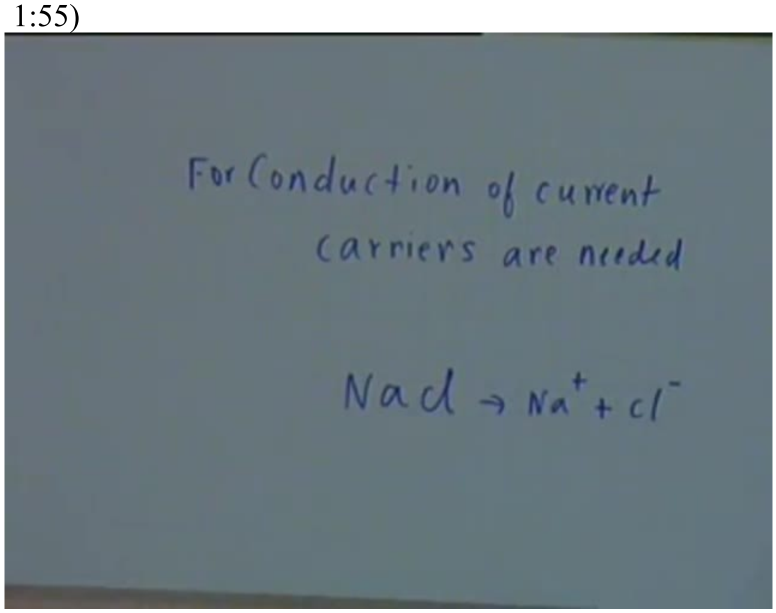
Introduction To Electronic Circuits
Professor S.C. Dutta Roy
Department of Electrical Engineering
Indian Institute of Technology Delhi
Module No 01
Lecture 25: Semiconductor Physics

This is the 25th lecture and we are starting electronics today. We start with a bit of physics which is enough to understand the operation of electronic devices. Should you be interested in more physics, Semiconductor physics, you should take one of the electives in physics or the course on physical electronics offered by the electrical engineering department. We shall do only that much that is needed to understand the operation of a diode and a transistor.

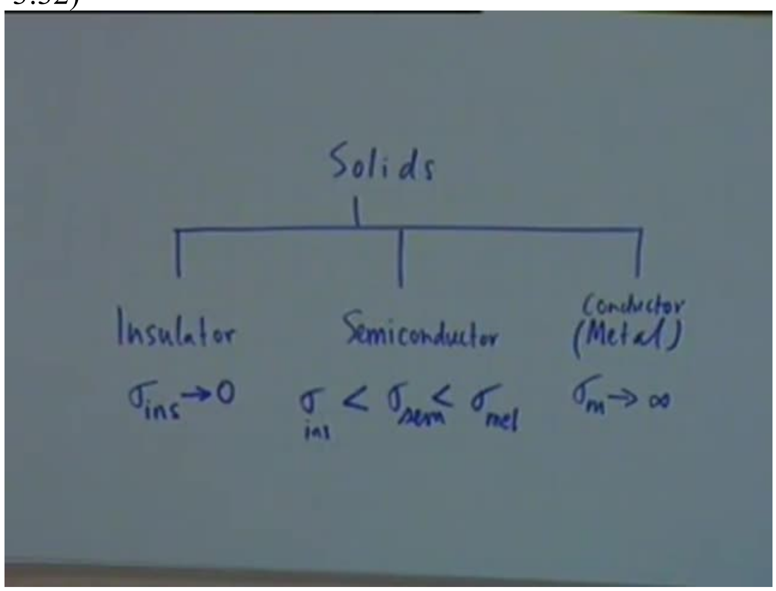
(Refer Slide Time: 1:55)



The 1st uhh concept that has to be understood or is already known, the conduction of current, current in any medium, whether it be gas or liquid or solid, conduction of current has to be done by carriers. For conduction of current, you need to charge carriers. For example, in gases it is the positive ions and electrons which carry current. In liquids, in electrolytes for example, the molecules break up into 2 parts, positive and negative ions. For example, a dilute sodium chloride solution breaks up into sodium and chlorine. One is positively charged and the other is negatively charged.

And under the action of an electric field which happens if you put 2 electrodes, Uhh an anode and a cathode, then the negative charges are attracted towards the positive electrode and the positive charges are attracted towards the other electrode. And this is how current conduction happens. For current conduction, there must be charges and the charges cannot go from one place to another, they must be carried by a carrier, charge carriers are important.

