5. Nano Devices

Quantum confinement - Quantum structures - quantum wells, wires and dots - Zener - Bloch oscillations - Resonant tunneling - Quantum interference effects - Mesoscopic structures - Single electron phenomena - Single electron Transistor. Semiconductor photonic structures - 1D, 2D and 3D photonic crystal. - Photo processes - Spintronics - Carbon nanotubes: properties and applications.

5.1. Introduction

A nanometer is one billionth ($1/10^9$) of a meter. For comparison, thickness of a single human hair is about 80,000 nm (80 μm), a red blood cell is approximately 7000 nm (7 μm) wide and a water molecule is almost 0.3nm across. Scientist and engineers are now-a-days interested in Nanoscale which is from 1 nm to 100 nm. At Nanoscale, the properties of materials are very different from those at larger scale. Therefore, the nano-world is in between quantum world and macro world.

Nanoscience

It is concerned with the study of phenomena and application of structures, devices and systems by controlling shape and size at the nanometer scale. Nanotechnology means making use of the unique physical properties of atoms, molecules and other materials measuring roughly 1 to 100 nanometre. The word "nano" comes from nanos, a Greek word meaning drawf. Presently, we are making devices made of nanoelectronic devices. The microelectronics industry was born out of the invention of the bipolar transistor in 1947 and by the invention of the integrated circuit (IC) in 1958. Gordon Moore (INTEL founder) observed that the number of transistor per square inch on IC chip roughly doubled by every 18 to 24 months. This general rule of thumb is now called as "**Moore's law**". In 1960, the minimum size of a transistor was approximately 100 nm. At present, manufacturing technology is at transistor size of 22 nm. Because of the diminishing feature size of transistors and other components, we can say that the electrons industry is already doing "nanotechnology".

Nanomaterials

Definition

Nanophase materials are newly developed materials with grain size at the nanometer range (10^{-9}m). ie., in the order of 1 -100 nm. The particle size in a nanomaterial is 1 – 100 nm. They are simply called nanomaterials.

Different forms of Nanomaterials

Nanostructured material

The structures whose characteristic variations in design length is at the Nanoscale

Nanoparticles

The particle size is in the order of 10^{-9}m are called nanoparticles

Nano dots

Nanoparticles which consist of homogeneous material, especially those that are almost spherical or cubical in shape

Nano rods

Nanostructures which are shaped like long sticks or rods with diameter in Nanoscale and a length very much longer.

Nanotubes

Nanotubes are Nanoscale materials that has a tube like (hollow cylinder) structure.

Nanowires

Nanowires are solid rod like material with diameter of few nanometers or less

Fullerenes

A form of carbon having a large molecule consisting of an empty cage of 60 or more carbon atoms.

Nanocomposites

Composite structures whose characteristics dimensions are foun at Nanoscale

Cluster

A collection of units (atoms or reactive molecules) upto few tens of units.

Colloids

A stable liquid phase containing particles in the 1 – 1000 nm range.

Nanoelectronics

It refers to the use of nanotechnology in electronic components, especially transistors. It often refers to transistor devices that are so small that interatomic interactions and quantum mechanical properties need to be studied extensively. Besides, being small and allowing more transistors to be packed into a single chip, the uniform and symmetrical structure of nanotubes allows a higher electron mobility, a symmetrical electron/hole characteristic.

Need for Nanotechnology in electronics

Today microelectronics are used to solve most of the problems. The two exceptional disadvantages of microelectronics are: Physical size, increasing cost of fabrication of ICs. To overcome these disadvantages, nanotechnology is used.

Advantages of using Nanotechnology in Electronics

Increasing the density of memory chips.

Decreasing the weight and thickness of the screens

Nanolithography is used for fabrication of chips.

Reducing the size of transistors used in integrated circuits.

Improving display screen on electronic devices.

Reducing power consumption.

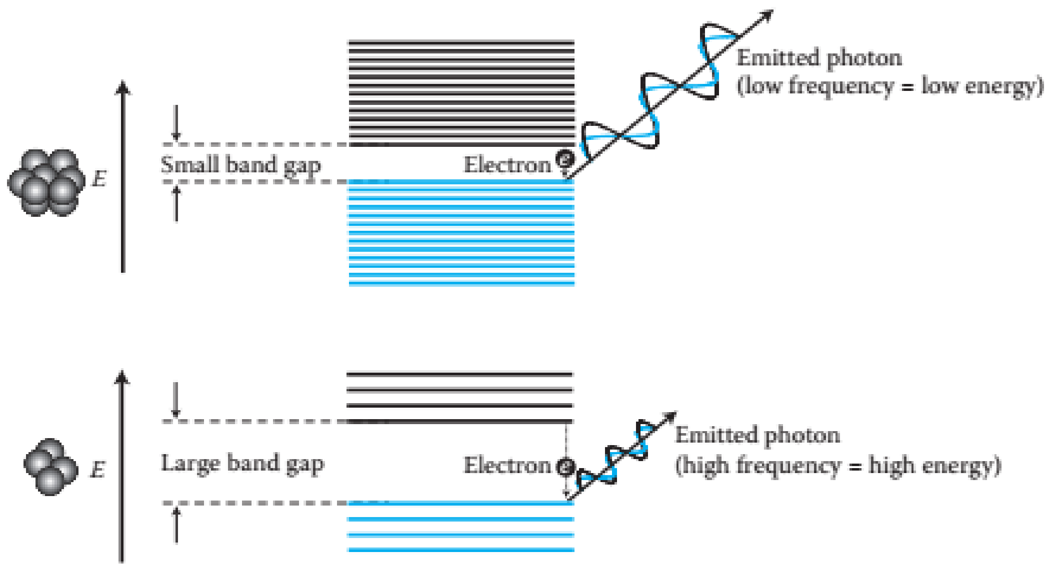
5.2. Quantum confinement

Definition

It is a process of reduction of the size of the solid such that the energy levels inside becomes discrete

Explanation

When the size of a nanocrystal becomes smaller than the deBroglie wavelength, electrons an holes gets spatially confined, electrical dipoles gets generated, the discrete energy levels are formed. As the size of the material decreases, the energy separation between adjacent levels increases. The density of states of nanocrystals is positioned in between discrete (as that of atoms and molecules) and continuous (as in crystals).
Quantum size effect is most significant for semiconductor nanoparticles. In semiconductors, the bandgap energy is of the order of few electron volts and increases with a decrease in particle size. When photons of light fall in a semiconductor, only those photons with energy are absorbed and a sudden rise in absorption is observed when the photon energy is equal to the bandgap.
As the size of the particle decreases, absorption shifts towards the shorter wavelength (blue shifts) indicating an increase in the bandgap energy .A change in absorption causes a change in the colour of the semiconductor nanoparticle.
For example, bulk cadmium sulphide is orange in colour and has a bandgap of $2.42eV$. It becomes yellow and then ultimately white as its particle size decreases and the bandgap increases.



5.2. Quantum structures- Quantum wells, Wires and Dots

Volume is the three-dimensional quantity. To reduce the volume of the box, we can shorten its length, its width or its height. The same is true for the region occupied by the electrons in a solid.

There are three dimensions to confine and achieving quantum confinement typically requires confining at least one of these dimensions to less than 100 *nm* or just few nanometers.

A quantum confined structure is one in which the motion of the electrons or holes are confined in one or more directions by potential barriers.

Based on the confinement direction, a quantum confined structure will be classified into three categories as quantum well, quantum wire and quantum dot.

Quantum well

When we constrain electrons inside a region of minimal width we create a quantum well. In other words, if one dimensional is reduced to the nano range while the other two dimensions remain large than we get a structure known as *quantum well*

Construction

Quantum wells are made from alternative layers of different semiconductors or by deposition of very thin metal films.

Explanation

The well is like a cage in which the carrier particles (the excitons) are trapped. These trapped particles can be considered to be quantum confinement. Due to this quantum confinement, the motion of carriers is reduced. In a quantum well, the excitons can move freely sideways in the plane of a thin layers, but they might like to move in the forward and backward directions as well. Due to the confinement of carriers, the structure quantum well has important applications in making useful devices.

