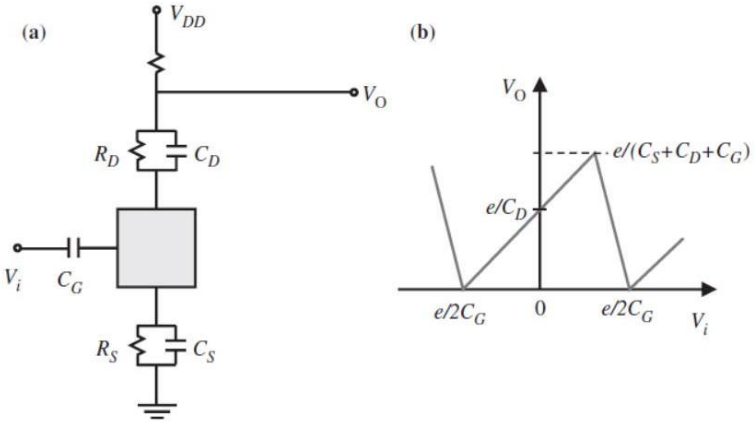
- The applied voltage induces a charge *CV*G in the opposite plate of the capacitor, which is compensated by the tunnelling of a single electron that enters the quantum dot.

- Thus, some kind of competence between the induced charge and the discrete one that tunnels through the barriers is established, that results in the so-called *Coulomb oscillations*

- *Coulomb oscillations* is associated with the current flow due to the discrete charges that tunnel through the barriers.

- Between two consecutive peaks, the number of electrons in the quantum dot is fixed and therefore no current flows.

- logic circuits based on SETs can be implemented.



(a) Schematic representation of a SET as an inverter; (b) ideal transfer characteristic.

- For exapmle, an inverter with SET.

- each tunnel barrier is represented by a resistance in parallel with a capacitor.

- The periodicity of the output voltage is *e/C*G and its amplitude is given by *e/(C*S + *C*D + *C*G*)*.

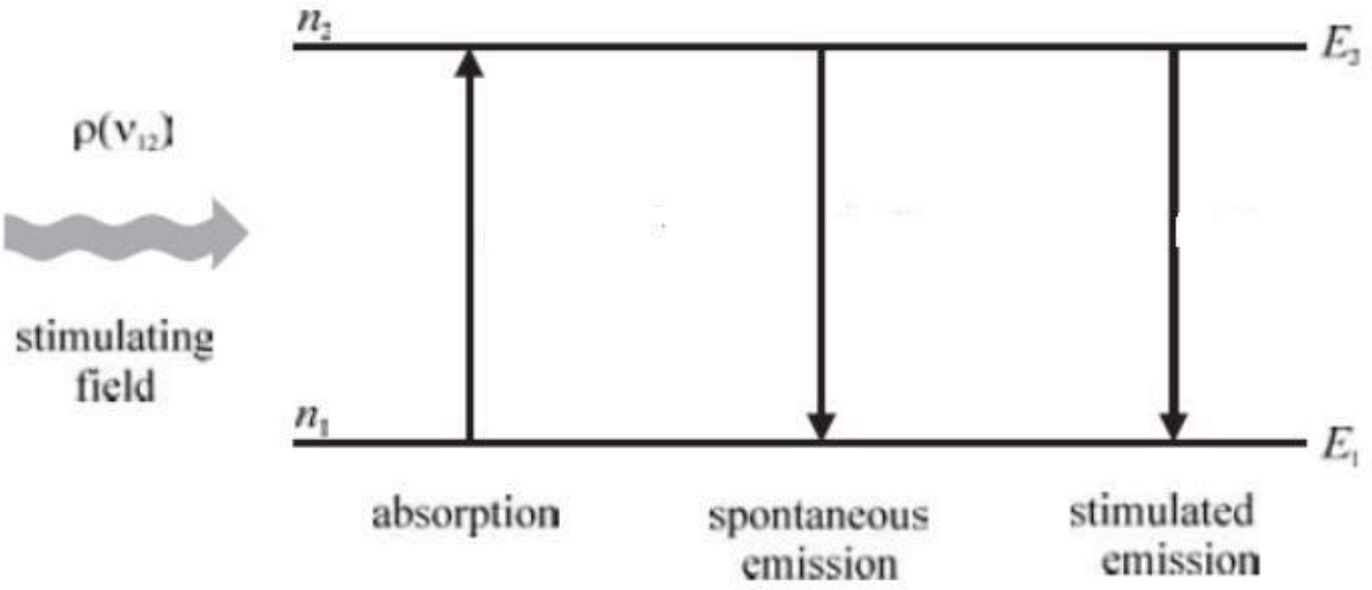
- The above inverters have been already used in the design of logical circuits and as unit memory cells.

Comparison of SETs and MOSFETs

- It is well known that until recently MOSFETs have been the basic devices of semiconductor chips, but we are already approaching their limiting feature size.
- SETs would present the advantage of fabricating devices with smaller sizes.
- They would also dissipate less power,
- One significant disadvantage of SETs is given by their high output impedance, due to the resistance associated to tunnel barriers.
- Another disadvantage is related to the size of the quantum dot, since for room temperature operation its capacitance should be as a small as possible.

Stimulated Emission

- Suppose a simple electron system of just two energy levels $E1$ and $E2$ ($E2 > E1$).
- Electrons in the ground state $E1$ can jump to the excited state $E2$ if they absorb photons of energy $E2-E1$.
- On the contrary, photons of energy $E2-E1$ are emitted when the electron drops from $E2$ to $E1$.
- In general, the emission of light by a transition from the excited state $E2$ to the ground state $E1$, is proportional to the population of electrons $n2$ at the level $E2$. This is called *spontaneous emission.*
- Electrons can also drop from $E2$ to $E1$ if they are stimulated by photons of energy $h\nu = E2 - E1$.
- This process is therefore called *stimulated emission* and is proportional to the density $\rho(\nu)$ of photons.
- One very interesting aspect of stimulated emission is that the emitted photons are in phase with the stimulating ones.
- In order to dominate over absorption (proportional to $n1$) we should have $n2 > n1$. This condition is known as Population Inversion.



