Module 4

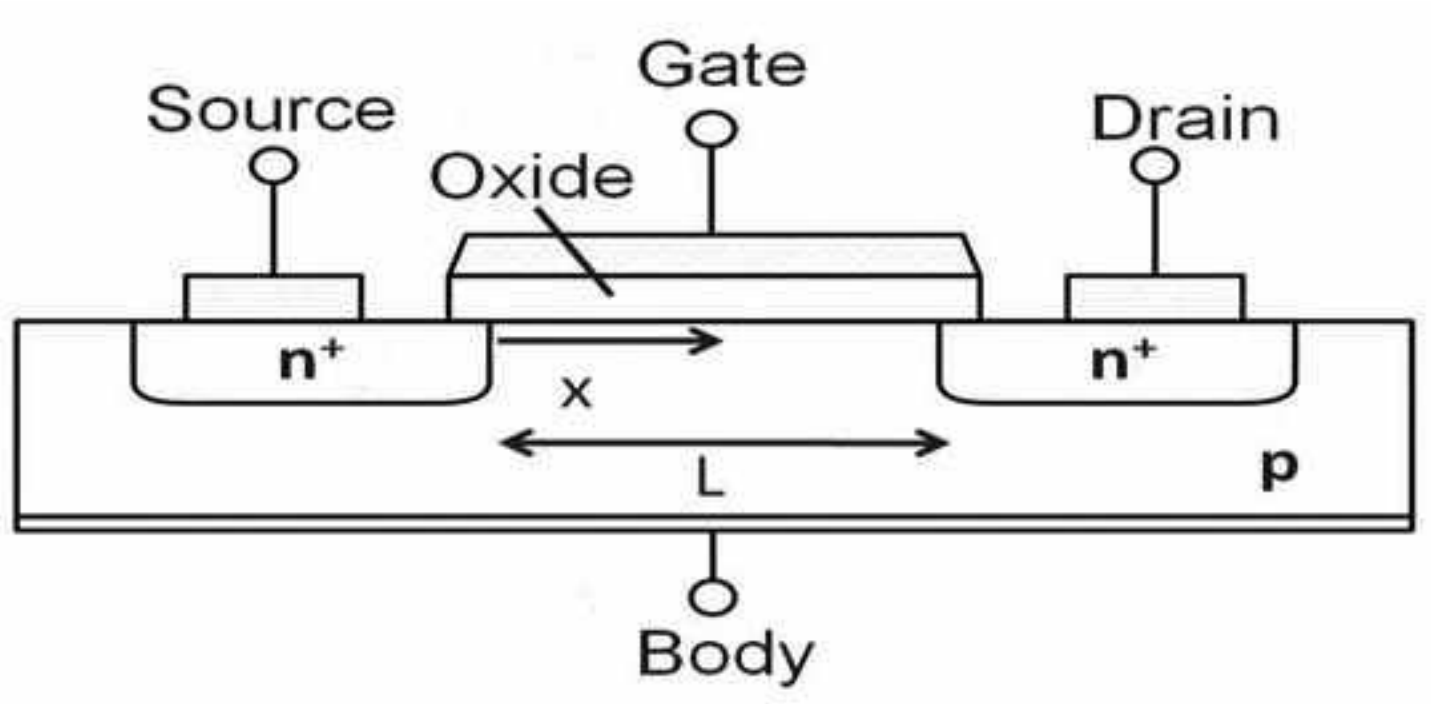
MOSFET

- The MOSFET (Metal Oxide Semiconductor Field Effect Transistor) transistor is a semiconductor device which is widely used for switching and amplifying electronic signals in the electronic devices.

- The MOSFET is a core of integrated circuit and it can be designed and fabricated in a single chip because of very small sizes.

- The MOSFET is a four terminal device with source(S), gate (G), drain (D) and body (B) terminals.

- The body of the MOSFET is frequently connected to the source terminal so making it a three terminal device like field effect transistor.


Gate
Source
Drain
Oxide
n+
n+
x
L
p
Body

- MOS structure is obtained by growing a layer of silicon dioxide (SiO_2) on top of a silicon substrate and depositing a layer of metal or polycrystalline silicon (the latter is commonly used).

- its structure is equivalent to a planar capacitor, with one of the electrodes replaced by a semiconductor.

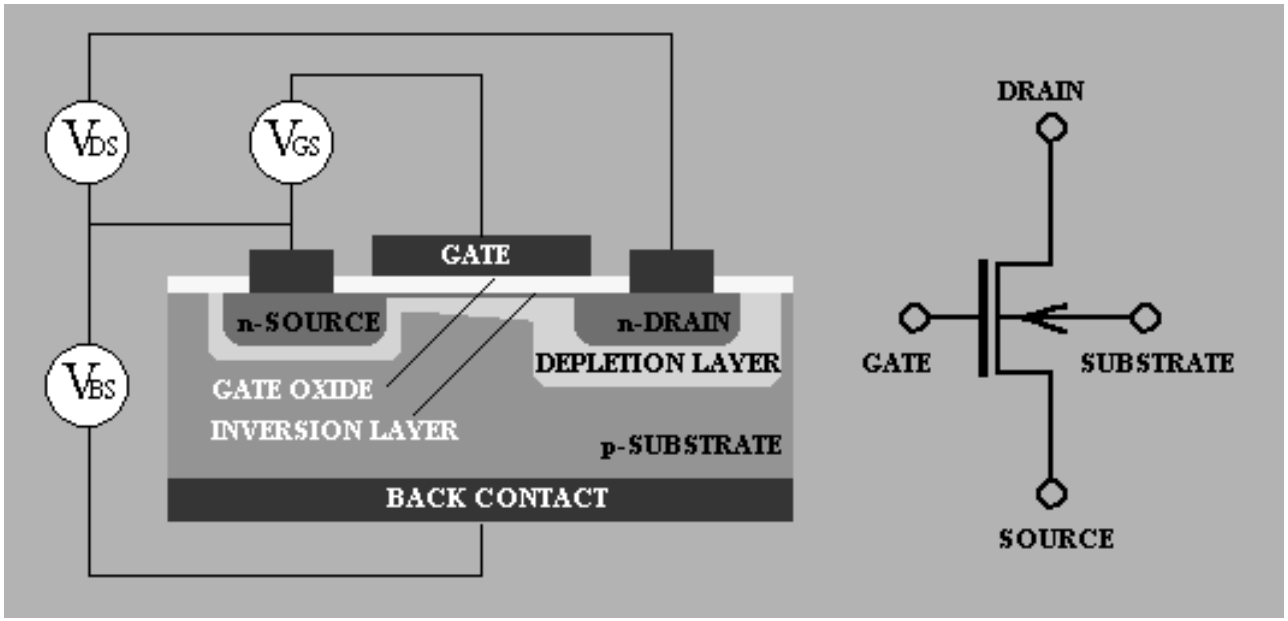
- The n-type (MOSFET) consists of a **source** and a **drain**, two highly conducting n-type semiconductor regions which are isolated from the p-type **substrate**.

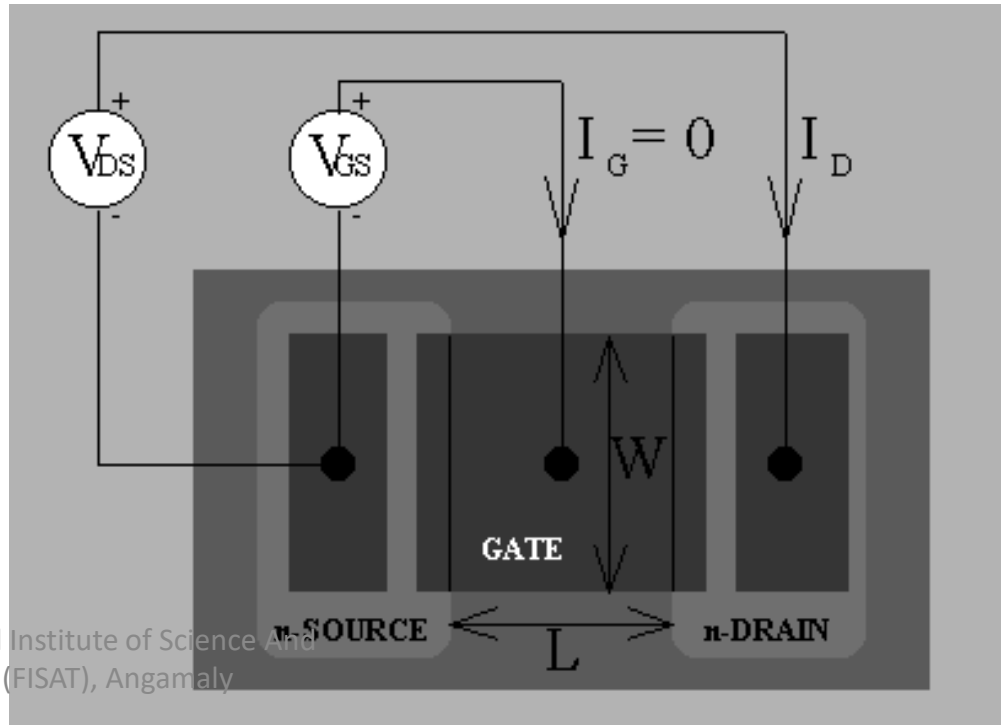
- A metal (or poly-silicone) **gate** covers the region between source and drain, but is separated from the semiconductor by the **gate oxide**.

- The source and drain regions are identical.

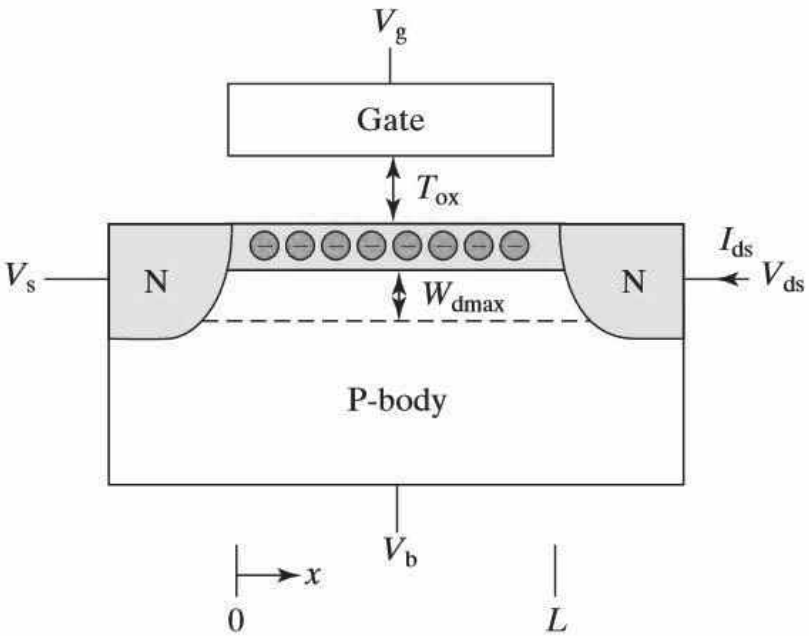
- It is the applied voltages which determine which n-type region provides the electrons and becomes the source, while the other n-type region collects the electrons and becomes the drain.

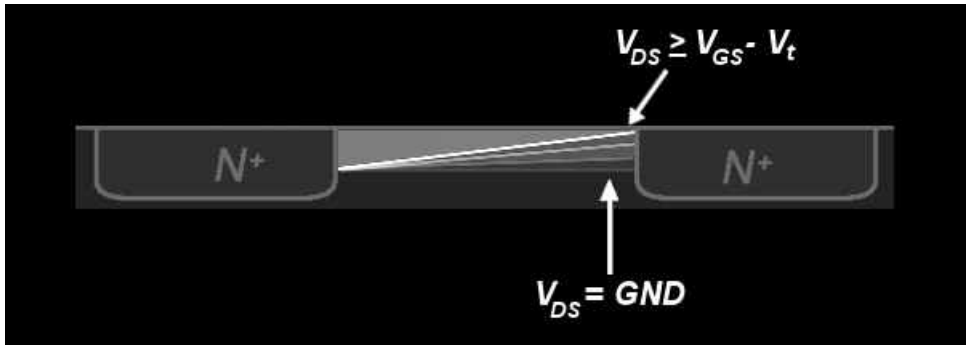
- The MOSFET works by electronically varying the width of a channel along which charge carriers flow (electrons or holes).
- The charge carriers enter the channel at source and exit via the drain.
- The width of the channel is controlled by the voltage on an electrode is called gate which is located between source and drain.
- It is insulated from the channel near an extremely thin layer of metal oxide.

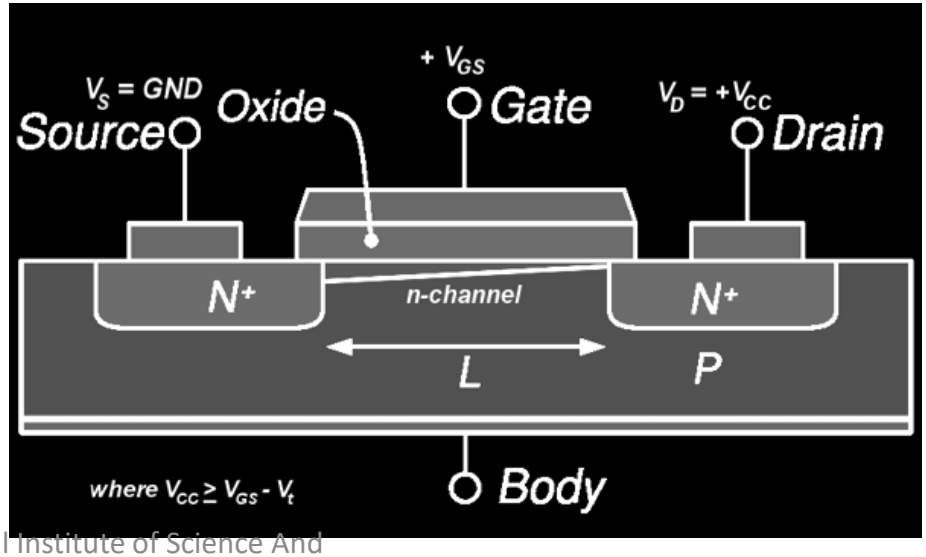

VDS
VGS
VBS
GATE
n-SOURCE
n-DRAIN
DEPLETION LAYER
GATE OXIDE
INVERSION LAYER
p-SUBSTRATE
BACK CONTACT
DRAIN
GATE
SUBSTRATE
SOURCE

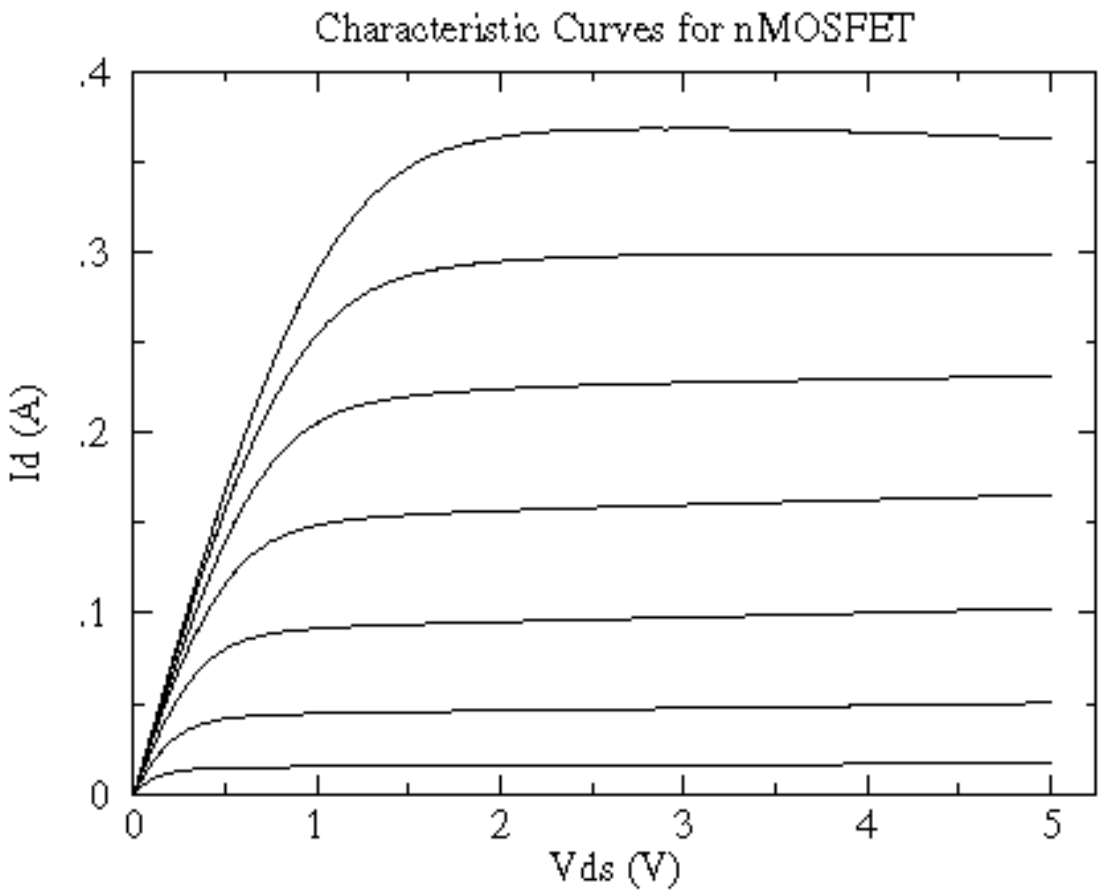

VDS
VGS
I G = 0
I D
W
GATE
n-SOURCE
n-DRAIN
L

- Consider NMOS.
- First, while applying positive V_{GS}, it causes a field that starts to repulse the majority carriers at the substrate.
- This causes "the depletion region" i.e depleted from majority carriers.
- On increasing V_{GS} more, the field starts to attract minority carriers from the substrate and form the channel. This is called "inversion".
- Now, if a voltage is applied between the drain and source, the current flows freely between the source and drain and the gate voltage controls the electrons in the channel


V_g
Gate
T_{ox}
V_s
N
N
I_{ds}
V_{ds}
W_{dmax}
P-body
V_b
x
0
L


$V_{DS} \geq V_{GS} - V_t$
N+
N+
V_{DS} = GND


V_S = GND
Source
Oxide
+ V_{GS}
Gate
V_D = +V_{CC}
Drain
N+
n-channel
N+
L
P
where $V_{CC} \geq V_{GS} - V_t$
Body


Characteristic Curves for nMOSFET
.4
.3
.2
.1
0
Id (A)
0
1
2
3
4
5
Vds (V)

- Inversion layer can be considered a 2D system of electrons immersed in a triangular-shaped quantum well.
- Quantized values for the energy of confinement is given as

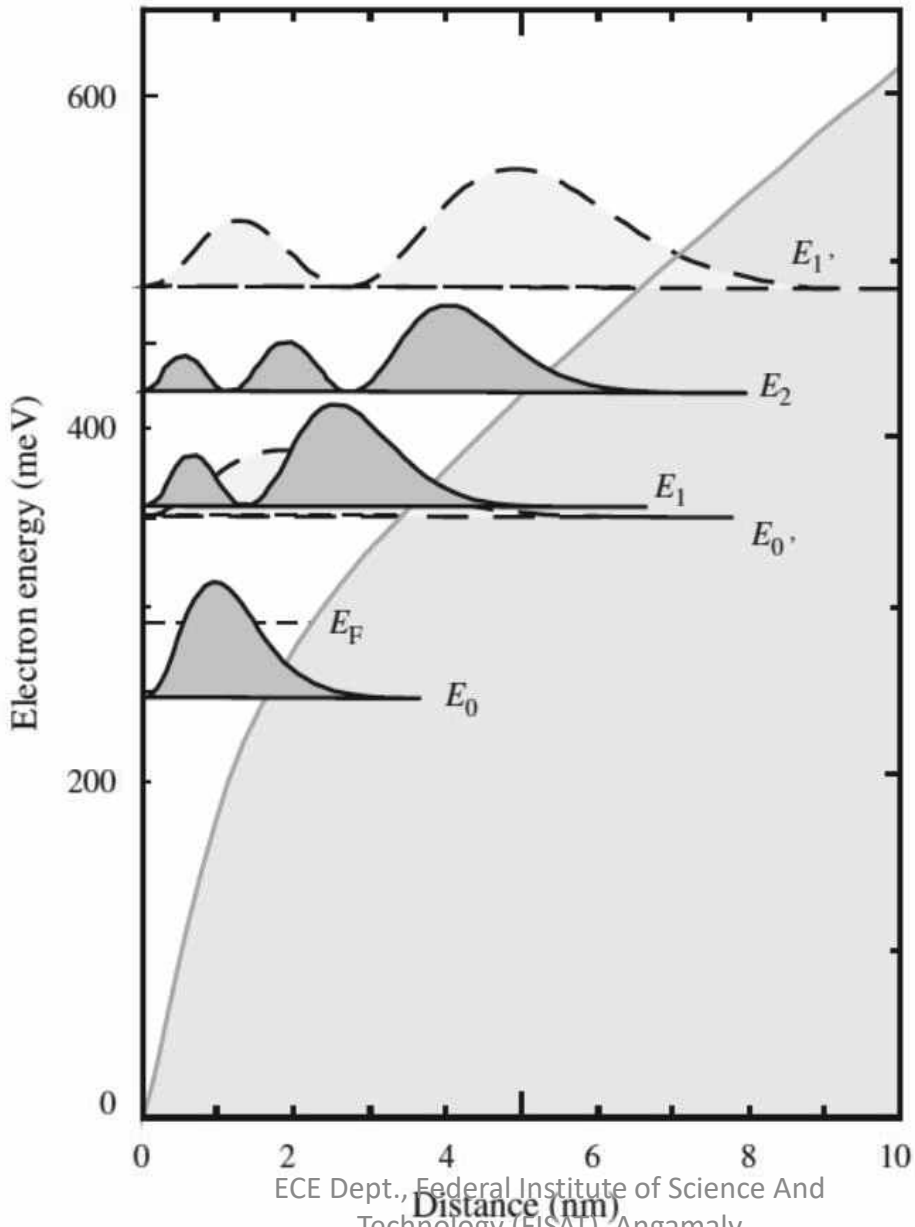
$$E = E_n + \frac{\hbar^2}{2m_x^*}k_x^2 + \frac{\hbar^2}{2m_y^*}k_y^2$$

- where *En* corresponds to the quantized energy for the triangular well

$$E_n \approx \left[\frac{3}{2}\pi\left(n - \frac{1}{4}\right)\right]^{2/3}\left(\frac{e^2F^2\hbar^2}{2m_z^*}\right)^{1/3}, \quad n = 1, 2, \ldots$$

- The density of states (DOS) function corresponds to the 2D case and is given by

$$g(E) = g_{\mathrm{v}} \frac{m_{\mathrm{T}}^{*}}{\pi \hbar^{2}}$$


600
400
200
0
Electron energy (meV)
$E_{1'}$
E_2
E_1
$E_{0'}$
E_F
E_0
0
2
4
6
8
10
Distance (nm)

HETEROJUNCTIONS

- Interfaces between two semiconductors of different gaps are called hetrojunction.

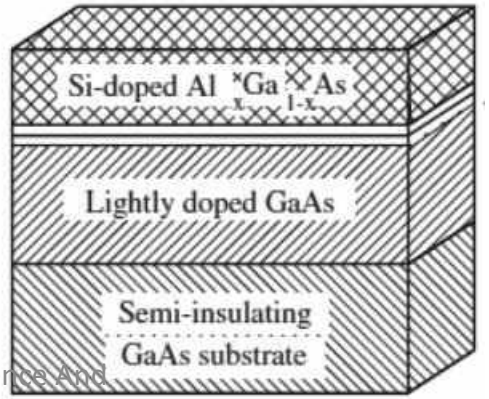
- If the dopants of the two sides are of the same type then it is called isotype heterojunction else called anisotype heterojunction.

- The most studied heterostructure is the one formed by n-type $Al_xGa_{1-x}As$ and almost intrinsic or lightly doped p-type GaAs.

AlGaAs–GaAs interface

- Here the left material is gallium arsenide doped with aluminium and the right one is near-intrinsic GaAs.

- This structure is called a modulation-doped heterojunction and the method to produce it is known as modulation doping.

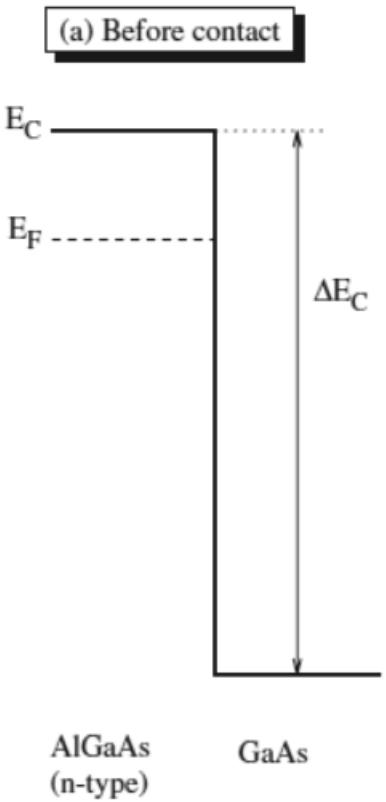


Before contact

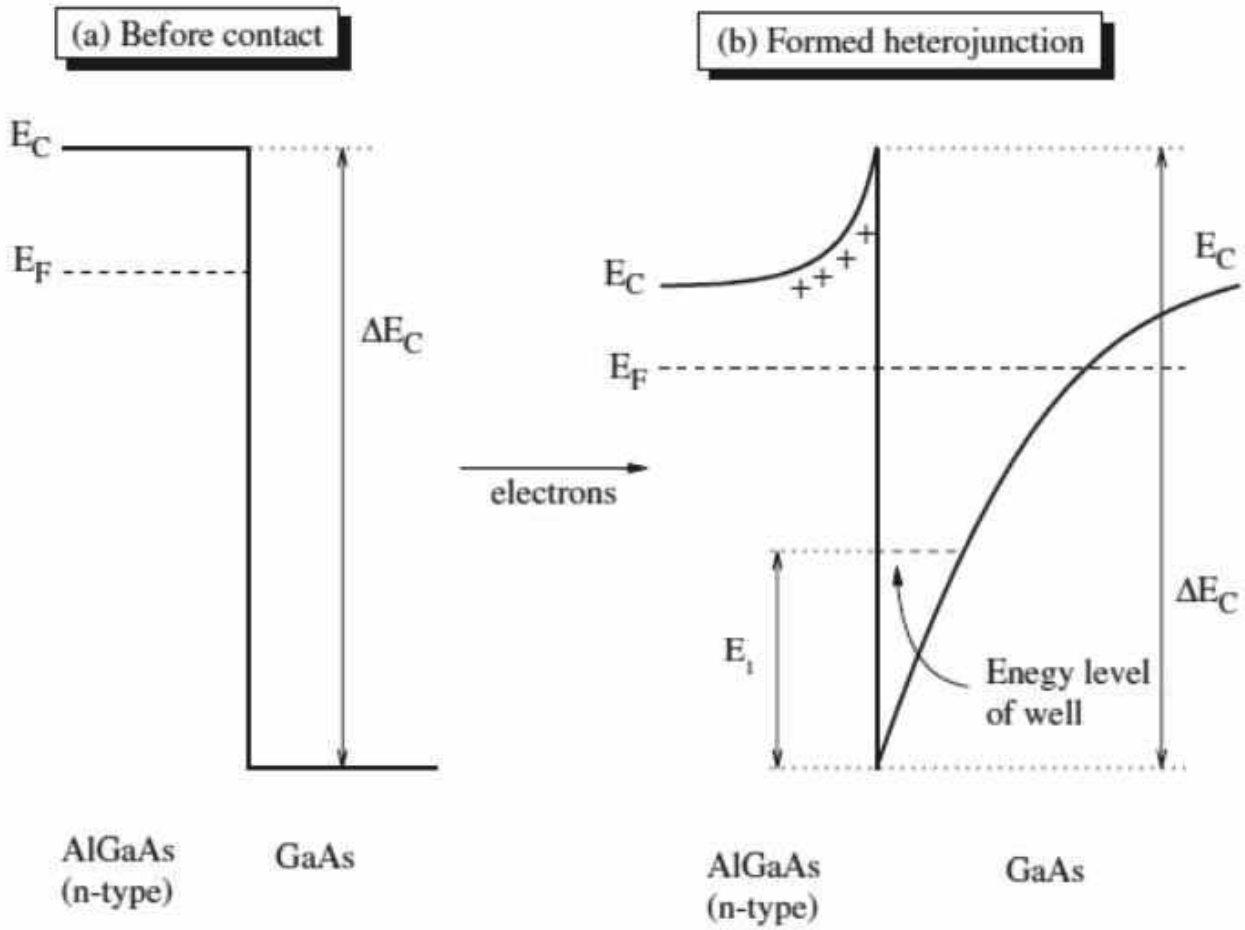
- Fermi level of n-type AlGaAs is close to the conduction band, and for lightly p-doped GaAs is located close to the middle of the gap.

- Here the bands are flat because the materials have uniform doping.

- The barrier between them in the conduction band, vE_c , can be found using Anderson's rule and is approximately 0.35 eV



After Contact



- When both materials, AlGaAs and GaAs, enter in contact, some of the electrons from the donors of the n-material will cross the interface reaching the undoped GaAs.