Use

Quantum wells are now widely used to make semiconductor layers and other important devices

(ii) **Quantum wire (1 dimension)**

Definition

If we constrain width and depth of electron's domain, we create a quantum wire. In other words, if two dimensions are so reduced and one remains large, the resulting structure is quantum wire.

Explanation

The carriers trapped in such structures can be considered to be in 1-D quantum confinement. In this case, an exciton is only free to choose its trajectory along the wire. However, for each motion of its movement, the exciton can have various ways of being confined.

Example

Examples of quantum wire structures are nanowires, nanorod and nanotube.

(iii) Quantum Dots (0-Dimension)

Definition

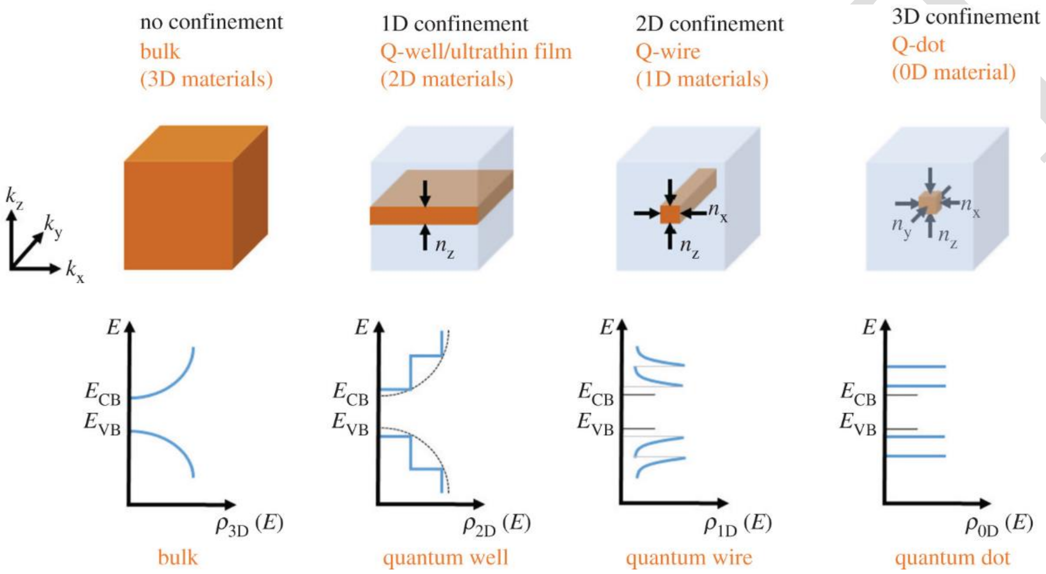
When all three dimensions are minimized the resulting structure is quantum dot. The dot can be particle located inside a larger structure or on its surface. It can also be a place where electrons have been trapped using electric fields.

Explanation

Hence, in this situation, the exciton only has confined states i.e., there are no freely moving excitons. Although a quantum dot has many thousands of atoms, but due to its peculiar properties, it is considered more like a single atom rather than many atoms.

Use

Quantum dot may be used as a basic building block in making a quantum computer.



5.4. Zener Bloch Oscillations

Definition

Zener Bloch oscillation was first observed by **Bloch and Zener** while examining the electrical properties of crystal.

*A particle in a periodic potential with an additional constant force performs oscillations and these oscillations are called **Bloch oscillations**.*

Modulating every second period of the potential, the original Bloch band splits into two sub-bands. *The dynamics of quantum particles shows a coherent superposition of Bloch oscillations and Zener tunneling between the sub-bands which is called as Zener-Bloch oscillations*

Occurrence of Bloch Oscillations

It is very difficult to observe Bloch oscillations in natural crystals. This is due to the scattering of electrons by lattice defects.

But, Bloch oscillations have been experimentally observed for various systems; electrons in semiconductor super lattices, cold atoms in optical lattices, light pulses in photonic crystals and even mechanical systems may perform Block oscillations.

Theory

The one-dimensional equation of motion for an electron in a constant electric field is

$$F = \frac{dP}{dt} = \hbar \frac{dk}{dt} = -eE \qquad (1)$$

The solution of Eqn. (1) is $k(t) = k(0) - \frac{eEt}{\hbar}$ (2)

The position of electron x is given by $x(t) = x(0) - \frac{A}{eE} cos\left(\frac{aeE}{\hbar} t\right)$ (3)

Equation (3) shows the electron oscillates in real space. From equation (3), the angular frequency of the oscillations is given by $\omega_B = \frac{ae|E|}{\hbar}$ (4)

Explanation

Tunneling between Bloch bands is possible only for strong external field. Normally, successive Zener tunneling to even higher bands will force to decay because the band gaps generally decreases with increasing energy. This decay can be observed as pulsed output for electrons in semiconductor super lattices.

A system of atleast two bands are necessary for knowing the relationship between Bloch oscillations and Zener tunneling. These two bands are well separated from all other bands. This is attained by implementing another weak potential with doubled period length. Because of this perturbation, the ground band splits into two mini bands and Zener tunneling between the mini bands must be considered.

Use

The Bloch Zener oscillations can be utilized for the construction of a matter wave beam splitters.

5.5. Resonant Tunneling

If a particle is impinging on a potential barrier with energy certainly less than the height of the potential barrier, it will not necessarily be reflected by the barrier but there is always a probability that it may cross the barrier and continues its forward motion. This surprising phenomenon is known as tunneling and forms the basis of a number of electronic devices.

Definition

Resonant tunneling refers to tunneling in which the electron transmission coefficient through a structure is sharply parked about certain energies.

Explanation

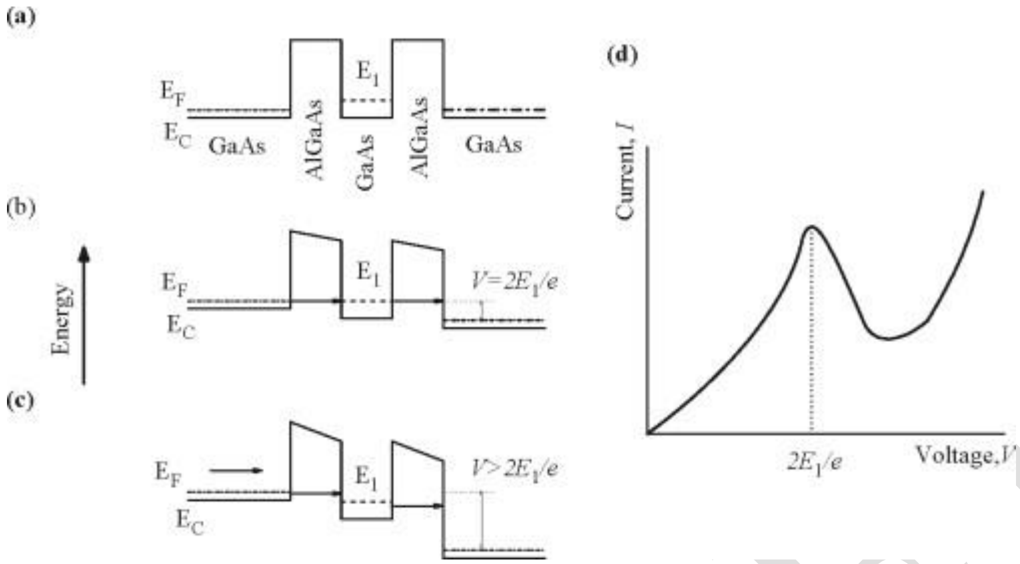
By introducing infinite walls as boundary conditions, the emergence of these peaks can be qualitatively explained. This can be achieved by using quantum well. Then the calculation of the quantized energy levels in a quantum well of arbitrary shape is the solution for an eigenvalue problem. For electrons with an energy approximately corresponding to the virtual resonant energy level of the quantum well, the transmission coefficient is close to one. This is, an electron with this resonant energy can cross the double barrier without being reflected.

Resonant Tunneling Diode [RTD]

The double barrier junction has important applications to a device known as resonant tunneling diode. The operation of these diodes can be explained by considering the influence of bias on the energy band diagrams for the double barrier system.