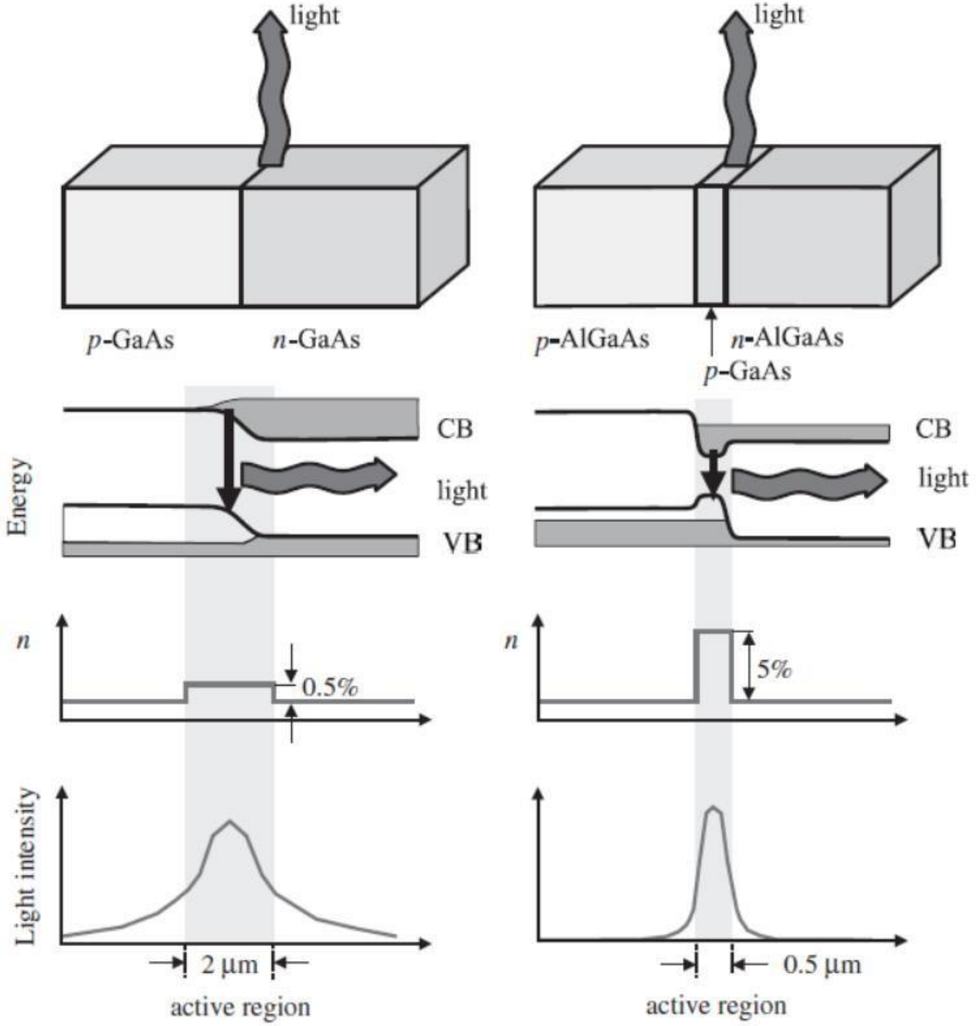
(a) Absorption; (b) spontaneous emission; (c) stimulated emission

HETEROSTRUCTURE SEMICONDUCTOR LASERS

- Lasers based on p–n junctions of the same semiconductor, as for example GaAs, have several drawbacks:
  - Bad definition of the light emitting active region, with a size of about the diffusion length *L*D.
  - The threshold current, i.e. the minimum current necessary for laser action, is quite large.

- In the 1970s that *double heterostructure (DH) lasers*, which provide both carrier and optical confinement, could be much more efficient than homojunction lasers and show threshold density currents (∼1000Acm−2) at least one order of magnitude lower.

- Figures (a) and (b) show the basic structures of homojunction and DH lasers.



'. Comparison of the structure and characteristics of semiconductor lasers: (a) homojunction; (b) double heterostructure. From top to bottom: semiconductor regions forming the laser structure, band diagram which shows the potential wells for electrons and holes, profile of the refractive index, and optical confinement in the

- In the double heterostructure, stimulated emission occurs only within a thin active layer of *GaAs*, which is sandwiched between p- and n- doped *AlGaAs* layers(cladding layers) that have a wider band gap.

- The surrounding cladding layers provide an energy barrier to confine carriers to the active region.

- When a bias voltage is applied in the forward direction, electrons and holes are injected into the active layer.

- Since the band gap energy is larger in the cladding layers than in the active layer, the injected electrons and holes are prevented from diffusing across the junction by the potential barriers formed between the active layer and cladding layers.

- The electrons and holes confined to the active layer create a state of population inversion, allowing the amplification of light by stimulated emission.

- The cladding layers serve two functions. First, inject charge carriers. Second, light confinement.

- The actual operation wavelengths may range from 750 - 880 nm due to the effects of dopants, the size of the active region, and the compositions of the active and cladding layers.

- When a certain parameter is fixed, the wavelength can vary in several nanometers due to other variables.

- refractive index of active region is slightly larger than that of the surrounding layers and this helps to confine the light.

- The heterojunctions allow the formation of potential wells for electrons and holes, as shown in Figure.

- Which increases the carrier concentration and, more importantly, the degree of inversion of the population of electrons and holes.

- In optics, the *refractive index* or *index* of *refraction* of a material is a dimensionless number that describes how fast light propagates through the material.

- One interesting additional aspect of DH lasers is that larger value (∼5%) of the GaAs refractive index in comparison with the AlGaAs surrounding material. This difference is enough to provide an excellent optical confinement.

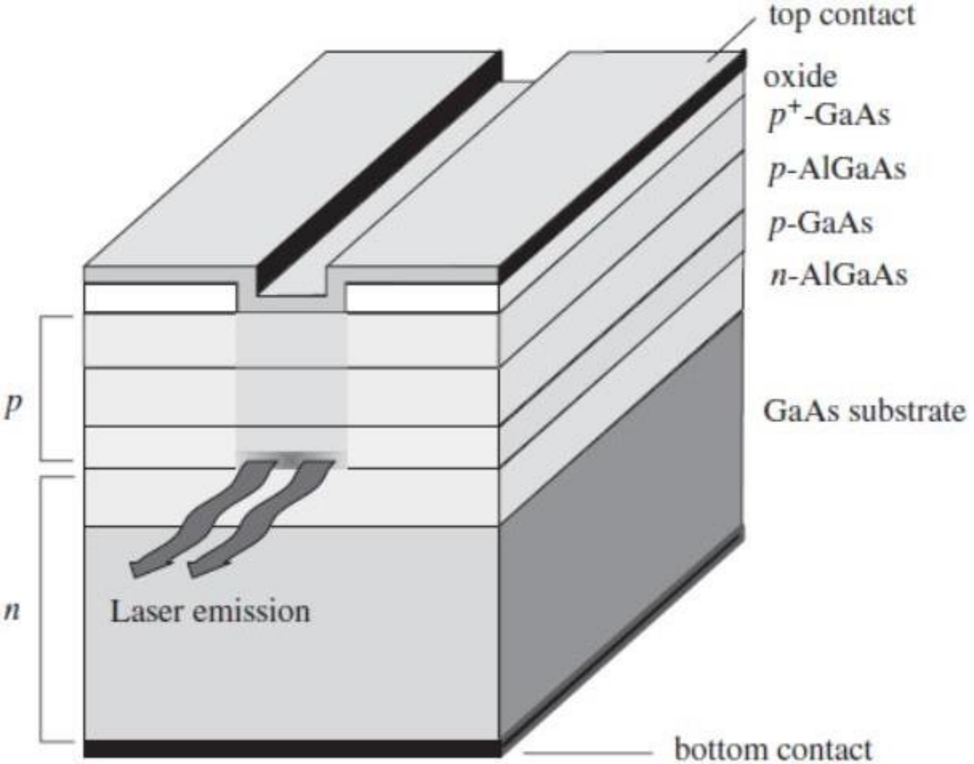
- The *optical confinement factor ,* which indicates what fraction of the photon density is located within the active laser region and can approach unity.

