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Paper - 2

NATIONAL TESTING AGENCY (NTA)

ELECTRONIC SCIENCE

Paper 2 – Volume 1

SIERRA INNOVATIONS

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Schottky Diode:

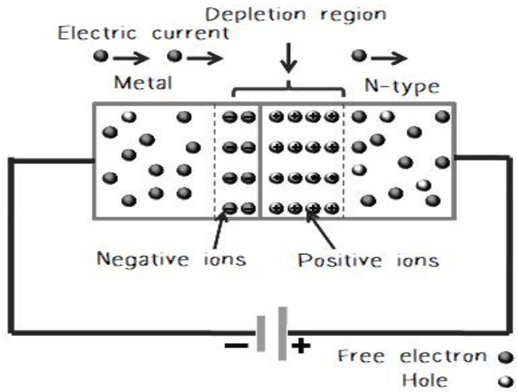
* Schottky diode is a metal-semiconductor junction diode that has less forward voltage drop than the P-N junction diode and can be used in high-speed switching applications.
* In a normal p-n junction diode, a p-type semiconductor and an n-type semiconductor are used to form the p-n junction.
* When a p-type semiconductor is joined with an n-type semiconductor, a junction is formed between the P-type and N-type semiconductor. This junction is known as P-N junction.
* In Schottky diode, metals such as aluminum or platinum replace the P-type semiconductor. The Schottky diode is named after German physicist Walter H. Schottky.
* Schottky diode is also known as Schottky barrier diode, surface barrier diode, majority carrier device, hot-electron diode, or hot carrier diode.
* Schottky diodes are widely used in radio frequency (RF) applications.
* When aluminum or platinum metal is joined with N-type semiconductor, a junction is formed between the metal and N-type semiconductor. This junction is known as a metal-semiconductor junction or M-S junction.
* A metal-semiconductor junction formed between a metal and n-type semiconductor creates a barrier or depletion layer known as a Schottky barrier.
* Schottky diode can switch on and off much faster than the p-n junction diode. Also, the Schottky diode produces less unwanted noise than p-n junction diode. These two characteristics of the Schottky diode make it very useful in high-speed switching power circuits.
* When sufficient voltage is applied to the Schottky diode, current starts flowing in the forward direction. Because of this current flow, a small voltage loss occurs across the terminals of the Schottky diode. This voltage loss is known as voltage drop.
* A silicon diode has a voltage drop of 0.6 to 0.7 volts, while a Schottky diode has a voltage drop of 0.2 to 0.3 volts. Voltage loss or voltage drop is the amount of voltage wasted to turn on a diode.
* In silicon diode, 0.6 to 0.7 volts is wasted to turn on the diode, whereas in Schottky diode, 0.2 to 0.3 volts is wasted to turn on the diode. Therefore, the Schottky diode consumes less voltage to turn on.
* The voltage needed to turn on the Schottky diode is same as that of a germanium diode. But germanium diodes are rarely used because the switching speed of germanium diodes is very low as compared to the Schottky diodes.

Symbol of Schottky Diode

Working of Schottky Diode

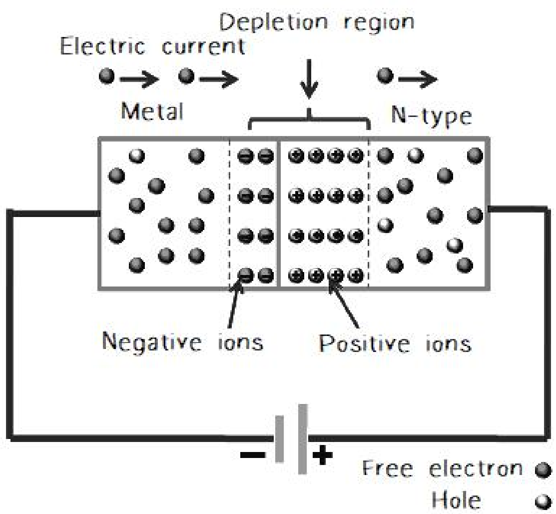
* When the metal is joined with the n-type semiconductor, the conduction band electrons (free electrons) in the n-type semiconductor will move from n-type semiconductor to metal to establish an equilibrium state.
* We know that when a neutral atom loses an electron it becomes a positive ion similarly when a neutral atom gains an extra electron it becomes a negative ion. The conduction band electrons or free electrons that are crossing the junction will provide extra electrons to the atoms in the metal. As a result, the atoms at the metal junction gains extra electrons and the atoms at the n-side junction lose electrons.
* The atoms that lose electrons at the n-side junction will become positive ions whereas the atoms that gain extra electrons at the metal junction will become negative ions. Thus, positive ions are created the n-side junction and negative ions are created at the metal junction. These positive and negative ions are nothing but the depletion region.
* Since the metal has a sea of free electrons, the width over which these electrons move into the metal is negligibly thin as compared to the width inside the n-type semiconductor. So the built-in-potential or built-in-voltage is primarily present inside the n-type semiconductor. The built-in-voltage is the barrier seen by the conduction band electrons of the n-type semiconductor when trying to move into the metal.
* To overcome this barrier, the free electrons need energy greater than the built-in-voltage. In unbiased Schottky diode, only a small number of electrons will flow from n-type semiconductor to metal. The built-in-voltage prevents further electron flow from the semiconductor conduction band into the metal. The transfer of free electrons from the n-type semiconductor into metal results in energy band bending near the contact.