Explanation

For example, consider that incident electrons have energy E, and that at first all of the quasi-bound states E_n lie above E, as shown in figure



As E increases tunneling will increase, reaching a peak when $E = E_1$. After that point, a further increase in E will result in a decreasing current, as shown in figure. This decrease of current with an increase of bias is called negative resistance. Further peaks and valleys will occur as E approaches, and then moves past, other quasi bound states. A typical structure is made by using *n*-type GaAs for the well region, and AlGaAs for the barrier material.

Tunnel control

Tunneling is controlled by applying a bias voltage across the device

Without applied bias

For the case of no applied bias, the energy band diagram is similar to that shown in figure.

With applied bias

For an applied bias V_0, positive on the right side of the double junction an appreciable current begins to flow when the quasi-bound state is pulled down to the Fermi level of the left region, as shown in figure.

Current reaches a maximum when the level of the quasi-bound state is equal to the conduction band-edge of the left region.

5.6. Quantum Interference Effects

Definition

A physical phenomena when two or more particles that are space and time independent have an interaction, construction or destructing their wave functions is known as ***quantum interference.***

Quantum interference is one of the most challenging principles of quantum theory. Basically, the concept states that elementary particles cannot only be in more than one place at any given time (through superposition), but that an individual particle, such as a photon (light particles) can cross its own trajectory and interfere with the direction of its path.

Theories

In the seventeenth century, Isaac Newton proclaimed that light consisted of a stream of particles. In the early nineteenth century, Thomas Young devised the double-slit experiment to prove that it consisted of waves. Although the suggestions of Young's experiment are difficult to accept, it has reliably yielded proof of quantum interference through repeated trials.

The noted physicist Richard Feynman claimed that the essentials of quantum mechanics could be grasped from an exploration of the double slit experiment.

Illustration

For this variation of Young's experiment, a beam of light is directed at a barrier with two vertical silts. The light passes through the slits and the resulting pattern is recorded on a photographic plate. If one slit is covered, the pattern is a single line of light, aligned with whichever slit is open. Automatically, one would expect that it both slits are open, the pattern of light will reflect that two lines of light, aligned with the slits. In fact, we get multiple lines of lightness and darkness in varying degrees. What is being illustrated by this result is that interference is taking place between the waves/ particles going through the slits, in what, seemingly, should be two non-crossing trajectories. We would expect that if the beam of photons is slowed enough to ensure that individual photons are hitting the plate, there could be no interference and the pattern of light would be two lines of light, aligned with the slits.

However, the resulting pattern still indicates interference which means that single particles are interfering with themselves. This seems impossible because we expect that a single photon will go through one slit or the other, and will end up in one of two possible light line areas. But this is not actually happens.

Experimental results

According to Feynman, each photon goes through both slits and also simultaneously traverses every possible trajectory on the way to the target. In order to see how this occur, experiments have focused on tracking the paths of individual photons. But the measurement in somehow disturbs the trajectory of photons. Therefore, the experimental results will be similar with classical physics (two bright lines on the photographic plate, aligned with the slits in the barrier). If we stop measuring, the pattern will again become multiple lines in varying degrees of lightness and darkness.

Applications

Quantum interference research is being applied in a growing number of applications, such as the superconducting quantum interference device (SQUID), quantum cryptography and quantum computing.

5.7. Mesoscopic structures

We know Nano science is the study of materials whose physical size is on the nanometer scale in the range of (1-1000 nm). Nano means precisely small, *meso* is a broader term, which means intermediate between the microscopic (molecule) and macroscopic (bulk) scales. In practice, the Mesoscopic regime partly overlaps the description of nanoscopic.

Definition

The prefix *meso* means in between or intermediate. *Mesoscopic* system are those that are larger than **atoms** and yet very much smaller than the larger scale everyday objects that we can see and touch.

Explanation

Mesoscopic are hundred thousand times smaller than the diameter of a human hair and they range in size from several hundred nanometres or billionths of a meter. That is why materials composed of Mesoscopic parts are also known as nanostructures and the technology based on these systems is referred to as nanotechnology. Since one nanometre is less than the width of ten atoms in a row, Mesoscopic systems are made up of less than a thousand atoms. *A macroscopic device, when scaled down to a meso-size, starts revealing quantum mechanical properties.*

Difference between macroscopic level and microscopic level

For example, at the macroscopic level the conductance of a wire increases continuously with its diameter. However, at the mesoscopic level, the wire's conductance is quantized. i.e., the increase occur in discrete or individual whole steps.

Mesoscopic devices

During research, mesoscopic devices are constructed, measured and observed experimentally and theoretically in order to advance understanding of the physics of insulators, semiconductors, metals and superconductors. The applied science of mesoscopic physics deals with the potential of building nano devices.

Connection between mesoscopic and nanotechnology

There is no rigid definition for *mesoscopic* physics but the system studied are normally in the range of 100 nm (the size of a typical virus) to 1000 nm (the size of a typical bacterium): 100 nanometres is the approximate upper limit for a nano particle.

Thus, mesoscopic physics has a close connection to the fields of nano fabrication and nanotechnology.

Devices used in nanotechnology are examples of mesoscopic systems.

Three categories of new phenomena in such systems are

(i) Interference effects (ii) Quantum confinement effects and (iii) Charging effects.

Importance of mesoscopic system

(i) Mesoscopic or nanoscale systems behave very differently from large scale objects and they often have unusual physical and chemical properties.
(ii) By manipulating systems on the nanoscale, they can make computers, sensors and other devices that have exactly the properties they want.
(iii) Mesoscopic materials form the subset of nanostructured materials for which the nanoscopic scale is large compared with the elementary constituents of the material, i.e., atoms, molecules, or the crystal lattice.
(iv) For the specific property under consideration, these materials can be described in terms of continuous, homogeneous media on scale less than that of the nanostructure
(v) The term *mesoscopic* is often reserved for electronic transport phenomena in systems structured on scales below the phase-coherence length of the carriers.

Example

There are many examples of mesoscopic systems in nature

(i) The molecules in our bodies that break down the foods in our stomachs and intestines, and the molecules that carry oxygen from the lungs to other parts of the body, are nothing but nanoscale machines.
(ii) Artificial nanostructures, such as multilayered nanostructures, made up of thin mesoscopic layers of different materials, have been used in devices such as high-efficiency lasers and light emitting diodes (LEDs)
(iii) Researchers have used the STM to create a switch that could be used in computers, with a single atom which moves back and forth rapidly between two positions. Biologists are

trying to manipulate large molecules such as proteins which could be used in the future for tasks such as the repair of damaged organs.

5.8. Single electron phenomena

Transistors are what computers used to compute-tiny switches turning on and off, transferring and amplifying signals, making logic decisions. Today, microchips have over a billion transistors, each one turning on and off a billion times every second. These chips require manufacturing processes with roughly 100-nm resolution. And every year this resolution drops, enabling even smaller transistors, so that even more of them can be squeezed into the same amount of space. Rather than moving torrents of electrons through transistors, it may very well be practical and necessary to move electrons *one at a time.* We can use transistors to make sensitive amplifiers, electrometers, switches, oscillators, and other digital electronic circuits all of which operate using single electrons

Rules for single electron phenomena to occur

Tunnelling is the way electrons cross both the physical barriers and the energy barriers separating a quantum dot from the bulk material that surrounds it. If any electron on one side of the barrier could just tunnel across it, there would not be any isolation. The dot would not be a quantum dot because it would still essentially be part of the bulk.

So we need to be able to control the addition and subtraction of electrons. We can do this with voltage biases that force the electrons around. There are two rules for preventing electrons from tunnelling back and forth from a quantum dot.

(i) Coulomb blockade effect
(ii) Overcoming uncertainity

Rule1: Coulomb Blockade effect

A quantum dot has a capacitance, C_{dot}, a measure of how much electric charge it can store

$$C_{dot} = G\,\varepsilon\,d \qquad (1)$$

Here, ε is the permittivity of the material surrounding the dot, *d* is the diameter of the dot, and *G* is a geometrical term (if the quantum dot is a disk, *G* = 4; if it is a spherical particle, *G* = 2π). An object isolated in space can store charge on its own and therefore can have a capacitance.