(Refer Slide Time: 3:32)



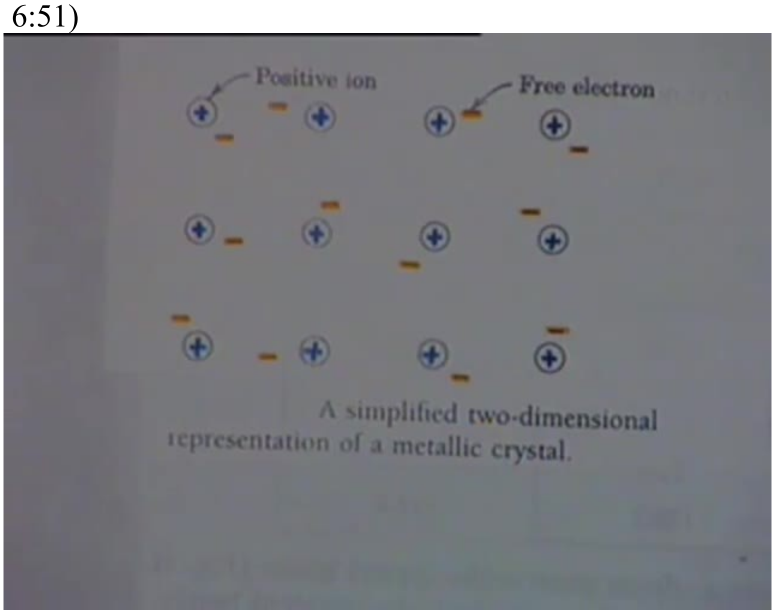
In solids, depending on the kind of solids, there can be various types of charge carriers. And solids according to their capability of conducting current are basically or broadly divided into 3 classes. The 1st is an insulator. An insulator has no charge carrier and therefore, no conduction of current occurs through an insulator. For example, the dielectric that you put between 2 plates of a parallel plate capacitor, ideally is required to be an insulator all right? It is not in practice but that is a different story.

An insulator, the conductivity of an insulator, sigma ins tends to 0. It does not conduct electric current. It tends to 0. For an ideal one, it is exactly equal to 0. On the other end of the spectrum, we have the metals. Metals are very good conductors, that is sigma metal is very very large. It tends to infinity. They are almost perfect conductors. Well and if current has to be conducted very easily in a metal, obviously there must be a very large number of charge carriers. And how this happens, we shall look into it. In between insulators and very good conductors, I have used (())(4:59) metal, I should have used a conductor, a very good inductor.

As for example, metal. In between an insulator and a conductor, there exists an an a kite kind of material called a semiconductor that is not as poor as an insulator but not as good as a conductor or a metal. In other words, the conductivity of a Semiconductor lies between that of an insulator and a metal. The Semiconductor normally, is a poor conductor of electricity, normally is a poor conductor of electricity and at absolute 0 temperature, a Semiconductor is an insulator. At absolute 0 of temperature, there are no charge carriers and it behaves like an insulator but at elevated temperatures, the Semiconductor conducts not as purely as an insulator, not as good as a conductor but in between.

Now to understand the theory of Semiconductor, let us have a quick look a how metal conducts electricity. In a metal as you know, in any solid for that matter the the structure is such, the atoms are closely packed and there is a regular arrangement of the atoms which goes by the name of a crystal arrangement or arrangement of atoms in a periodic fashion. It is also known as a lattice arrangement alright?

(Refer Slide Time: 6:51)