Unbiased of Schottky Diode



Forward biased Schottky diode:

* If the positive terminal of the battery is connected to the metal and the negative terminal of the battery is connected to the n-type semiconductor, the Schottky diode is said to be forward biased.
* When a forward bias voltage is applied to the Schottky diode, a large number of free electrons are generated in the n-type semiconductor and metal.
* However, the free electrons in n-type semiconductor and metal cannot cross the junction unless the applied voltage is greater than 0.2 volts.

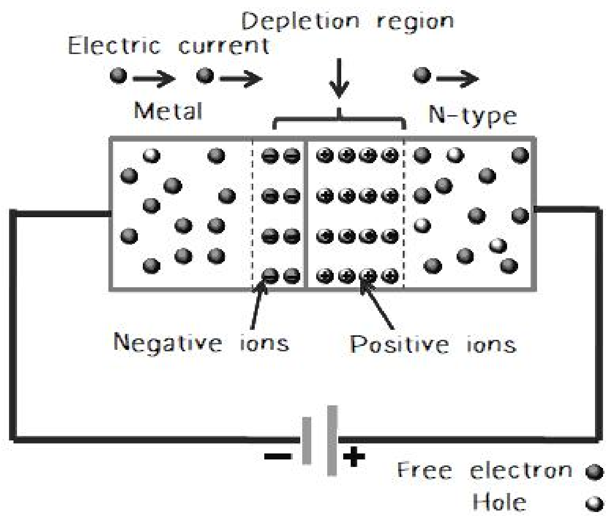


* If the applied voltage is greater than 0.2 volts, the free electrons gain enough energy and overcomes the built-in-voltage of the depletion region. As a result, electric current starts flowing through the Schottky diode.
* If the applied voltage is continuously increased, the depletion region becomes very thin and finally disappears.

Reverse bias Schottky diode:

* If the negative terminal of the battery is connected to the metal and the positive terminal of the battery is connected to the n-type semiconductor, the Schottky diode is said to be reverse biased.
* When a reverse bias voltage is applied to the Schottky diode, the depletion width increases. As a result, the electric current stops flowing. However, a small leakage current flows due to the thermally excited electrons in the metal.