The energy needed to add one negatively charged electron to the dot is known as the charging energy, $E_C = \frac{e^2}{2C_{dot}}$ (2)

We know that the coulomb blockade can prevent unwanted tunnelling. Hence we can keep the quantum dot isolated, the condition for this is given by $E_C \gg K_B T$ (3)

Rule2: Overcoming uncertainity

The uncertainty in the energy of a system is inversely proportional to how much time we have to measure it. Specifically, the energy uncertainty, Δ*E*, adheres to this relationship

$$\Delta E \approx \frac{h}{\Delta t} \qquad (4)$$

Here, h is Planck's constant and Δt is the measurement time. Since it is a tiny capacitor, the time we use for Δt is the capacitor's time constant (the characteristic time a capacitor takes to acquire most of its charge). The time constant of a capacitor is RC, where R is the resistance and C is the capacitance. In our case, the resistance is the tunnelling resistance, R_t, and the capacitance is C_{dot}. This gives us $\Delta t = R_t C_{dot}$ (5)

Our goal is to keep electrons from tunnelling freely back and forth to and from the dot. To ensure this, *the uncertainty of the charging energy must be less than the charging energy itself*.

For maintaining electron isolation in quantum dot, we need $\Delta E_c < E_c$ (6)

Substituting equation (2), (4) and (5) in (6), we get $\frac{h}{R_t C_{dot}} < \frac{e^2}{2C_{dot}}$ (7)

In otherwords, $R_t \gg \frac{h}{e^2}$ (8)

Meeting this criterion is often as simple as making sure the insulating material surrounding the dot is thick enough. These two rules help in building a single-electron transistor (SET)

5.9. Single electron transistor (SET)

Principle

A transistor with three terminal switching device made from a quantum dot that controls the current from source to rain one electron at a time is called single electron transistor

Construction

The single electron transistor (SET) is built like a conventional Field Emitting Transistor (FET). It has tunnelling junctions in place of *pn* – junctions and quantum dot in place of the channel region of the FET. To control tunnelling, a voltage bias to the gate electrode is applied. A separate voltage bias is applied between source and drain electrodes for the current direction. For current to flow, gate bias voltage must be large enough to overcome the coulomb blockade energy.

Working

1. The purpose of SET is to individually control the tunnelling of electrons into an out of the quantum dot. To do this, we must first stop random tunnelling by choosing the right circuit geometry and materials. If an electron comes or goes from the dot. It will on purpose
2. To control tunnelling, we apply a voltage bias to the gate electrode. There is also a voltage difference between the source and the drain that indicates the direction of current. Here, we can say that current and electron flow in the same direction and we will consider the electrode from which the electrons originate.
3. This is similar to the working of FET, where the gate voltage creates an electric field that alters the conductivity of the semiconducting channel below it, enabling current to flow from source to drain.
4. Applying a voltage to the gate in an SET creates an electric field and change the potential energy of the dot with respect to the source and drain. This gate voltage controlled potential difference can make electrons in the source attracted to the dot and simultaneously electrons in the dot attracted to the drain.

5. For current to flow, this potential difference must be atleast large enough to overcome the energy of the coulomb blockade.

The energy "*E*" needed to move a charge *e* across a potential difference *V* is given by $E=Ve$

So, the voltage that will move an electron onto or off the quantum dot is given by

$$V = \frac{E_c}{e} \quad (or) \quad V = \frac{\frac{e^2}{2C_{dot}}}{e} = \frac{e}{2C_{dot}} \qquad (1)$$

With this voltage applied to quantum dot, an electron can tunnel through coulomb blockade of the quantum dot.

Working for single electron transistor in nutshell

A single electron transistor is shown in figure. As opposed to the semiconductor channel in a field effect transistor, the SET has an electrically isolated quantum dot located between the source and drain.

1. The SET is OFF mode. The corresponding potential energy diagram shows that it is not energetically favourable for electrons in the source to tunnel to the dot as shown in figure.
2. The SET is ON mode. At the lowest setting electrons tunnel one at a time, via the dot, from the source to the drain as shown in figure.
3. This is made possible by first applying the proper gate voltage, $V_{gate} = e/2C_{dot}$, so that the potential energy of the dot is made low enough to encourage an electron to tunnel through the coulomb blockade energy barrier to the quantum dot.
4. Once the electron is on it, the dots potential energy rises as shown in figure
5. The electron then tunnels through the coulomb blockade on the other side to reach the lower potential energy at the drain as shown in figure.
6. With the dot empty and the potential lower again the process repeats as shown in figure.

Advantages

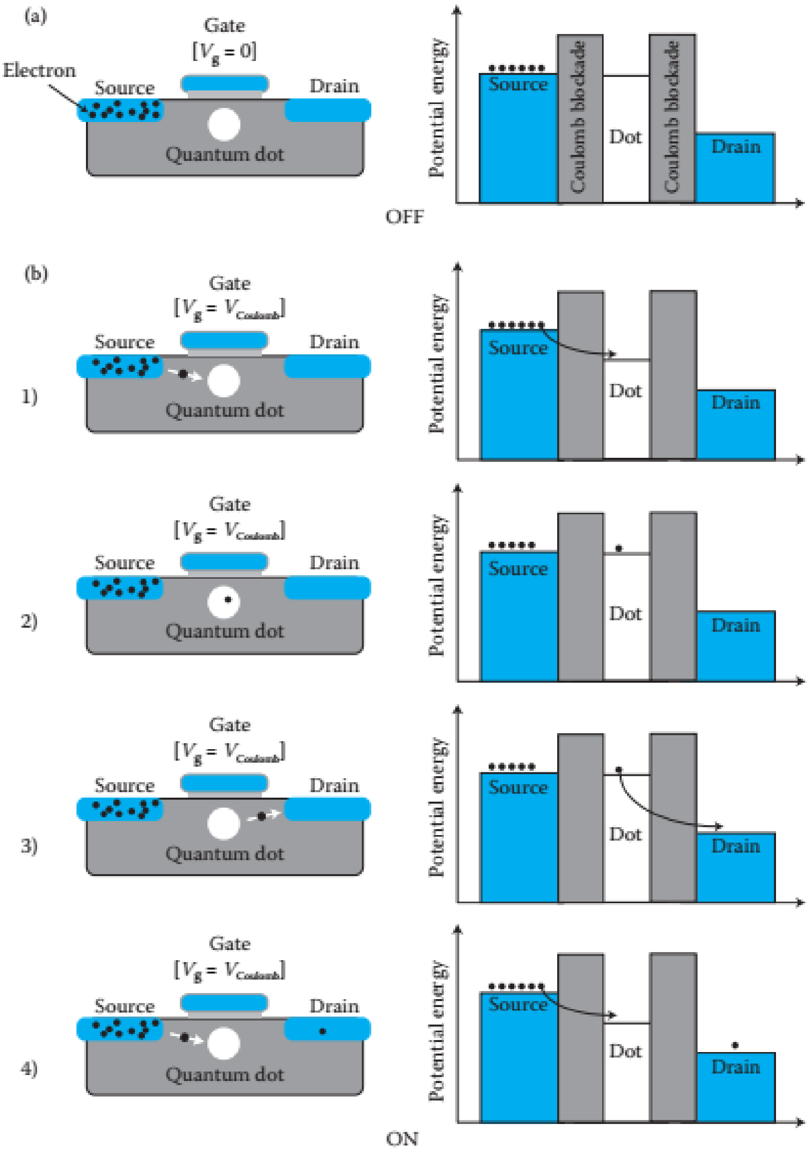
1. The fast information transfer velocity between cells is carried out via electrostatic interactions only.
2. No wire is needed between arrays. The size of each cell can be can be as small as 2.5nm. This made them suitable for high density memory.
3. This can be used for the next generation quantum computer.

Limitations

1. In order to operate SET circuit at room temperature, the size of the quantum dot should be smaller than 10*nm*
2. It is very hard to fabricate by traditional optical lithography and semiconductor processes
3. The method must be developed for connecting the individual structures into logic circuits and these circuits must be arranged into larger 2D patterns.