- At equilibrium, the two Fermi levels line up, the bands are bent like in the case of the p–n junction.

- a quantum well for the electrons has been formed which is limited by a potential well of height v$E_{c.}$

- The quantum well for the electrons produced at the AlGaAs–GaAs interface has a shape close to a triangle as in the case of the MOS structure.

- The wells cannot be assumed to be of infinite height, since in our case $E_c \approx 0.3$ eV.

- So as in first module energy for the motion along z is quantized in potential well.

- The most important aspect of this heterojunction is that the charge carriers are located in a region (mainly in the GaAs), spatially separated from the AlGaAs semiconductor which originates the free electrons.

- The electrons in the well should have very high mobility for their motion along the (x, y) plane, since they move within the GaAs which is free of dopant impurities and it is well known that impurity scattering is one of the main factors which limit carrier mobility.

- Devices based on AlGaAs structures can be used to much higher frequencies than silicon devices due to the high mobility of electrons in GaAs.

- Transistors made with above hetrojunctions are called modulation-doped field effect transitor (MODFET) or high electron mobility transistor (HEMT).

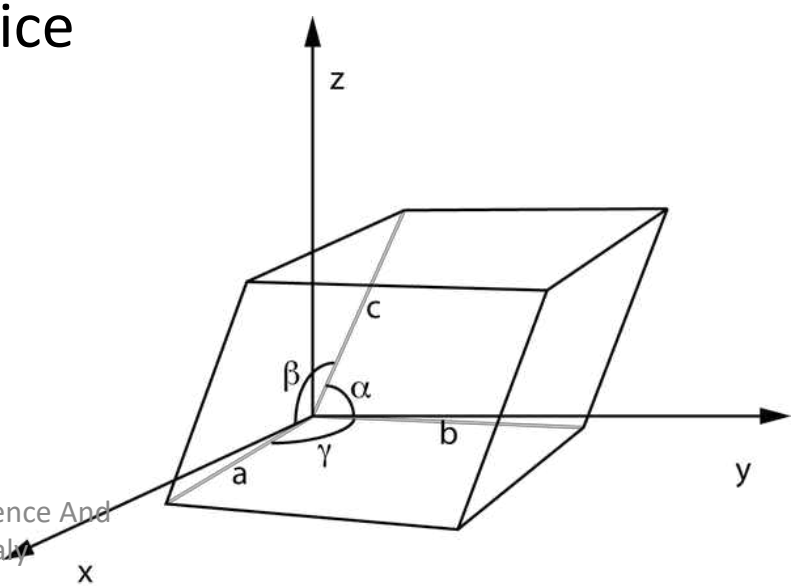
- MODFET can use in many high-frequency applications due to the very high electron mobility of the electrons in the channel.

Lattice constant

- The lattice constant is the physical dimension of the smallest repeating unit that possesses all the symmetry of the crystal structure.

- A 3D crystal is considered to have 3 lattice constants in terms of length of the unit cell edges *a, b* & *c* and 3 lattice constants in terms of the angles between them α, β & γ.

- This set of 6 constants are termed lattice parameters and give the entire structure of the lattice



STRAINED LAYERS

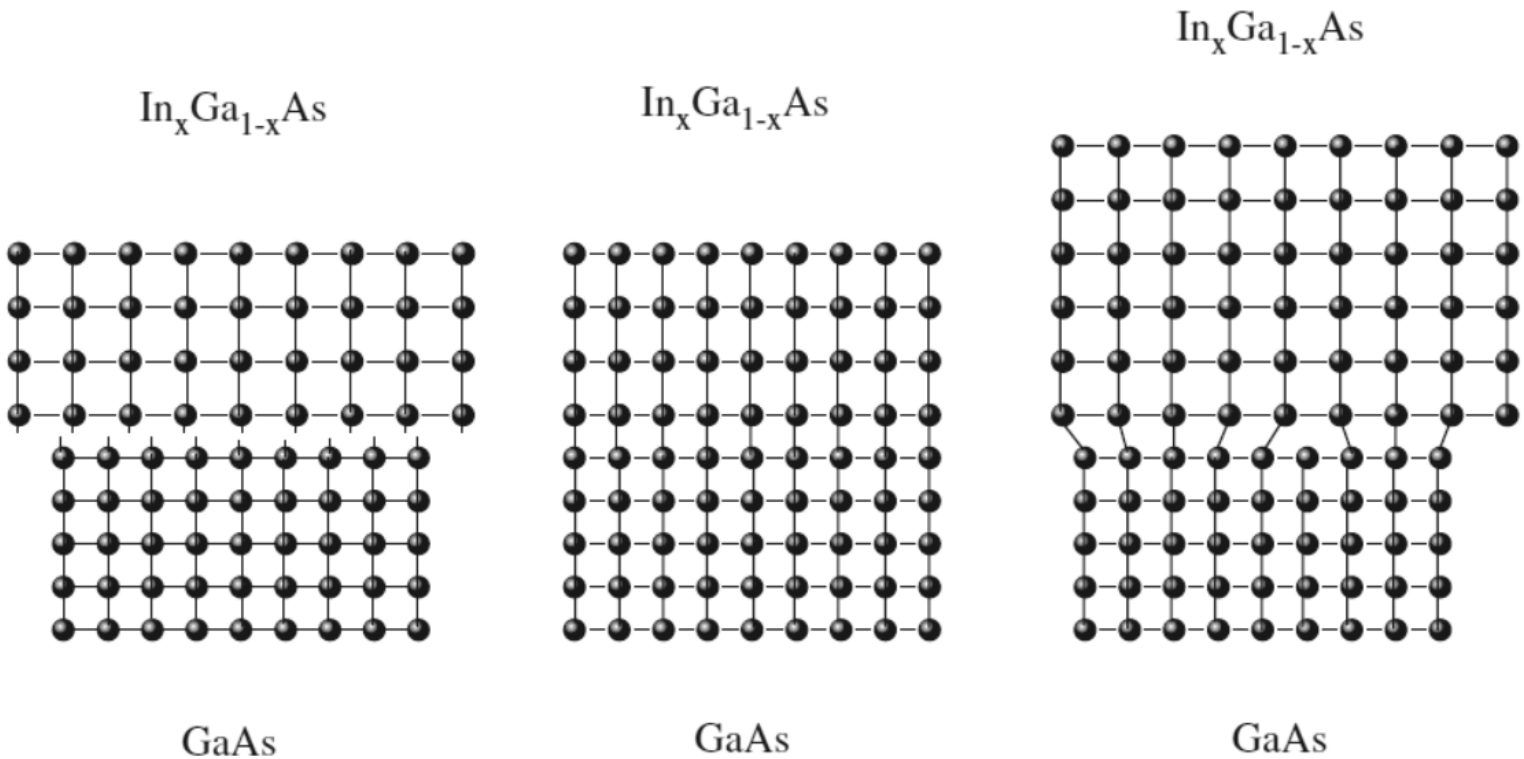
- The quality of an interface between two materials depends greatly on the relative size of the lattice constants.

- If the lattice constants are very similar, as in the case of the Al*x*Ga1−*x*As–GaAs heterojunctions (0.2% diffrence), the thermal expansion coefficients are similar and no stresses are introduced at the interface.

- Heterojunctions with differences in lattice constants up to 6% are fabricated (for instance, In*x*Ga1−*x*As–GaAs). In this case strong stresses appear at the interface.

- In the above case, only very thin films of a few monolayers can be grown on a given substrate.

STRAINED LAYERS FORMATION



- (a) The layer is not yet deposited over the substrate;
- (b) the layer is subjected to a compressive stress;
- (c) Dislocations are formed at the interface.

- Suppose that a layer of lattice constant aL is grown on a substrate of lattice constant aS. The strain ε of the layer is defined as

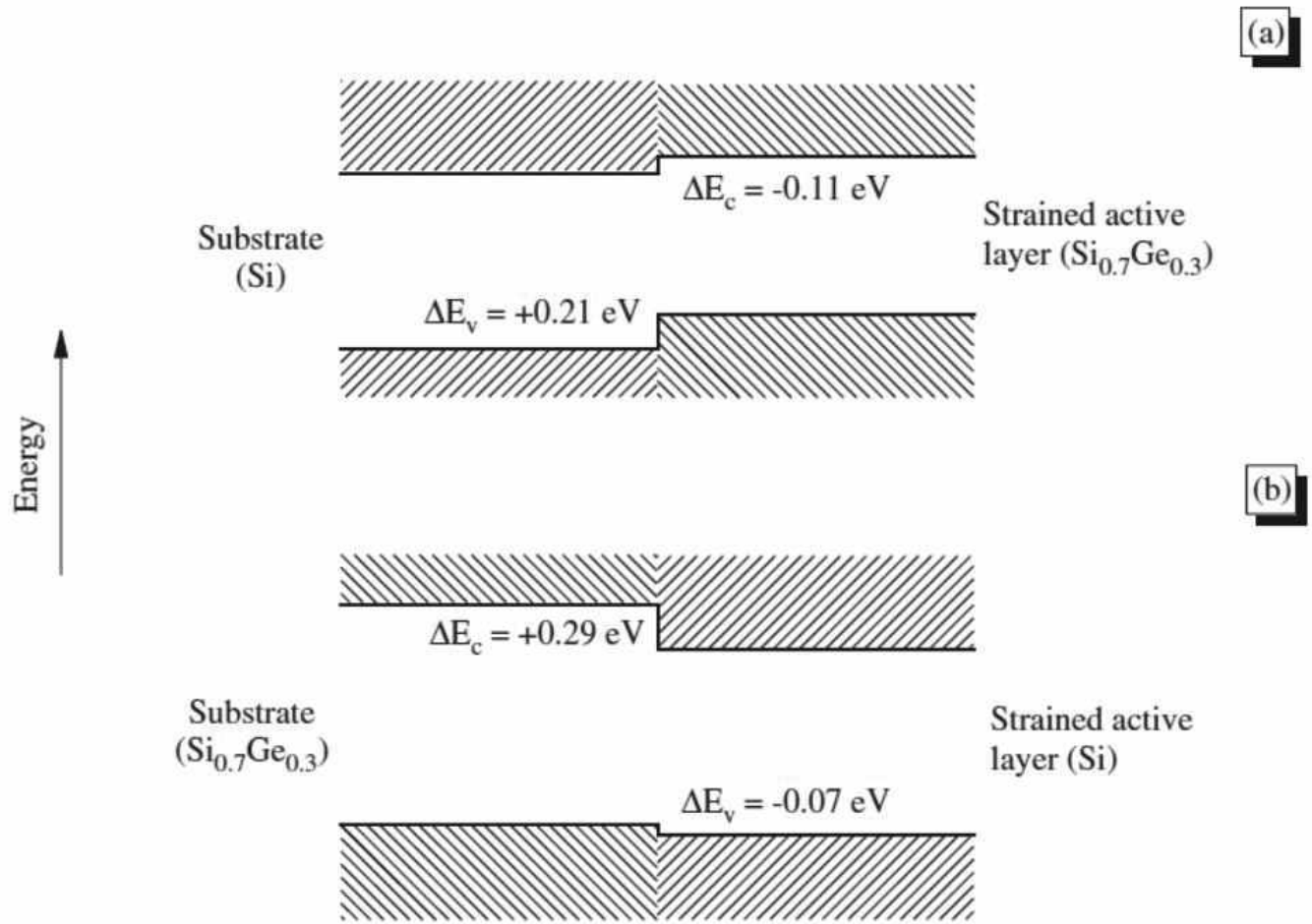
$$\varepsilon = \frac{a_{\mathrm{L}} - a_{\mathrm{S}}}{a_{\mathrm{S}}}$$

SiGe strained heterostructure

- SiGe heterojunctions did not attract too much attention at first because of the large lattice constant difference between Si and Ge (around 4%).

- This means that the layers grow strained over the substrate.

- SiGe heterostructures have found interesting applications in several fields such as high frequency transistors and IR photodetectors.

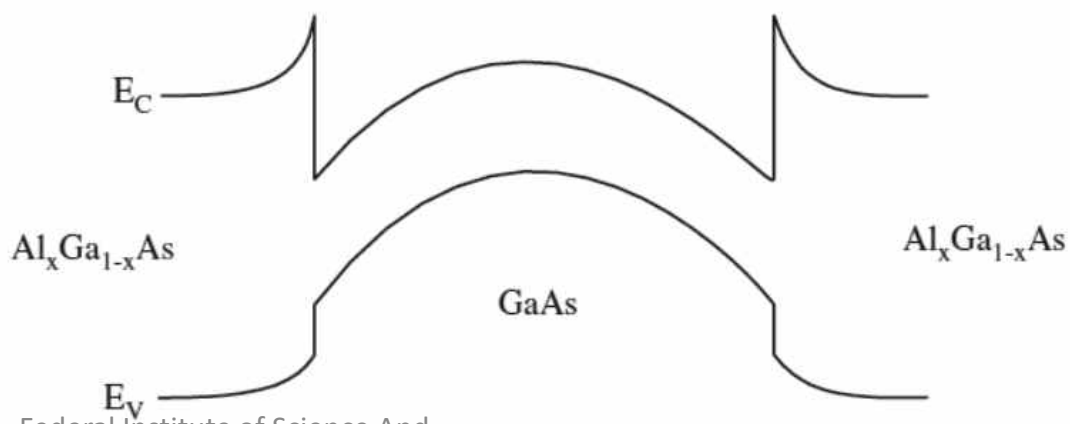


Simplified band diagram of two strained SiGe heterostructures. In (a) the active layer is SiGe, while in (b) the SiGe acts as a substrate.

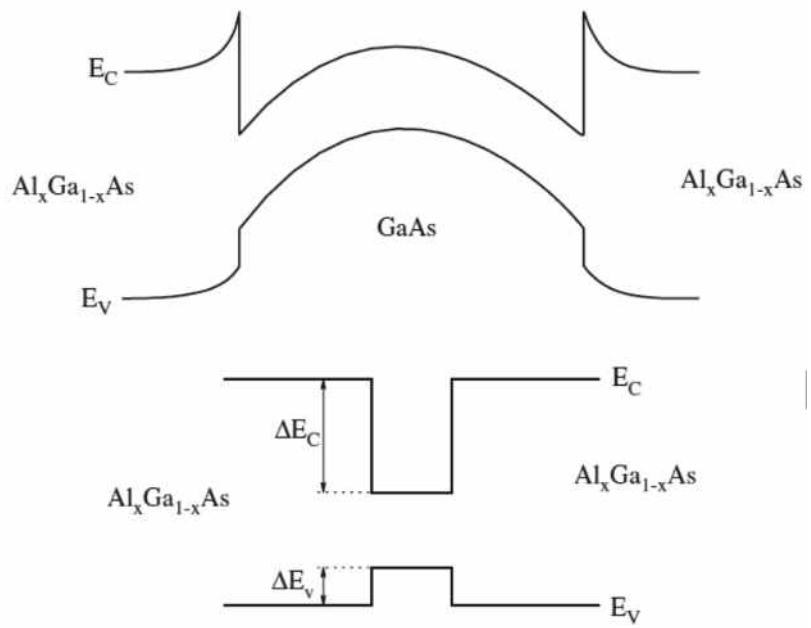
- In first case the conduction band offset is rather small, in contrast to the valence band offset.
- In second case the discontinuity in the conduction band is fairly large.

Modulation-doped quantum well

- Let us consider that we build a symmetric well by facing two AlGaAs–GaAs heterojunctions opposing each other.
- The wide gap semiconductor material Al*x*Ga1−*x*As is located at the ends and the GaAs in the middle.



- The distance between the two interfaces is made sufficiently small.
- Then the resulting well for electrons and holes would be almost square with a barrier on each side of the same height.



- The electrons inside the well, which originated at the neighbouring AlGaAs donor-material, can move into the GaAs region or channel with very high mobility.

- Quantum well structures with either high or low mobility for electrons can be fabricated by introducing a controlled amount of impurities.

- A double quantum well structure with high and low mobilities constitutes the base of the velocity-modulation transistors.

- Velocity-modulation transistors can be operated at very high frequencies.

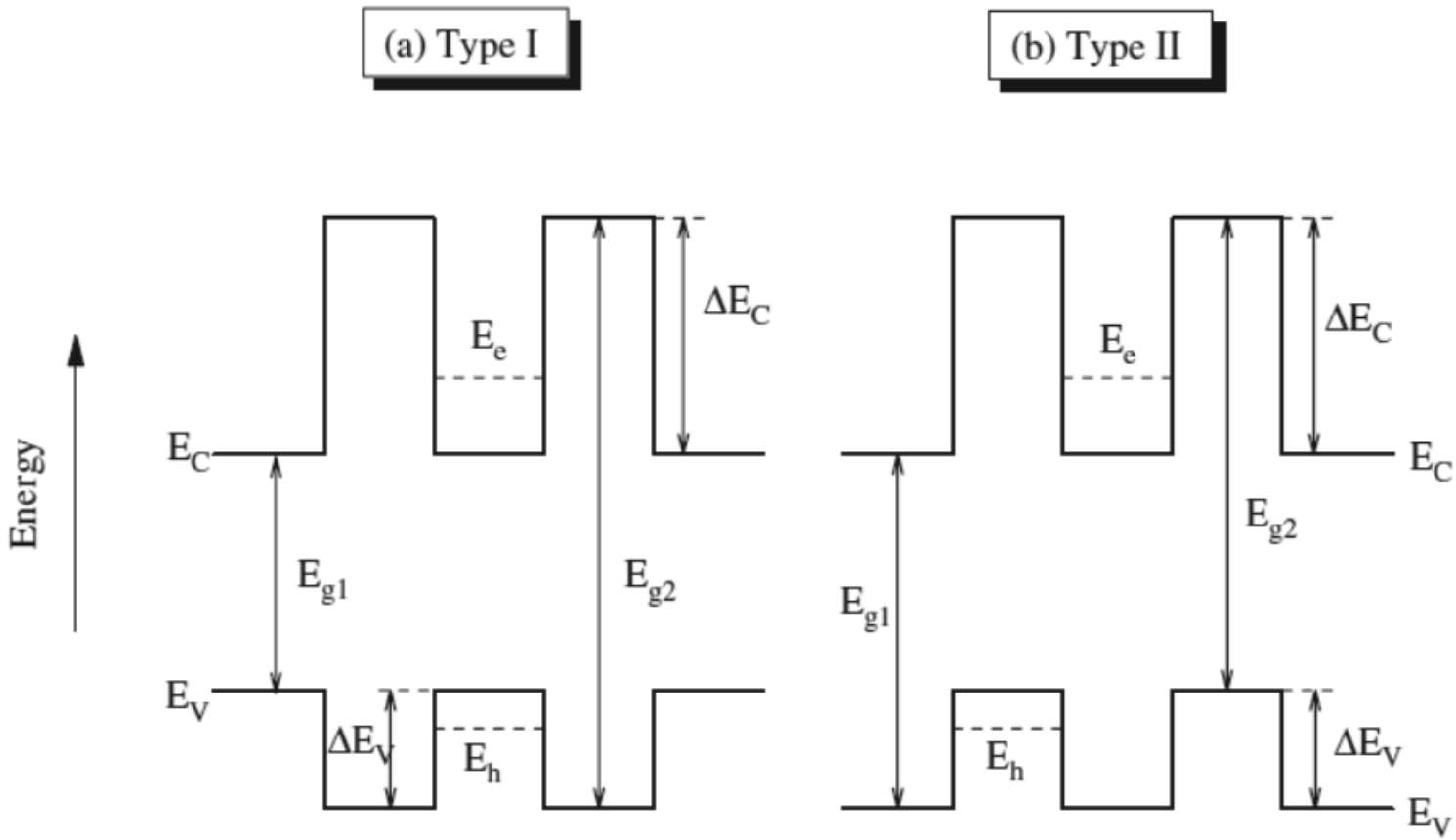
- The occupation of levels depends on the electron concentration in the well, and for low concentrations usually the first level is the only one occupied.

Multiple quantum wells (MQW)

- It is an array of quantum wells formed by several single quantum wells.

- If the wells for electrons and holes are located in the same space location, the MQW is called *Type I*

- while the name *Type II* is used when the corresponding wells are located alternatively as in Figure.


(a) Type I
(b) Type II
Energy
E_C
E_V
E_e
E_h
E_{g1}
E_{g2}
ΔE_C
ΔE_V

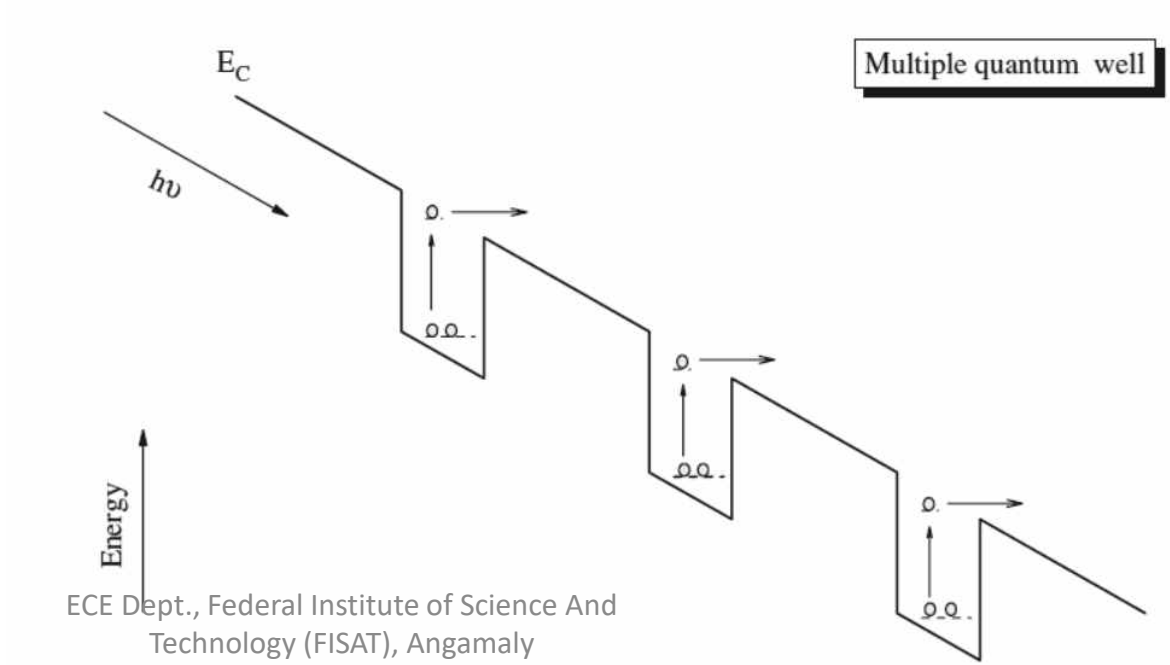
- In a MQW system it is assumed that there is no interaction between neighbouring quantum wells, because the barriers separating the wells are thick enough, usually more than about 10 nm.

- However, if the energy barriers between consecutive wells are thin enough, the wells will be coupled to each other by tunnelling effects.

- the discrete energy levels of the quantum wells are then transformed into energy bands.

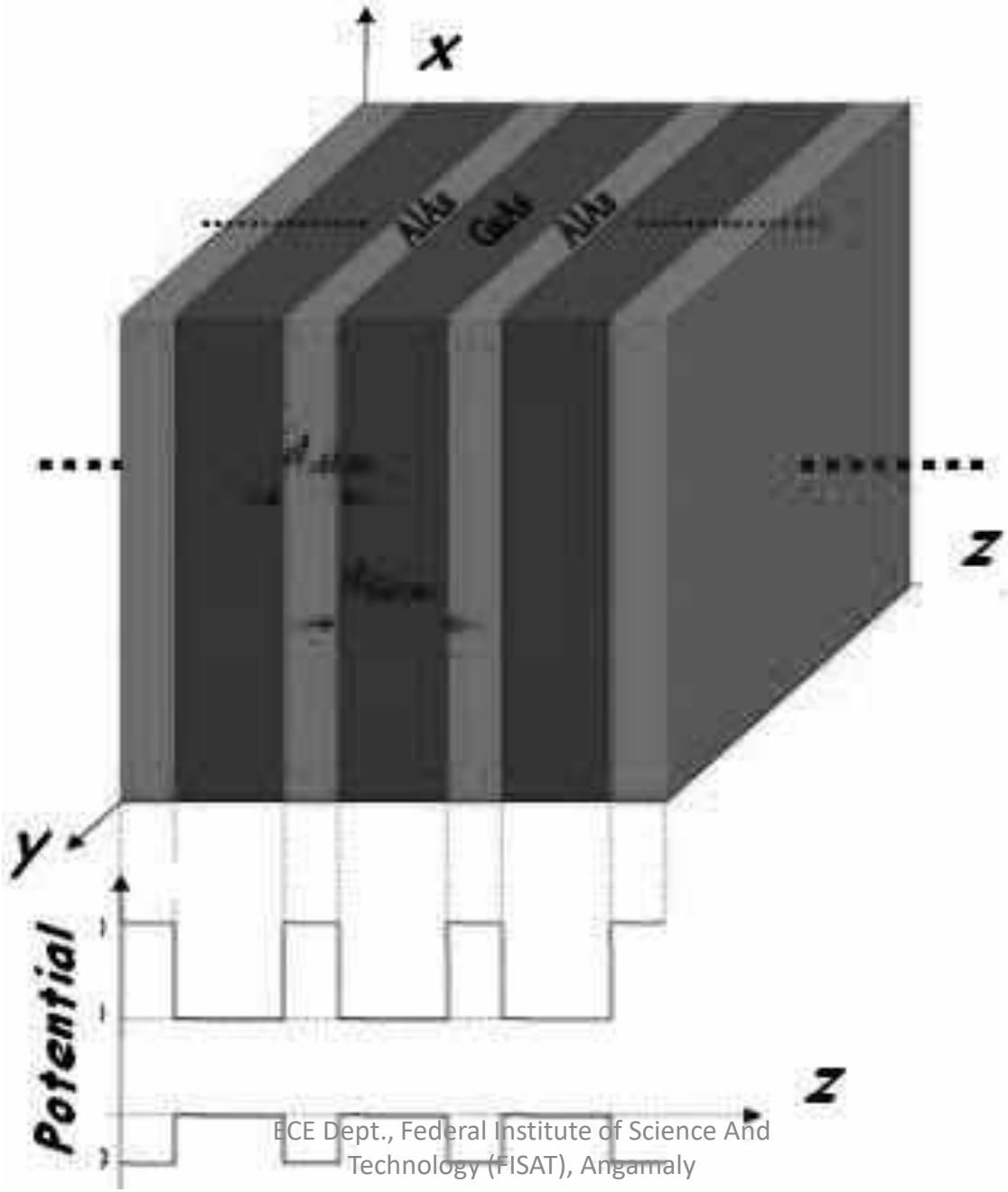
- In this case, the system of MQWs is called a superlattice and the energy spectrum shows very interesting new features.

- In optoelectronics, MQWs are frequently used and are made of about 50 single wells.
- thickness of each well is not exactly the same for all.
- Figure shows the band structure of a typical MQW for applications in IR photo detectors.



SUPERLATTICES

- A **superlattice** is a periodic structure of layers of two (or more) materials.
- Typically, the thickness of one layer is several nanometers.
- It can also define as an array of quantum wells.
- Layers are fabricated by molecular beam epitaxy (MBE) techniques.
- Conditions of each quantum well will affect charge flow through the structure.


x
AlAs
GaAs
AlAs
z
y
Potential
z

- A superlattice consists of a periodic set of MQW in which the thickness of the energy barriers separating the individual wells is made sufficiently small.

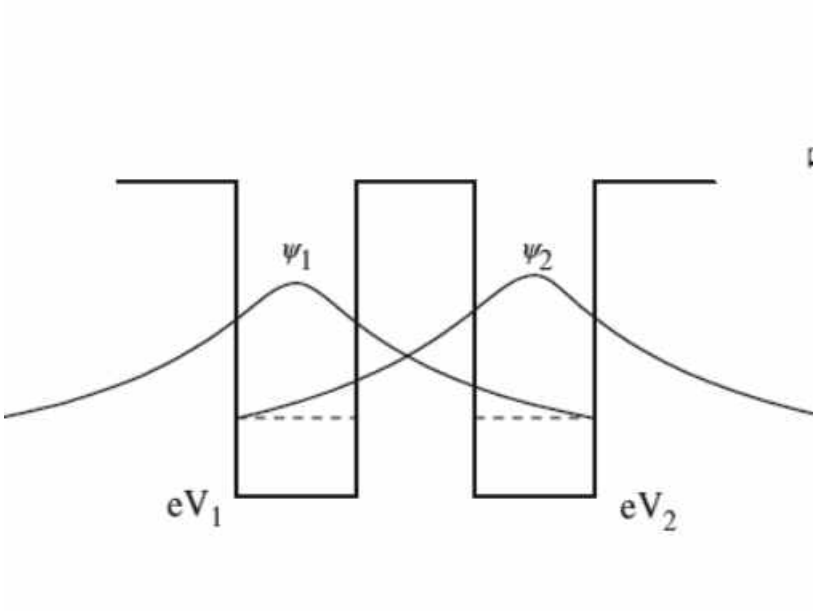
- As the barriers become thinner, the electron wave functions corresponding to the wells overlap due to the tunnelling effect.