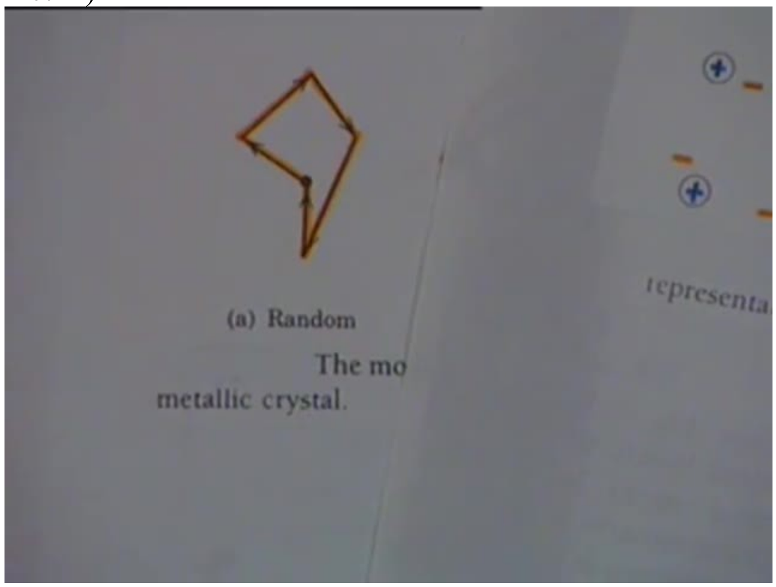
Now in a metal, a typical metal, is this visible on the screen? In a typical metal, the outermost electrons are usually very loosely bound to the nucleus and therefore a small amount of energy, maybe a raise in temperature is enough to dislodge some of these outermost shell electrons and they they wander around freely and therefore in a metal a two-dimensional, in a two-dimensional representation, these are the atoms, the nuclei along with their innermost inner shells of electrons rotating around them. And when the electron leaves a particular atom, it becomes positively charged.

So this is a positive ion and there are free electrons. And these electrons are so free that the situation can be compared to a gas and the electrons, the free electrons are said to constitute what is known as an electron gas. At absolute 0 temperature however, at absolute 0 temperature these electrons can move so freely that the conductivity tends to infinity or the resistance to movement of these charge carriers is absolutely 0 and therefore at absolute 0, a good conductor shows 0 resistance.

When the temperature increases when the temperature increases, these nuclei or the ions they gain temperature, they gain energy and this energy is kinetic energy proportional to KT. K is the Boltzmann constant and T is the absolute temperature and that also explains that the energy, the kinetic energy is 0 at T equal to 0. Alright? So these atoms or these ions gain kinetic energy due to an elevated temperature and they vibrate around their neutral position. They vibrate and this energy, the kinetic energy therefore exposes itself or demonstrates itself in the form of vibrational energy.

And as they as they vibrate around their neutral positions, electrons clash with this. Electrons collide with the vibrating ions. As a result, the electron loses energy to the vibrating nucleus and what happens normal what happens normally is that these vibrations are random. The vibrations of the, there is a certain amount of uncertainty, certain amount of uncertainty in the vibrating pattern of the nuclei and this uncertainty is reflected in the form of collisions with free electrons. The collisions can be elastic as well as an elastic. However, we shall consider only inelastic collisions in which the electron if it had some energy, it loses completely. Alright? So the situation is like this.

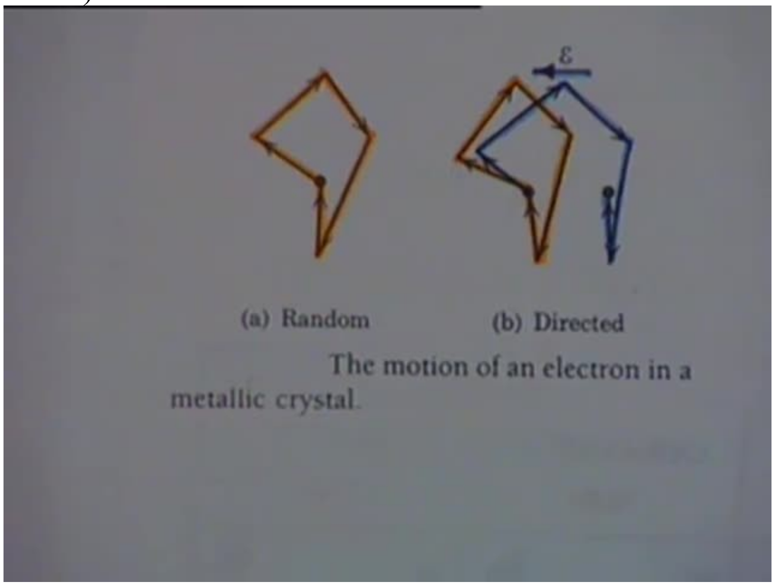
(Refer Slide Time: 10:21)



In absence of an electric field, you forget about this part, in absence of an electric field, that is normally if this is the position of the electron, well it moves a certain distance before it encounters a vibrating ions all right? It encounters a vibrating ion here and it loses its energy, it loses its energy, gets deflected in some other direction alright, then after travelling a certain distance, this distance is called the mean free path, that is before a the distance between 2 collisions, the distance that an electron can move freely in free space, which is not a constant. It is not a constant.