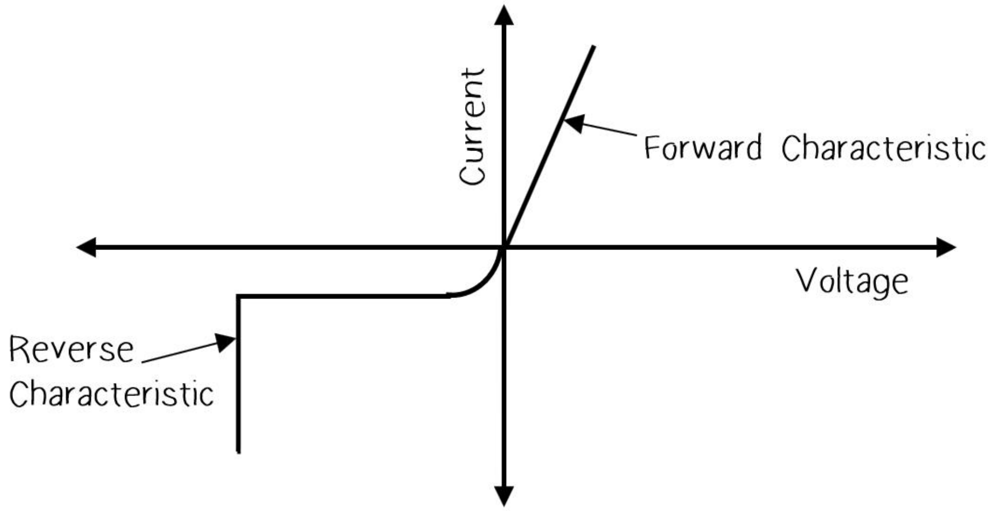
Reverse biased Schottky Diode



* If the reverse bias voltage is continuously increased, the electric current gradually increases due to the weak barrier.
* If the reverse bias voltage is largely increased, a sudden rise in electric current takes place. This sudden rise in electric current causes depletion region to break down which may permanently damage the device.

V-I characteristics of Schottky diode:

* The V-I (Voltage-Current) characteristics of Schottky diode is shown in the below figure. The vertical line in the below figure represents the current flow in the Schottky diode and the horizontal line represents the voltage applied across the Schottky diode.
* The V-I characteristics of Schottky diode is almost similar to the PN junction diode. However, the forward voltage drop of Schottky diode is very low as compared to the P-N junction diode.



Applications of Schottky diodes:

* Schottky diodes are used as general-purpose rectifiers.
* Schottky diodes are used in radio frequency (RF) applications.
* Schottky diodes are widely used in power supplies.
* Schottky diodes are used to detect signals.
* Schottky diodes are used in logic circuits.

Low-Dimensional Structures

* When one or more of the dimensions of a solid are reduced sufficiently, its physicochemical characteristics notably depart from those of the bulk solid. With reduction in size, novel electrical, mechanical, chemical, magnetic, and optical properties can be introduced. The resulting structure is then called a low-dimensional structure (or system).
* The confinement of particles, usually electrons or holes, to a low- dimensional structure leads to a dramatic change in their behavior and to the manifestation of size effects that usually fall into the category of quantum-size effects.
* The low dimensional materials exhibit new physicochemical properties not shown by the corresponding large-scale structures of the same composition.
* Nanostructures constitute a bridge between molecules and bulk materials. Suitable control of the properties and responses of nanostructures can lead to new devices and technologies.

Classification of Low-dimensional Materials

* Low-dimensional structures are usually classified according to the number of reduced dimensions they have. More precisely, the dimensionality refers to the number of degrees of freedom in the particle momentum. Accordingly, depending on the dimensionality, the following classification is made:

1. Three-dimensional (3D) structure or bulk structure: No quantization of the particle motion occurs, i.e., the particle is free.
2. Two-dimensional (2D) structure or quantum well: Quantization of the particle motion occurs in one direction, while the particle is free to move in the other two directions.
3. One-dimensional (1D) structure or quantum wire: Quantization occurs in two directions, leading to free movement along only one direction.
4. Zero-dimensional (0D) structure or quantum dot (sometimes called "quantum box"): Quantization occurs in all three directions.

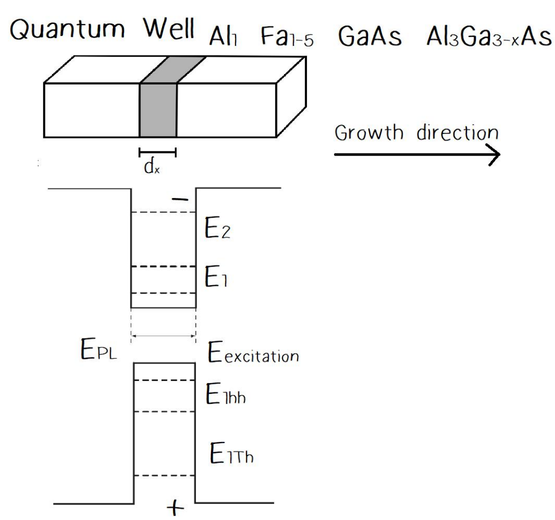
Tradition has determined that reduced-dimensionality structures are labeled by the remaining degrees of freedom in the particle motion, rather than by the number of directions with confinement.