- In order to make the DH laser more efficient, the transverse *stripe geometry* configuration has been adopted almost universally.

- In this geometry, the transverse or horizontal dimension of the active region, and consequently the threshold current, is greatly reduced.

- Because of the shape of the active region, stripe geometry lasers are much easier to couple with fibres, waveguides, etc.

- These lasers are called *index guided lasers* or buried DH lasers.



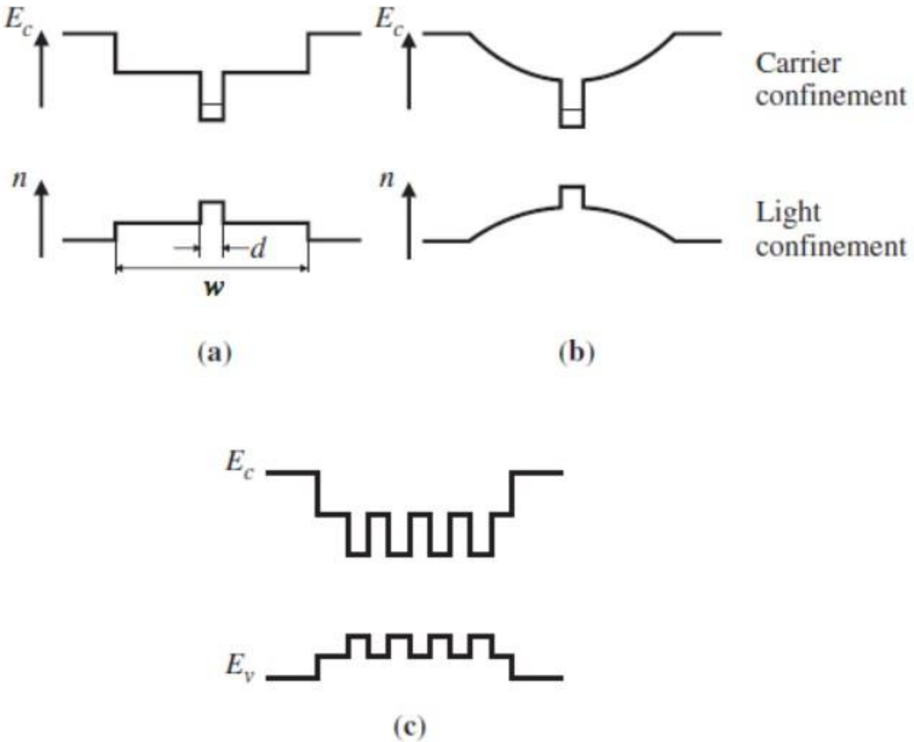
Stripe geometry double heterostructure semiconductor laser.

QUANTUM WELL SEMICONDUCTOR LASERS

- Regular double heterostructure (DH) semiconductor lasers have an active region of 0.1 to 0.2um thick.
- Since the 1980s, lasers with very thin active regions, quantum well lasers, were being developed in many research laboratories.
- A quantum well laser is a laser diode in which the active region of the device is so narrow that quantum confinement occurs.
- This results in a set of discrete energy levels and the density of states is modified to a two-dimensional-like density of states.
- The wavelength of the light emitted by a quantum well laser is determined by the thickness of the active region rather than just the bandgap of the material from which it is constructed.
- This means that much shorter wavelengths can be obtained from quantum well lasers than from conventional laser diodes using a particular semiconductor material.
- The efficiency of a quantum well laser is also greater than a conventional laser diode due to the stepwise form of its density of states function.

- improved characteristics of quantum well lasers are mainly due to the properties of the 2D density of states function and characteristic of quantum wells.

- Figures (a) and (b) show two separate structures frequently used.



Separate confinement structures of quantum wells inside optical cavities: (a) profile of the conduction band and index of refraction; (b) GRINSCH structure; (c) multiple quantum well separated confinement heterostructure.

- Quantum well lasers require fewer electrons and holes to reach threshold than conventional double heterostructure lasers.

- A well-designed quantum well laser can have an exceedingly low threshold current.

- To compensate for the reduction in active layer thickness, a small number of identical quantum wells are often used. This is called a multi-quantum well laser.

- These structures are obtained for instance by grading the composition of AlxGa1−xAs compounds with values of x between zero and about 0.30, the value of the gap increasing from 1.41 eV to about 2.0 eV.

- The waveguiding effect can be further improved by grading the refractive index, as shown in the lower part of Figure (b), in the so called *graded index separate confinement heterostructures (GRINSCH)*.

- Very often, in order to enlarge the emitted laser signal, a structure with *multiple quantum wells* is implemented (Figure (c)) instead of just one single quantum well.

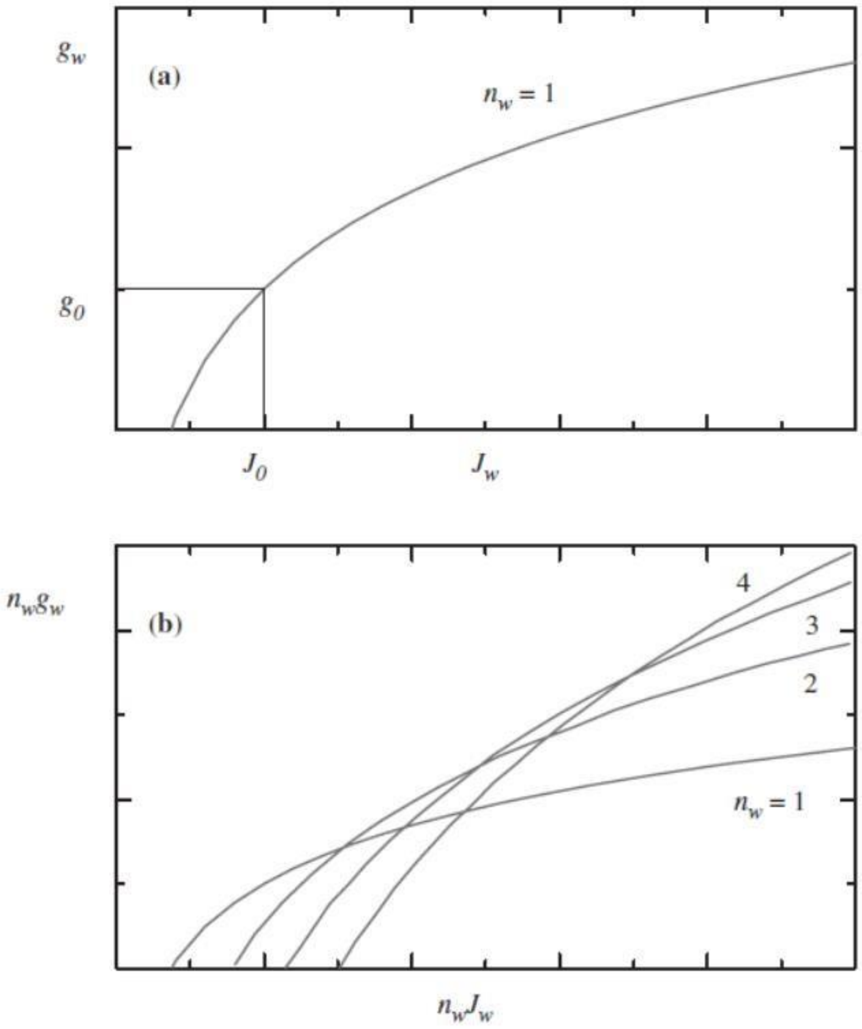
- The gain can be related to the current density J by assuming a value of τ for the recombination time, since $J = end\tau^{-1}$, where d is the thickness of the active region; alternatively, τ could be obtained from the rate of radiative recombination.