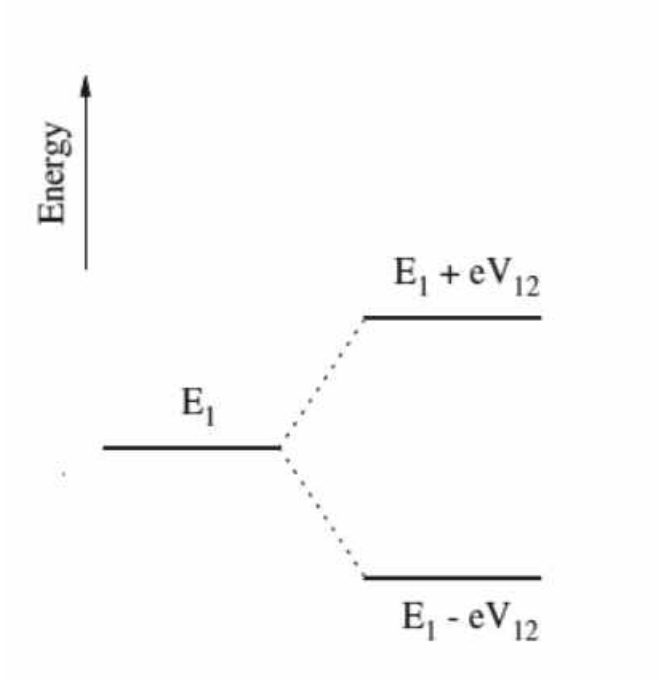
- As a consequence, the discrete energy levels of the wells broaden and produce energy bands.

- Superlattice have periodicity *d* in the material, which is equal to the breadth of the well *a*, plus the thickness of the barrier *b.*

- Typical thicknesses for *a* and *b* could be 4 and 2 nm, respectively.

- let us consider first the overlapping between the electron states for a simple two-well system.





- Above figure shows two neighboring identical quantum wells and corresponding wave functions of what is known as the double coupled quantum well system.

- Each original energy level, say $E1$, of the isolated wells splits into two, with energies

$$E = E1 \pm |V12|$$

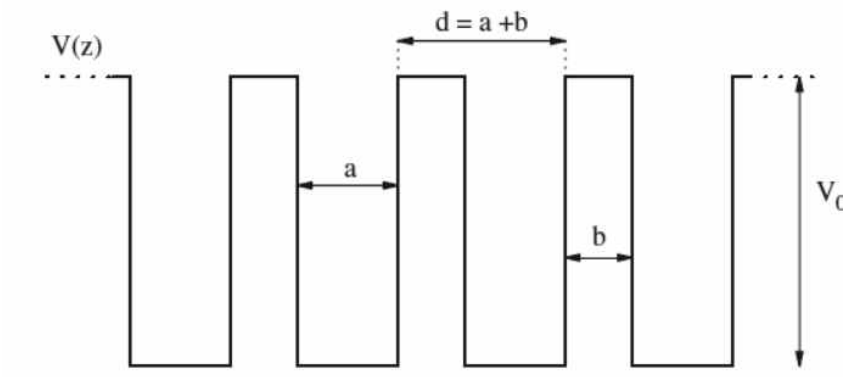
$V12$: overlap integral.

- where the magnitude of $V12$ is an indication of how much one well can influence the energy states of the neighboring one, hence the name overlap integral.

$$V_{12} = \int_{-\infty}^{+\infty} \psi_1^* V(z) \psi_2 dz$$

Kronig–Penney model of a superlattice.

- As per Kronig and Penney model, periodic potential seen by the electrons was precisely that of the square type for a superlattice potential.



Scheme of the periodic potential of a superlattice.

- This periodic one-dimensional potential is characterized by the following parameters: well thickness *a*, barrier thickness *b*, and barrier height *V*0.

- The spatial periodicity is $d = a+b$.

Wave function in Kronig–Penney model

- In the well region ($0 < z < a$), $V = 0$

$$\psi(z) = Ae^{ik_0 z} + Be^{-ik_0 z}$$

$$k_0^2 = \frac{2mE}{\hbar^2}$$

- In the barrier region $-b < z < 0$, V= $V0$

$$\psi(z) = Ce^{qz} + De^{-qz}$$

A, *B*, *C*, and *D are amplitudes of the wave*

- Wave vector and the energy are related by

$$V_0 - E = \frac{\hbar^2 q^2}{2m}$$

- Kronig and Penney suggested that

  A+ B= C+D

  $ik0(A - B) = q(C - D)$

- Applying this for the above case

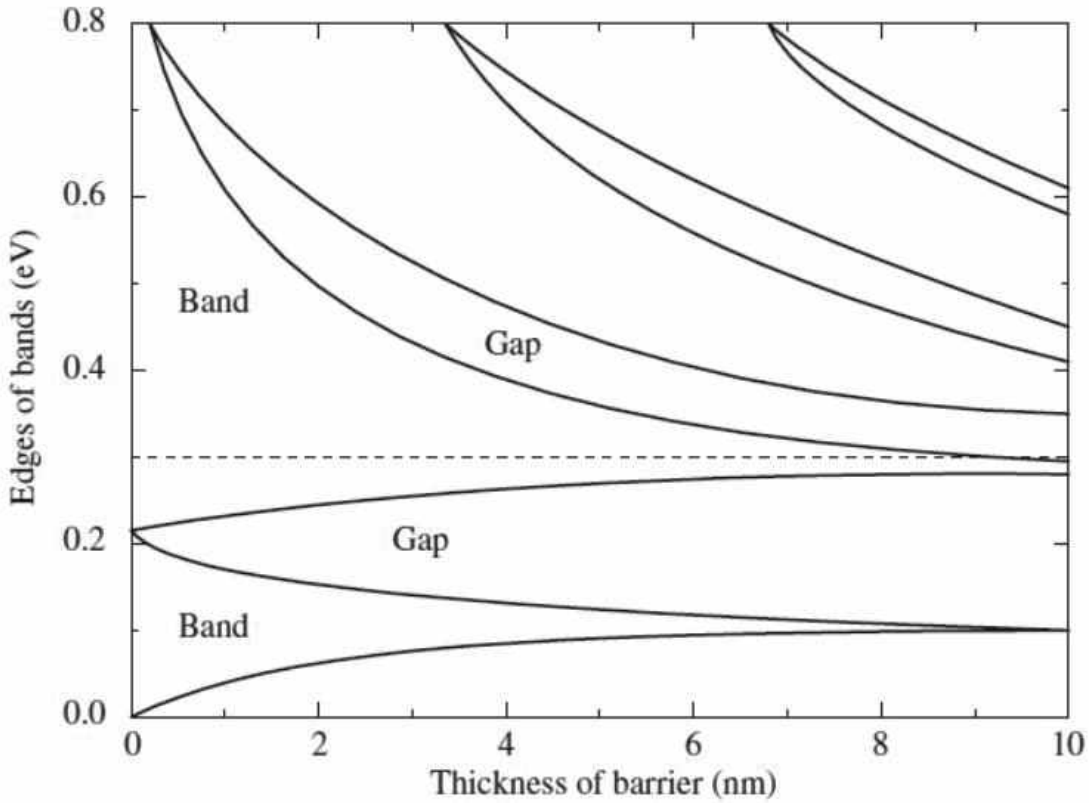
$$Ae^{ik_0a} + Be^{-ik_0a} = (Ce^{-qb} + De^{qb})e^{ik_0(a+b)}$$

$$ik_0(Ae^{ik_0a} - Be^{-ik_0a}) = q(Ce^{-qb} - De^{-qb})e^{ik_0(a+b)}$$

- On solving above two expressions

$$\frac{q - k_0^2}{2qk_0} \sin k_0a \sinh qb + \cos qa \cosh qb = \cos q(a + b)$$

Energy band diagram of a superlattice

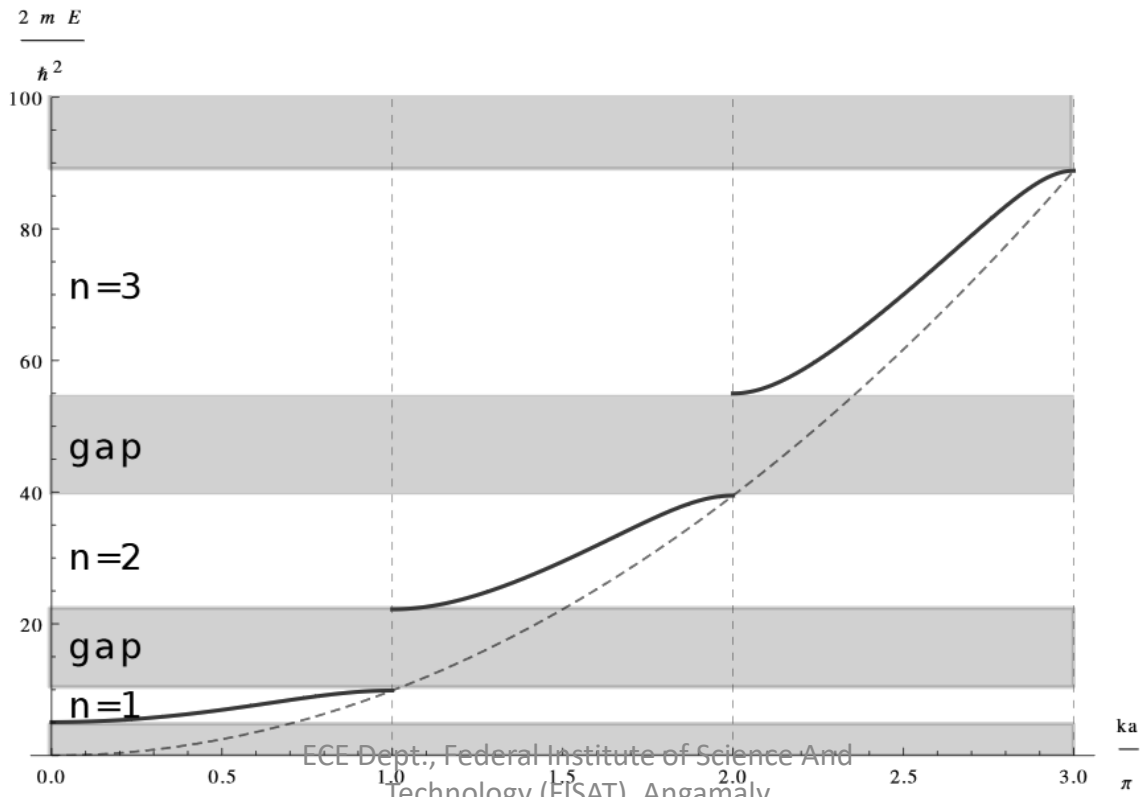


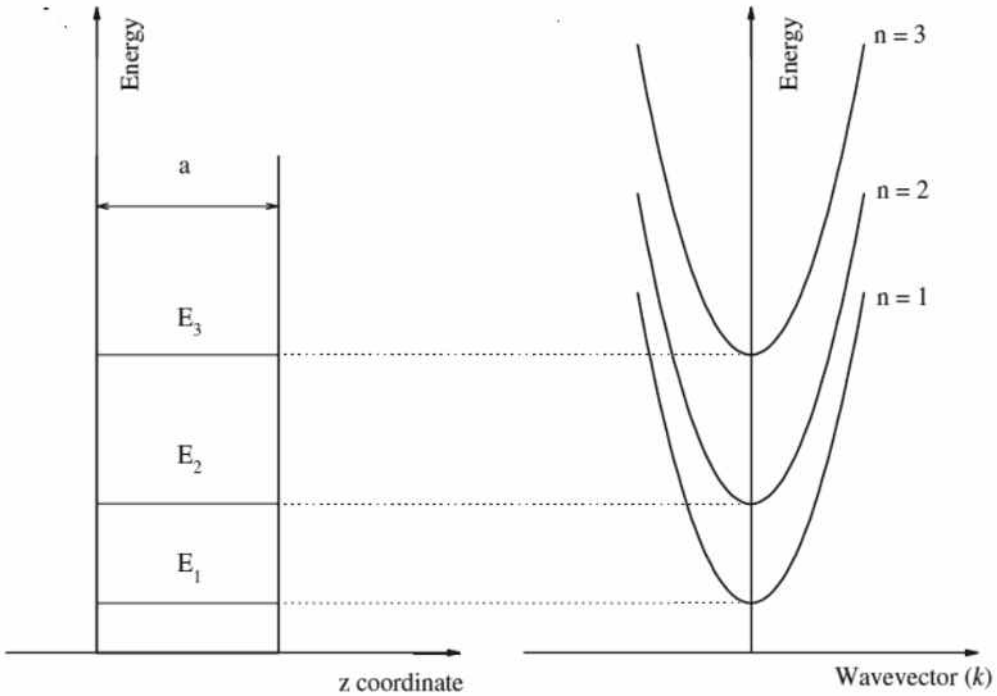
Energy band diagram of a superlattice with the width of the barrier equal to the width of the wells.

- When barrier thickness is greater than 10nm, each wells are isolated and will acts as quantum wells.
- Thus energy states are quantized and there will not be any separation in bands.
- For values of *a* larger than about 10 nm, the electron energies are well defined and correspond to the individual quantum wells.
- When barrier thickness is lesser than 6nm, wells are connected together and hence the structure become a normal material. This will separate quantized energy levels into different bands and forbidden states.
- When the barrier width is smaller than about 6 nm, bands as well as forbidden zones arise.

Energy and formation of bands

- In super lattice the free electron parabola, breaks down into several bands and gaps.

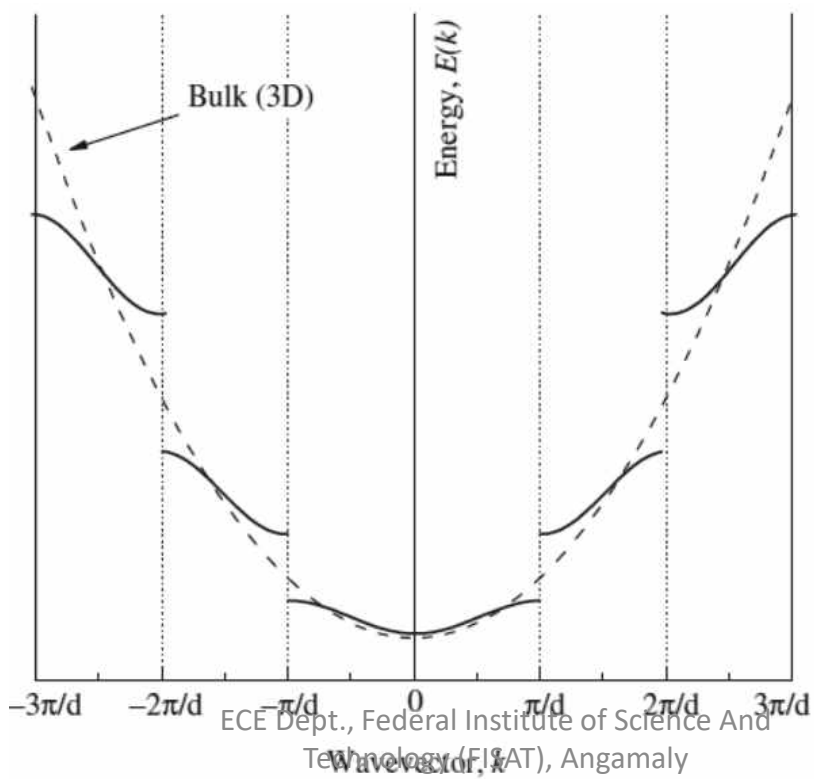




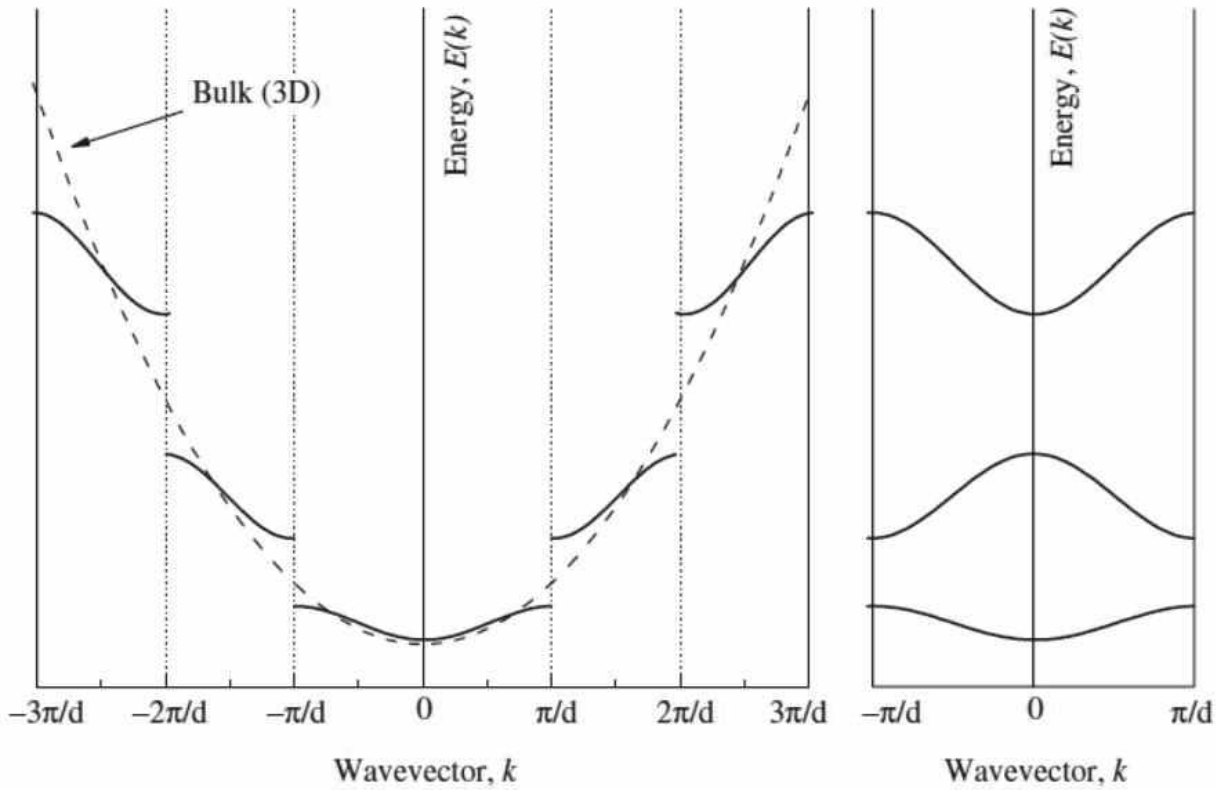
Energy levels in quantum well

Energy subbands

- The dashed line is the parabola corresponding to free electrons.($k_0^2 = \frac{2mE}{\hbar^2}$)



- The portions of the bands can be translated to the reduced zone.



- This band folding procedure is typical of superlattices and is called *zone folding* since it implies that the pieces of the band in the extended representation are zone-folded into the smaller zone.

Module 5

Electric Field Transport in Nanostructures

- Quantum wells are formed at interfaces between semiconductors of different gaps.
- Conduction band electrons in these quasi-2D wells behave almost as free carriers for their motion along planes parallel to the interfaces of the well.
- Above kind of transport, usually called *parallel transport.*
- Transport through the potential barriers at the interfaces is known as *perpendicular transport* which is based on the quantum tunnelling effect.

PARALLEL TRANSPORT

- Electronic transport is parallel to the potential barriers at the interfaces.
- There are chances for electron scattering during the transport since we are dealing with low-dimensional system.
- Parallel transport in nanostructures was happening in all Nano devices like MOSFET, MODFET etc..
- Electron motion takes place in a region free of charged dopants, and therefore, electrons can reach very high motilities.

Electron scattering mechanisms

- Following are the main scattering mechanisms for parallel transport in semiconductor nanostructures.
- ***(i) Electron–phonon scattering***
- ***(ii) Impurity scattering***
- ***(iii) Surface roughness scattering***
- ***(iv) Intersubband scattering***

Electron–phonon scattering

- The quantum of a lattice vibration is commonly referred as a Phonon.
- It is similar to photon and it carries heat in the material.
- Electron-Phonon interaction is commonly observed in most of the materials.
- In reality at room temperature, the lattice of materials is not static and atoms, they actually vibrate about their mean positions.
- The vibrations of the lattice increase with the increase in temperature.
- Phonon scattering mechanism is the predominant one for temperatures higher than about 50 K.

- The electrons will have a chance to make collisions with the vibrating lattice during their motion and such collision is referred as electron-phonon collision or scattering.

- Phonon scattering becomes very considerable in low-dimensional semiconductors since the width *a* of the quantum wells is very small.

- In semiconductors, the electron-phonon scattering results in a decrease in mobility of charge carriers involved.

Impurity scattering

- Impurity scattering constitutes the largest contribution to scattering in low-dimensional semiconductors **at low temperatures**.

- In modulation-doped heterostructures, the charged donors are located in the AlGaAs, while electron motion takes place in a separated region in the GaAs parallel to the interface which is separated from impurities.

- Similarly, in a MOS structure, electrons move within the inversion channel, which is separated from impurities located in the thin gate oxide.

- For the calculation of impurity scattering in MODFET quantum heterostructures some simplifying assumptions are usually made.
  - Impurities are supposed to be located in a 2D plane at a distance *d* of the electron channel.
  - However, there is an optimum value of *d*, because if *d* is too large, the concentration of electrons in the channel diminishes significantly, as a consequence of the decrease in the electric field, and the transconductance of MODFETs is greatly reduced.
  - Electrons in the channel which participate in the scattering events are those with energies very close to the Fermi level.
  - Also assumed that the concentration of impurities is not too high,

Surface roughness scattering

- Interface scattering is due to the interaction of electrons with a roughened surface, in contrast to an ideal perfect flat surface.

- Interfaces have a roughness at the atomic level, which produces non-specular reflections of carriers, and therefore, a loss of momentum.

- The role of interface scattering for parallel transport in modulation-doped heterostructures is not very important, due to the high perfection of the interfaces when growth techniques such as molecular beam epitaxy are used.

- In the case of MOS structures, interface scattering becomes more important since the oxide is grown thermally and the interface is not as perfect as in the modulation-doped heterostructure.

- The contribution of interface scattering in MOS structures depends on the quantum well width.

- As the width decreases the electron wave function penetrates deeper into the oxide-semiconductor potential barriers, i.e. the electrons are more exposed to the interface roughness and the corresponding scattering increases.

- Roughness scattering, like impurity scattering, only becomes significant at temperatures low enough for phonon scattering to be negligible.

Intersubband scattering

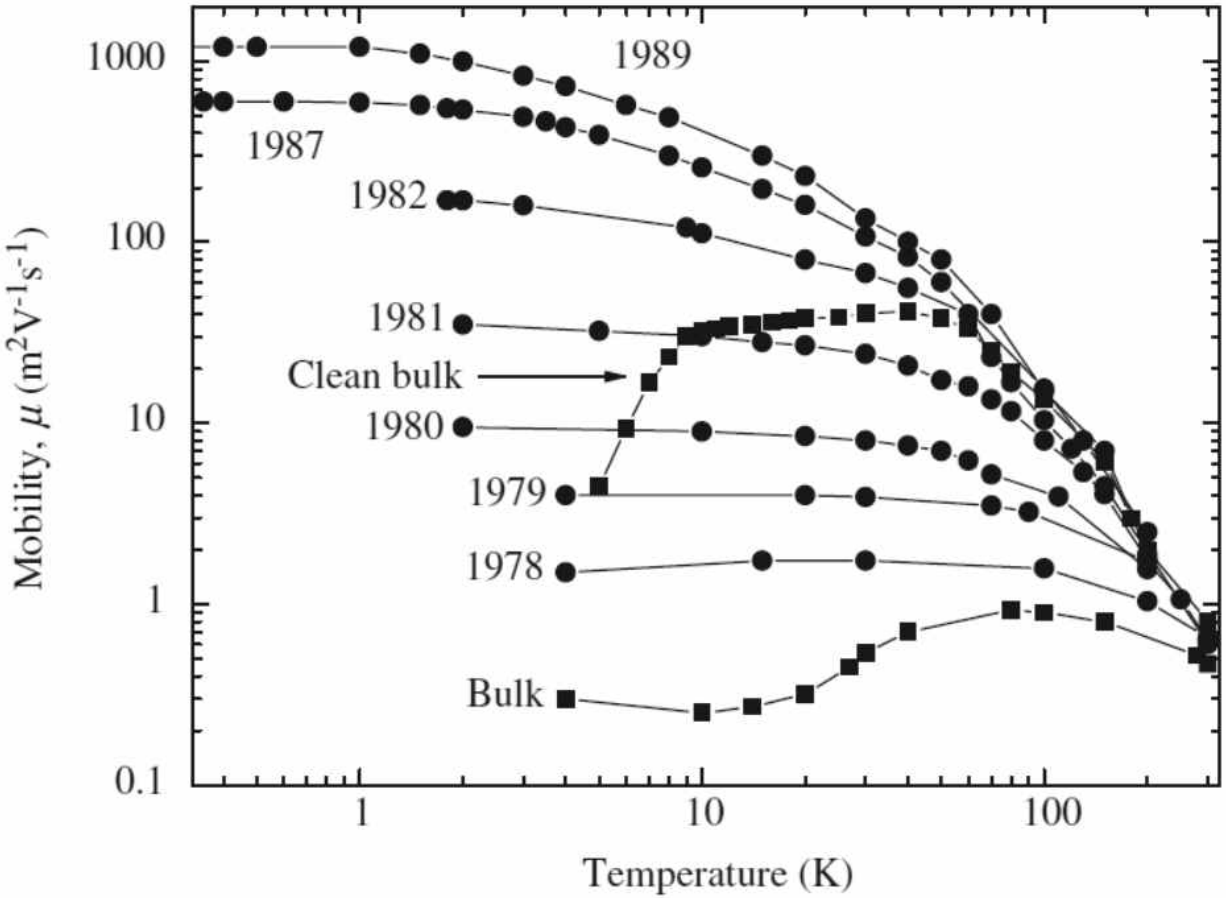
- For large electron concentrations in the well, the levels with energies higher than the first one $E1$ will start to become filled.

- Then, electrons with energies can undergo an intraband scattering transition within the subband n=2 or an interband transition between subbands n = 1 and n = 2.

- As a consequence, the electron mobility should become smaller.

- In summary, as the electron concentration in a quantum well increases, additional scattering channels start to contribute to the overall scattering rate, and the mobility of the electron decreases.

Mobility improvements



Increase of the mobility for parallel electron motion

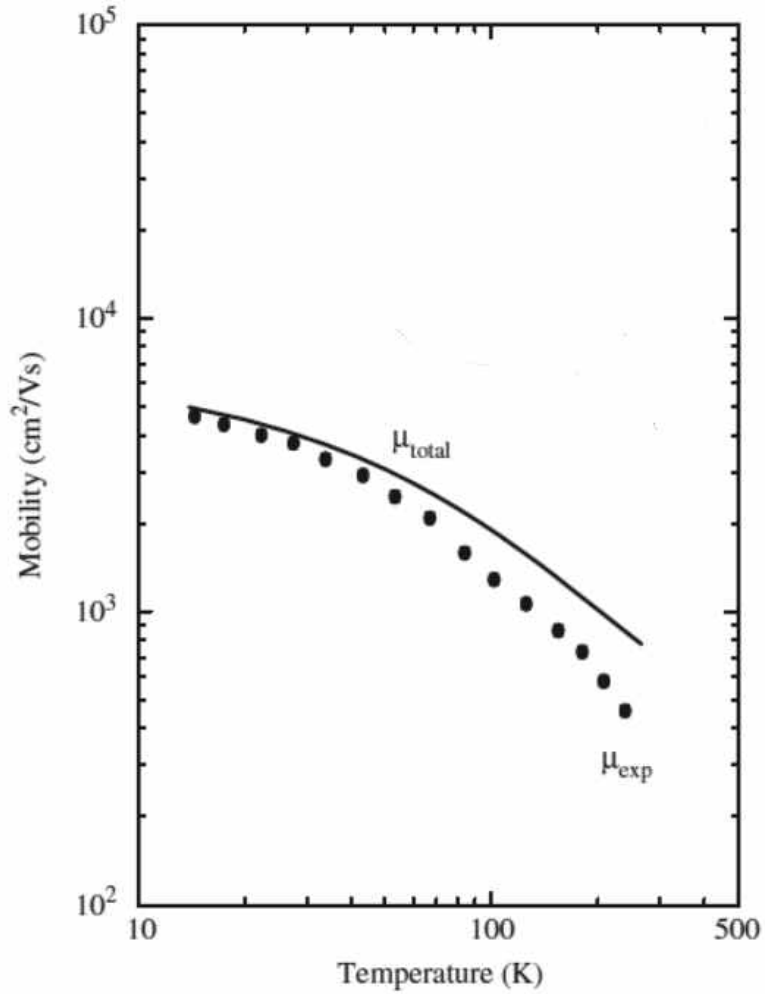
- It is observed a large improvement in electron mobility of parallel transport at low temperatures in GaAs-based nanostructures.

- There are several reasons for this
  - The main reason, is due to the physical separation between dopants and carriers in modulation-doped heterostructures.
    - A semi-insulating layer, called a spacer, is added between the donor layer and the 2D electrons in the conducting channel.
    - This spacer is especially effective at low temperatures for which the impurity–electron scattering mechanism becomes predominant.

  - Another reason for the large increase in the electron mobility is the high purity of the bulk material, caused by the improvement in the growth techniques such as molecular beam epitaxy.