Quantum Wells:

* To build a lower dimensional material deliberately, researchers must pay heed to quantum mechanics. Squeezing one side of a 3-D plane until it is no thicker than one electron wavelength traps electrons in a 2-D plane.
* In 2-D, the so-called density of states (the energy levels that electrons can occupy), becomes quantized. After determining what layer thickness induces what energy level, researchers can design the precise characteristics of a material.
* Electrons are not really confined to physical barriers. To trap electrons, one need only sandwich a material, typically a crystalline semiconductor, filled with low energy electrons, between two slices of semiconductor with higher energy electrons.
* Any Electrons in the lower energy slice will be confined, unable to cross the barrier between the two different semiconductors if the barrier is sufficiently thick. The interface where the two semiconductor crystals meet is known as a heterojunction (junction between two dissimilar semiconductor materials with different bandgaps). In turn heterostructures are formed from multiple heterojunctions.
* The energy of the electrons in these semiconductors is outlined by the band theory. Valence electrons determine some of the material's properties, especially

chemical ones but they do not contribute to current flow because they are fairly tightly bound to atoms. To conduct electricity electrons must be in a higher energy band known as the conduction band. In metals many of the electrons normally occupy this band enabling conduction of electric current.

* Semiconductors on the other hand can be made to conduct by introducing impurities called dopants that deposit electrons into the conduction band. Electrons can also be introduced by illuminating the semiconductor, which promotes electrons to the conduction band from the valence band. Alternatively, electrons can be injected into the semiconductor by applying a
* voltage to electrical contacts at the surface of the crystal. This method proves most useful as we shall see later on. The energy needed to propel an electron from valence band to conduction band is the bandgap energy (VB ->CB Energy difference) typically measured in electron-volts.
* Scientists first began attempting to exploit these principles of quantum wells in the late 1960's.
  "Confine an electron to 2-D and it changes everything"
* It was the invention of MBE at Bell Labs by Alfred Y Cho and John Arthur in the late 1960's that finally moved quantum research from theoretical to the practical realm. At the heart of the MBE (molecular beam epitaxy) machine is an ultrahigh vacuum chamber which allows layers of atoms to be deposited as thin as 0.2nm on a heated semiconductor substrate Their aim was to create a quantum well, which is made by depositing a very thin layer of lower bandgap material between layers of higher bandgap material as described earlier.
* Figure below shows a schematic structure of a GaAs/Al x Ga 1-x As quantum well. The GaAs has smaller band gap then Al x Ga 1-x As and forms not only a quantum well for the conduction band electrons, it also forms a quantum well for the valence band holes, so that the carriers are confined in this layer. The diagram below this displays the energy level for electrons and holes in the quantum well.

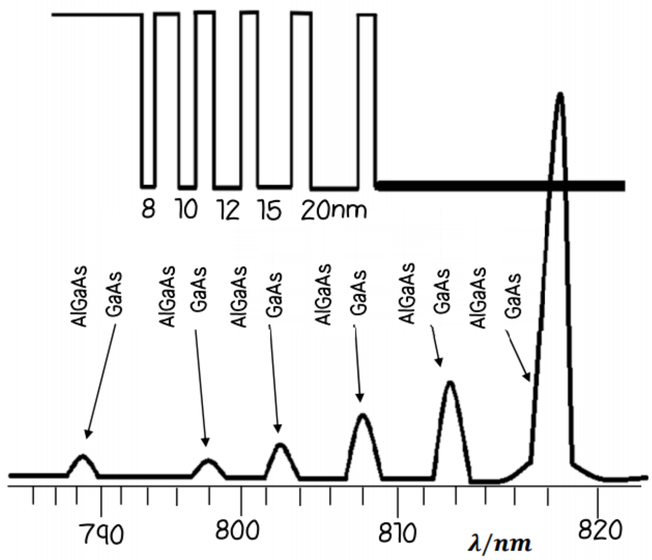


* The idea was to trap electrons in the lower bandgap semiconductor, gallium arsenide (GaAs) for example, which has a bandgap energy of 1.5 eV. The electrons would be unable to cross the heterojunction barrier into the layers of Aluminum Gallium Arsenide (Al GaAs) which has a bandgap of 3.1eV. If the GaAs, the actual quantum well was just tens of atomic layers ~30nm, quantum effects would then be observed, i.e., electron has a substantial probability of passing through, tunneling, into the high bandgap material.
* The first real quantum device to exploit this phenomenon was the resonant tunneling diode The trick is to apply just the right voltage to the contact layers so that the energy of the electrons entering the well matches the energy of the well itself.
* In this resonant tunneling phenomenon, many of the entering electrons will tunnel through the barriers giving rise to a high current.
* Electrons may be caused to tunnel from one QW to another in a complex device, which has many QW's (superlattice). Bell Labs Quantum Cascade laser is such a device.
* Alternatively, the tunneling itself can be the end result, if the device is a diode or transistor, where the point is to have current flow.