- For the case of MQW structures with n_w quantum wells, each with a gain g_w, the total gain $n_w g_w$ as a function of the total injection current density nJ is plotted in Figure (b) for $n_w = 1, 2, 3$, and 4.

- In order to obtain a high differential gain one should use a MQW structure.

- QW lasers also show a higher efficiency and smaller internal losses than DH lasers.

- For the high-speed operation of QW lasers, a proper design of the separate confinement well heterostructure is important.



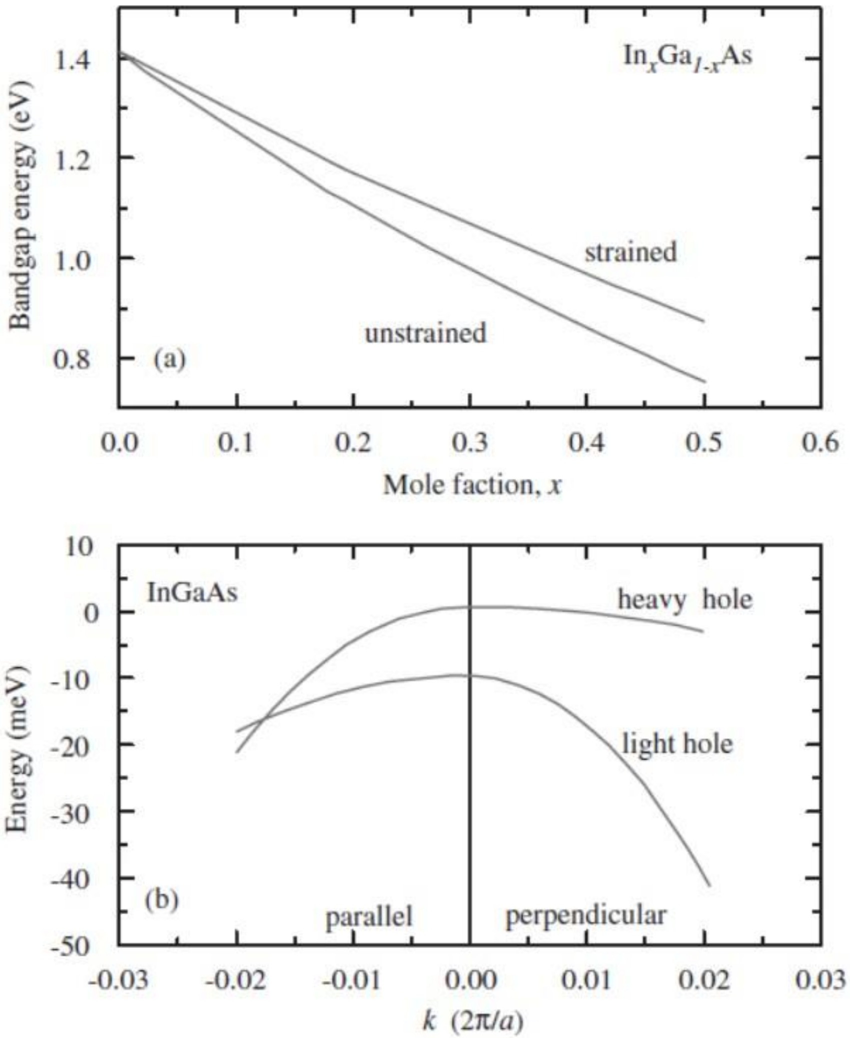
Gain as a function of injection current density for: (a) one single quantum well; (b) multiple quantum wells system with $n = 1$, 2, 3, and 4 single quantum wells.

Strained Quantum-Well Lasers

- Quantum well lasers have also been fabricated using an active layer whose lattice constant differs slightly from that of the substrate and cladding layers. Such lasers are known as strained quantum-well lasers.

- They show many desirable properties such as low-threshold current density and lower linewidth than regular Multi-Quantum-Well (MQW)