- As the temperature approaches 100K and gets close to room temperature, the dominant scattering mechanisms are due to phonons.

MOSFET vs MODFET mobility



Temperature dependence of electron mobility in a silicon MOSFET.

- Mobility of electrons in a silicon MOSFET is much lower than in a MODFET.

- There are several reasons for this
  - The effective mass of electrons in Si is much higher than in GaAs.
  - the effect of impurity scattering in a Si MOSFET, caused by charges and impurities in the oxide and the interface, is larger than in the case of AlGaAs/GaAs
  - The silicon–oxide interface, grown thermally, is not as perfect as the AlGaAs/GaAs interface and hence surface roughness scattering is higher at low temperature.

Hot electrons in parallel transport

- Electrons are accelerated by the electric field to kinetic energies much higher than their energies at thermal equilibrium.

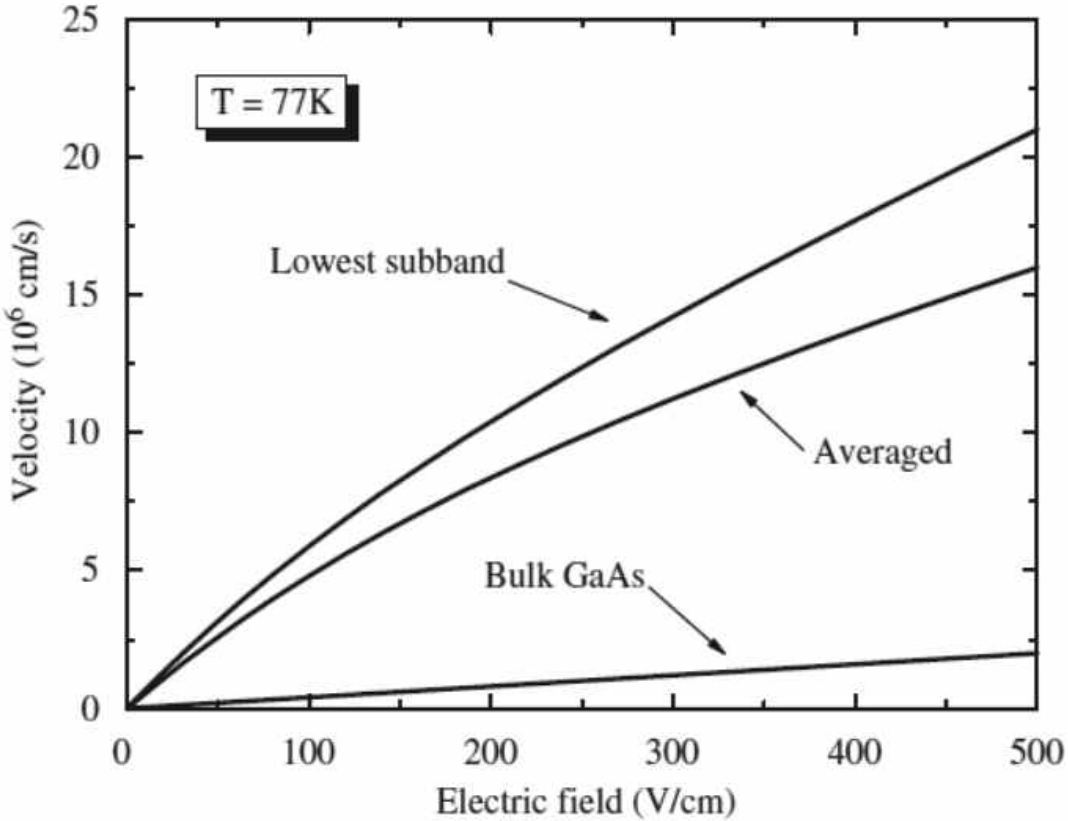
- After the acceleration by high electric fields, the electron energy distribution corresponds to an effective temperature higher than that of the crystal lattice, and the electrons receive the name *hot electrons*.

- average energy *E* is defined by the equation

$$\overline{E} = \frac{3}{2} k T_e$$

- The electron velocities reached under the action of an electric field are higher than in bulk GaAs and that the difference becomes larger at low temperatures.

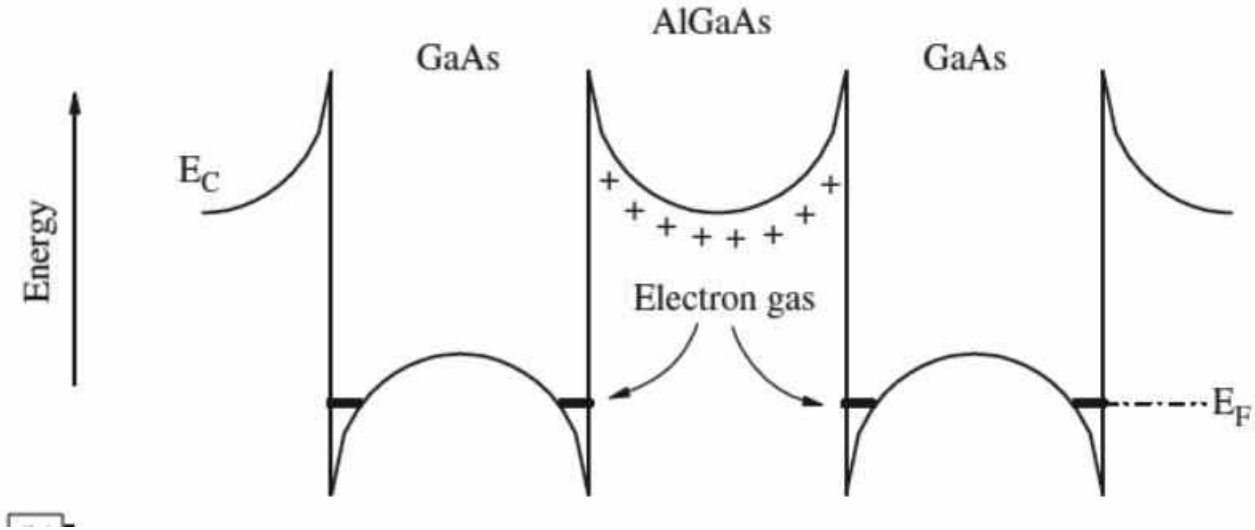
- The value of the velocity is specially high for the lowest subband (E=E_1) in comparison to the second subband (E=E_2) for which the electron wave function extends much more outside the barrier region.

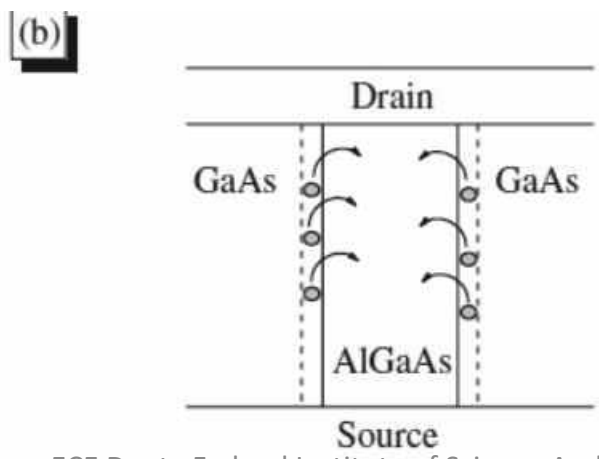


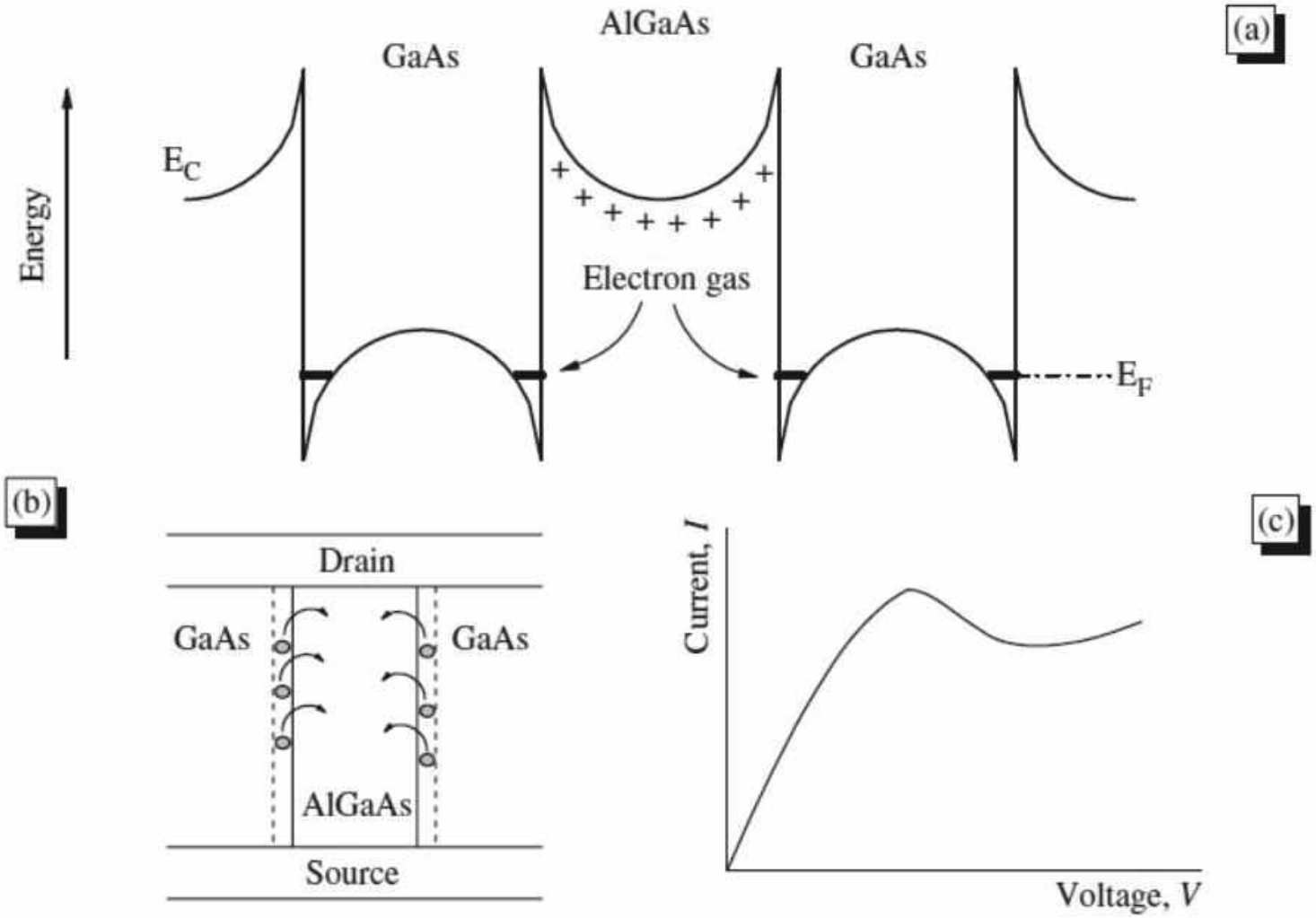
Electron drift velocity for parallel motion in AlGaAs–GaAs modulation-doped heterostructures

Real-Space Transfer (RST)

- An interesting effect, called *real-space transfer (RST)*, arises for hot electron parallel transport in quantum heterostructures.
- If the energy of the hot electrons is high enough, some of them will be able to escape from the well.
- electrons are transferred from the undoped GaAs to the surrounding AlGaAs doped semiconductor.
- It means, electrons can be transferred from a high electron mobility material (GaAs) to one with a lower mobility (AlGaAs) as the voltage between source and drain is increased.
- As a consequence, a *negative differential resistance (NDR)* region in the *I–V* characteristics is observed.
- the NDR effect leads to new kinds of devices such as resonant tunnelling transistors.


AlGaAs
GaAs
GaAs
Energy
E_C
Electron gas
E_F


(b)
Drain
GaAs
GaAs
AlGaAs
Source



(a) Schematics of the RST mechanism; (b) structure of a device based on RST; (c) *I–V* characteristics.

PERPENDICULAR TRANSPORT

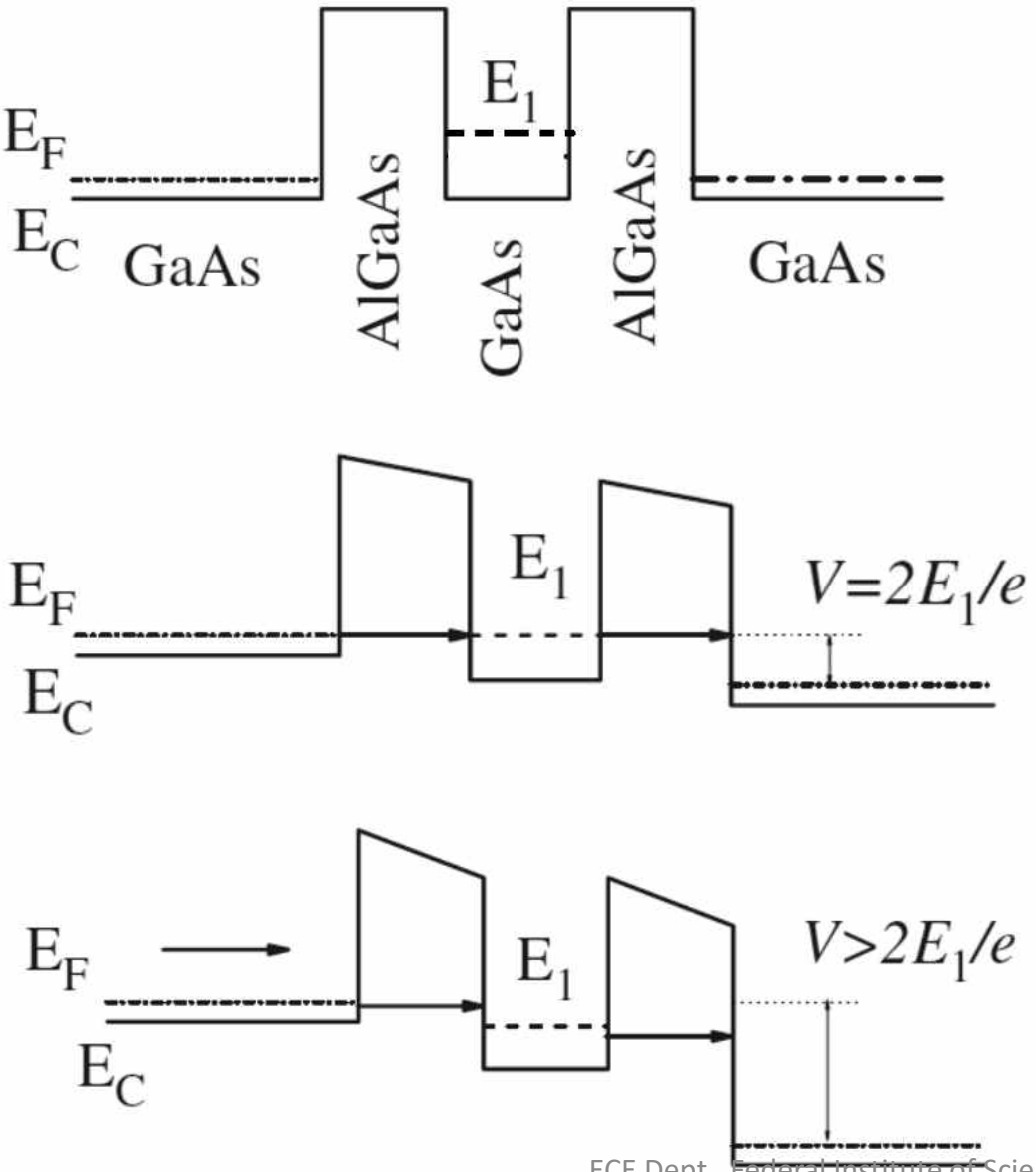
- Motion of the carriers perpendicularly to the planes of the potential barriers separating quantum heterostructures.

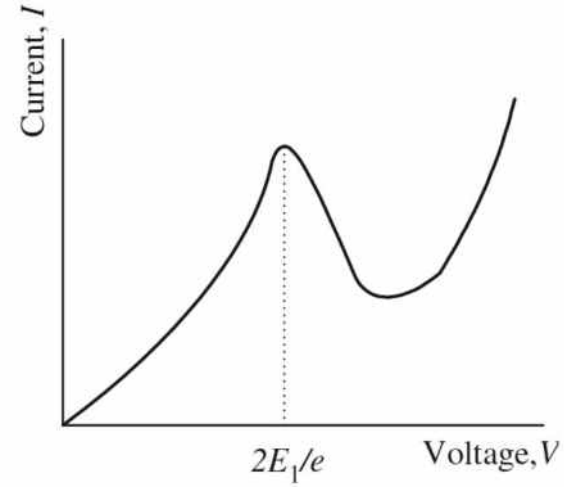
- This kind of transport is often associated to quantum transmission or tunnelling.

Resonant tunnelling

- It has more applications in high frequency electronic diodes and transistor.

- Consider a nanostructure made of undoped GaAs surrounded by AlGaAs in each side.


E1
EF
EC
GaAs
AlGaAs
GaAs
AlGaAs
GaAs
EF
EC
E1
V=2E1/e
EF
EC
E1
V>2E1/e


Current, I
2E1/e
Voltage, V

- RT occurs for a voltage $V1 = 2\ E/e$, where E coincides with the quantized energy level $E1$.

- In this situation, the Fermi level EF of the metallic contact on the left coincides with the n=1 level in the well.

- Then, the tunnelling transmission coefficient approaches unity and a large current flows through the structure.

- As the voltage increases over $2E1/e$, EF surpasses $E1$ and the current through the structure decreases.

- In the *I–V* characteristics of Figure, after the maximum, the slope of the curve becomes negative, i.e. there exists a region with differential negative resistance.

- Transmission probability of a double barrier *T(E)*

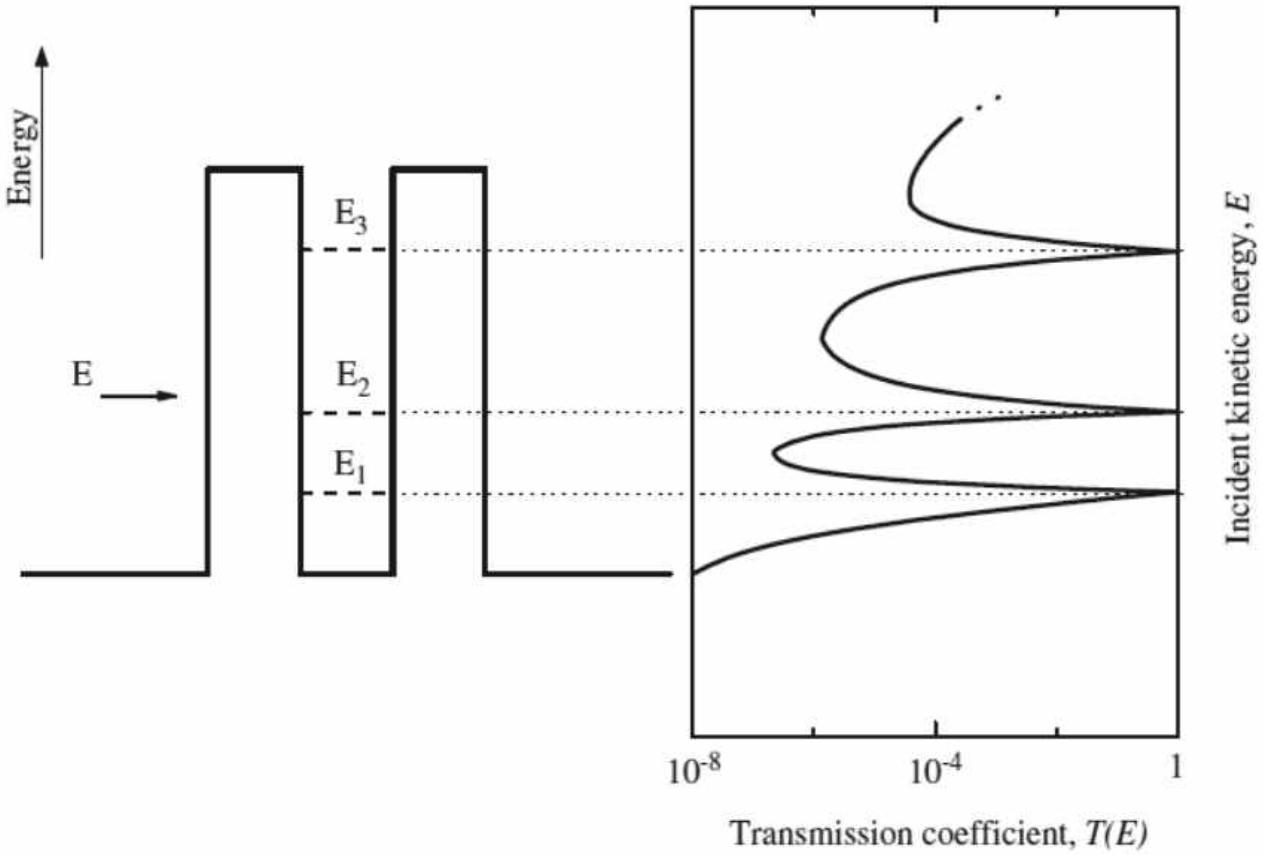
  $T(E) = TE * TC$

  where *T*E is for the first barrier and *T*C is for the second barrier.

$$T(E) = \frac{T_0^2}{T_0^2 + 4R_0 \cos^2(ka - \theta)}$$

  – where *T*0 and *R*0 are the transmission and reflection coefficients of the barrier, *a* is the well thickness, *k* the electron wave number of the wave function in the well, and ϑ is the phase angle.

Dependence of *T(E)* as a function of *E*



- Consider an RT structure with three energy levels in the quantum well.

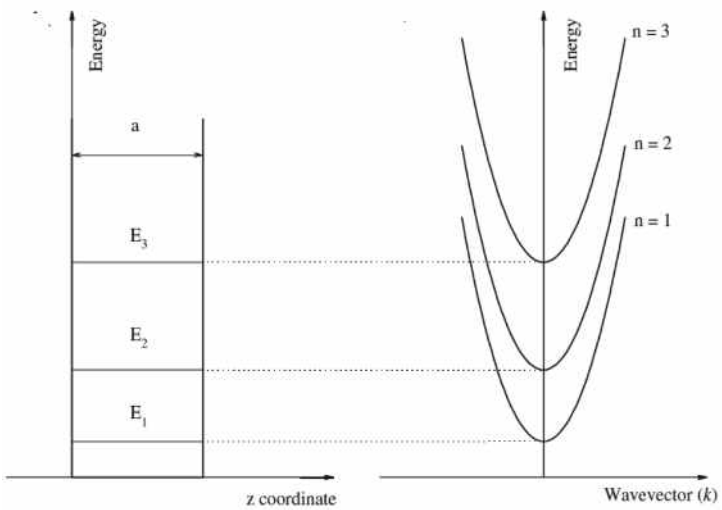
- Observe that the transmission coefficient is one, at energies corresponding to the three levels. Or when the energy of the incident electron is aligned with these levels.

Electric field effects in superlattices

- Electron states in superlattices are grouped in electronic bands or minibands, which are very narrow in comparison with bands in crystals.

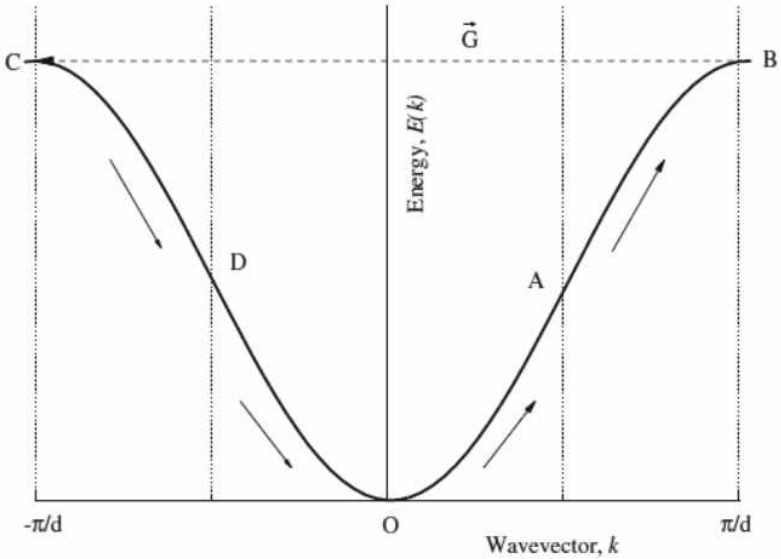
- Electrons in narrow bands, under the action of an electric field will reveal some observable effects, such as *Bloch oscillations*.

- Suppose an electronic band in *k*-space such as the one shown in Figure which is similar to the first miniband of a superlattice.



Energy levels in quantum well

Energy subbands



- The equation of motion for an electron in this band, under the action of an electric field is

$$\hbar \frac{dk}{dt} = -eF$$

- The solution of above equation for the wave number is

$$k(t) = k(0) - \frac{eF}{\hbar} t$$

- Electron is initially at rest at the origin O.

- Electron starts to move from O towards A until it reaches the point B.

- At B, the electron is transferred to point C and it moves in *k*-space towards D by the action of the field, closing one cycle in *k*-space when the electron reaches O again.

- The motion of the electron is periodic and the velocity is given by equation:

$$v = \frac{1}{\hbar}\frac{dE}{dk}$$

- The period *T*B of the oscillatory motion.

$$T_{\mathrm{B}} = \frac{2\pi}{\omega_{\mathrm{B}}} = \frac{2\pi\hbar}{eFd}$$

- In order to experimentally observe Bloch oscillations, TB should be shorter that the relaxation time due to scattering.

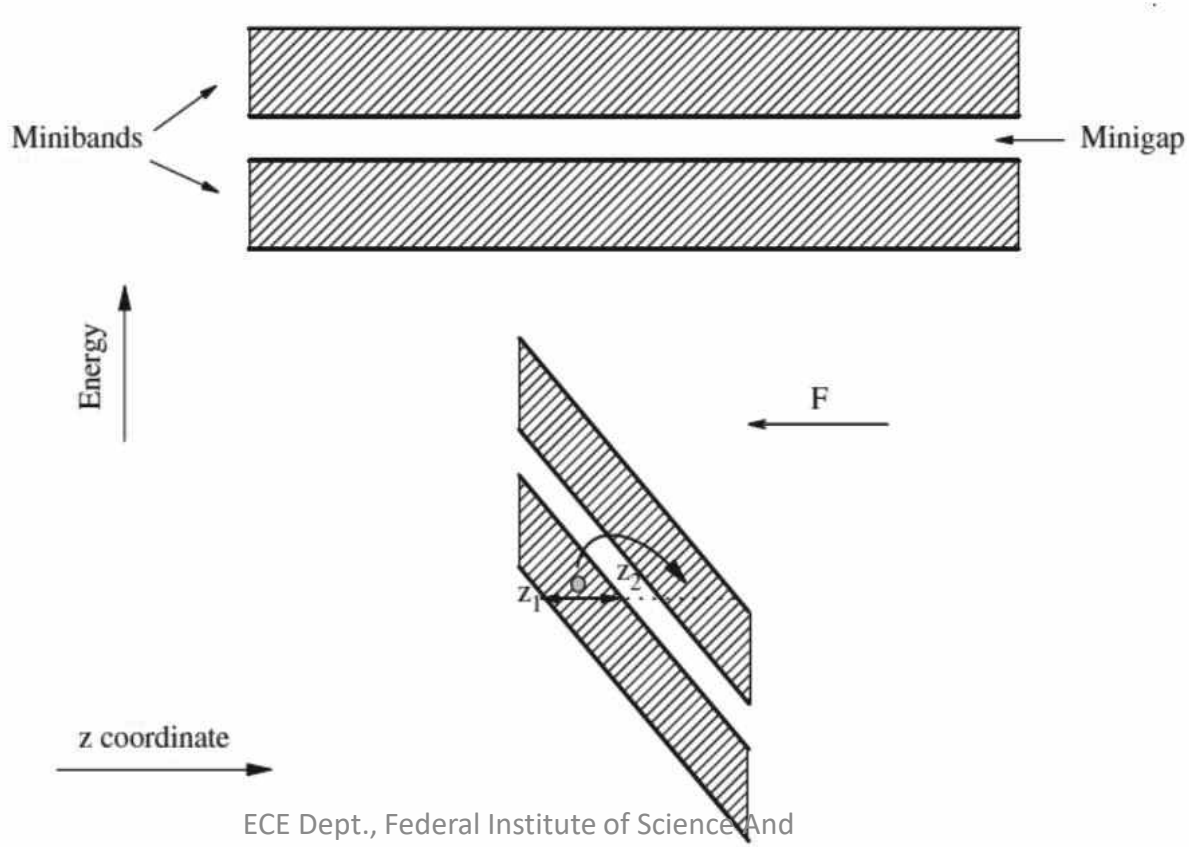
- Bloch oscillations cannot be observed in bulk solids because their typical values of TB are much longer than the corresponding ones in a superlattices.

- In practice, the value of TB cannot be made very low by making the values of F very high since this would produce Zenner tunnelling and Bloch oscillations would not be produced.