It varies but you can define what is called a mean free path, an average free path. So it travels this distance. Then again occurs, again there occurs an inelastic collision, the electron is diverted and this motion, this zigzag motion is random so that there is no net motion in any direction. If you observed a particular electron under the microscope for a long enough time, the there is every probability that the electron shall come back to its original position. Alright?

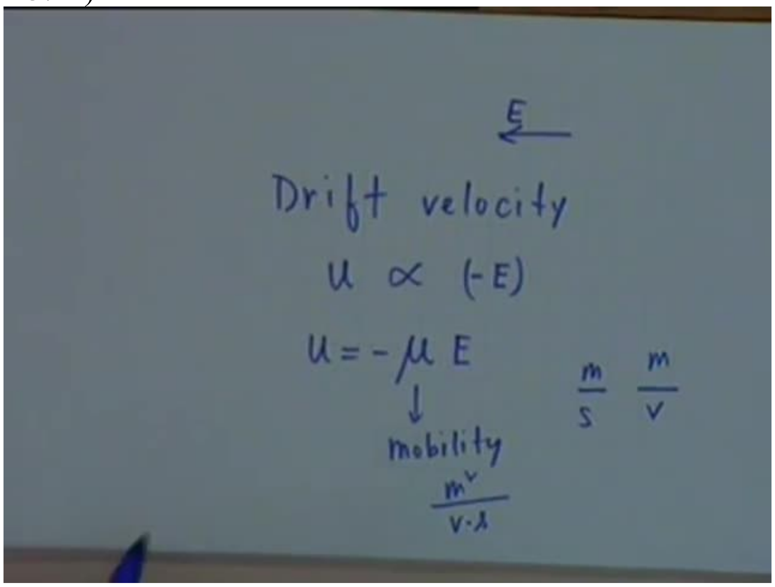
(Refer Slide Time: 11:37)



On the other hand, if you have an electric field, then an electron, let us say this electron in an electric field, it is accelerated by the electric field. The force acting upon the electron is equal to the electric field multiplied by the charge. Alright? And you also know that the electron being negatively charged, it moves opposite to the direction of the electric field. But then, there is thermal energy and therefore it does not just move, it cannot move because the space is not free. There are ions which are vibrating and therefore it does not have to suffer inelastic collisions. Without the electric field, the path is shown by this yellow line.

With electric field, there is now bias. There is a small velocity, there is a small velocity attributed or contributed by the electric field. Actually the electric electric field contributes to an acceleration in the direction opposite to that of the electric field. Electric field is in this direction. The electron instead of going if it was free motion, it would go like this but it follows the blue path. There is a slight tendency to go opposite to the direction of the electric field so that after some time, after 10 number of inelastic collisions, the position of the electron it it does not come back to its original position. It shifts a distance in the direction opposite to that of the electric field. Is that okay? Now this being a restricted motion, the if you observe this for a sufficient interval than one concludes that what the electric field does to impart a certain velocity called the drift velocity in the direction opposite to that of the electric field.

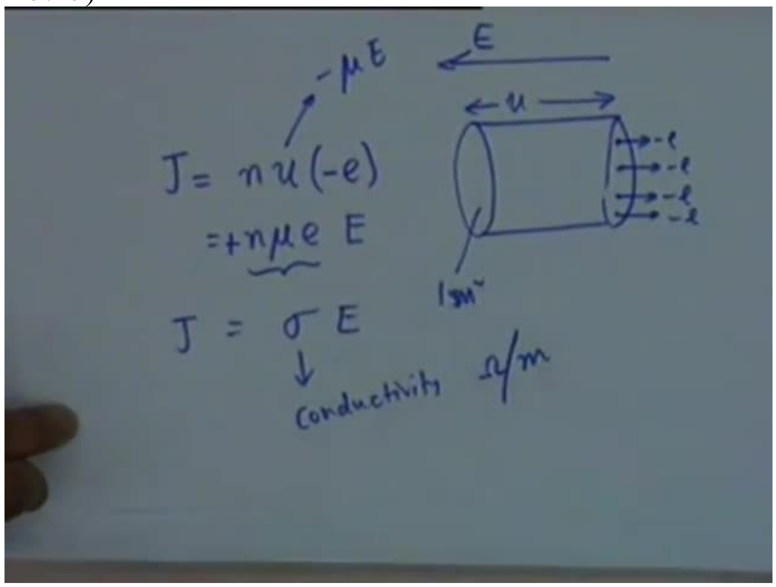
(Refer Slide Time: 13:44)