How does this transfer to laser technology?

* To achieve lasing action, two conditions have to be met. First, the higher energy level, say E2, must have a larger number of electrons than the lower, which is E1. This condition is known as population inversion, and ensures that the light is amplified rather than attenuated.
* Maintaining a population inversion demands that electrons be cleared away from E1, which requires yet another level say E0, to which electrons can be deposited after they have served their purpose.
* In a quantum well laser, such as the quantum cascade (QC) laser, these three energy levels are engineered into a series of active regions, each consisting of three quantum wells. This does not mean that there is a one-to-one correspondence between energy levels and the wells. The energy levels exist across all three wells.
* In operation, electrons pumped to a high energy level tunnel into and are captured by the first two wells, i.e. energy level E2. Electrons then drop from E2 to E1, emitting a photon in the process. The wavelength of the photon is in fact determined by the energy difference between E2 and E1. This fact was discovered by the Danish Physicist Niels Bohr in 1913.

* The electrons then tunnel into the third quantum well where they drop to E0 before tunneling out of the laser and exiting the three well structure. The ingenious feature of the QC laser for example, is that it generates photons not from one three well structures but from 25 of them!
* Each three well complex are the active regions, where each successive active region is at a lower energy than the one before it, so that the active regions are like steps in a staircase. In between the active regions are injector/ relaxation regions, which collect the electrons coming out at one active region, and pass them on to the next, lower energy one.
* All the active and injector/ relaxation regions are engineered to allow electrons to move efficiently from the top of the staircase to the bottom.
* The end result is that a single electron passing through the laser emits not one but 25 photons. The structure discussed above is shown below, where also the quantized energies depend upon the thickness of the quantum well.



Quantum Wires:

* While some hail the Quantum Cascade laser as the latest manifestation of the utility of quantum wells, others wonder when the more 'exotic quantum structures', wires and dots, are going to catch up.
* Physics suggests that if the 2-D realm is promising then the one (wire) or zero (dot) dimensions is even more promising.
* Electrons scatter less and attain higher mobilities when travelling through a quantum wire. What this means is that lower dimensional lasers could be powered by far less current. Such lasers would also have lower threshold current, which means that lower populations of free electrons and holes would be necessary to get them to emit laser radiation. This characteristic in turn would mean that the lasers could be modulated at higher frequencies and thus transmit information at a higher rate!

* Currently the leading technique for creating symmetrical quantum wires is the "cleaved-edge over growth method", first demonstrated at Bell Labs by researcher Loren Pfeiffer in 1991. The method creates two quantum wells that intersect perpendicularly in a quantum wire. i.e., to well up four sides of a low bandgap material with higher band gap barriers thin enough to let electrons tunnel through on command In 1993, Pfeiffer and his colleagues demonstrated that a quantum wire laser emits photons that arise from the recombination of excitons, which are bound electron-hole pairs. In semiconductor lasers or even QW lasers photons are emitted from the mutual annihilation of free electrons and holes rather than the recombination of free electrons and holes already paired together in excitons. This leads to a major difference in the way the lasers radiate!
* As the intensity of an ordinary semiconductor laser is increased, the energy of the emitted photon is reduced which causes the laser's emission frequency to shift downwards, which in turn could inhibit the performance if the laser is being used for spectroscopy or to transmit information.
* In the confinement at a wire or dot, however, the excitons do not fragment, so the frequency remains stable when input current and thus output power is increased.

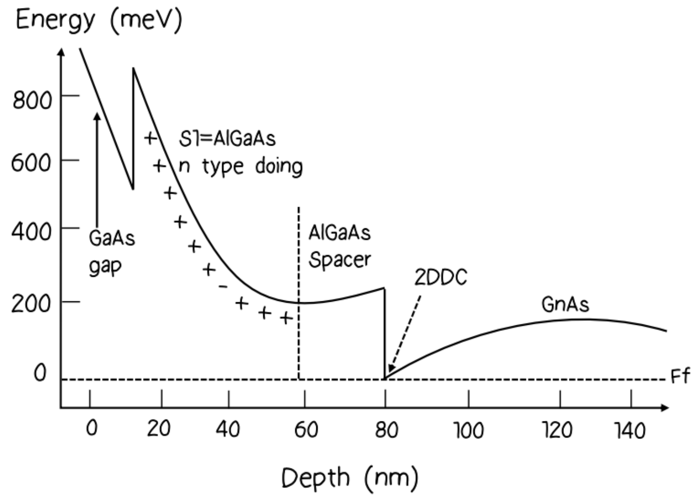
Quantum Dots:

* The quantum dot, the ultimate in confinement, is still the subject of intensive research particularly in University Laboratories in North America, Japan, and Europe. Quantum Dots have been called artificial atoms, in spite of the fact that they generally consist of thousands of hundreds of thousands of atoms. Contained in a dot or box, electrons should occupy discrete energy levels. It should be possible therefore to dial up precise energy levels by adjusting the construction of the quantum box and also by varying the voltage.
* The most intriguing phenomenon related to the creation of dots is the self-assembly techniques. Researchers had noticed that often times, clumps would form spontaneously on the surface of extraordinary thin layers of certain materials grown with Molecular Beam Epitaxy. Suppose a single monolayer of Indium Arsenide perfectly and evenly covers a substrate of Gallium Arsenide.
* When enough Indium atoms have been laid down so that the average coverage is between 1.6 and 1.8 monolayers the clumping begins. By the time enough material has been laid down for three even monolayers, what has formed instead is a culmination of an enormous number of clumps, each five or six monolayers high separated by much shallower regions. Scientists soon realized that these clumps could function as quantum dots.
* This achievement was an important step toward the integration of many dots into a useful device.

* Although electron devices such as memories, in which each dot is a memory element are distant, optical devices such as lasers have already been demonstrated by several groups including National Research Council of Canada and Fujitsu in Japan, in which radiation in the far infrared comes from the dots and not from the underlying substrate which is usually a quantum well.
* James S. Harries, professor of Electrical Engineering at Stanford adds that "the dot arrays have impressive characteristics but are not yet in the same league with the best Quantum Well Lasers".

High electron mobility transistors (HEMT)

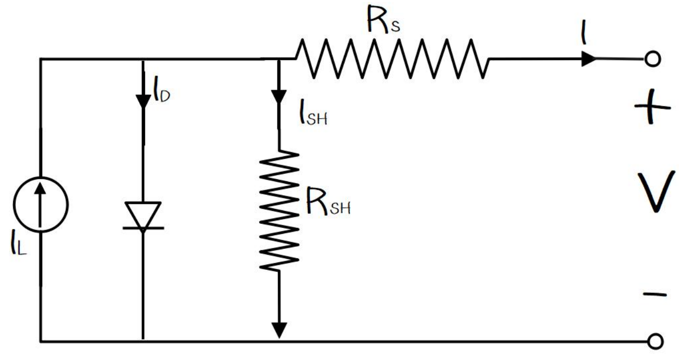
* If a vertical electric field is superimposed on the band structure, then a narrow quantum well can be formed at an AlGaAs/GaAs interface.
* Electrons in this well populate the lowest sub-band and form a two-dimensional electron gas (2DEG).
* These electrons can come from donors in a doped layer which is separated by a spacer layer. This is called modulation doping and gives rise to high mobilities, as the charged impurities are well removed from the carriers.
* Such structures are used in high electron mobility transistors, more commonly known as HEMTs.
* Mobilities of 106-107 cm2/Vs can be routinely achieved, compared to 6000 cm2/Vs in Si-MOSFETs, which gives the possibility of much faster devices.
* A more complicated band structure occurs in the simple heterostructure, see Figure where it is necessary to understand the band bending which gives rise to a triangular confinement well.
* To increase the purity of the heterojunction it is modulation doped - this means that the n-type dopant (in this case Si) is introduced into the wide band gap AlGaAs at some distance from the 2DEG formed at the heterojunction interface. This means that the positive ionized Si atoms, upon donating their electrons will be situated further from the 2DEG, leaving the narrow band gap GaAs free from intentional doping.



* Conduction band profile of a modulation doped GaAs-lxGa1–xAs heterostructure. A triangular potential well is formed in the undoped GaAs at the interface with the n-doped AlGaAs. The spatial extension of the electron wavefunction in the growth direction is typically 100 °A.