- If a constant electric field *F* is applied in the *z*-direction, the bands become tilted with a slope equal to *–eF.*

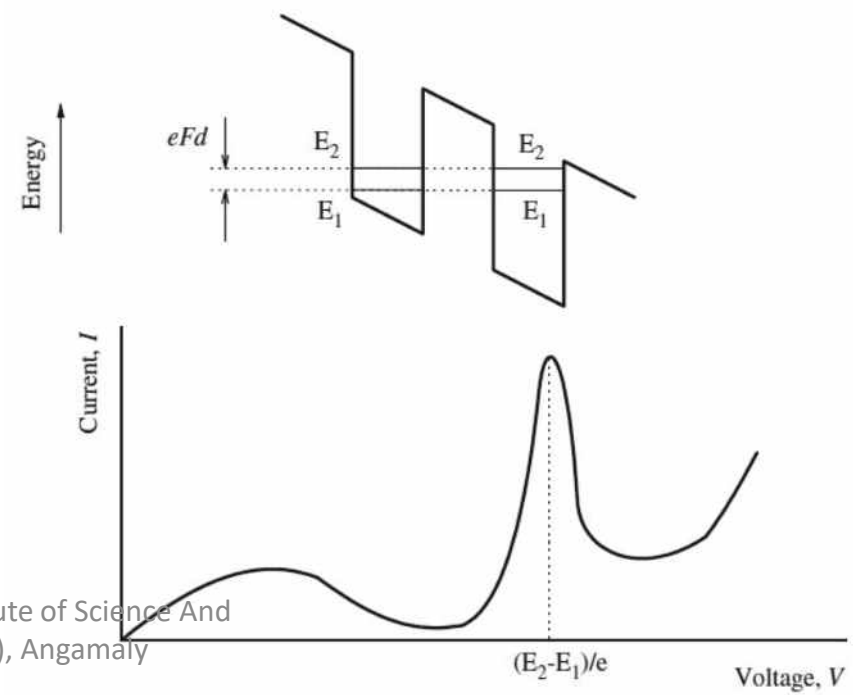
- *Now t*he expression of the potential energy becomes

$$E(z) = E0 - eF\,z$$ *where E0 is the energy at origin.*



- An electron with total energy E_T will oscillate in space between locations $z1$ and $z2$.
- Energy levels in each quantum well of width a of the superlattice will form a ladder of step height eFa, where F is the applied electric field.
- Resonant tunnelling occurs when high electric fields are applied through the structure and the successive quantum wells differ in energy by about eFd.

$$E2 - E1 = eF\,d$$

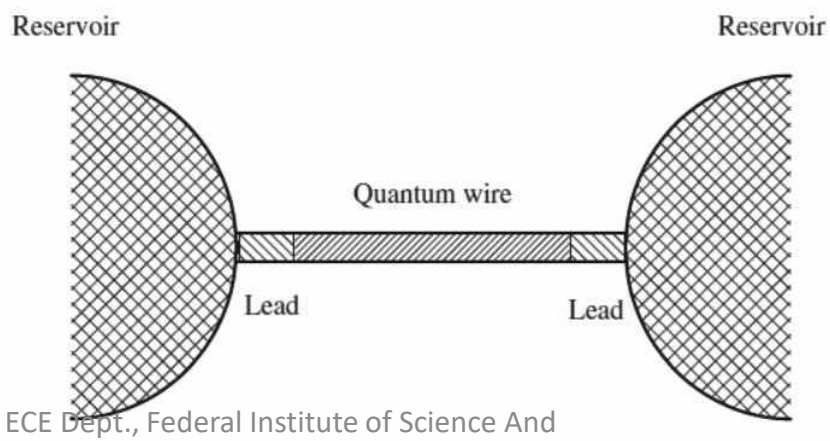


QUANTUM TRANSPORT IN NANOSTRUCTURES

- It happened when nanostructures are connected to an external current by means of contacts or leads.
- This transport is also called mesoscopic transport.
- In order to observe quantum transport effects in semiconductor nanostructures, some conditions must be met.
- Quantum transport will be more easily revealed in nanostructures in which the electron effective mass is small, since this implies high electron mobilities.
- Transport in mesoscopic devices is usually ballistic, since the dimensions of the devices are smaller that the mean free path of electrons.

Quantized conductance

- Let us consider a 1D mesoscopic semiconductor structures like quantum wires.
- The 1D quantum wire is connected through ideal contacts, which do not produce scattering events, to reservoirs characterized by Fermi levels *E*F1 and *E*F2.
- In order for the current to flow through the quantum wire, a small voltage *V* is applied between the reservoirs.
- As a consequence, there is a potential energy *eV* between the two reservoirs equal to *E*F1 − *E*F2.
- If the wire is short enough, i.e. shorter than the electron mean free path in the material, there would be no scattering and the transport is ballistic.



Schematics of a 1D mesoscopic system

- Current through the wire is defined as

$$I = \frac{2e^2}{h} V$$

- The value of the conductance $G \equiv (I/V)$ is therefore:

$$G = \frac{2e^2}{h}$$

- It is interesting to observe that the conductance of the quantum wire is length independent.

- Since the quantity $2e^2/h$ appears very often, it is usually called *fundamental conductance*.

- $G_0 = \frac{e^2}{h}$ is called the *quantum unit of conductance* and corresponds to a *quantum resistance* of value

$$R_0 = \frac{h}{e^2} = 25.812807\,\mathrm{k}\Omega$$

- Assuming the existence of several channels(Subbands) between the reservoirs.

- let us suppose that the leads can inject electrons in any channel or mode m and after interacting the electrons emerge through any channel n.

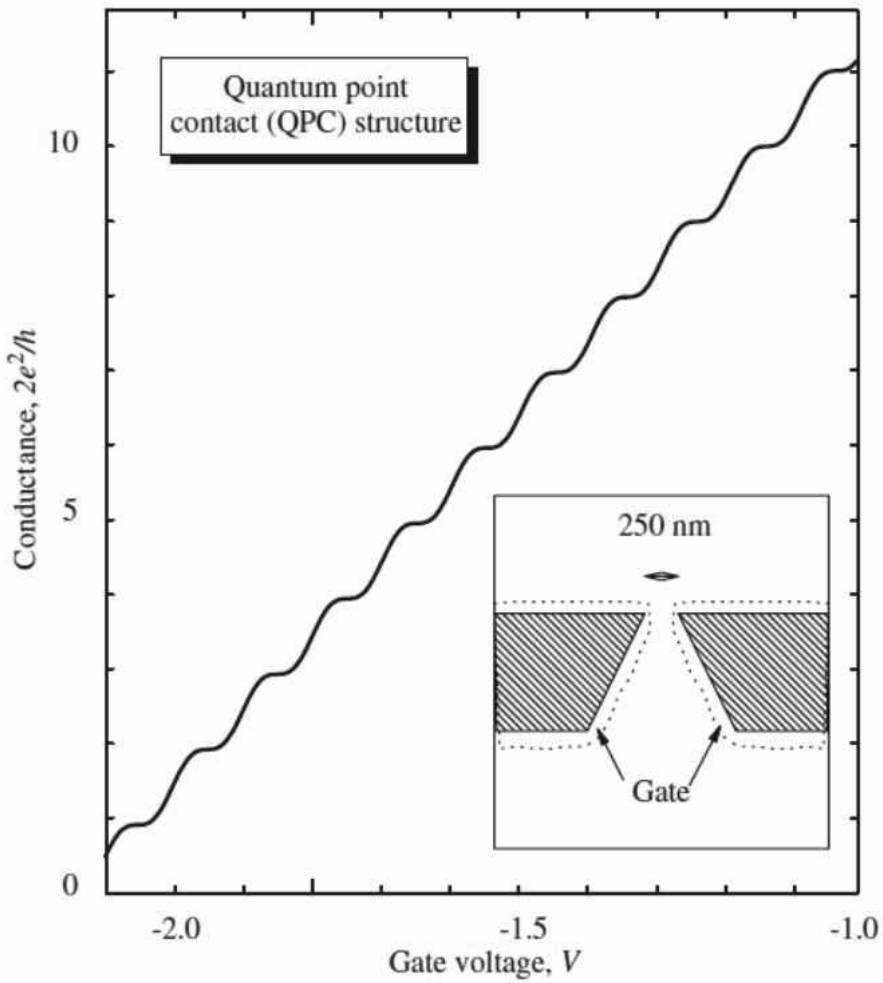
- The total conductance will be obtained by adding over all channels:

$$G = \frac{2e^2}{h} \sum_{\mathrm{n,m}}^{N} |t_{\mathrm{nm}}|^2$$

  - where N is the number of quantum channels
  - $|t\mathrm{nm}|^2$ is the quantum mechanical transmission probability.

- The above expression is known as *Landauer formula*.

Quantum conductance as a function of voltage

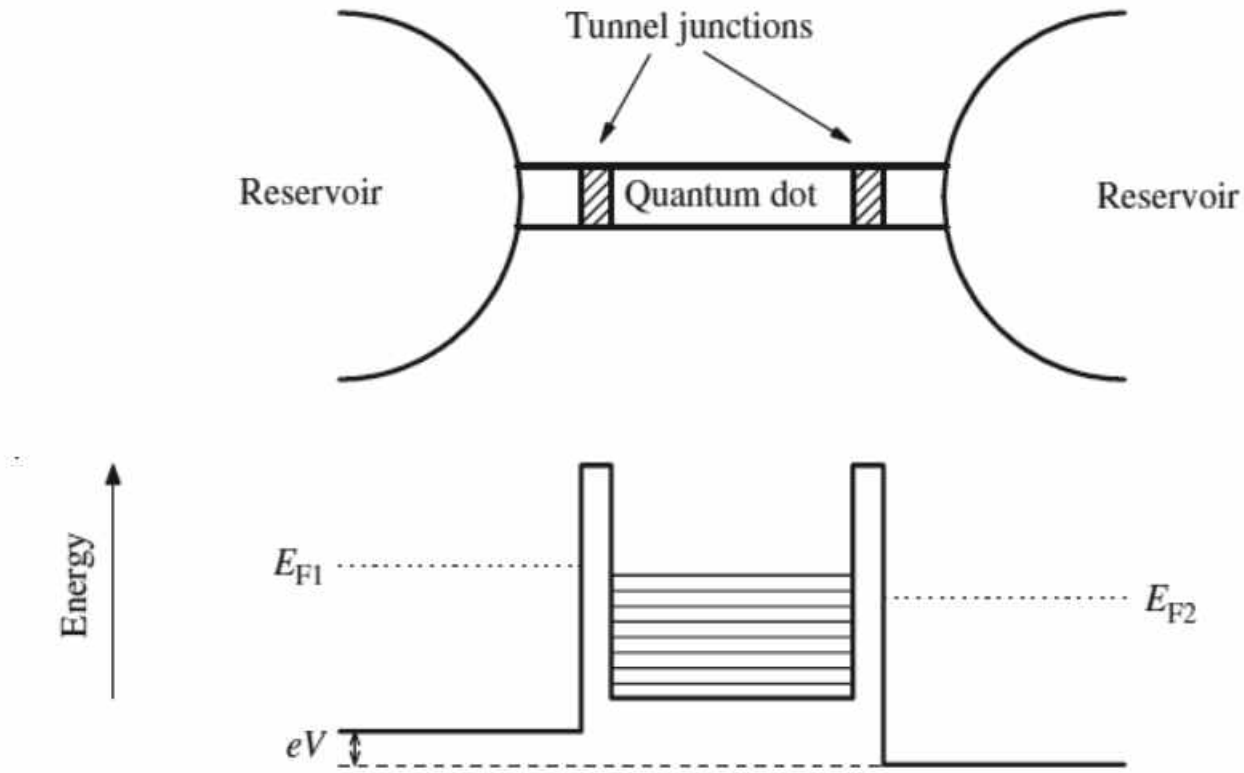


- Consider the structure illustrated in the inset of Figure with an external voltage is applied to the gate .
- The electrons in the 2D plane are constrained to travel through a very small or 1D region, as a consequence of the distribution in electrical voltage.
- This structure is called *quantum point contact (QPC).*
- It is observed that values of the conductance are quantized in multiples of the fundamental conductance $2e^2/h$ when the voltage is varied.

Coulomb blockade

- In semiconductor devices, the magnitude of the currents are reduced as the feature size of the device shrinks.
- A typical semiconductor device utilizes many electron; for example there can be $10^{11} – 10^{12}$ electrons in 1 cm^2 area of a typical MOSFET device.
- If the device size is very small, then a single electron may be involved in the device application.
- What happens when the current is transported by just one single electron.
- Even the change of one elementary charge in such small systems has a measurable effect in the electrical and transport properties of the dot. This phenomenon is known as *Coulomb blockade.*

- Let us imagine a semiconductor quantum dot structure, connected to electron reservoirs at each side by potential barriers or tunnel junctions.

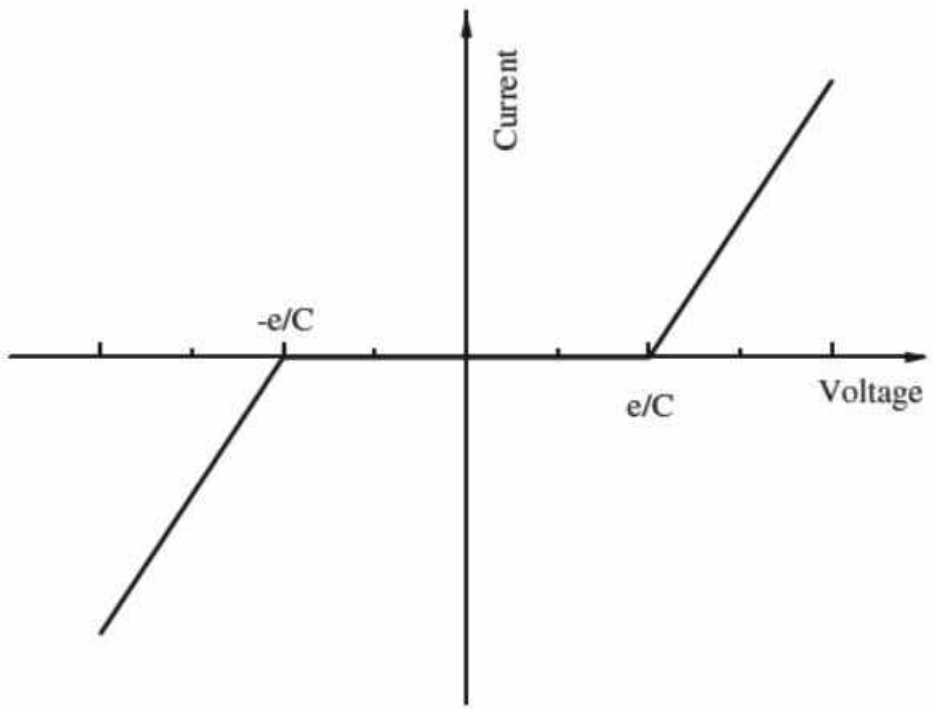


- In order to allow the transport of electrons to or from the reservoirs, the barriers will have to be sufficiently thin, so that the electrons can cross them by the tunnel effect.

- Suppose the number of electrons in the dot is *N*.
- we wish to change the number *N* of electrons in the dot by adding just one electron.
- The above electron will have to tunnel for instance from the left reservoir into the dot.
- For tunneling, we will have to provide the potential energy eV to the electron by means of a voltage source.
- Potential energy in a capacitor is $(1/2)CV^2$

  $Q=CV$
- Potential energy $=Q^2/2C$
- Therefore an energy of at least $e^2/2C$ will have to be provided to the electron.

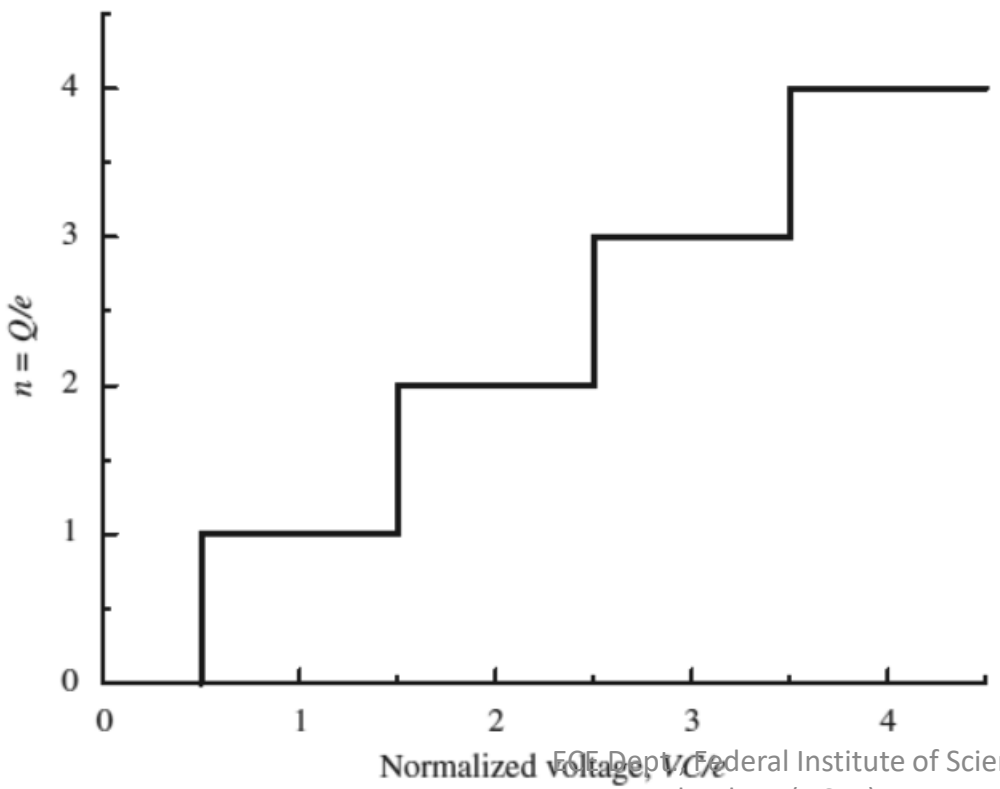
  $E=QV$
- It means that for the electron to enter the dot, the voltage will have to be raised to at least $e/2C$.
- we see that electrons cannot tunnel if $V< e/2C$
- Therefore, there is a voltage range, between $-e/2C$ and $e/2C$, in which current cannot go through the dot, hence the name of Coulomb blockade given to this phenomenon.



I–V characteristics in a quantum dot showing the Coulomb blockade effect.

- Evidently if the process is continued and we keep adding more electrons then it can observe discontinuities in the current through the quantum dot whenever the voltage acquires the values expressed by:

$$V = \left(\frac{1}{2C}\right)(2n+1)e, \qquad n = 0,\ 1,\ 2,\ \ldots$$



- As the size of the quantum dot is reduced, and therefore *C* gets smaller, the value of the energy necessary to change the number of electrons in the dot increases.

- In this case, it will be easier to observe the Coulomb blockade, since the changes in voltage and electric energy for electrons to enter the dot also increase.

- This change in electric energy has to be much larger than the thermal energy *kT* at the working temperature, in order to observe measurable Coulomb blockade effects.

- SO it is better to have $C \ll \frac{e^2}{kT}$

- For this condition to be fulfilled, either the capacitance of the dot should be very or we should work at very low temperatures, usually smaller than 1 K

Effect of Magnetic field on a crystal

- Application of high magnetic fields to a crystal will collapse energy states of conduction electrons into different levels.
- Above levels are called Landau levels.
- Consider a magnetic field *Bz*, applied in the *z*-direction.
- This will quantize energies in the conduction band into landau levels.

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega_c + \frac{\hbar^2 k_z^2}{2m_e^*}, \quad n = 0, 1, 2, \ldots$$

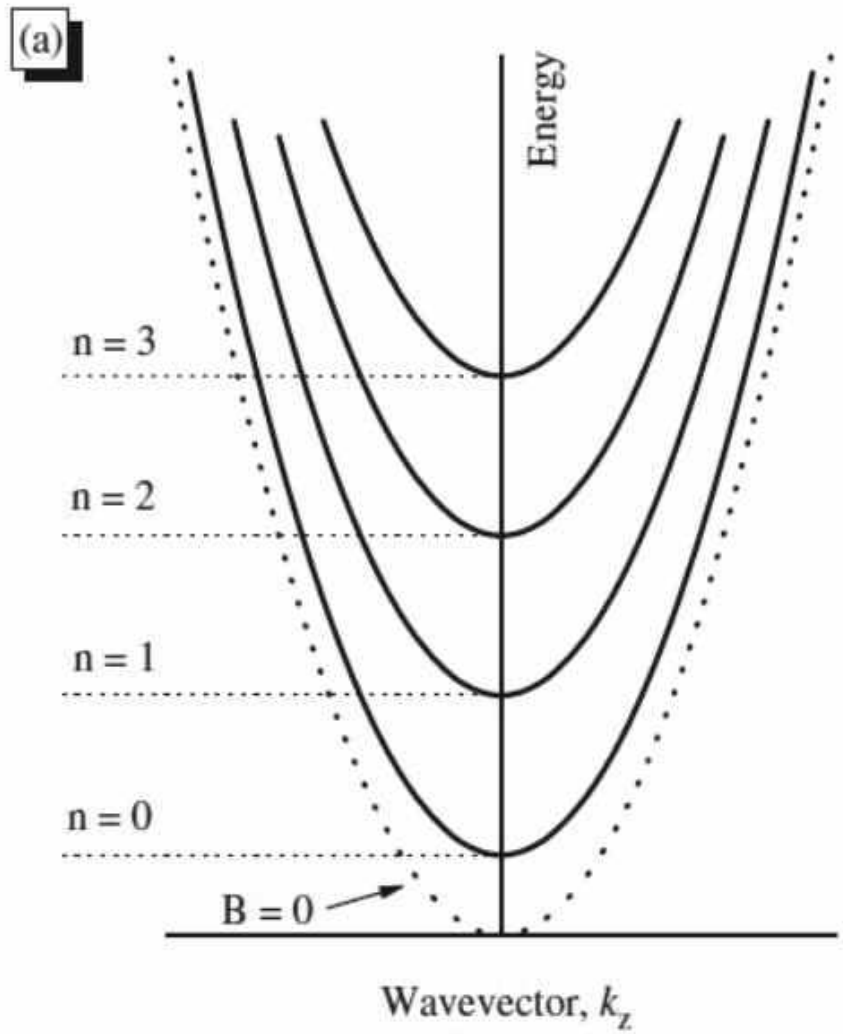
- where ωc is the frequency given by

$$\omega_c = \frac{eB_z}{m_e^*}$$

- In previous example, the field does not alter the motion of the electrons along the *z*-direction.

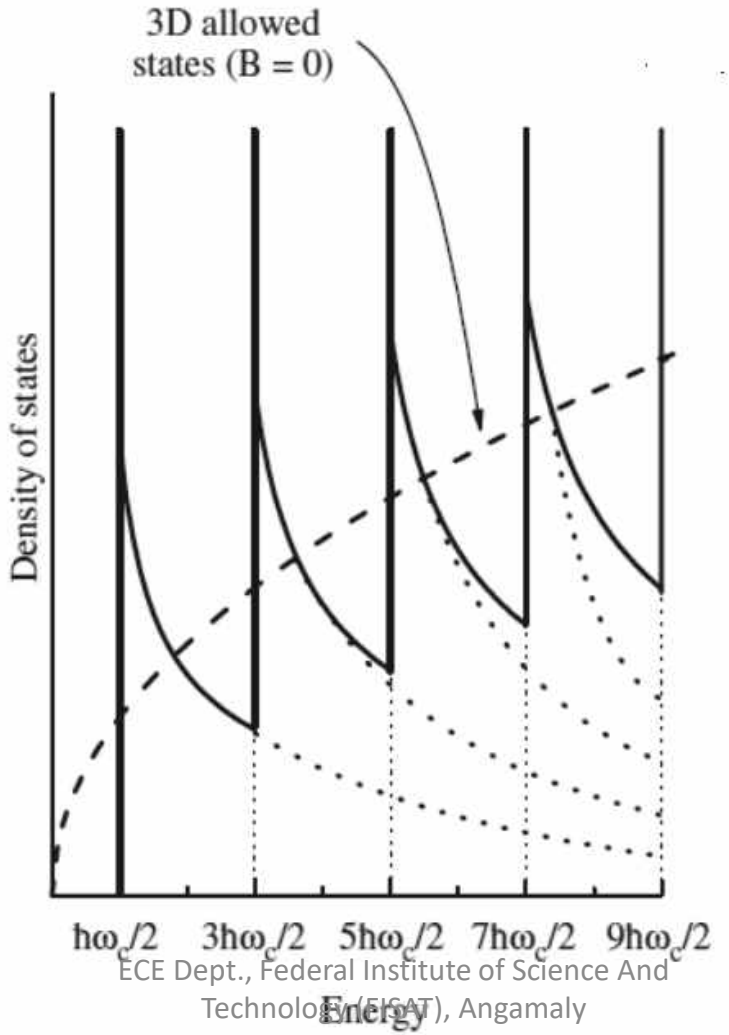
- The electrons behave with respect to the *z*-direction as if they were free.

- On the other hand, the electron motion in the *x* and *y* directions is quantized.



Electron energy bands for a 3D solid vs the *z*-direction wave vector for different Landau levels (n = 0, 1, 2 . . .)

Effect of magnetic field on 3D density of states



- For a 3D material DOS is proportional to the root of E.

- When a magnetic field *Bz* is applied, the 3D allowed states in *k*-space collapse with a degeneracy factor $g_n = eB/\pi h$.

LOW-DIMENSIONAL SYSTEMS IN MAGNETIC FIELDS

- In a 2D electron system, under the action of B, the energy spectrum becomes completely quantized.

- Schrödinger's equation for an electron in a 2D system under the action of a magnetic field applied in a direction (*z*) perpendicular to the low-dimensional system is given as

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}+\frac{1}{2m}\left(i\hbar\frac{\partial}{\partial y}+eBx\right)^2\right]\psi(x,y)=E\psi(x,y)$$

$$\left[-\frac{\hbar^2}{2m}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)-\frac{i\hbar eBx}{m}+\frac{(eBx)^2}{2m}\right]\psi(x,y)=E\psi(x,y)$$

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}+\frac{1}{2}m\omega_c^2(x-x_0)^2\right]\varphi(x)=E_n\varphi(x)$$

$$x_0=\frac{hk}{eB}$$

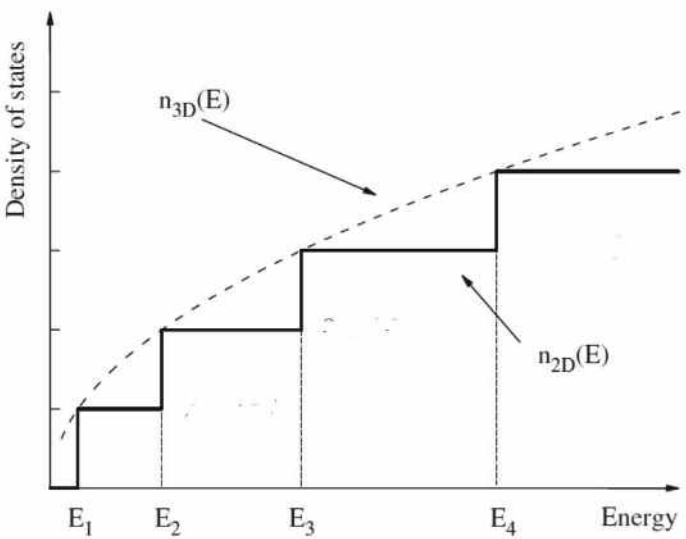
- Energy of landau levels is defined as

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega_c, \quad n = 0, 1, 2, 3, \ldots \qquad \omega_c = \frac{eB_z}{m_e^*}$$

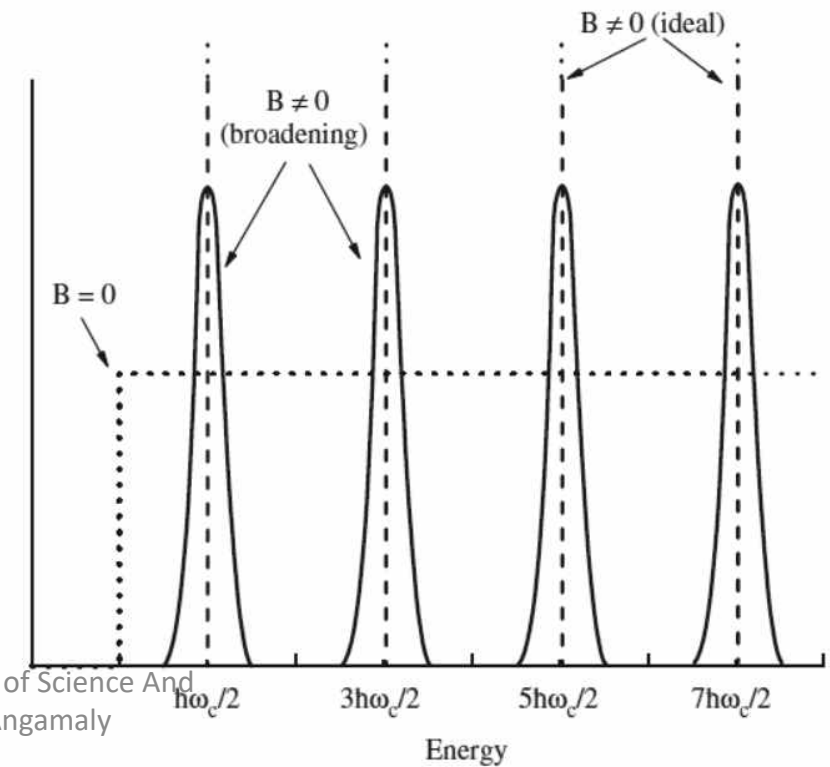
- Note that the energy attributed to the magnetic field depends only on the quantum number *n* and the magnetic field *B* through ωc.