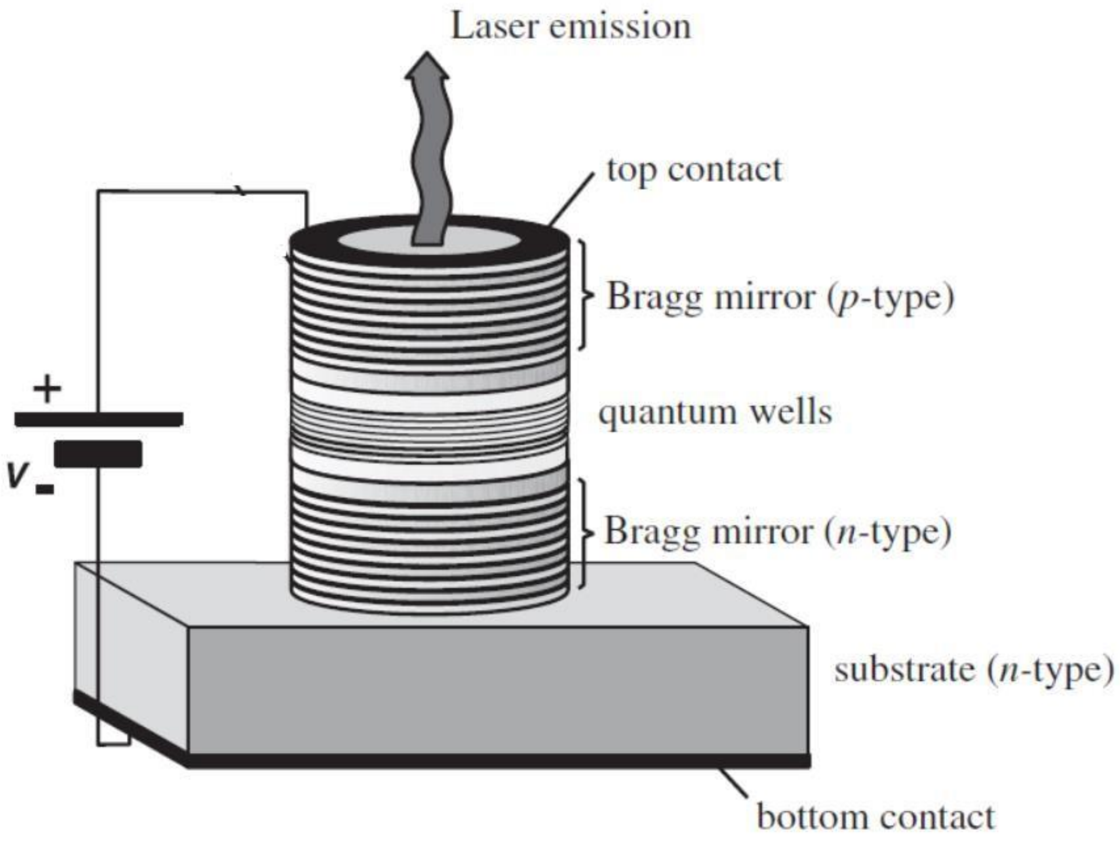
- strain introduces a new variable to extend wavelength tunability, in addition to controlling the width and barrier height of the quantum wells.
- The origin of the improved device performance lies in the band-structure changes induced by the mismatch-induced strain.
- One of the most investigated strained quantum wells for lasers is the GaAs-InGaAs– GaAs. In this case, the inner InGaAs layer is under compressive strain. This has important consequences in the band structure.
- it changes considerably the values of the hole effective masses and increases the value of the energy gap.



. Strained InGaAs layers surrounded by GaAs: (a) In$_x$Ga$_{1-x}$ As bandgap as a function of composition; (b) heavy hole and light hole valence bands of InGaAs under compressive strain.

VERTICAL CAVITY SURFACE EMITTING QUANTUM WELL LASERS (VCSELS)

- Light is emitted perpendicularly to the heterojunctions.
- There are several obvious advantages related to this geometry
  - Ease of testing at the wafer scale before packaging,
  - Construction of large arrays of light sources (more than one million on a single chip),
  - Easy fibre coupling.
  - Possibility of using chip-to-chip optical interconnects.



Schematic diagram of a vertical cavity surface emitting laser.

- The geometry consists of a vertical cavity along the direction of current flow.
- Light is extracted from the surface of the cavity rather than from the sides.
- Two very efficient reflectors are located at the top and bottom of the active layer.
- The reflectors are usually dielectric mirrors made of multiple quarter-wave thick layers of alternating high and low refractive indexes.

QUANTUM DOT LASERS

- A **quantum dot laser** is a semiconductor laser that uses quantum dots as the active laser medium in its light emitting region.
- Quantum dot and quantum wire lasers would exhibit higher and narrower gain spectrum, low threshold currents, better stability with temperature, lower diffusion of carriers to the device surfaces, and a narrower emission line than double heterostructure or quantum well lasers.
- the experimental values obtained for quantum wire lasers are still far from the theoretical predictions and hence we refer only to quantum dot lasers
- The growth technologies for quantum wire structures will have to improve, especially with respect to the quality of interfaces, uniformity of the wires.

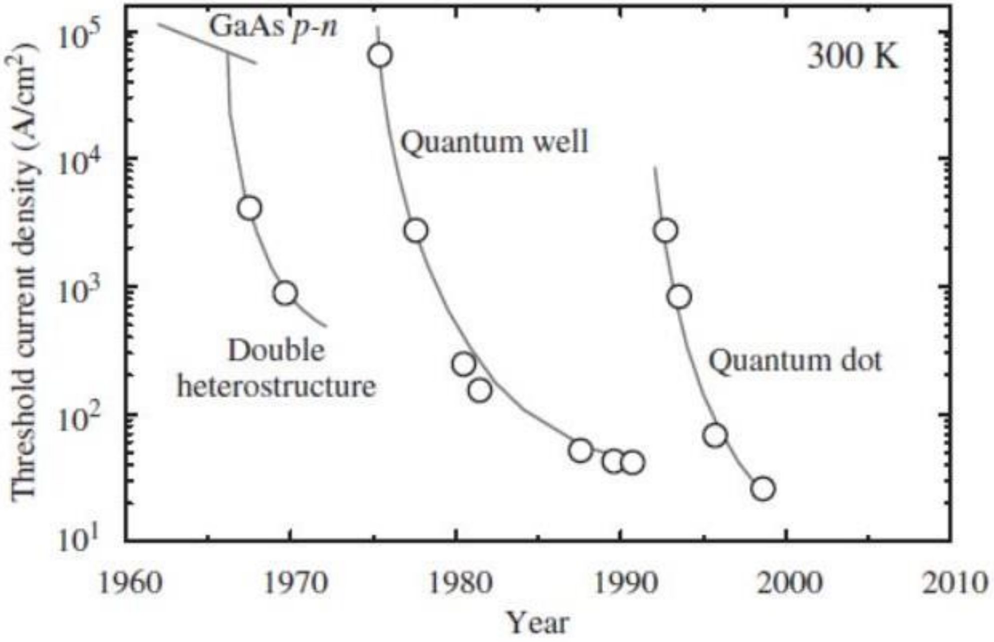
- Let us assume that the quantum dots are small enough so that the separation between the first two electron energy levels for both electrons and holes is much larger than the thermal energy *kT.*

- Then for an undoped system, injected electrons and holes will occupy only the lowest level.

- Therefore, all injected electrons will contribute to the lasing transition from the $E1$ to the $E2$ levels, reducing the threshold current with respect to other systems.

- The lowest threshold currents have already been reached for quantum dot lasers.

- an ideal quantum dot laser is very sharp and does not depend on temperature. Therefore, quantum dot lasers should have a better stability with temperature without the need for cooling.



Evolution of threshold current density for lasers

Quantum dots fabrication

- Traditional methods for fabricating quantum dots include semiconductor precipitates in a glass matrix or etching away a previously grown epitaxial layer.

- None of these methods can produce large densities of dots, and the control of size and shape is difficult.