That is the electron drifts in the direction opposite to that of the electric field and what it achieves is a drift velocity u in the direction opposite to that of the electric field. Why does not it get an acceleration? It does. In between collisions, it does get accelerated. So it accumulates kinetic energy but it loses all its energy after an inelastic collision alright? It loses to the vibrating ion. And this drift velocity in the direction opposite to that of the electric field is obviously proportional to the electric field.

u shall be proportional to the electric field and we show this as minus E because the direction of motion is opposite to that of the electric field. A proportionality constant is denoted by the Greek letter mew, minus mew E where mew is obviously a drift velocity per unit electric field. Mew is termed as the mobility mobility of the electron. This term is extremely important for semiconductor physics. It is called mobility and you can easily see that its unit shall be metres per seconds is the unit of u and the unit of E volts per metre and therefore mew should be metre square divided by volt second. Is that correct? The unit of mobility is metre square per volt second. This is an extremely important term. It is physically it is defined as the drift velocity of a charge carrier under the under the influence of a unit electric field. Unit electric field means 1 volt per metre alright?

(Refer Slide Time: 15:45)



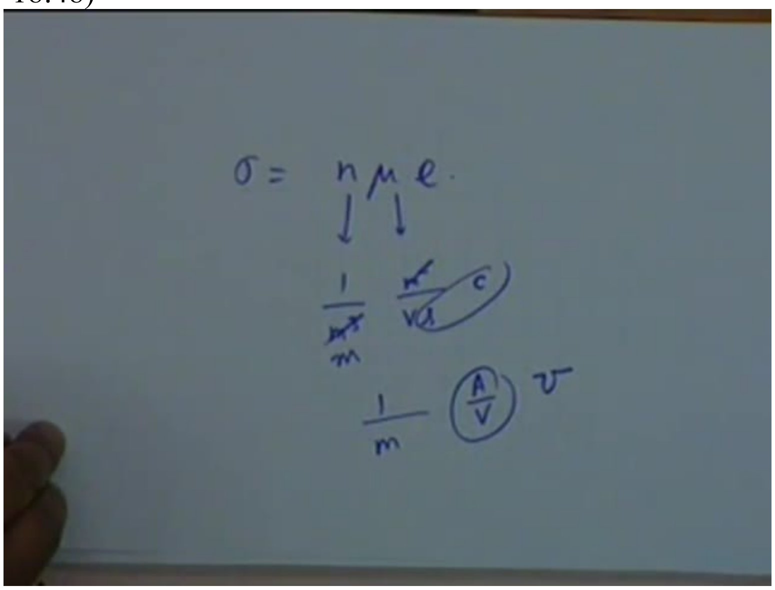
Suppose suppose there in a medium, you consider a cross-section, let us say, the electric field is in this direction, E. You consider a cross-section 1 metre square alright? And you consider a length of u, that is equal to the drift velocity. Alright? And electrons are coming out, electrons are moving in this direction alright? Not quite straight but after a zigzag motion. It is the drift velocity. If you consider only the drift velocity, then you can consider electrons coming out like this, minus E, minus E, minus E and so on. So if you consider the total number of charge, total charge that crosses a unit area, obviously this is the current density.

Total charge that crosses unit area per unit time is the current density J alright? The current density shall therefore be equal to the total number of charge carriers that cross this unit area in unit time multiplied by multiplied by the electronic charge alright? Now how many electrons will cross this unit area? Obviously, the number of electrons enclosed within this volume. So if the number of electrons per unit volume is n then the number of electrons contained in this cylinder is n times u and the charge is minus E and therefore this will be the current density but u u is equal to minus mew E.

Therefore this will be minus, minus and minus will cancel, u is minus mew e where mew is the mobility. So it shall be n mew e multiplied by E alright, which I can write, as we see the current, which direction does the current flow? Current flows in the direction of the electric field because the electron motion is the in the opposite direction and it has negative charge which is equivalent to a opposite charge flowing in the direction of the electric field. This quantity n new e if I denote this by Sigma, then I have the relationship current density is equal to Sigma times E and Sigma is called the conductivity.