Applications

1. SET are used in sensor and digital electronic circuits
2. Variety of digital logic functions, including AND or NOR gates, is obtained based on SET operating at room temperature.
3. It is used for mass storage
4. It is used in highly sensitive electrometer.
5. SET can be used as a temperature probe, particularly in the range of very low temperatures.
6. SET is a suitable measurement setup for single electron spectroscopy.
7. It is used for the fabrication of homo-dyn receiver operating at frequencies between 10 and 300 *MHz*.



5.10. Semiconductor photonic structures

Photonic structures are building blocks for many optical applications in which, light manipulation is required in optical filtering, lasing, light emitting diodes, sensing and photovoltaics.

Photonic structures that are made up of semiconducting materials are called semiconductor photonic structures.

The articially developed one-, two- and three-dimensional periodic structures are termed as 1D, 2D and 3D photonic crystals, respectively.

Here, because of the periodicity, the photonic structures under favourable condition will develop a photonic band gap and can open up a frequency band, in which Electromagnetic waves, especially light waves are forbidden, irrespective of the propagation direction in space.

Therefore, inside the photonic band gap, the optical modes, spontaneous emission and zero-point functuations are all absent

Hence, these semiconductor photonic structures will control the spontaneous emission of light in quantum optics, which are very useful in optoelectronic devices. Let us discuss about some of the semiconductor photonic structures like 1D, 2D and 3D photonic crystals and its applications.

5.11. Photonic crystal and its working principle

A photonic crystal is an optical nanostructure in which the refractive index changes periodically.

Photonic crystals are periodic dielectric structures that are designed to form the energy band structure for photons, which either allows (or) forbids the propagation of light waves of certain frequency ranges, making them ideal for light-harvesting applications.

Examples

(i) Photonic crystals usually occur in nature in the form of structural coloration and animal reflectors which are very useful in a wide range of applications
(ii) Wings of some butterflies contain photonic crystals and hence they show different colour due to their structure, which can selectively reflect certain band of wavelength.
(iii) The opal in the bracelet contains a natural periodic microstructure responsible for its iridescent colour. It is essentially a natural photonic crystal.

Principle

Let us consider a wave entering in one medium (Air) and interacting with another medium (Glass) of different refractive index as shown in figure

When the incident wave reaches the first interface (Air-Glass) a part of it is reflected from the interface and the rest is transmitted through the medium. The transmitted wave is again reflected from the second interface (Glass-Air) and part of it again transmitted through the (Glass) medium.

If both the reflected waves are in phase with each other, then we will have a strong intensity colour due t constructive interference. Conversely, if the reflected waves are out of phase with each other, then we cannot see any colour due to destructive interference.

If we consider a periodic photonic crystal with many planes, where the waves reflected are all in phase with each other, then constructive interference is formed. Suppose if the reflected waves are out of phase with each other then, destructive interference is formed.

Parameters

The following are two main factors responsible for constructive and destructive interference, etc.,

Refractive index of the medium

When the wave enters from low refractive index medium (Air) to high refractive index medium (Glass) then, the reflected wave will undergo a phase change of $\Delta\varphi = \pi$

Conversely, if the wave enters from high refractive index medium (Glass) to low refractive index mediu (Air), the reflected wave undergoes a phase change of $\Delta\varphi = 0$

Thickness of the medium or the periodicity of the crystal

For a minimum of thickness d, the reflected wave will undergo a phase change of $2d \cos \theta$ due to the total distance travelled in the medium.

If the thickness of medium is $\lambda/4$, the wave will undergo a constructive interference as shown in figure, whereas if the thickness of medium us $\lambda/2$ the wave will undergo destructive interference. Therefore, in photonic crystal (with many planes), if the periodicity is $\lambda/4$ we will get a constructive interference.

1D photonic crystal

In one dimensional photonic crystal, periodic modulation of the refractive index occurs in one direction.

Growth Technique

To produce a one-dimensional photonic crystal, thin film layers of different dielectric constant may be periodically deposited on a surface, which leads to a band gap in a particular propagation direction (such as normal to the surface)

Examples

(i) Dielectric bragg mirror
(ii) Bragg grating

Applications

(i) 1D photonic crystals are used in antireflection coatings by decreasing the reflectance and improving the quality of the lenses
(ii) 1D photonic crystals doped with bio-active metals (i.e., silver) are also used as sensing devices for bacteria contaminants.

(iii) Planar 1D photonic crystals made of polymers have been used to detect volatile organic compounds vapours in atmosphere.

2D photonic crystal

Photonic structures that are periodic in two directions and homogeneous in the third direction are called as two-dimensional photonic crystal.

Growth Technique

To produce a two-dimensional photonic crystal, holes may be drilled in a substrate that is transparent to the wavelength of radiation and the bandgap is designed to block the modes. Triangular and square lattices of holes have been successfully employed.

The Holey fiber (or) photonic crystal fiber can be made by taking cylindrical rods of glass in hexagonal lattice, and then heating and stretching them, the triangle-like airgaps between the glass rods become the holes that confine the modes.

Examples

(i) Dielectric rods in an air host
(ii) Crystals used in optical fibers.

Applications

(i) 2D photonic crystals show total internal reflection in the hollow core in order to propagate light which you cannot see in normal fiber optics
(ii) They are also used in non-linear devices and to guide exotic wavelength.

3D photonic crystal

Three dimensional photonic crystals have periodic modulation along three different axes. They reflect light that incident from any direction and behave as a highly directional reflective. Further, these crystals will control and manipulate the light flow.

Growth Technique

In a 3D photonic crystal, the dielectric constant is tailor made to vary periodically in three dimensions, giving rise to a so-callled photonic bandgap which prohibits electromagnetic propagation and substantially modifies the dispersion around a specific wavelength (frequency) region.

The woodpile structure –'rods' are repeatedly etched with beam lithography, filled in, and covered with a layer of new material. As the process repeats, the channels etched in each layer are perpendicular to the layer below, and parallel to and out of phase with the channels two layers below.

The process repeats until the structure is of the desired height. The fill-in material is then dissolved using an agent that dissolves the fill-in material but not the deposition material. It is generally hard to introduce defects into this structure.

Examples

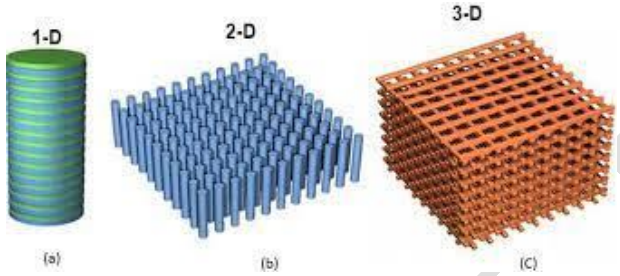
1. Three dimensional woodpile structures

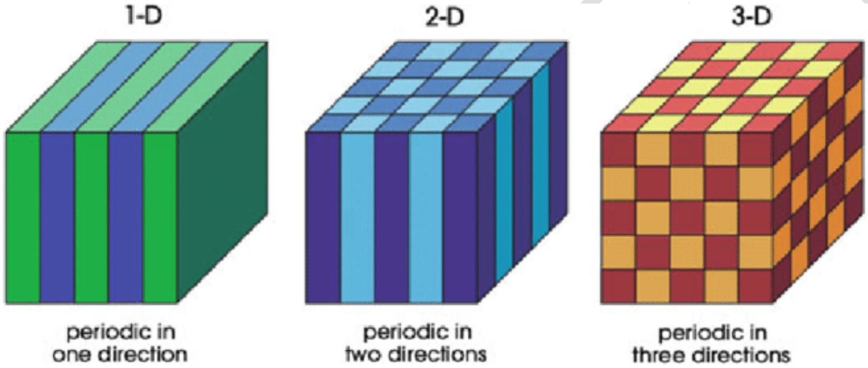
2. Sphere in a diamond lattice.

Applications

(i) A 3D optical microchip guide light through air regions in a 3D circuit such as the sunlight is trapped and absorbed as it flows in different patterns.

(ii) 3D-metallic photonic crystals are used to integrate various photonic transport phenomenon and has a wide range of applications in thermophoto voltaics.