- Moreover they introduce large defects into the dots and create many surface states that lead to non-radiative recombination methods

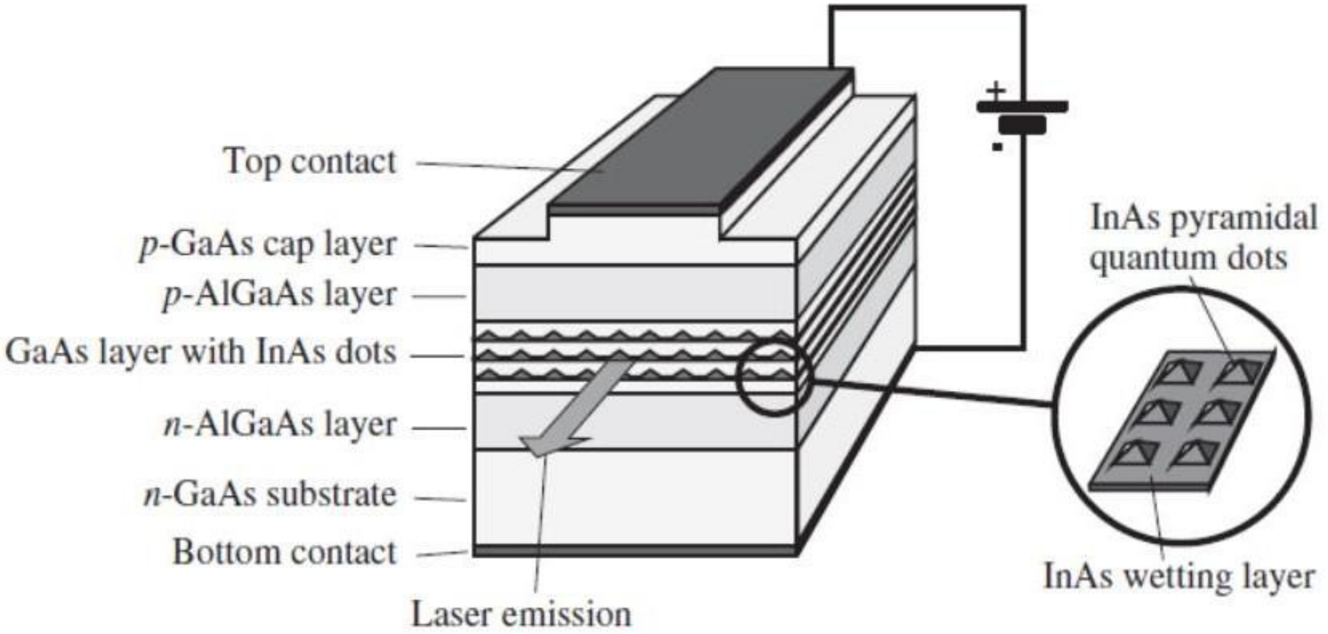
- The growth techniques of quantum dots not yet matured.

- The most successful method to date has been the growth of *self-assembled quantum dots* at the interface of two lattice-mismatched materials.

- In this method a material such as InAs is grown by chemical vapour deposition, metalorganic vapour phase epitaxy or molecular beam epitaxy on a substrate with a larger lattice parameter and a larger bandgap such as GaAs.

- The first few monolayers grow in a planar mode with a large tensile strain But beyond a critical thickness, it is more energetically favourable to form islands (the so-called Stranski–Krastanow regime) as shown in Figure

- Subsequently, a layer is overgrown epitaxially on top of the dots, creating an excellent heterostructure between two single-crystal materials:



'. Schematic illustration of a quantum dot laser based on self-assembled dots. The inset shows a detail of the wetting layer with the pyramidal quantum dots.

- Previous figure shows schematically an edge-emitting laser based on self-assembled quantum dots.

- The device consists of several layers forming a pin diode structure.

- The layers are, from bottom to top, the n-GaAs substrate, a n-AlGaAs layer, an intrinsic GaAs layer with the dots, a p-AlGaAs layer, and a p-GaAs cap layer.
- Metallic contacts on the substrate and the cap layer connect the device to an external circuit.
- Under a forward bias voltage, electrons and holes are injected into the middle intrinsic GaAs layer or active layer, where they fall into the quantum dots, which have a smaller bandgap, and recombine there.
- The emission wavelength corresponds to the interband transition of the InAs quantum dots.

- The GaAs layer, which is sandwiched between AlGaAs layers with a lower refractive index, confines the light and increases the interaction with the carriers.

- It is useful for telecommunication amplifiers and tunable lasers.

- Also dot present a better stability with operation temperature

PHOTODETECTORS

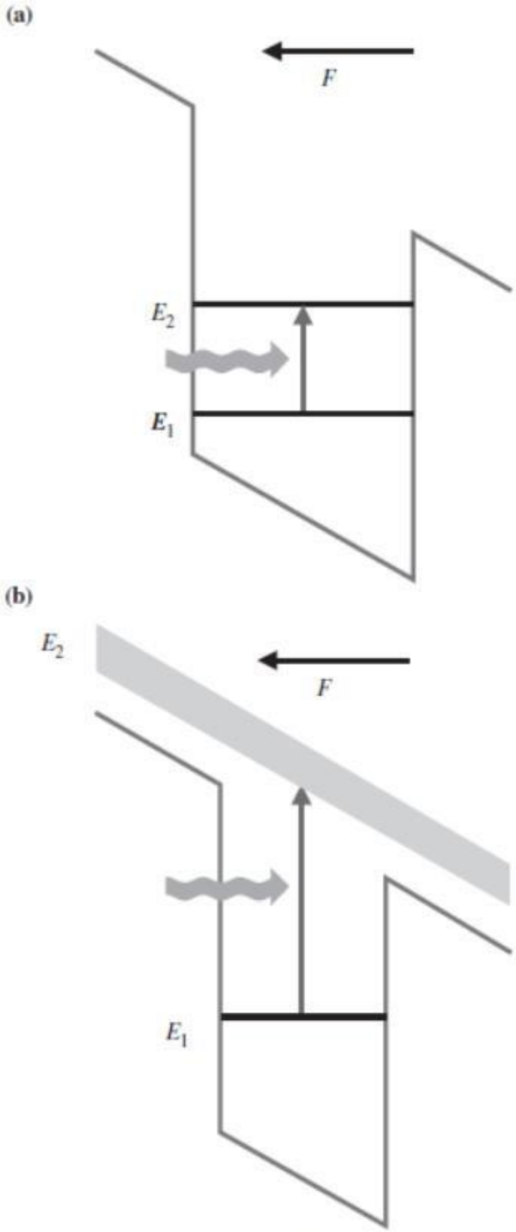
- Two types
- ***(a) Quantum well subband photodetectors***

  or

  Quantum Well Infrared Photodetector (QWIP)
- ***(b) Superlattice avalanche photodetectors***

Quantum well subband photodetectors

- Quantum wells can be used for the detection of light.
- It is commonly used in the IR region between 2 and 20μm.
- Quantum well photodetectors are preferably used for applications of night vision and thermal imaging.
- Normal photodiodes are based on band to band transitions across the semiconductor gap *E*g.
- This require materials with very low values of *E*g, which makes it necessary to work at cryogenic temperatures.
- The materials used for IR detection are normally quite soft, difficult to process, and have large dark currents. This makes quantum wells very appropriate for use in IR detection.