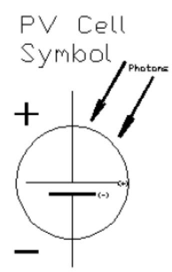
Solar Cell Basics

* Commonly made of silicon, solar cells, also known as photovoltaic cells, can convert sunlight to electricity with 15 to 30% energy efficiency. Panels of solar cells are often installed on rooftops or open fields to generate electricity.
* A solar cell's structure is identical to a PN junction diode but with finger-shaped or transparent electrodes so that light can strike the semiconductor.
* Silicon is the most widely used semiconductor material for constructing the photovoltaic cell.
* The silicon atom has four valence electrons. In a solid crystal, each silicon atom shares each of its four valence electrons with another nearest silicon atom hence creating covalent bonds between them. In this way, silicon crystal gets a tetrahedral lattice structure.
* While light ray strikes on any materials some portion of the light is reflected, some portion is transmitted through the materials and rest is absorbed by the materials.



* The same thing happens when light falls on a silicon crystal. If the intensity of incident light is high enough, sufficient numbers of photons are absorbed by the crystal and these photons, in turn, excite some of the electrons of covalent bonds.
* These excited electrons then get sufficient energy to migrate from valence band to conduction band. As the energy level of these electrons is in the conduction band, they leave from the covalent bond leaving a hole in the bond behind each removed electron. These are called free electrons move randomly inside the crystal structure of the silicon.
* These free electrons and holes have a vital role in creating electricity in photovoltaic cell. These electrons and holes are hence called light-generated electrons and holes respectively. This light generated electrons and holes cannot produce electricity in the silicon crystal alone. There should be some additional mechanism to do that.

Symbol of PV Cell



* When a pentavalent impurity such as phosphorus is added to silicon, the four valence electrons of each pentavalent phosphorous atom are shared through covalent bonds with four neighbor silicon atoms, and fifth valence electron does not get any chance to create a covalent bond.
* This fifth electron then relatively loosely bounded with its parent atom. Even at room temperature, the thermal energy available in the crystal is large enough to disassociate these relatively loose fifth electrons from their parent phosphorus atom.
* While this fifth relatively loose electron is disassociated from parent phosphorus atom, the phosphorous atom immobile positive ions. The said disassociated electron becomes free but does not have any incomplete covalent bond or hole in the crystal to be re-associated. These free electrons come from pentavalent impurity are always ready to conduct current in the semiconductor.
* Although there are numbers of free electrons, still the substance is electrically neutral as the number of positive phosphorous ions locked inside the crystal

structure is exactly equal to the number of the free electrons come out from them. The process of inserting impurities in the semiconductor is known as doping,

* And the impurities are doped are known as dopants. The pentavalent dopants which donate their fifth free electron to the semiconductor crystal are known as donors. The semiconductors doped by donor impurities are known as n-type or negative type semiconductor as there are plenty of free electrons which are negatively charged by nature.
* When instead pentavalent phosphorous atoms, trivalent impurity atoms like boron are added to a semiconductor crystal opposite type of semiconductor will be created. In this case, some silicon atoms in the crystal lattice will be replaced by boron atoms, in other words, the boron atoms will occupy the positions of replaced silicon atoms in the lattice structure. Three valance electrons of boron atom will pair with valance electron of three neighbor silicon atoms to create three complete covalent bonds.
* For this configuration, there will be a silicon atom for each boron atom, fourth valence electron of which will not find any neighbor valance electrons to complete its fourth covalent bond.
* Hence this fourth valence electron of these silicon atoms remains unpaired and behaves as incomplete bond. So, there will be lack of one electron in the incomplete bond, and hence an incomplete bond always attracts electron to fulfil this lack. As such, there is a vacancy for the electron to sit.
* This vacancy is conceptually called positive hole. In a trivalent impurity doped semiconductor, a significant number of covalent bonds are continually broken to complete other incomplete covalent bonds.
* When one bond is broken one hole is created in it. When one bond is completed, the hole in it disappears. In this way, one hole appears to disappear another neighbor hole. As such holes are having relative motion inside the semiconductor crystal.
* In the view of that, it can be said holes also can move freely as free electrons inside semiconductor crystal. As each of the holes can accept an electron, the trivalent impurities are known as acceptor dopants and the semiconductors doped with acceptor dopants are known as p-type or positive type semiconductor.
* In n-type semiconductor mainly the free electrons carry negative charge and in p-type semiconductor mainly the holes in turn carry positive charge therefore free electrons in n-type semiconductor and free holes in p-type semiconductor are called majority carrier in n-type semiconductor and p-type semiconductor respectively.
* There is always a potential barrier between n-type and p-type material. This potential barrier is essential for working of a photovoltaic or solar cell.