5.12. Active and passive optoelectronic devices

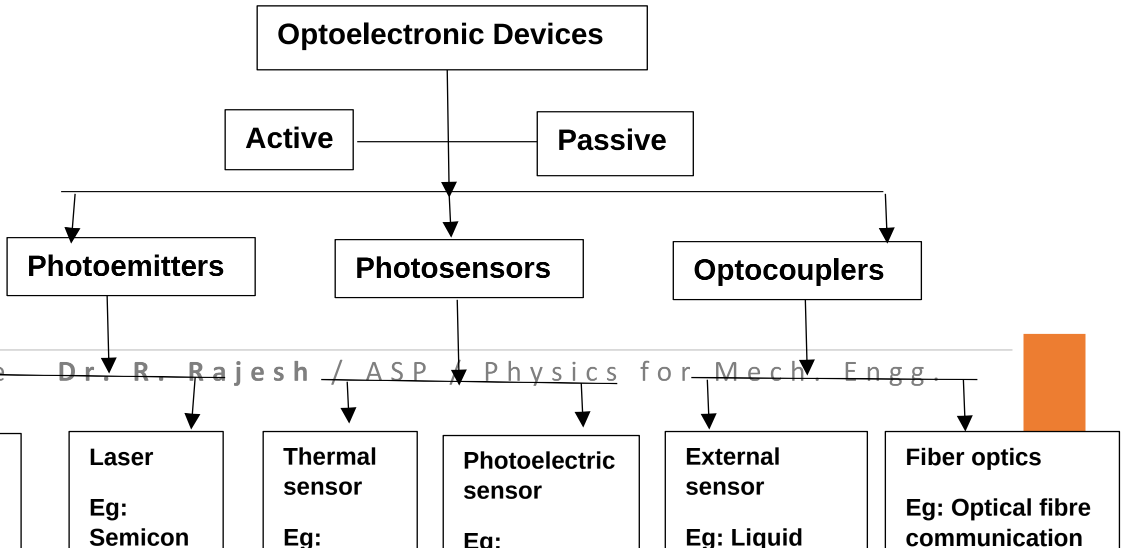
Optics and electronics together forms a new branch of study called us optoelectronics, which includes the design and manufacture of a hardware device that converts electrical energy into light energy and vice-versa through semiconductor. This device is made from solid crystalline materials which are lighter than metals and heavier than insulators.

Types of Optoelectronic devices

Optoelectronic devices are classified into different types such as

(i) Photo diode (ii) Solar cells (iii) Light emitting diode (iv) Optical fiber (v) Laser diodes (vi) Photodiode

They are further classified into various types as follows:



From the above classification we can generally categorize the optoelectronic devices into two types viz.

(i) Active optoelectronic devices
(ii) Passive optoelectronic devices

(i) Active optoelectronic devices

The devices which actively produce/detect the light are termed as active optoelectronic devices

(i) Photoemitters such as LED, LASERS etc.,
(ii) Photo-sensors such as phot-diodes, photo-multipliers etc.,

(ii) Passive optoelectronic devices

The devices which utilizes the active optoelectronic devices in order to sense/pass the information from one end to other are called passive optoelectronic devices.

Examples: (i) Fiber optic communication system (Laser) and detector (Photodiode) are active optoelectronic devices, which are used as a part of fibre optic communication system.

(iii) Laser doppler velocimeter, displacement sensor, liquid level sensor, etc.,

Applications of Optoelectronics Devices

1. LEDs could become the next generation of lighting and used anywhere like in indication lights
2. It is used in computer components, medical devices, watches, etc.,
3. In consumer electronics, these devices are used as household applications such as TV, Mobile, TAB, etc.,
4. These devices are used in automobile brake lights, seven segment displays and inactive displays
5. Photodiodes are used in many types of circuits and different applications such as cameras, medical instruments, safety equipments, industries, communication devices an industrial equipments.
6. They are also used in instrument panels, switches and fiber-optic communication.
7. Optical fibers are used in telecommunications, sensors, fiber lasers, bio-medicals and in many other industries.

5.13. Photo processes

The operation of almost all optoelectronic devices is based on the creation or annihilation of electron-hole pairs (or) so called photo process.

Pair formation essentially involves raising an electron from the valence band to the conduction band thereby leaving a hoke behind the valence band.

In principle, any energetic particle with energy equal to the band gap, when incident on a semiconductor, will make the valence electron to move to the conduction band, thereby creating electron-hole pairs. The simplest way to create electron-hole pair is to irradiate the semiconductor.

Photons with sufficient energy are absorbed, and these impart their energy to the valence band electrons and raise them to the conduction band. This process, is therefore called absorption.

The reverse process is electron-hole recombination, give up its excess energy. The recombination may be of two types viz

(i) Non-radiative transition process
(ii) Radiative transition process

Non-radiative transition process

In a non-radiative transition process, the excess energy due to recombination is usually imparted to photons and dissipated in the form of heat

Radiative transition process

In a radiative transition process, the excess energy is dissipated as photons usually having energy equal to the bandgap energy. This is called as luminescent process and hence emits light.

Examples

Some of the examples related to photo-process are as follows.

(i) Photo-luminescence is the process in which electron-hole pairs are created by injection of photons.
(ii) Cathodo-luminescence is the process in which electron-hole pairs are created by electron bombardment
(iii) Electro-luminescence is the process in which electron-hole pairs are created in an p-n junction.

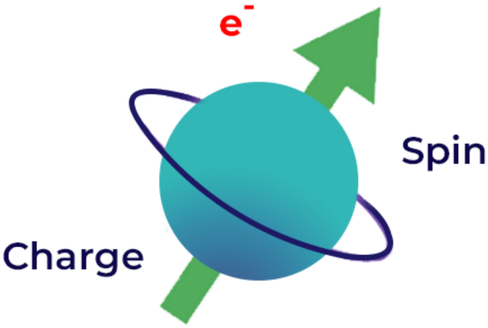
5.14. Spintronics

Spin based electronics is called Spintronics.

Spintronics is a Nano Technology which deals with spin dependent properties of an electron instead of charge dependent properties.

- Spintronics uses electron spin in addition to or in place of the electron charge.
- The rotational moments creates a small magnetic field
- Key concept is controlling the spin of electrons

Spintronics is intrinsic spin of the electron + its associated magnetic moment + its fundamental electronic charge



Principle

Spintronics is based on the spin of electrons rather than its charge. Every electron exists in one of the two states spin up and spin down with spins either positive half or negative half. In other words electrons can rotate either clock wise or anti clockwise around its own axis with constant frequency. The two possible spin state represent 0 and 1 in logical operation

Explanation

Spin is a characteristic that makes an electron a tiny magnet with north and south poles. The orientation of north-south axis depends on the particle's axis of spin. In ordinary materials, the up magnetic moments cancel the down magnetic moment so no surplus moment piles up. Ferromagnetic material like iron, cobalt and nickel is needed for designing of spin electronic devices. These have tiny regions called domains in which an excess of electrons has spins with axis pointing either up or down. The domain is randomly scattered and evenly divided between majority up and majority down.

But an externally applied magnetic field will line up the domains in the direction of the field. This results in a permanent magnet. When a pool of spin-polarized electrons is put in a magnetic field, precession occurs. The frequency and direction of rotation depends on the strength of magnetic field and characteristics of the material.

Working

All spintronic devices act according to the simple scheme:

1. The information is stored into spins as a particular spin orientation (up or down)
2. The spin being attached to mobile electrons, carry information along a wire and the information is read at a terminal
3. Spin orientation of conduction electrons survives for relatively long time (nanoseconds, compared to tens of femto seconds during which electron moment decays) which makes spintronic device useful for memory storage and magnetic sensor applications.
4. These are used for quantum computing where electron spin will represent a bit (called 'qubit') of information. When electron spins are aligned this creates a large-scale net magnetic moment.