DENSITY OF STATES OF A 2D SYSTEM IN A MAGNETIC FIELD

- The DOS function of the 2D gas (with B = 0), collapses into a δ-function at each Landau level as a consequence of the application of B.



Density of states function for a 2D electron system, as a function of energy.



- Since all the levels in an interval ωc collapse into the same Landau level when the field B is applied, the *degeneracy D* of each Landau level should be given by

$$D = \frac{m_e^*}{2\pi\hbar^2}\hbar\omega_c = \frac{eB}{2\pi\hbar}$$

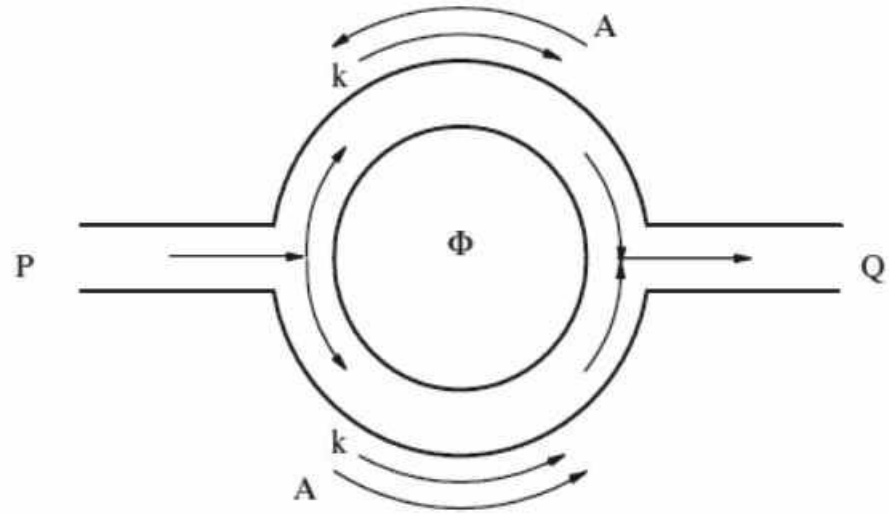
- It is observed that the degeneracy of the Landau levels increases linearly with the magnetic field, a fact which will have important consequences in the explanation of the quantum Hall effects

AHARONOV–BOHM EFFECT

- Magnetic fields can produce and control interference effects between the electrons in solids.

- In 1959, Aharonov and Bohm proposed that an electron wave in a solid has a phase factor which could be controlled by a magnetic field.

- This phenomenon was proved by Webb in 1985 at IBM with a structure similar to below.

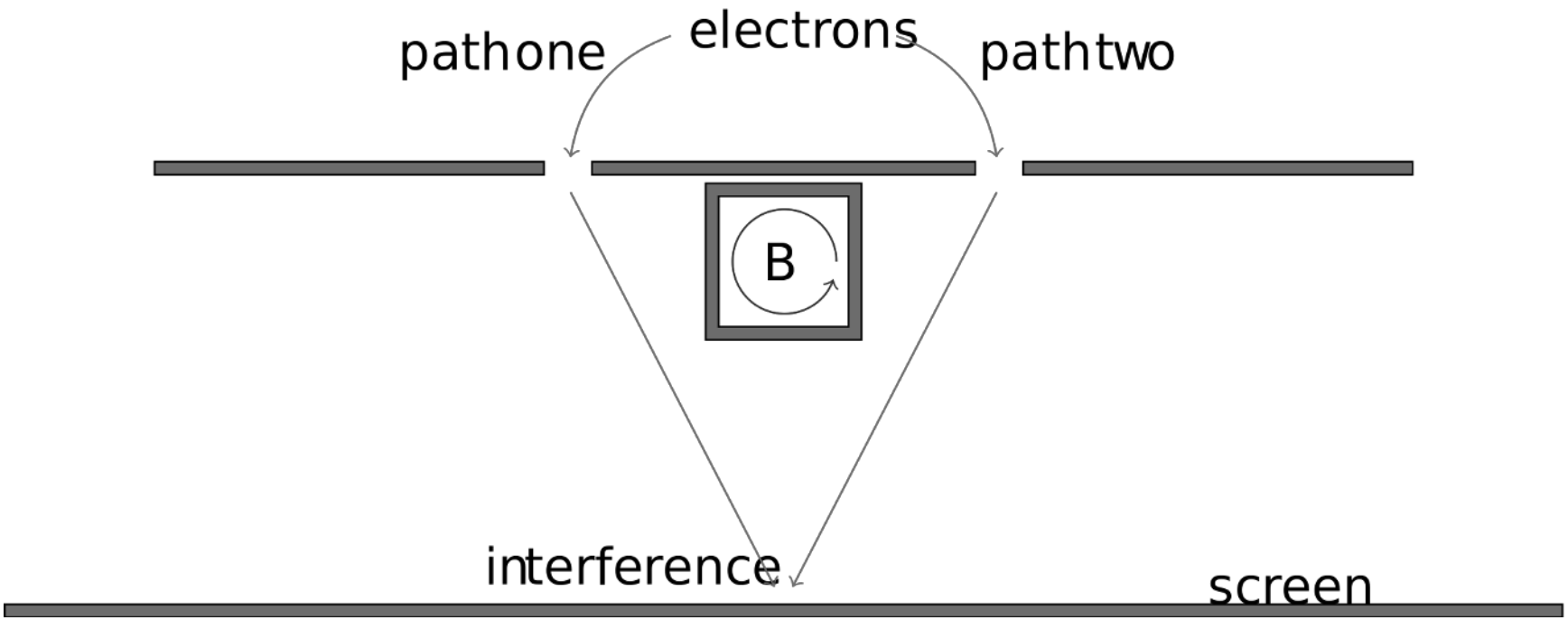


- It consisting of a metallic ring of diameter 800 nm made of a wire about 50 nm thick.

- The electrons entering the ring at *P* from the left have their wave function amplitude divided in two equal parts, each one travelling through a different arm of the ring.

- When the waves reach the exit at *Q*, they can interfere.

- Suppose that a magnetic flux produced by a solenoid passes through a region inside the ring and concentric to it.



Schematic of double-slit experiment in which the Aharonov–Bohm effect can be observed: electrons pass through two slits, interfering at an observation screen, with the interference pattern shifted when a magnetic field **B** is turned on in the cylindrical solenoid

- For an electron in a magnetic field *B,* its momentum(p) should be substituted by *p* + *e A* where *A* is the vector potential *(B = curl A)*.

- As the electron moves from *P* to *Q* the change in phase is given by

$$\vartheta(\vec{r}) = \frac{e}{\hbar}\int_P^Q \vec{A}\cdot d\vec{s}$$

- The difference in phase between a wave travelling around the upper path and the lower one in previous picture is

$$\Delta\vartheta = \vartheta_1 - \vartheta_2 = \frac{e}{\hbar}\left[\int_{\text{lower arm}} \vec{A}\cdot d\vec{s} - \int_{\text{upper arm}} \vec{A}\cdot d\vec{s}\right] = \frac{e}{\hbar}\int_{\text{circle}} \vec{A}\cdot d\vec{s}$$

- since in the top and bottom branches the electron waves advance in opposite directions to *A*

- Applying Stoke's theorem to previous equation

$$\int_C \vec{F} \cdot d\vec{r} = \iint_S \text{curl}\vec{F} \cdot d\vec{S}$$

$$\Delta\vartheta = \frac{e}{\hbar}\Phi$$

- Where

$$\Phi = \int_{\text{area}} (\text{curl}\vec{A}) \cdot d\vec{S} = \int_{\text{circle}} \vec{B} \cdot d\vec{S}$$

- The quantity $\Phi_0 = \frac{h}{e}$ is defined as the *quantum of flux*.

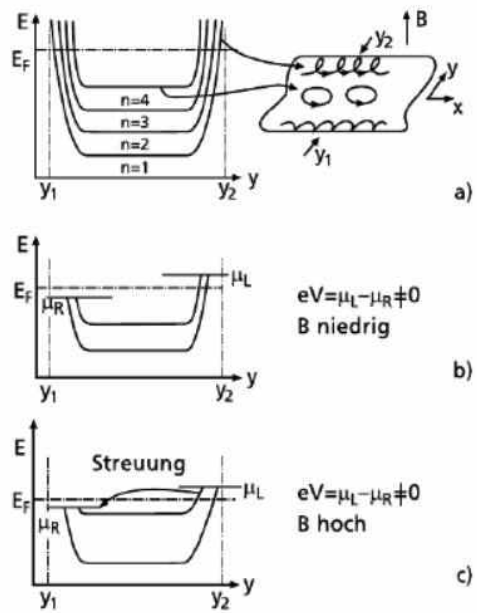
- One very interesting aspect of the Aharonov–Bohm effect is the observation that variations in phase can be induced by changing *B*, even if the electron waves are not directly subjected to the action of *B*.

- a vector potential *A* indeed exists in the region around the ring , and the changes in phase are produced by *A* accordingly.

- Aharonov–Bohm quantum interference effects are frequently observed even in samples of size in the micrometre range

SHUBNIKOV–DE HAAS EFFECT

- This defines the effect of magnetic fields on the electronic and transport properties of the 2D systems.
- An oscillation in the conductivity of a material that occurs at low temperatures in the presence of very intense magnetic fields is the **Shubnikov–de Haas effect** (**SdH**).
- At sufficiently low temperatures and high magnetic fields, the free electrons in the conduction band of a metal, semimetal, or narrow band gap semiconductor will behave like simple harmonic oscillators.
- When the magnetic field strength is changed, the oscillation period of the simple harmonic oscillators changes proportionally.
- The resulting energy spectrum is made up of Landau levels.
- In each Landau level the energies and the number of electron states all increase linearly with increasing magnetic field.
- Thus, as the magnetic field increases, the Landau levels move to higher energy.
- As each energy level passes through the Fermi energy, it depopulates as the electrons become free to flow as current. This causes to oscillate periodically, producing a measurable oscillation in the material's conductivity.



. a) the resulting Landau-levels after applying a magnetic field, b) highest Landau-level far away from Fermi-energy - no scattering, c) highest Landau-level near the Fermi-energy - scattering possible [3]

- As the intensity of *B* is varied, the energy and degeneracy of the Landau levels also varies.

- In many experimental conditions, the density in energy of the system is kept constant, while the magnitude of the magnetic field is varied.

- As *B* increases, the Landau levels move up in energy, Similarly the degeneracy *D* of each level also increases.

- A *filling factor v* is defined as

$$\nu = \frac{n_{2D}}{D} = \frac{2\pi\hbar n_{2D}}{eB}$$

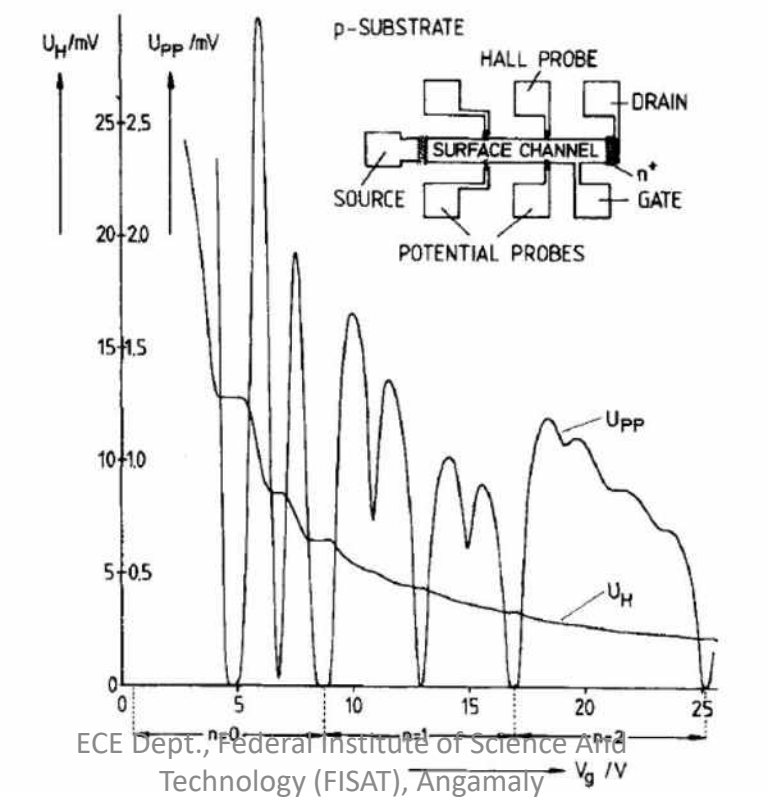
- It indicate the number *N* of Landau levels which are completely occupied.

- when the filling factor is an integer, all Landau levels are completely occupied.

- a small change in energy has a large effect and the conductivity of the sample should be large.

- Figure shows the oscillatory dependence on the gate voltage of the potential difference *U*PP between two probes situated along the length of the sample, like in the inset of the figure.

- In the case of figure, a magnetic field *B* of 18Tesla is applied perpendicularly to the 2D structure.



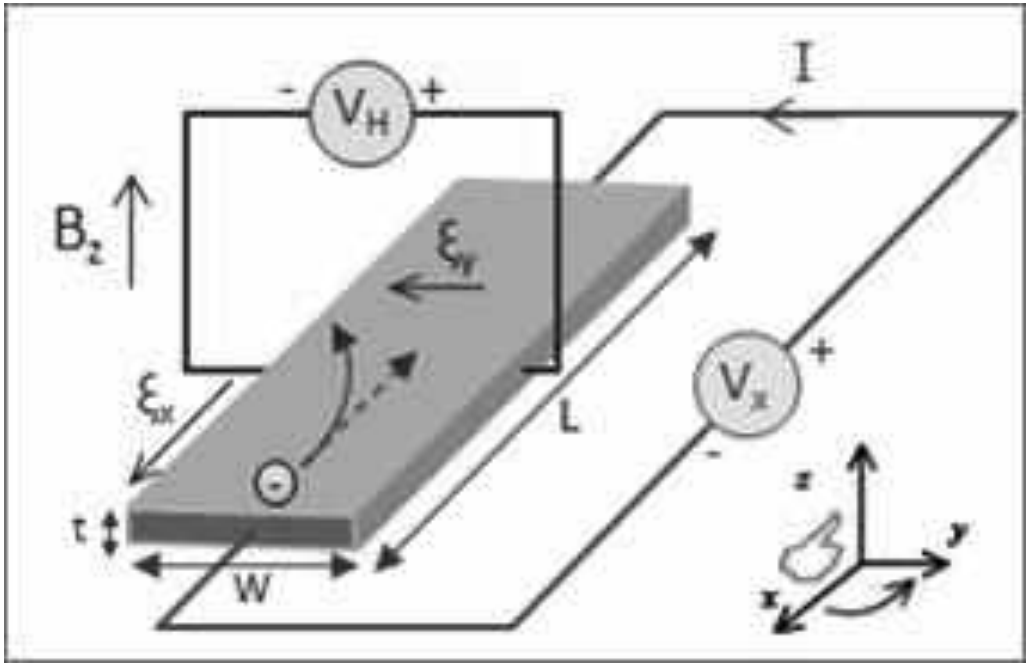
- In previous experiment, the filling factor of the Landau levels is changed by the positive gate voltage, which controls the electron concentration .

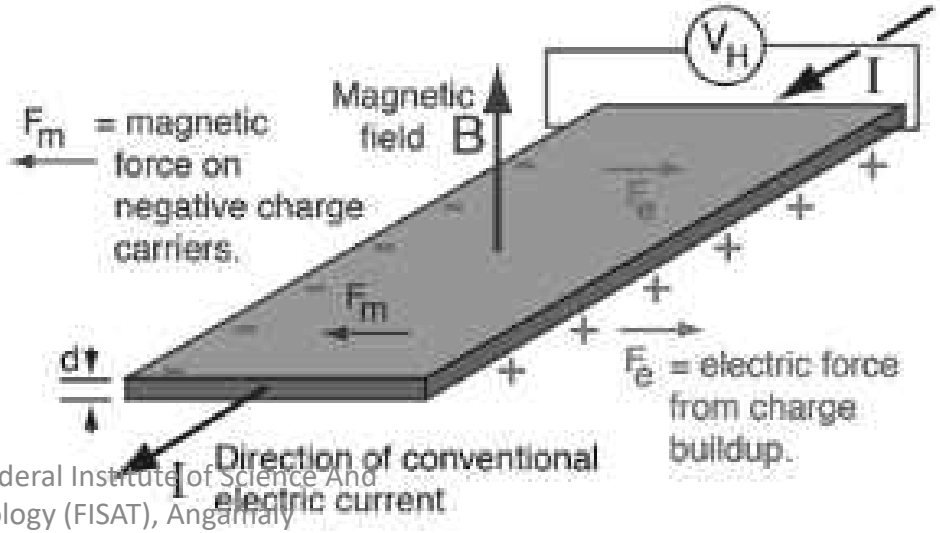
- Shubnikov–de Haas oscillations in the 2D systems depend only on the component of *B* perpendicular to the interface.

- These oscillations were previously observed in bulk semiconductors, but they were much weaker and dependent on both components of *B* , the perpendicular and the in-plane ones.

THE HALL EFFECT

- If an electric current flows through a conductor in a magnetic field, the magnetic field exerts a transverse force (Lorentz force) on the moving charge carriers which tends to push them to one side of the conductor.
- When such a magnetic field is absent, the charges follow approximately straight.
- The moving charges accumulate on one face of the material.
- A buildup of charge at the sides of the conductors will balance this magnetic influence, producing a measurable voltage between the two sides of the conductor.
- The presence of this measurable transverse voltage is called the Hall effect


I
V_H
B_z
ξ_y
ξ_x
L
V_x
τ
W
z
y
x


V_H
I
Magnetic field B
F_m = magnetic force on negative charge carriers.
F_e
F_m
d
F_e = electric force from charge buildup.
I
Direction of conventional electric current

Integer quantum hall effect

- Experimental setup

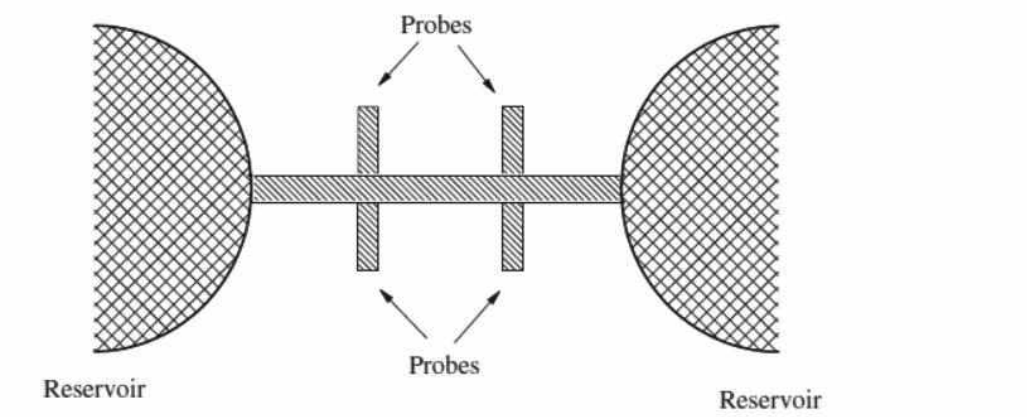


Diagram of a typical nanostructure used to make quantum Hall effect measurements

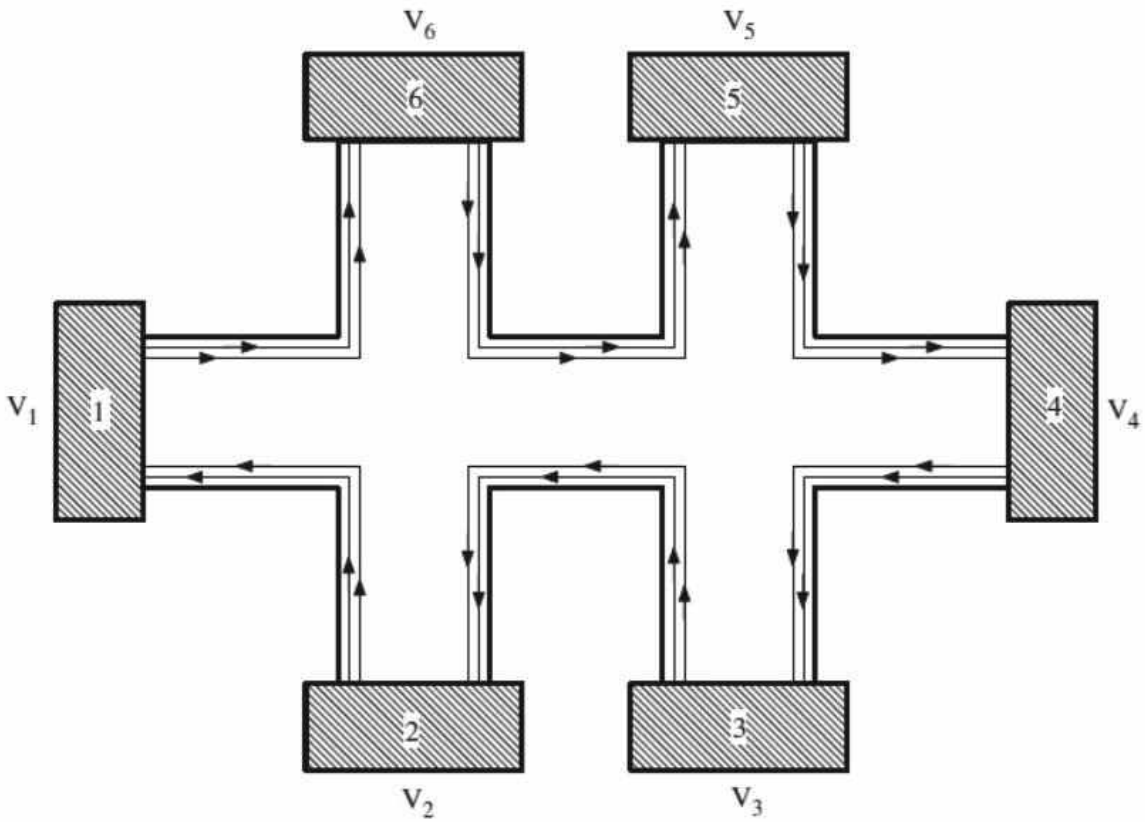
- System consist of two current leads connected to corresponding reservoirs and several voltage probes.

- The reservoirs serve as an infinite source and sink of electrons and are kept at constant temperature.

- Expression for total current is obtained as

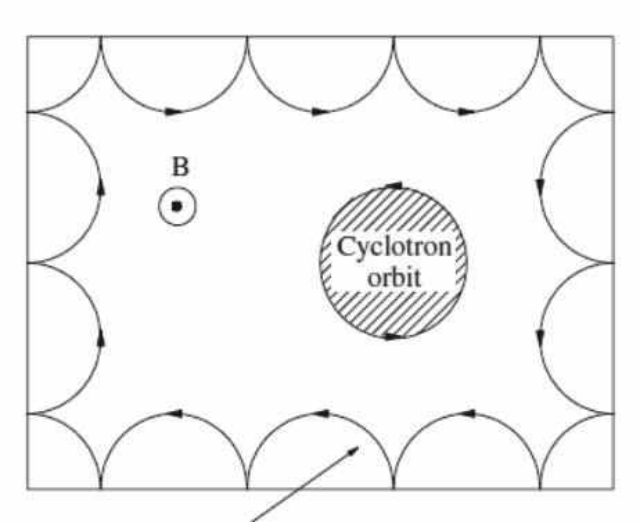
$$I_i = \frac{2e^2}{h}\left[(N_i - R_i)\,V_i - \sum_{j\neq i} T_{ij} V_j\right]$$

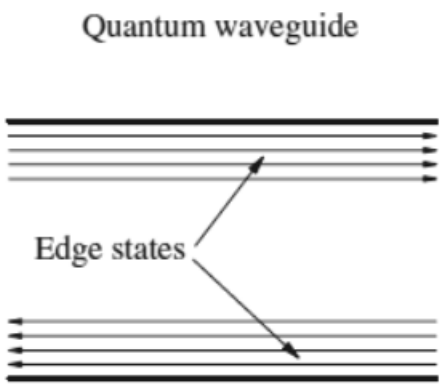
- Where *T*ij is transmission coefficients



Two-dimensional test sample for the measurement of the quantum Hall effect. The current goes from probe 1 to 4. The Hall voltage can be measured from probes 6 and 2 or, alternatively, 5 and 3. The voltage drop in the direction of the current is measured from probes 5 and 6 or 3 and 2. The edge currents (two in the figure) are also shown.

- Consider an electric current flows through the system in a magnetic field.
- cyclotron orbits are created to the various Landau levels by the perpendicular magnetic field.
- Let the cyclotron orbits are directed counterclockwise.





- The closed cyclotron orbits, which do not carry current on the average, are no longer possible near the edges of the sample.
- the electrons at the edges move with a net drift velocity and the orbits are called *skipping orbits*.
- Quantum mechanically, the states associated with the skipping orbits are called *edge states*.
- The upper edge states have a positive velocity, while the lower ones have negative velocity.

- Let us assume that the edge current contains *N* channels, although in Figure we have represented only two.

- Current only flows in or out of the sample through the contact leads 1 and 4 and the Hall voltage arises between probe contacts 6 and 2 or, alternatively, 5 and 3.'

- The longitudinal resistance of the sample can be measured between contacts 5 and 6 or 3 and 2.

- the current arising at contact 1 enters into probe 6, but since this is a voltage probe, it cannot take net current or $I_6 = 0$.

- The same argument can be applied to the other voltage probes 2, 3, and 5.

- Also observed that *N* states propagate from contact 1 to contact 6.

- $T32 = T43 = T54 = T65 = T16 = N$ and $T23 = T34 = T45 = T56 = T61 = 0$. All remaining Tij are zero since currents cannot jump contacts

$$I_i = \frac{2e^2}{h}\left[(N_i - R_i)\,V_i - \sum_{j\neq i} T_{ij} V_j\right]$$

- let us write above equation in matrix form as

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} = \begin{bmatrix} -I \\ 0 \\ 0 \\ I \\ 0 \\ 0 \end{bmatrix} = \frac{Ne^2}{h} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix}$$

- We have written $I1 = -I$ and $I4 = I$ since the arrows in figure indicate the electron motion.

- In order to calculate the Hall resistance we have to divide the voltage between probes 6 and 2 by the current I between contacts 1 and 4

$$R_{14,62} = \frac{V_6 - V_2}{I}$$

- Substituting $V6$ and $V2$ by their expressions obtained from matrix, we get for the Hall resistance:

$$R_H = \frac{h}{e^2}\frac{1}{N}$$

- The *quantification of the values of the Hall resistance* is given, with an outstanding precision, by the equation:

$$R_{\mathrm{H}} = \frac{h}{e^2}\frac{1}{n} = 25812.807\,\Omega\left(\frac{1}{n}\right), \quad n = 1, 2, \ldots$$

- It means that, they remain constant for each L level. So VH also.
- Above expression with n=1 is known as the *von Klitzing constant* and is written as R_K.

- The above expression can also prove with classical physics.

- *VH=bBv (b* is the width of the sample and *v* the carrier drift velocity) and the current *I= bnev*.

$$R_H = \frac{V_H}{I} = \frac{B}{en}$$

- Expression for magnetic field *BN* when the levels are completely filled is

$$B_N = \frac{1}{N} \quad \frac{\hbar n}{e} \quad , \quad (N = 1, 2, \ldots)$$

- Substituting above gives

$$R_H = \frac{h}{e^2}\frac{1}{N}$$

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.

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

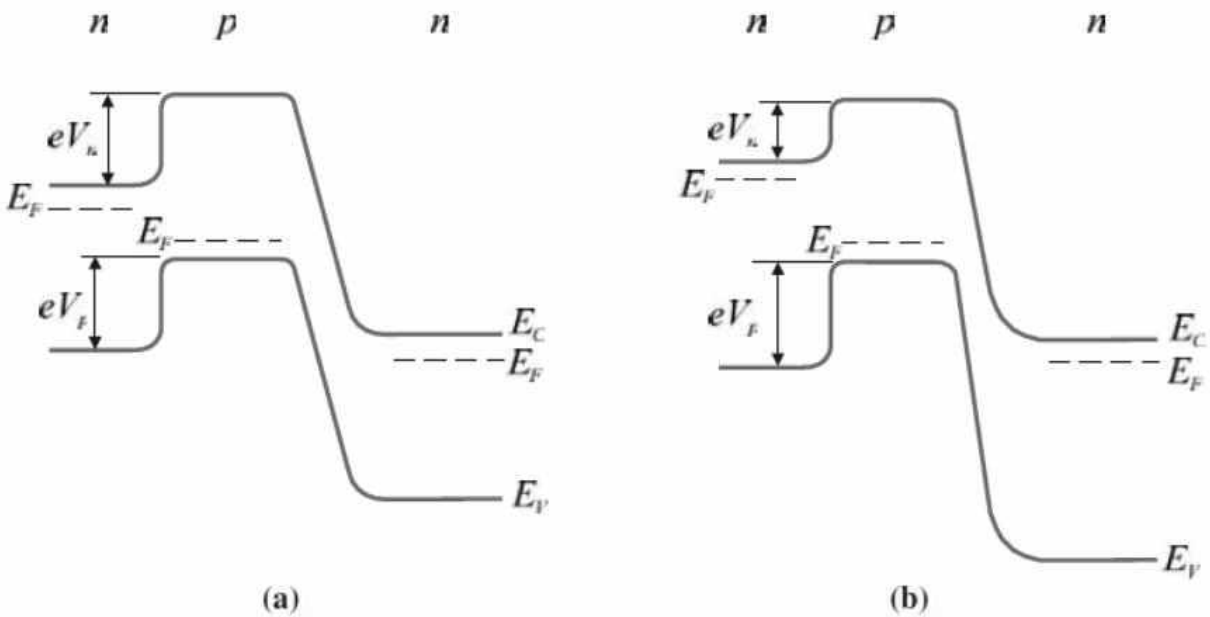
- In order to obtain a high *β*, both the current gain through the base, *α*, and the injection efficiency factor of the emitter, *γ* , should be as close as possible to unity.