Optical absorption transitions for IR detection in a quantum well: (a) intersubband transitions; (b) transition from a bound state to the continuum narrow band outside the potential wells. (F is the applied electric field.)

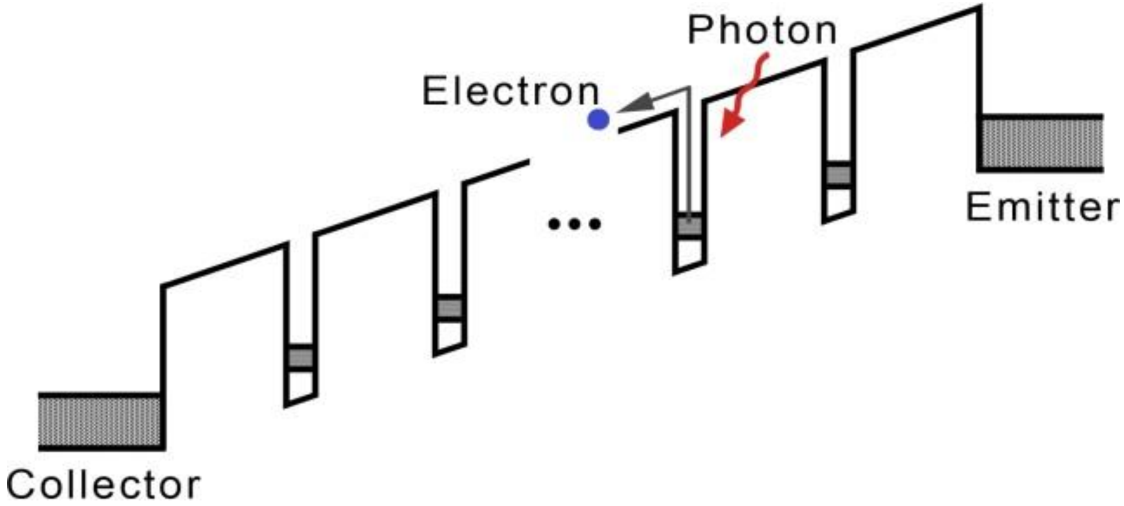
- Figure shows the absorption transitions suitable for IR detection for a single quantum well under the action of an applied electric field.

- Practical devices are made with MQWs.

- The separation between levels should be in the range 0.1–0.2 eV, which for III-V compounds implies a width of the wells of about 10 nm.

- Polarization of the incident radiation should be parallel to the confinement direction.

- Under light irradiation, this type of photodetectors generates a current by tunnelling of the carriers outside the wells.


Photon
Electron
Emitter
Collector

- A **Quantum Well Infrared Photodetector**(**QWIP**) is an infrared photodetector , which uses in electronic intersubband transitions quantum wells to absorb photons.

- When a bias voltage is applied to the QWIP, the entire conduction band is tilted.

- Without light the electrons in the quantum wells just sit in the ground state.

- When the QWIP is illuminated with light of the same or higher energy as the intersubband transition energy, an electron is excited.

- Once the electron is in an excited state, it can escape into the continuum and be measured as photocurrent.

Superlattice avalanche photodetectors

- As the name implies, it uses the avalanche process.
- It operates under a high reverse bias condition.
- This enables avalanche multiplication of the holes and electrons created by the photon / light impact.
- charge carriers will be pulled by the very high electric field away from one another.
- Their velocity will increase to such an extent that when they collide with the lattice, they will create further hole electron pairs and the process will repeat.
- avalanche photodetectors (APD) based on semiconductors can present a high level of noise if precautions are not taken.
- The noise can be gradually reduced if the avalanche multiplication coefficient, α, is much larger for one of the carriers, for instance electrons, in comparison to the other carrier (hole) multiplication coefficient.
- In this sense, silicon is a very appropriate semiconductor for APDs, since the ratio αe/αh has a value of about 30.

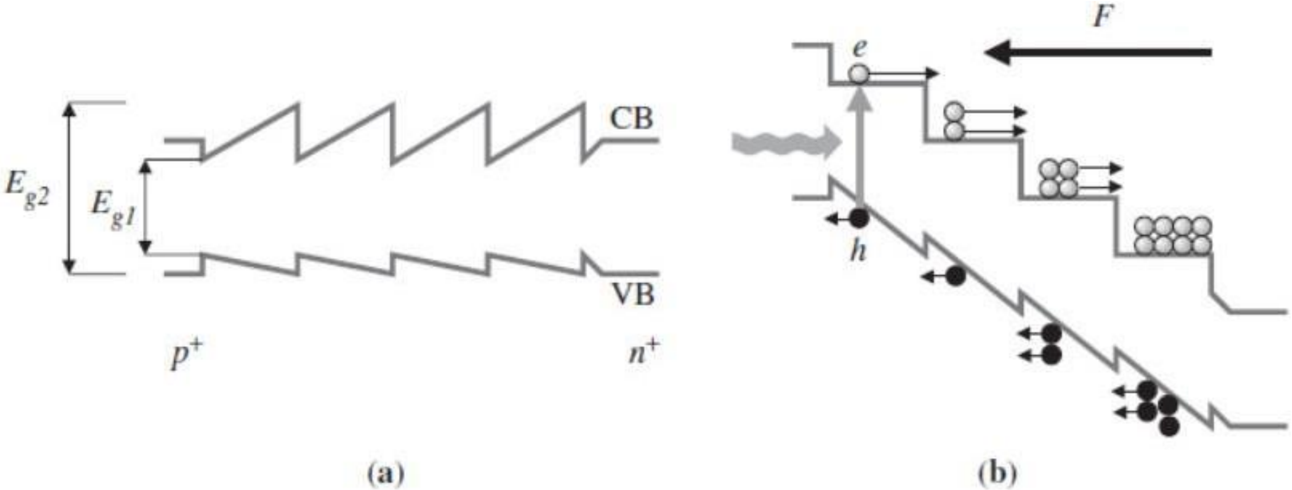
- Quantum wells, on the other hand, allow a design control of αe/αh.

- a superlattice or MQW structure can be designed such that the conduction band discontinuities V*E*c are much larger than the V*E*v ones corresponding to the valence band.

- In this way, the electrons gain much more kinetic energy than the holes when they cross the band discontinuity.
- The same objective can be achieved by the design of a staircase profile superlattice for which the bandgap is graded in each well.
- In this case, the electrons have an extra kinetic energy *E*c when they enter the next quantum well.

- This extra energy makes the impact ionization phenomenon very efficient so that electron avalanches are easily generated under the action of an electric field *F.*

- However, it should be mentioned that staircase superlattices are difficult to fabricate since their production requires strict control of the deposition parameters



. Superlattice avalanche photodetectors: (a) energy band diagram of a staircase superlattice; (b) formation of electron avalanche in the biased detector under light irradiation.