* While n-type semiconductor and p-type semiconductor contact each other, the free electrons near to the contact surface of n-type semiconductor get plenty of adjacent holes of p-type material. Hence free electrons in n-type semiconductor near to its contact surface jump to the adjacent holes of p-type material to recombine.
* Not only free electrons, but valence electrons of n-type material near the contact surface also come out from the covalent bond and recombine with more nearby holes in the p-type semiconductor.
* As the covalent bonds are broken, there will be a number of holes created in the n-type material near the contact surface. Hence, near contact zone, the holes in the p-type materials disappear due to recombination on the other hand holes appear in the n-type material near same contact zone.
* This is as such equivalent to the migration of holes from p-type to the n-type semiconductor. So as soon as one n-type semiconductor and one p-type semiconductor come into contact the electrons from n-type will transfer to p-type and holes from p-type will transfer to n-type. The process is very fast but does not continue forever.
* After some instant, there will be a layer of negative charge (excess electrons) in the p-type semiconductor adjacent to the contact along the contact surface. Similarly, there will be a layer of positive charge (positive ions) in the n-type semiconductor adjacent to contact along the contact surface.
* The thickness of these negative and positive charge layer increases up to a certain extent, but after that, no more electrons will migrate from n-type semiconductor to p-type semiconductor. This is because, while any electron of n-type semiconductor tries to migrate over p-type semiconductor it faces a sufficiently thick layer of positive ions in n-type semiconductor itself where it will drop without crossing it.
* Similarly, holes will no longer migrate to n-type semiconductor from p-type. The holes when trying to cross the negative layer in p-type semiconductor these will recombine with electrons and no more movement toward n-type region.
* In other words, negative charge layer in the p-type side and positive charge layer in n-type side together form a barrier which opposes migration of charge carriers from its one side to other. Similarly, holes in the p-type region are held back from entering the n-type region. Due to positive and negative charged layer, there will be an electric field across the region and this region is called depletion layer.
* Now let us come to the silicon crystal. When light ray strikes on the crystal, some portion of the light is absorbed by the crystal, and consequently, some of the valence electrons are excited and come out from the covalent bond resulting free electron-hole pairs.

* If light strikes on n-type semiconductor the electrons from such light-generated electron-hole pairs are unable to migrate to the p-region since they are not able to cross the potential barrier due to the repulsion of an electric field across depletion layer.
* At the same time, the light-generated holes cross the depletion region due to the attraction of electric field of depletion layer where they recombine with electrons, and then the lack of electrons here is compensated by valence electrons of p-region, and this makes as many numbers of holes in the p-region. As such light generated holes are shifted to the p-region where they are trapped because once they come to the p-region cannot be able to come back to n-type region due to the repulsion of potential barrier.
* As the negative charge (light generated electrons) is trapped in one side and positive charge (light generated holes) is trapped in opposite side of a cell, there will be a potential difference between these two sides of the cell. This potential difference is typically 0.5 V. This is how a photovoltaic cells or solar cells produce potential difference.
* We have already seen that a voltage, without light, can produce a diode current

$$\boldsymbol{I = I_0\left(e^{\frac{qV}{kT}} - 1\right)}$$

* Light is also a driving force that can produce a diode current without voltage, i.e., with the two diode terminals short-circuited so that $V = 0$.
* Figure shows that when light shines on the PN junction, the minority carriers that are generated by light within a diffusion length (more or less) from the junction can diffuse to the junction, be swept across the junction by the built-in field, and cause a current to flow out of the P terminal through the external short circuit and back into the N-terminal. This current is called the short-circuit current, Isc. Isc is proportional to the light intensity and to the cell area, of course.
* The total diode (solar cell) current is the sum of the current generated by the voltage and that generated by light.

$$I = I_0\left(e^{\frac{qV}{kT}} - 1\right) - I_{sc}$$

* The negative sign indicates that the direction of Isc (see Fig. a) is opposite to that of the voltage-generated current (see Fig.).
* The solar cell *IV* curve is shown in Fig. b Solar cell operates in the fourth quadrant of the *IV* plot. Since *I* and *V* have opposite signs, solar cell *generates* power. Each silicon solar cell produces about 0.6 V. Many cells are connected in series to obtain the desired voltage.