- 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.

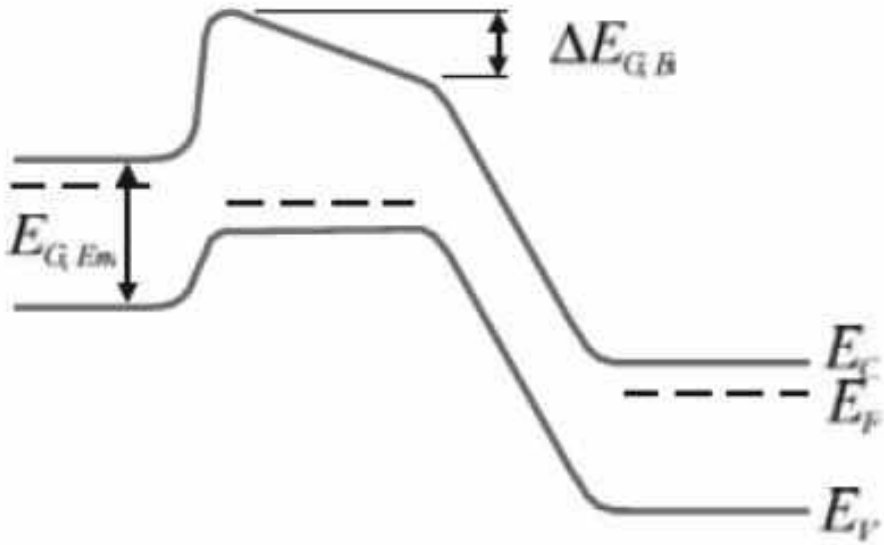
- Thus emitter could be fabricated by using a wide bandgap semiconductor.

- Bipolar transistors fabricated by using heterojuntions are called *heterostructure bipolar transistors (HBT)*



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

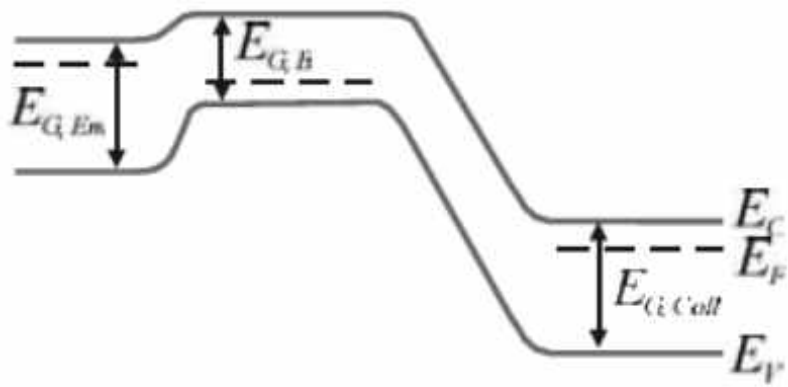
- Note that in second figure the band gap of the emitter is larger than that of the base region.
- Similarly, the barrier for the injection of electrons from the emitter to the base, *eV*n, is lower.
- The barrier height difference has an enormous influence on carrier injection through the emitter–base 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.

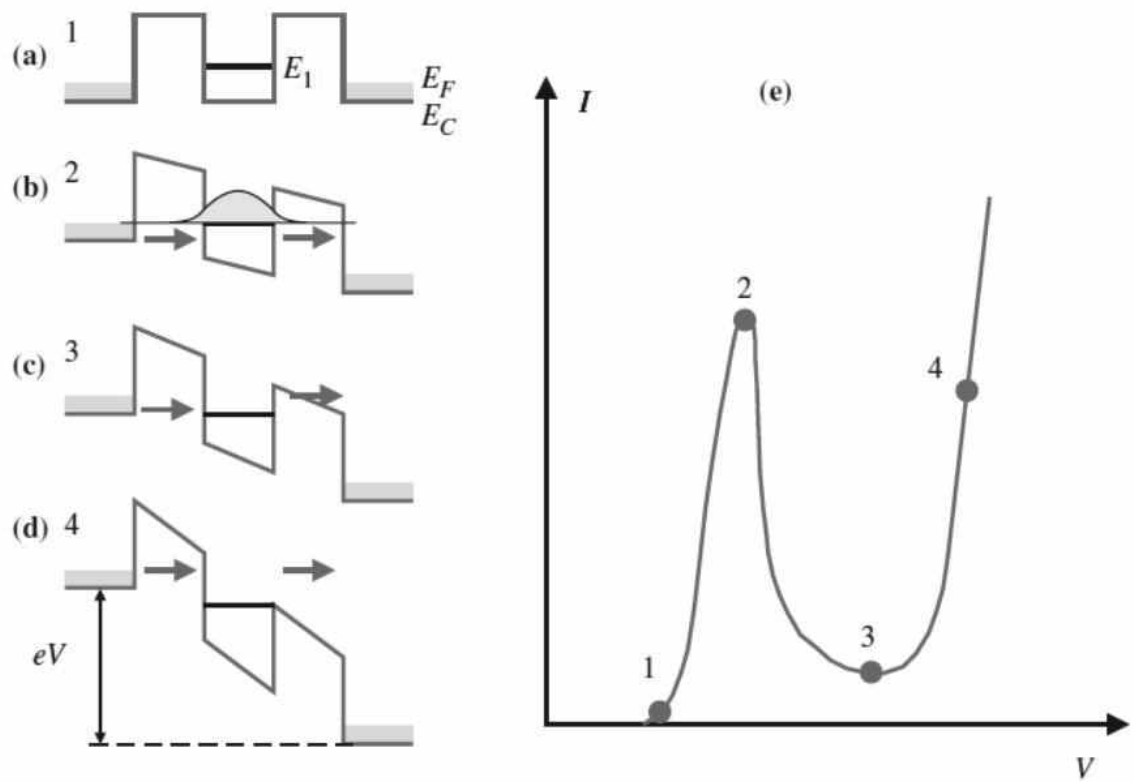
- Commercial HBTs have cut-off frequencies over 100 GHz, while research devices have reached values close to 400 GHz

- 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 $E1$ 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, analogue-todigital 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*.

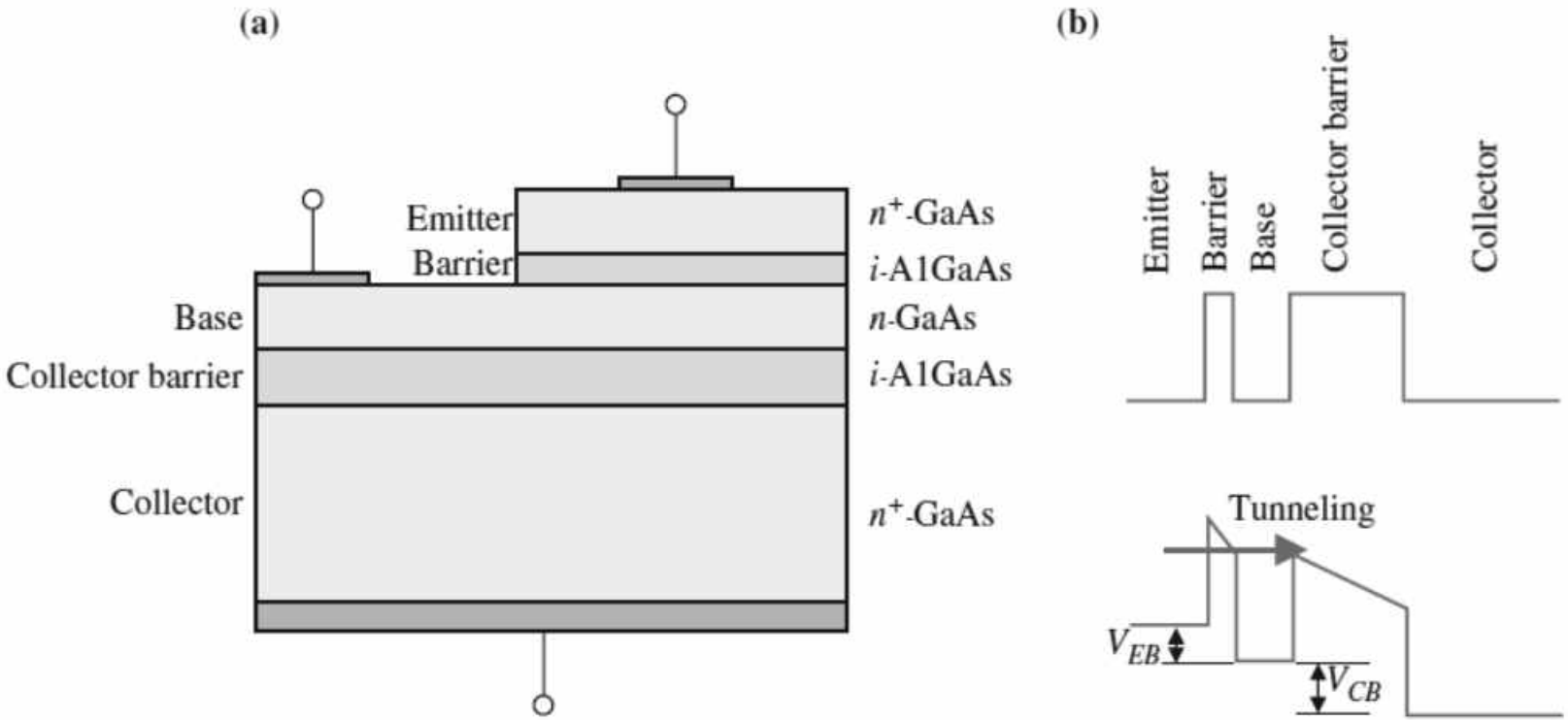
- **Heterojunctions between different gap semiconductors allow the generation of hot electrons, since the electrons will acquire a kinetic energy, given by the energy discontinuity in the conduction band V*E*c, when travelling from a wide bandgap semiconductor to one with smaller bandgap.**

- 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.

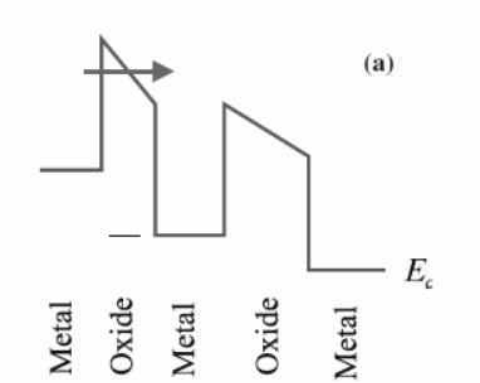
- The velocity of the injected electrons is much higher than in other type of transistors.

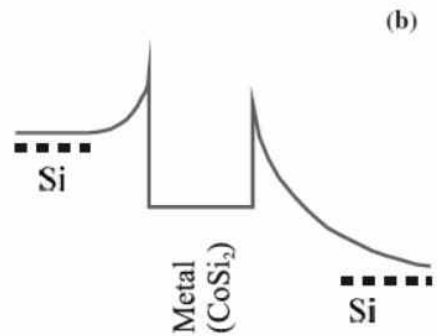
- The base transit time when the transistor is polarized can be of the order of tens of femtoseconds, but that associated to the crossing of the collector barrier is relatively higher.

- 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)*.

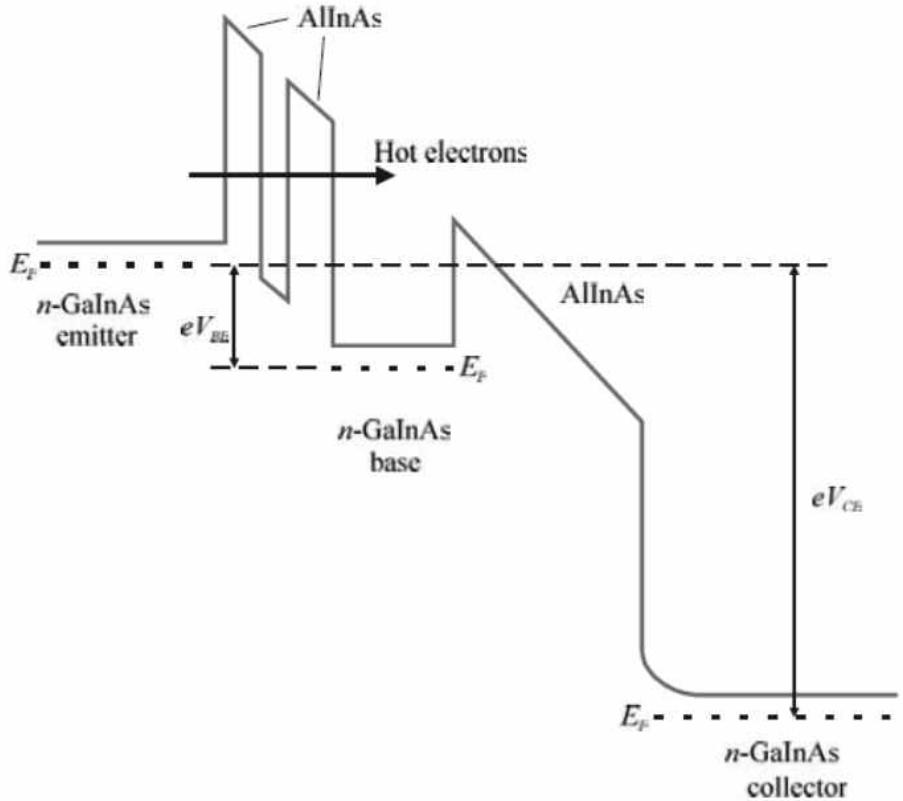




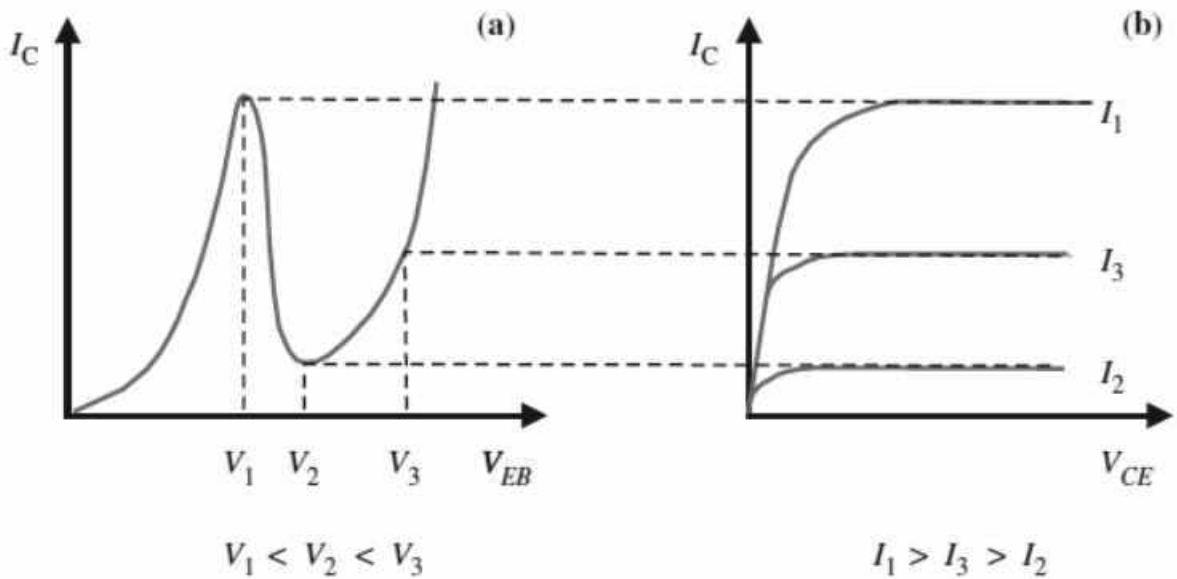
- The two most common MBTs structures are represented in figure
- For the base region of MBTs, materials such as cobalt silicide (CoSi2) is used; this silicide shows a conductivity almost as high as that of metals and is chemically compatible with silicon technology.
- shows the band structure of a device 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 in high quality interfaces
- In these transistors, hot electrons behave as ballistic electrons they practically do not suffer scattering since their mean free path is larger than the thickness of the base region.
- the most significant advantages of MBTs 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.

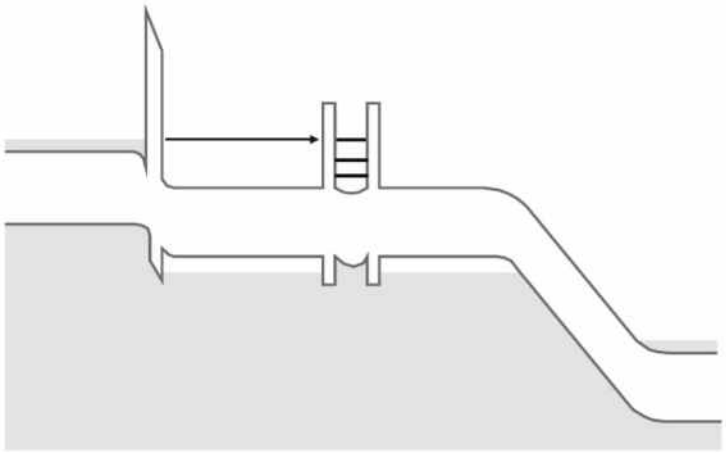


Qualitative dependence of the collector current of a resonant tunnelling transistor as a function of: (a) base–emitter voltage; (b) collector–emitter voltage.

- 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.

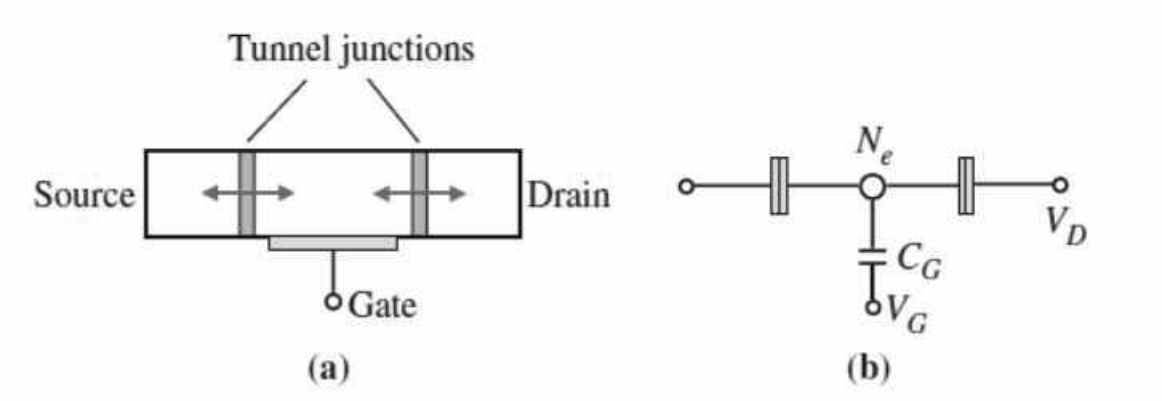
- One of the most interesting properties of these structures is called *Coulomb blockade effect.*

- 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

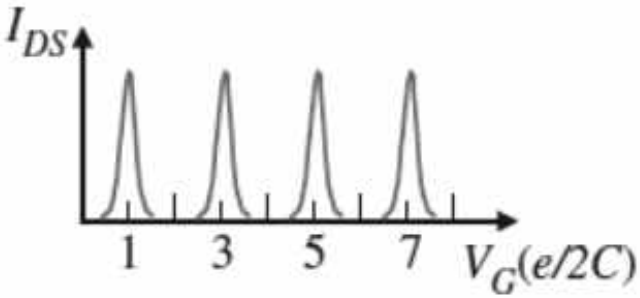


- Figure (a) shows the schematic representation of a SET and Figure (b) is its equivalent circuit as a three-terminal device.

- 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.

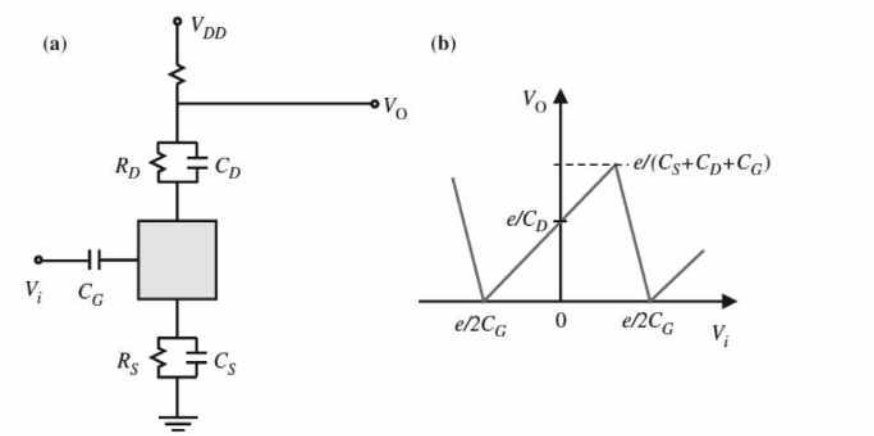
- The applied voltage induces a charge *CV*G in the opposite plate of the capacitor, which is compensated by the tunnelling of a single electron that enters the quantum dot.

- 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*)*.

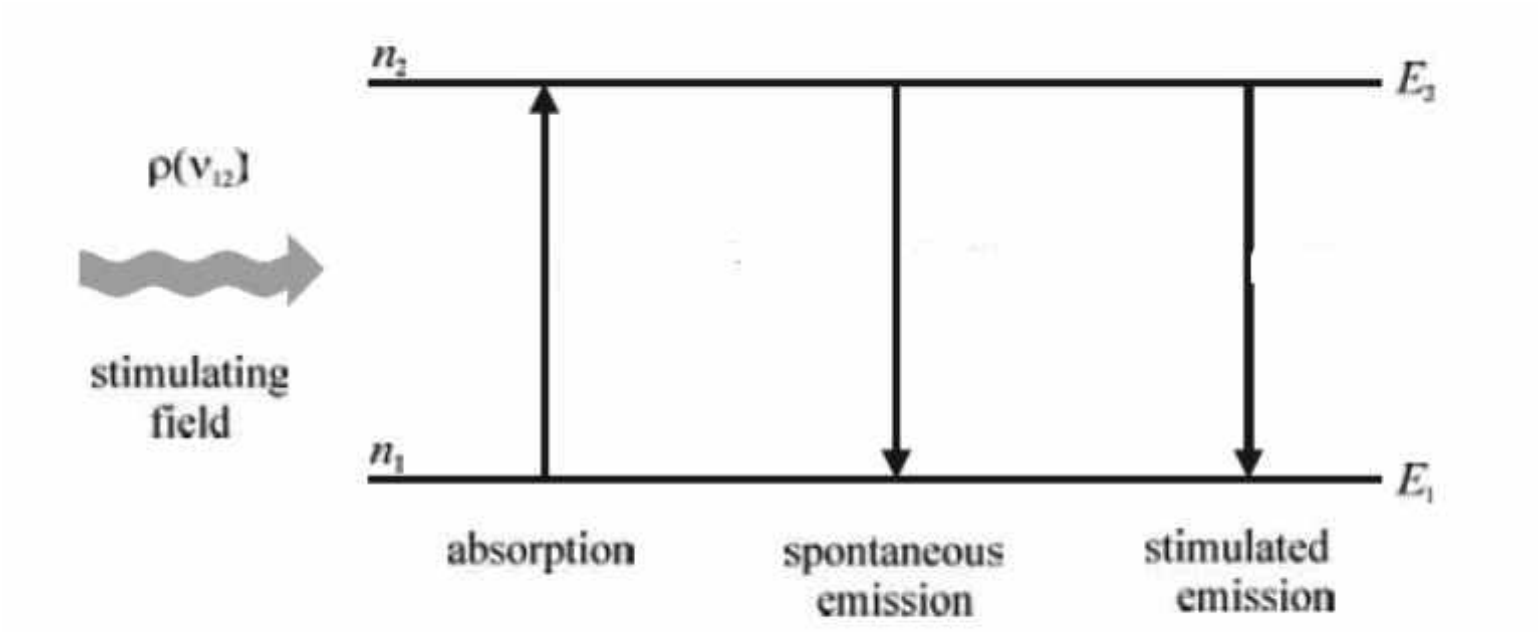
- The above inverters have been already used in the design of logical circuits and as unit memory cells.

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 $hv = E2 - E1$.
- This process is therefore called *stimulated emission* and is proportional to the density $\rho(v)$ 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.*



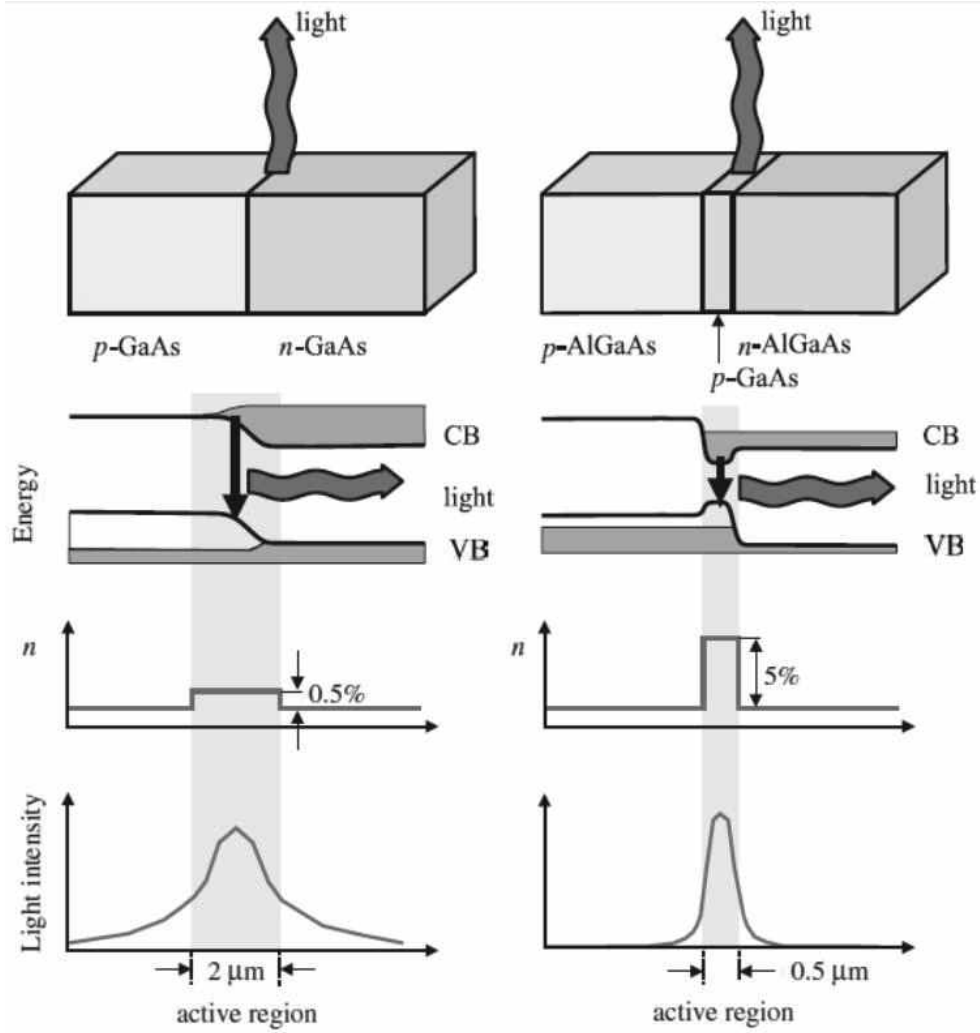
(a) Absorption; (b) spontaneous emission; (c) stimulated emission

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.