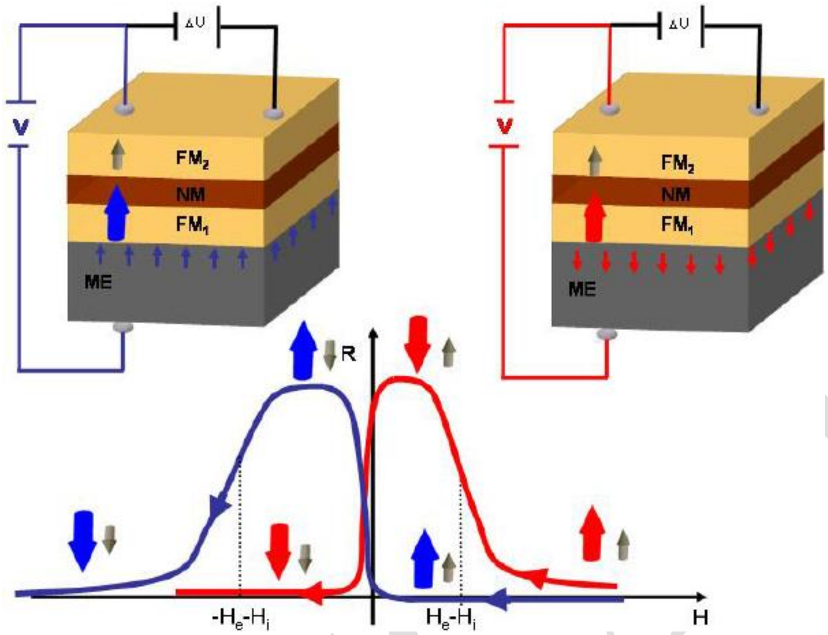
Applications of Spintronics

(1) Giant Magnetoresistance (GMR)

Definition

Giant magnetoresistance is a quantum mechanical phenomenon in which electrons travelling in ultra-thin magnetic film multilayer structures experience large scattering according to their spin states which give rise to correspondingly large changes in electrical resistance (typically greater than 10%)

The most common practical application of spin polarization involves what is called giant magnetoresistance effect. GMR discovery is accepted as birth of *Spintronics*. A giant magnetoresistance device is made of atleast two ferromagnetic layers, such as *Co*, separated by a very thin (on order of nm) non-magnetic conducting spacer layer. Such as *Cu* as shown in figure.



Working

Each ferromagnetic (FM) layer has a magnetization vector **M,** and when these vectors are parallel, an electric current can pass through the device. This is due to several reasons.

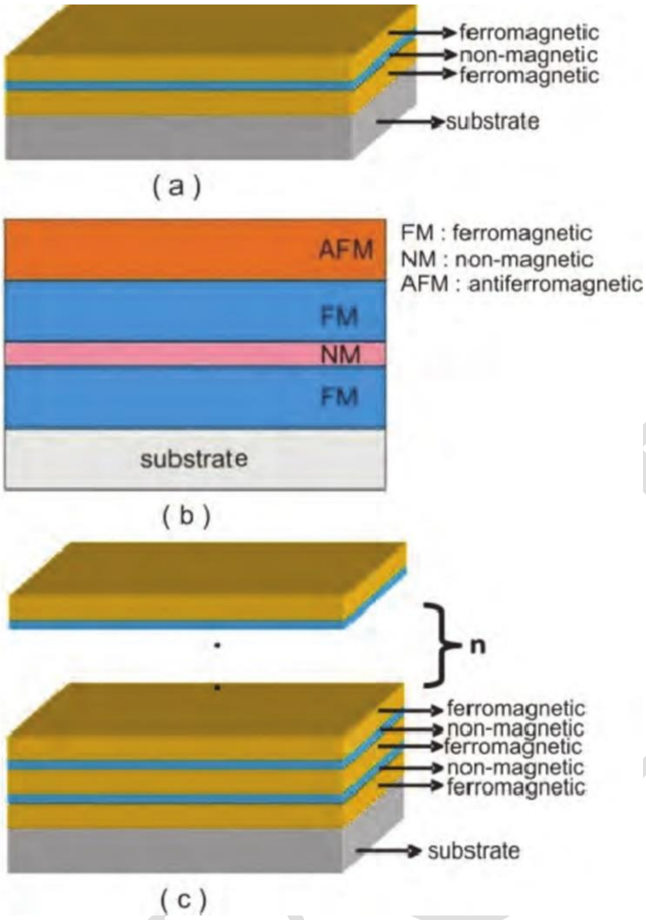
1. First, since the spacer layer is thin, spin can be diffuse across the spacer to read, the other ferromagnetic material.
2. Since that material's magnetization is parallel to the magnetization of the first layer, the density of states for those spin direction is relatively high and so there is low scattering.
3. Thus, the flow of electrons can occur, resulting in a low electrical resistance. However, if the magnetization vector of the second ferromagnetic material is antiparallel with that of the first material, the majority spin electrons and spin scattering is high
4. This is reflected by a much larger resistance to current flow, depicted in Figure.
5. This resistance to current flow is called magnetoresistance and the percentage ratio of the large and small resistance values is called GMR ratio.

(ii) Spin value

Definition

A spin value is a micro electronic device in which high and low resistance states are realized by using both the charge and spin of carriers.

Construction



A very important device based on GMR effect is called spin valve as shown in figure.

1. Here, one of the ferromagnetic layers has a fixed magnetization direction due to the presence of the antiferromagnetic layer and the other ferromagnetic layer magnetization is free to rotate upon application of magnetic field
2. An applied field, perhaps die to a magnetic bit on a hard drive, rotates the magnetization vector of the free layer and when the two magnetization vectors are aligned a minimum in device resistance is achieved.
3. When the applied magnetic field results in antiparallel magnetization vectors, resistance of the device is gradually increased.
4. Because of the strong GMR effect, spin valve can be used as extremely sensitive magnetic read heads, allowing the storage capacity of a hard disk to increase considerably.

(iii) Other applications in spintronics include

Solid state non-volatile memories

Quantum information processing and quantum computation

Spin based transistors.

5.15. Carbon Nanotubes

The hexagonal lattice of carbon is simply graphite. A single layer of graphite is called graphene. CNT consists of a graphene layer rolled up into a cylindrical shape like a single molecule where each molecule nanotube is made up of a hexagonal network of covalently bonded carbon atoms Eg: fullerene. In some cases, the hexagon are arranged in a spiral form, the layer appears like a net having a large hexagonal mesh. The carbon nanotubes are hollow cylinders of extremely thin diameter, 10,000 times smaller than a human hair.

Structures of CNT

The CNTs have many structures on the basis of their length, type of spiral and number of layers. Their electrical properties depend on their structure and they act as either a metal or a semiconductor.

Types of CNT:

(i) Arm chair
(ii) Zigzag
(iii) Chiral

- The axis of tube parallel to c-c bonds of the carbon hexagons are arm chair
- The axis of the tube is perpendicular to c-c are zigzag structure
- The axis of tube is inclined to c-c are chiral structure

Classification:

(i) Single walled CNTs
(ii) Multi walled CNTs

in Multiwalled CNTs more than one CNTs are coaxially arranged

Properties:

Electrical:

(i) CNTs are metallic (or) semi conducting depending on diameter of chirality
(ii) The energy gap of semiconducting chiral carbon nanotubes is inversely proportional to the diameter of tube.
(iii) The energy gap also varies along the tube axis and reaches a minimum value at the tube ends. This is due to the presence of localised defects at the ends due to the extra energy states.
(iv) In SWCNT conduction occurs through discrete electronic states that are coherent between the electrical contacts.

Mechanical:

(i) The strength of C – C bond is very high leading to ultimate tensile strength
(ii) Young's modules is 5 times greater than steel.
(iii) Tensile strength is 50 times higher than steel
(iv) Carbon nanotubes have ability to withstand extreme strength
(v) It can recover from severe structural distortions due to rehybridization
(vi) The strength of sp^2 C-C bond gives high hardness for CNTs

Physical

(i) It have a high strength to weight ratio. This is indeed useful for light weight applications. (SWCNT →ρ = 0.8 g/cm^3; MWCNT →ρ = 1.8 g/cm^3).

(ii) The surface are of nanotubes is of the order of 10-20 m^2/g which is higher than that of graphite.

Chemical

(1) They are highly resistant to any chemical reaction.it is difficult to oxidize them and the on set of oxidation in nanotubes is 100° C higher than that of carbon fibres.