QUANTUM WELL MODULATORS

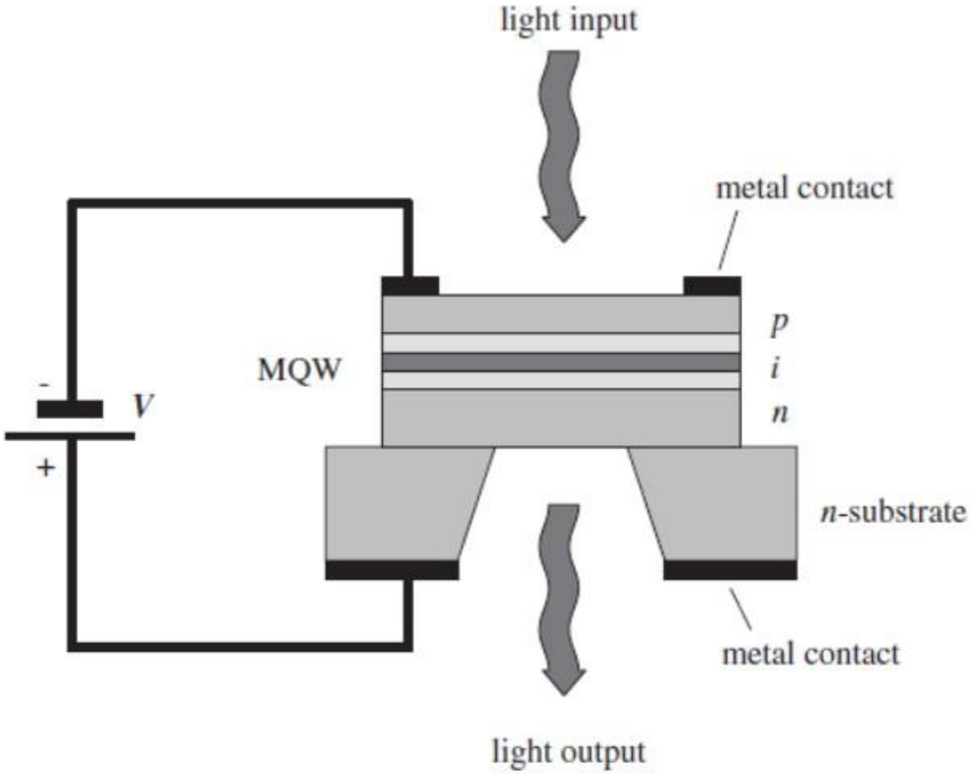
- Quantum wells can be conveniently used for the direct modulation of light, since they show much larger electro-optic effects than bulk semiconductors.

- Electro-optic effects are rather weak in bulk semiconductors and, for this reason conventional modulators make use of materials such as lithium niobate.

- due to the quantum confined Stark effect (QCSE), large changes in the optical absorption spectrum of quantum wells could be induced by the application of electric fields.

- *Electroabsorptionmodulators* are basedon the change of the optical absorption coefficient in a quantum well under effect of an electric field.
- An **electro-absorption modulator** (EAM) is a semiconductor device which can be used for modulating the intensity of a laser beam via an electric

  voltage.



Mesa-etched electroabsorption modulator based on the quantum confined Stark effect.

- Previous Figure shows a mesa-etched modulator.
- To make the effect more significant, one uses a set of multiple quantum wells (MQW).
- The MQWs tructure consists generally of an array of several quantum wells (5 to 10 nm in thickness each) of the type AlGaAs–GaAs–AlGaAs.
- The structure is placed between the p+ and n+ sides of a reverse biased junction.
- Since the whole MQW structure has a thickness of about 0.5μm, small reverse voltages can produce electric fields in the 104 to 105 Vcm−1 range.
- These fields induce changes in the excitonic absorption edge in the energy range 0.01–0.05 eV

- Electroabsorption modulators, such as the one described, allow high speed modulation with a large contrast ratio of transmitted light through the device.

- The contrast ratio can be as high as 100 by working in the reflection mode instead of the transmission one.

- This is done by depositing a metal layer substrate and forcing light to make two passes.

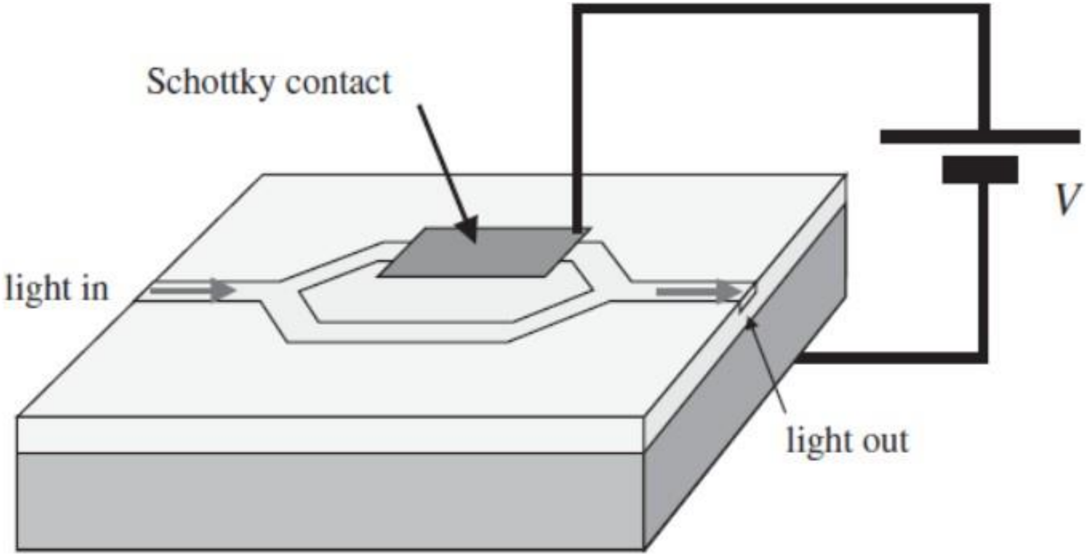
- The modulation factor can also be improved by working at low temperatures.

- Electroabsorption modulators can operate up to frequencies of several tens of GHz and if high electric fields are applied, the maximum frequency can approach 100 GHz.

- For low fields, the generated electron–hole pairs during absorption are unable to escape from the quantum well.

- However, if the fields are high enough, the electrons and holes can escape from the wells by tunnelling with a characteristic time of a few

  picoseconds.



Schematic of a Mach–Zehnder interferometer.

- The incoming signal from an optical waveguide is split in two beams of the same intensity which travel through different channels in the material of the same length before they recombine again.

- An electric field is applied to one of the branches causing differences in phase between the two beams and causing interference patterns at the meeting point.