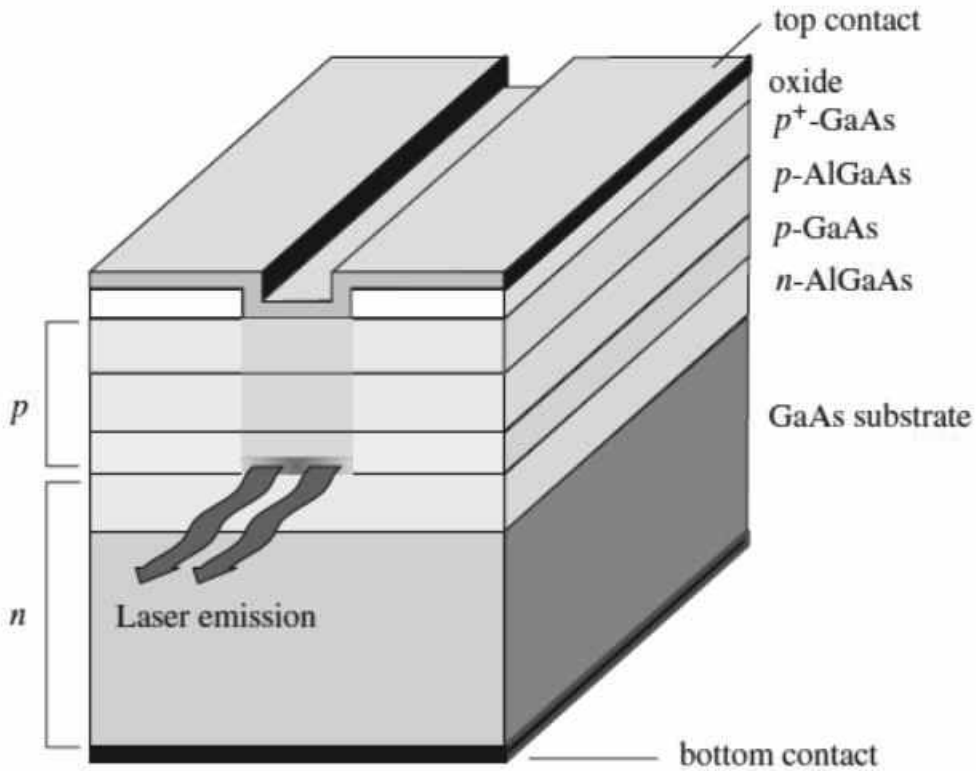
- The *optical confinement factor ,* which indicates what fraction of the photon density is located within the active laser region and can approach unity.

- 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.



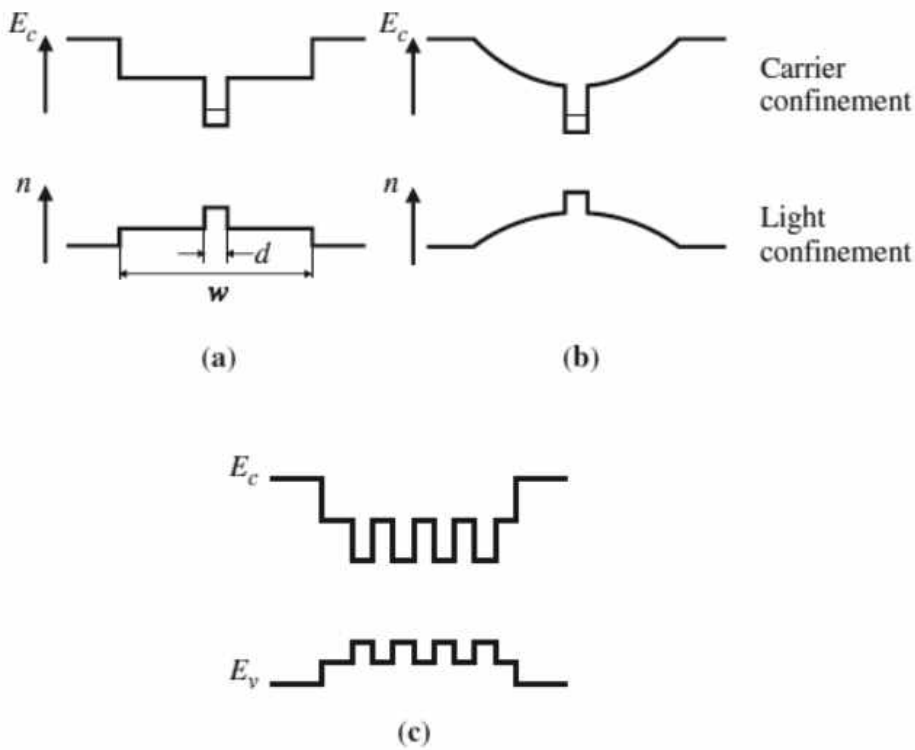
Stripe geometry double heterostructure semiconductor laser.

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 Al*x*Ga1−*x*As 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.

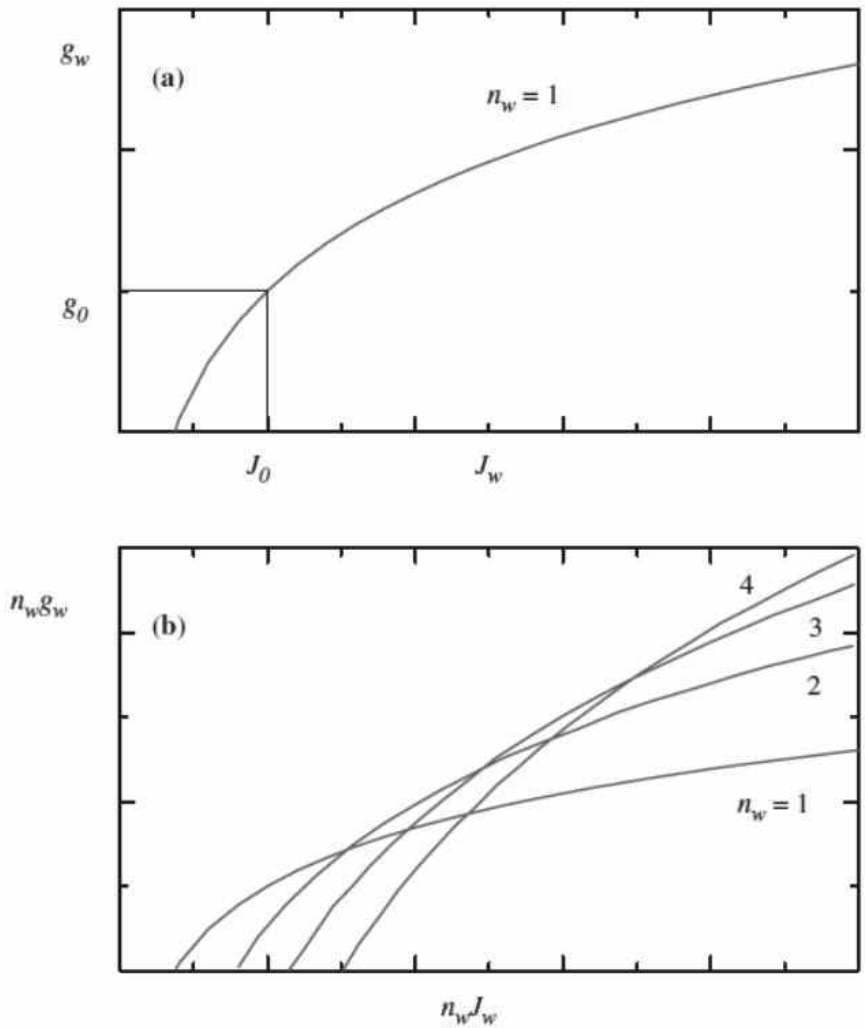
- The gain can be related to the current density J by assuming a value of τ for the recombination time, since $J = end\tau^{-1}$, where d is the thickness of the active region; alternatively, τ could be obtained from the rate of radiative recombination.

- 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.

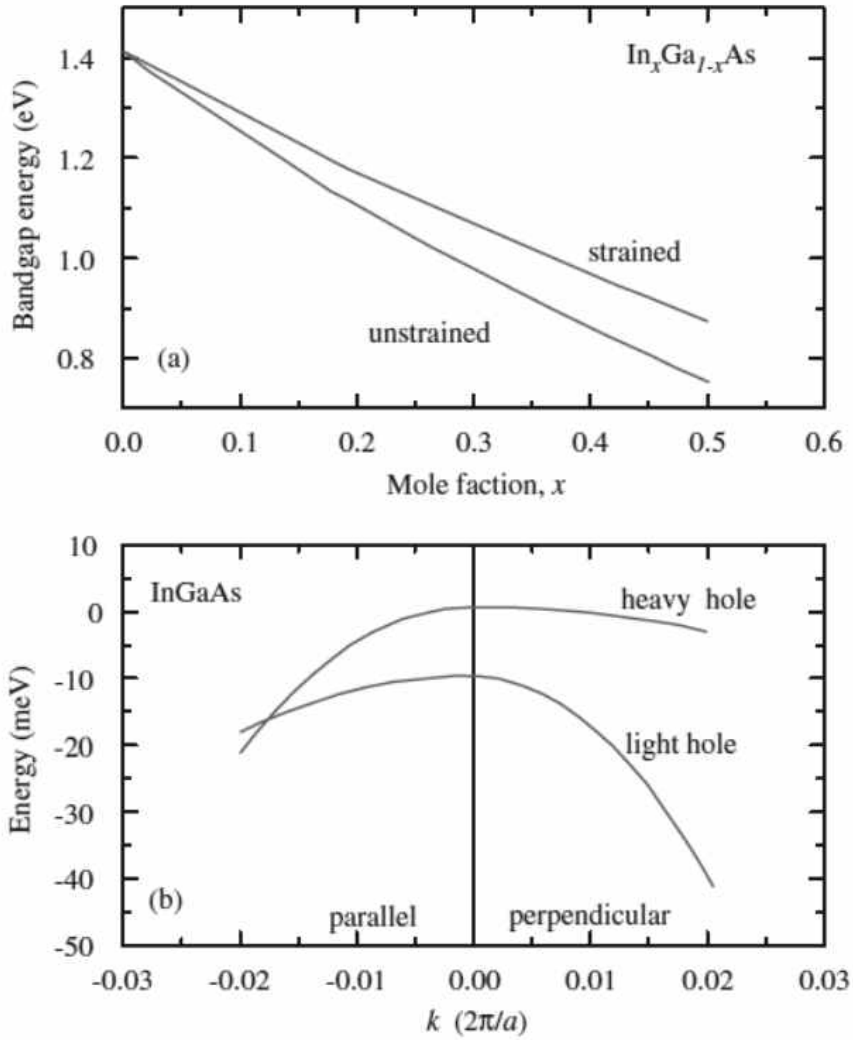
- They show many desirable properties such as low-threshold current density and lower linewidth than regular Multi-Quantum-Well (MQW)

- 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.

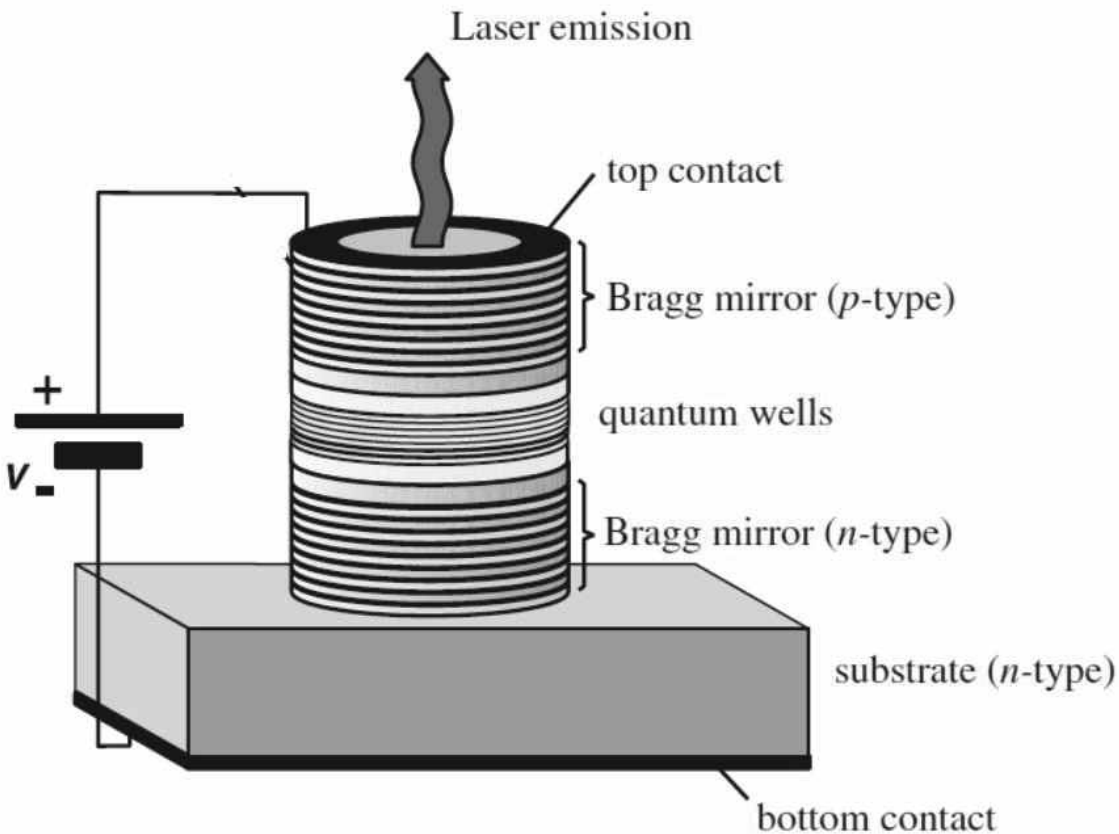
- it changes considerably the values of the hole effective masses and increases the value of the energy gap.



. Strained InGaAs layers surrounded by GaAs: (a) In_xGa_{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.

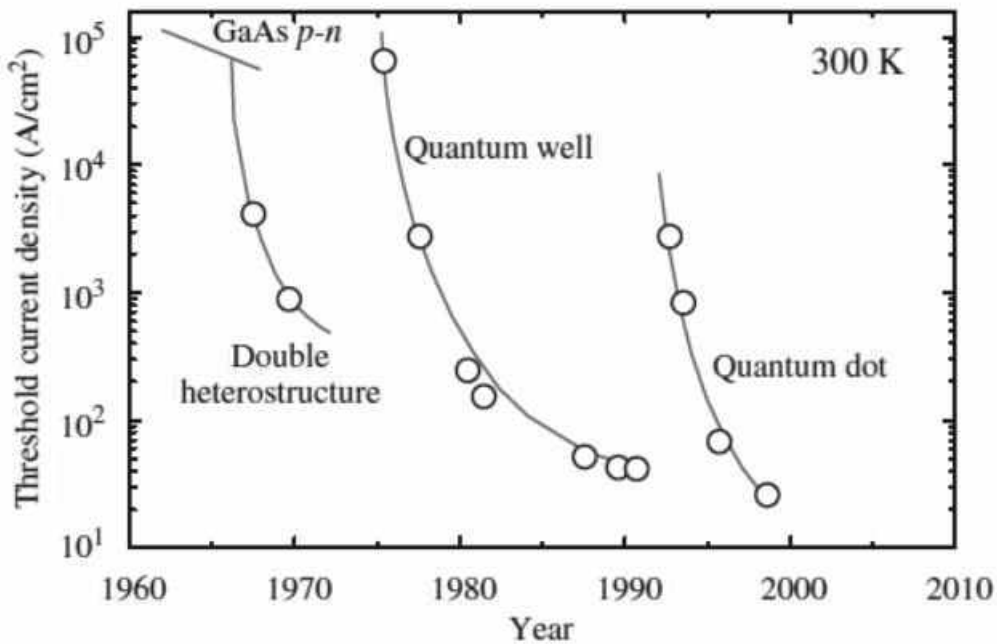
- Let us assume that the quantum dots are small enough so that the separation between the first two electron energy levels for both electrons and holes is much larger than the thermal energy kT.

- 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

- The gain spectrum calculated for lasers based on different ideal quantum confinement structures is shown in Figure

- Quantum dots should have the narrowest spectrum and the highest gain.
- Also they should have a symmetrical spectrum, which would produce no jitter.

quantum dots fabrication

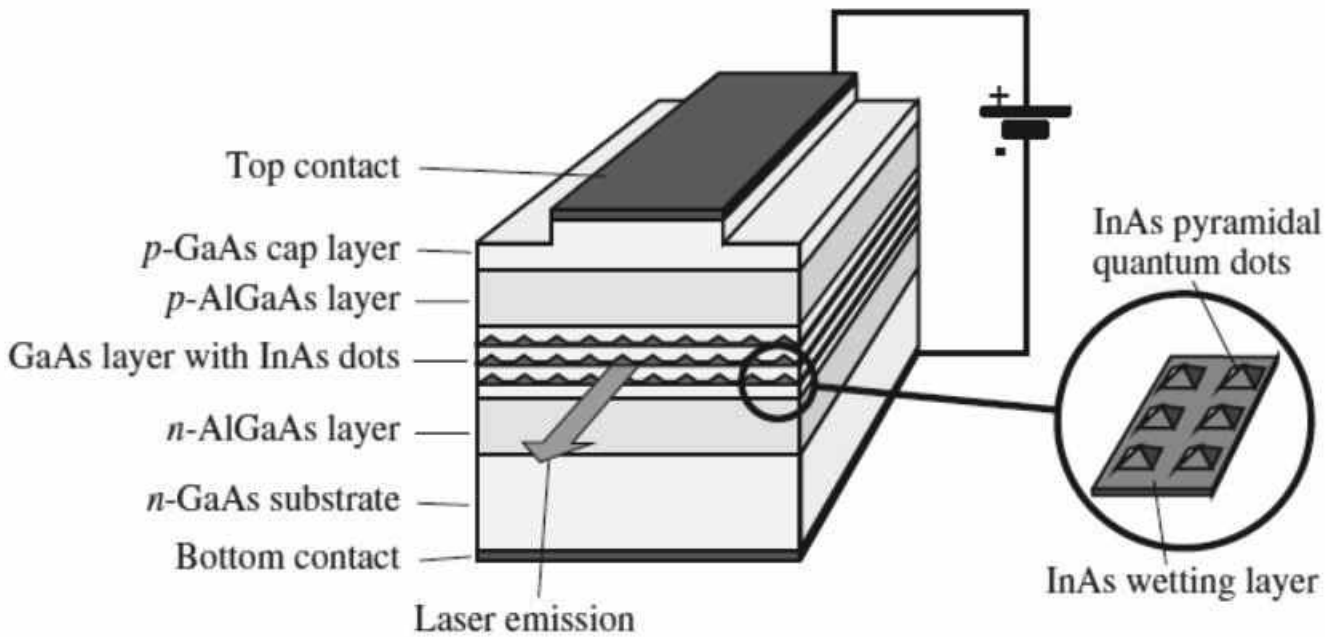
- Traditional methods for fabricating quantum dots include semiconductor precipitates in a glass matrix or etching away a previously grown epitaxial layer.
- None of these methods can produce large densities of dots, and the control of size and shape is difficult.
- Moreover they introduce large defects 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***

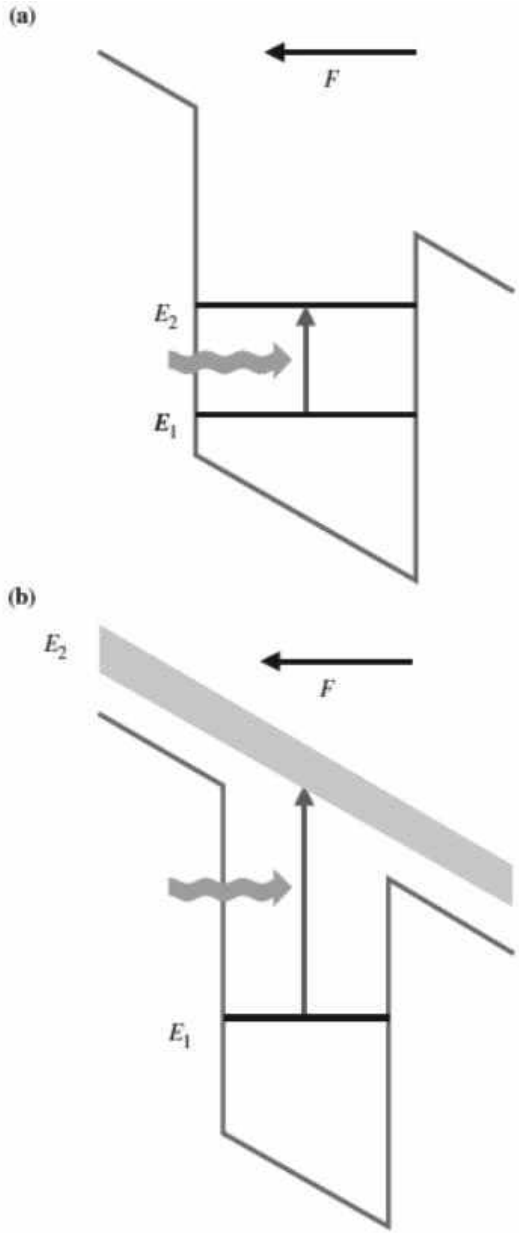
  or

  Quantum Well Infrared Photodetector (QWIP)

- ***(b) Superlattice avalanche photodetectors***

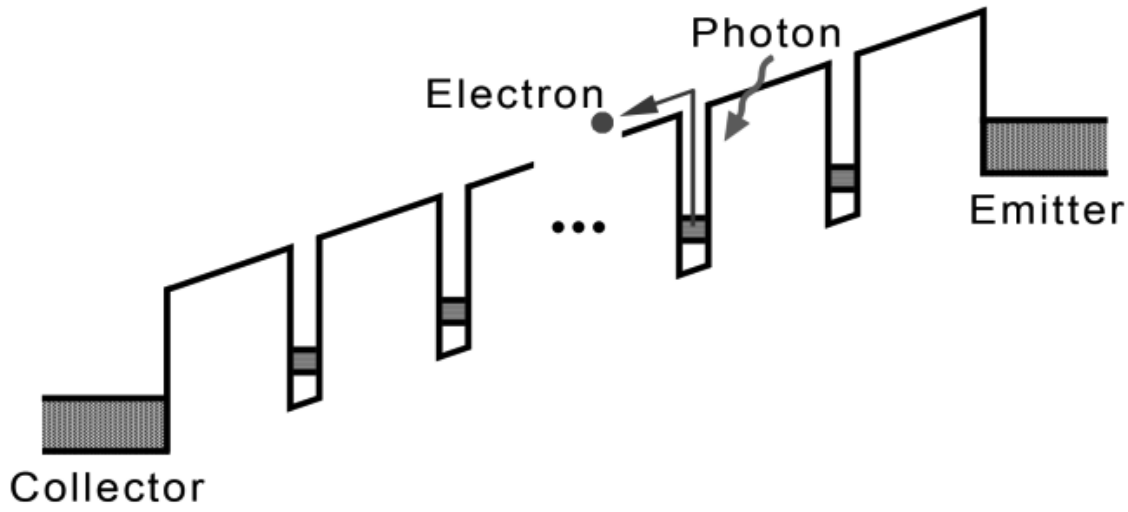
Quantum well subband photodetectors

- 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 electronic intersubband transitions in 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.

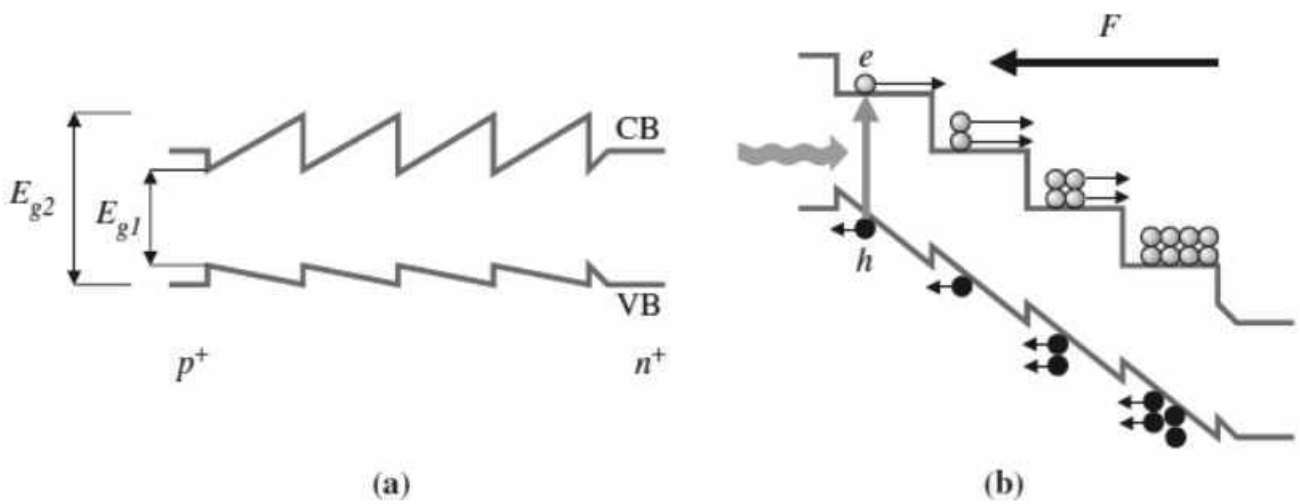
- When the QWIP is illuminated with light of the same or higher energy as the intersubband transition energy, an electron is excited.

- 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 $\alpha e/\alpha h$ has a value of about 30.
- For a given semiconductor the ratio $\alpha e/\alpha h$ is practically fixed by the semiconductor band structure.

- Quantum wells, on the other hand, allow a design control of $\alpha e/\alpha h$.
- 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

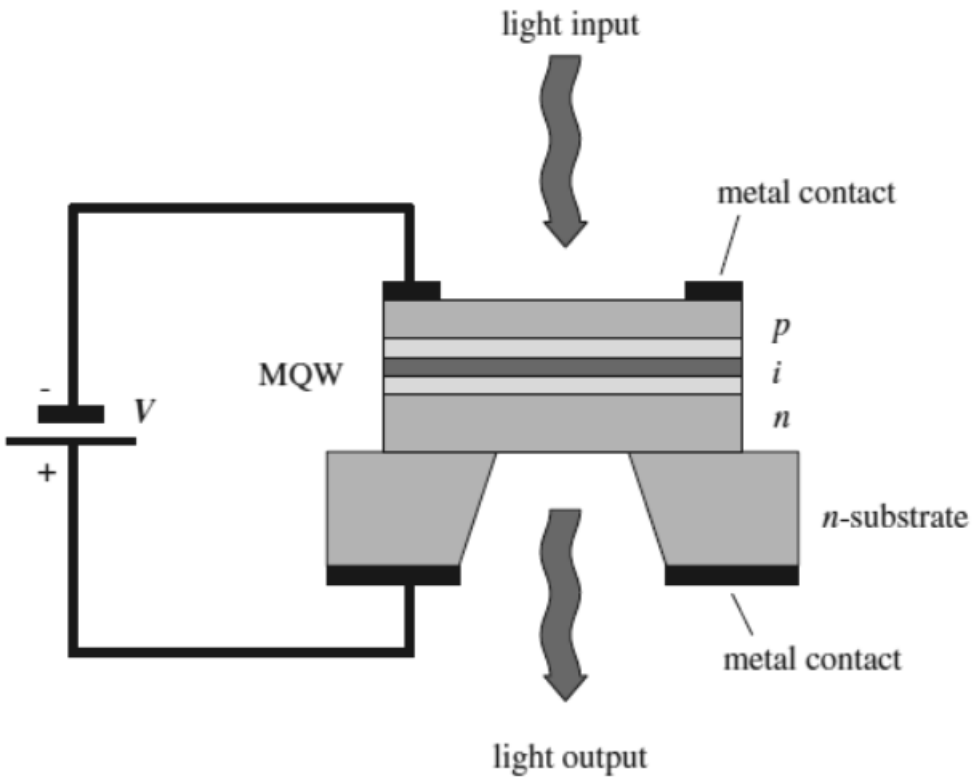
- Quantum wells can be conveniently used for the direct modulation of light, since they show much larger electro-optic effects than bulk semiconductors.

- 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.

- *Electroabsorption modulators* are based on 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.

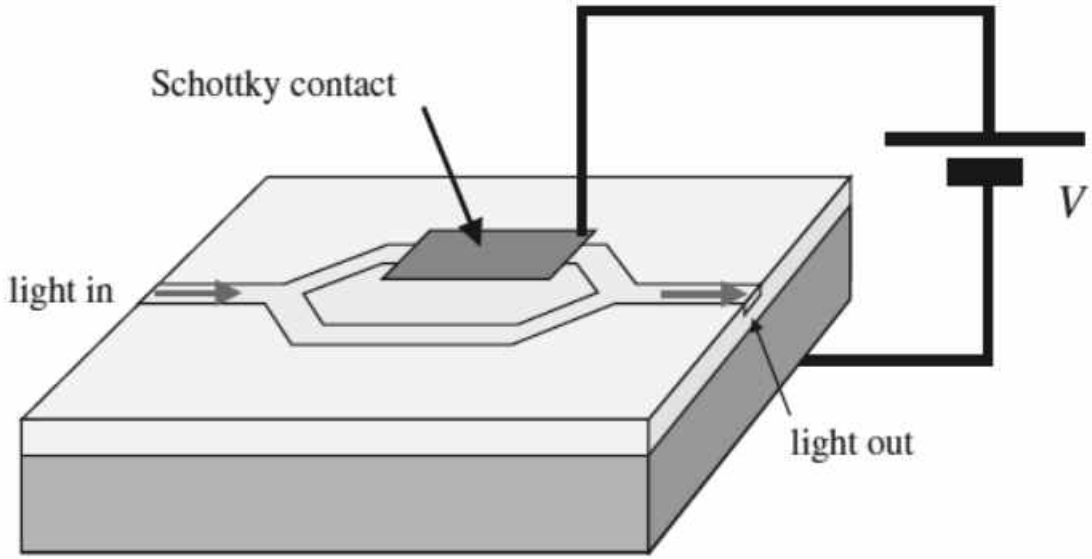
- This is done by depositing a metal layer substrate and forcing light to make two passes.

- 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.