Thermal

Nanotubes have a high thermal conductivity and the value increase with decrease in diameter

Applications:

(i) It is used in development of flat panel displays
(ii) It is used to design LEDs, FET and as switching devices
(iii) It is used to produce battery, solar and fuel cells
(iv) It is used as sensitive detector of various gases.
(v) It is used as a catalyst for chemical reactions.
(vi) It provides light weight shielding material for electromagnetic radiation
(vii) It is used in nano scale electronic devices
(viii) CNTs are used in drug delivery

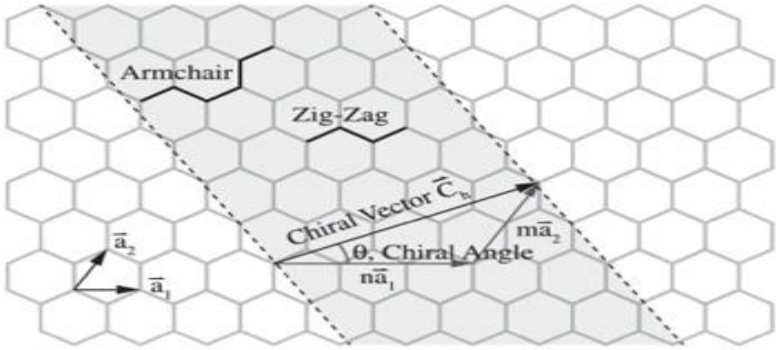


Figure 1. Schematic representation of rolling graphene layer to create CNT[15].

Part – A questions and answers

1. **Define nano materials**
   Nano phase materials are newly developed materials with grain size at the nanometre range (10^{-9}) in the order of 1 - 100 nm.
2. **What is quantum structure?**
   When a bulk material is reduced in its size, atleast one of its dimensions, in order of few nanometres, then the structure is known as quantum structure.
3. **What is quantum confinement?**
   The effect is achieved by reducing the volume of a solid so that the energy levels within it becomes discrete is called quantum confinement.
4. **Define coulomb blockade effect**
   The charging effect which blocks the injection or rejection of a single charge into or from a quantum dot is called Coulomb blockade effect.

5. **What is single electron phenomena?**
The phenomena of keeping single electron or quantum dot in isolation without tunnelling
6. **What is single electron transistor?**
A transistor made from a quantum dot that controls the current from source to drain one electron at a time is called single electron transistor.
7. **What is single electron tunnelling?**
The quantization of charge can dominate and tunnelling of single electron across leaky capacitors carriers the current. This is called single electron tunnelling.
8. **What is a carbon nano tube?**
The carbon nano tubes are the wires of pure carbon with rolled sheets of graphite like a soda straw
9. **What are the types of carbon nano tube structure?**
(1) Armchair structure (ii) Zig- zag structure (iii) Chiral structure
10. **How carbon nanotubes are classified?**
Based on number of layers, the carbon nanotubes are classified as
(i) Single walled carbon nano tubes (SWCNT) (ii) Multi walled carbon nanotubes (MWCNT). In MWCNT, more than one CNTs are coaxially arranged.
11. **What is meant by Tunnelling?**
The phenomenon in which a particle, like an electron, encounters an energy barrier in an electronic structure and suddenly penetrates is known as tunnelling.
12. **Define quantum well, quantum wire and quantum dot**
An electrically isolated region, like a thin film, where electrons are constrained in one dimension and exhibiting quantum behaviour is called quantum well
An electrically isolate region, like a nanotube or nano wire, where electrons constrained in two dimensions and exhibiting quantum behaviour is called quantum wire
An electrically isolated region, such as a particle or a portion of a bulk semiconductor, where electrons are constrained in all three directions, creating an artificial atom that exhibit quantum behaviour is called quantum dot.
13. **Explain the rules which used for the single electron phenomena?**
The energy needed to add one electron to the dot, or charging energy E_C must be significantly higher than the thermal energy of an electron $E_c = \frac{e^2}{2C_{dot}} >> K_B T$
The uncertainity of the charging energy must be less than the charging energy itself.
$$R_t >> \frac{h}{e^2}$$
14. **Write down any two applications of carbon nano tube.**
(i) It is used to make a computer switching device
(ii) It is used in battery technology in which lithium (charge carriers) can be stored inside nanotube.
(iii) It is used for storing hydrogen which is used in the development of fuel cells
(iv) It can be used to increase the tensile strength of steel
(v) Plastic composite CNT provides shielding from electromagnetic radiation.
(vi) It acts as catalysts for some chemical reactions.
15. **What will happen when the volume is reduce from that of solid to a nano material? (or) what is quantum size effect?**

If we decrease the size of the particle to nano size smaller than de Broglie wavelength, the decrease in confining size creates the energy levels discrete. The formation of discrete energy levels widens the band gap and finally the band gap energy also increases. Quantum size effect is most significant for nanoparticle semiconductor.

16. What is quantum structure?

When a bulk material is reduced in its size, atleast one of its dimensions, in the order of few nanometres, then the structure is known as quantum structure.

17. What is meant by photonic crystal? Give example

A photonic crystal is an optical nanostructure in which the refractive index changes periodically.

Examples

(i) Photonic crystals usually occur in nature in the form of structural coloration and animal reflectors which are very useful in a wide range of applications

(ii) Wings of some butterflies contain photonic crystals and hence they show different colour due to their structure, which can selectively reflect certain band of wavelength.

18. What is Bloch oscillation?

A particle in a periodic potential with an additional constant force performs oscillations and these oscillations are called Bloch oscillations.

19. What is Zener-Bloch oscillations?

The Dynamics of quantum particles shows a coherent superposition of Bloch oscillations and Zener tunneling between the sub-bands which is called Zener-Bloch oscillations.

20. Define resonant tunneling

It refers to tunneling in which the electron transmission coefficient through a structure is sharply peaked about certain energies

21. Define quantum interference.

A physical phenomenon when two or more particles that are space and time independent have an interaction, constructing or destructing their wave function is known as quantum interference

22. List any two applications of quantum interference.

(i) Superconducting quantum interference device (SQUID)
(ii) Quantum cryptography
(iii) Qunatum computing

23. Define mesoscopic.

Mesoscopic means intermediate between the microscopic and macroscopic scales

24. What is meant by 1D photonic crystal? Give examples.

In one dimensional photonic crystal, periodic modulation of the refractive index occurs in one direction.

Examples: Dielectric Bragg mirror, Bragg grating

25. What is meant by 2D photonic crystal? Give examples.

Photonic structures that are periodic in two directions and homogeneous in the third direction are called as two-dimensional photonic crystal.

Examples: Dielectric rods in an air host ; Crystals used in optical fibers.

26. What is meant by 3D photonic crystal? Give examples.

Three dimensional photonic crystals have periodic modulation along three different axes. They reflect light that incident from any direction and behave as a highly directional reflective. Further, these crystals will control and manipulate the light flow.

Examples: Three-dimensional woodpile structures, Sphere in a diamond lattice.

27. What are spintronics?

Spintronics is nanotechnology which deals with spin dependent properties of an electron instead of charge dependent properties

28. What are the applications of spintronics?

(i) Solid state ion volatile memories
(ii) Quantum information processing and quantum computation
(iii) Spin based transistors

29. Distinguish between electronic and spintronic devices?

S.NO	Electronic devices	Spintronic devices
1.	Based on properties of charge of the electron	Based on intrinsic property pin of electron
2.	Classical property	Quantum property
3	Materials: conductors and semiconductors	Materials: Ferromagnetic materials
4	Based on the number of charges and their energy	Two basic spin states: spin-up and spin-down
5.	Speed is limited and power dissipation is high	Based on direction of spin and spin coupling, high speed

30. What do you understand by the term "photo process"?

The operation of almost all optoelectronic devices is based on the creation or annihilation of electron-hole pairs are so called photo process

Part -B questions

1. **Explain quantum well, quantum wire and quantum dot**
2. **Write a short note on Bloch Zener Oscillation**
3. **Write a short note of resonant tunneling diode.**
4. **Describe the construction and working of single electron transistor**
5. **Explain the concept of spintronics and its applications**
6. **Explain the growth techniques of 1D,2D and 3D photonic crystals and mention its applications**
7. **Describe the method of formation of carbon nano tubes. Discuss its properties and its applications**