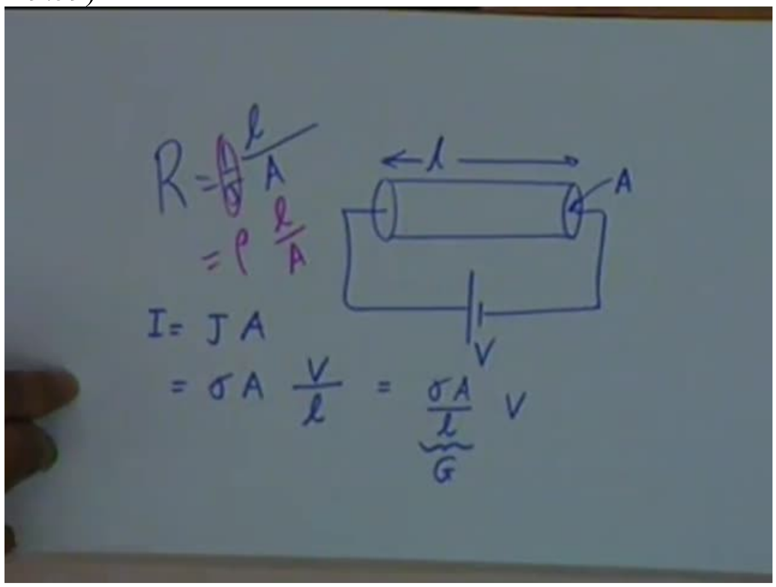
The unit of Sigma, if you take the units of n, mew and E, you can see that this will be mho, yes? What is the unit of Sigma? Mho metre alright? Why not? Let us look at this.

(Refer Slide Time: 18:48)



It is very important to to understand this. n is per metre cube. So 1 by metre cube number per metre cube. Mew is metre square divided by volt second and e is charge, therefore it is in coulombs alright? Now metre square metre cube becomes metre. Coulomb per second becomes current, amperes. So this becomes 1 by m Ampere by Volt, this is mho and therefore the unit is mho per metre, not mho metre alright? mho per metre. Conductivity. I have written this also wrongly. This should have been mho. M H O, mho. mho per metre alright. So Sigma is the conductivity. Now how does this relate to the famous Ohm's law?

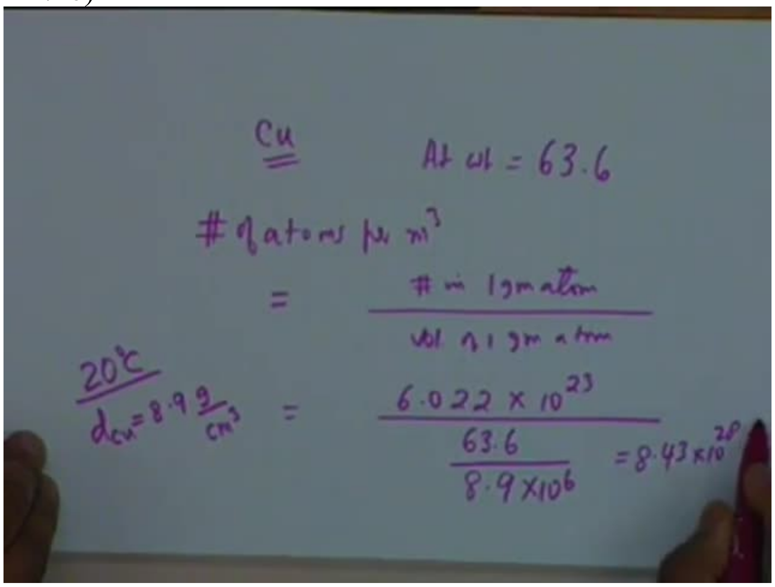
(Refer Slide Time: 19:59)



Well, this is another expression for ohms law. J equal to Sigma A, that is the current density is proportional to the electric field is another form of ohms law and if you were not convinced, let us consider a conductor. Let us consider the conductor of length l, potential difference is V and the cross-sectional area is A. Then the current flowing, capital I shall be equal to current density multiplied by A and current density is Sigma E but what is E? E is V by l all right? So this is equal to Sigma A by l times V and if you denote this by capital G, then you get ohm's law that the current is proportional to the impressed voltage.

The proportionality constant is the conductance. Or if you write it the other way round, obviously the resistance, capital R is equal to l divided by A 1 by Sigma and you know that 1 by Sigma is called the resistivity rho l by A, the famous relationship for resistance of a conductor all right? So this is simply ohms law stated in a slightly different manner. Now let us look at we were talking of metals.

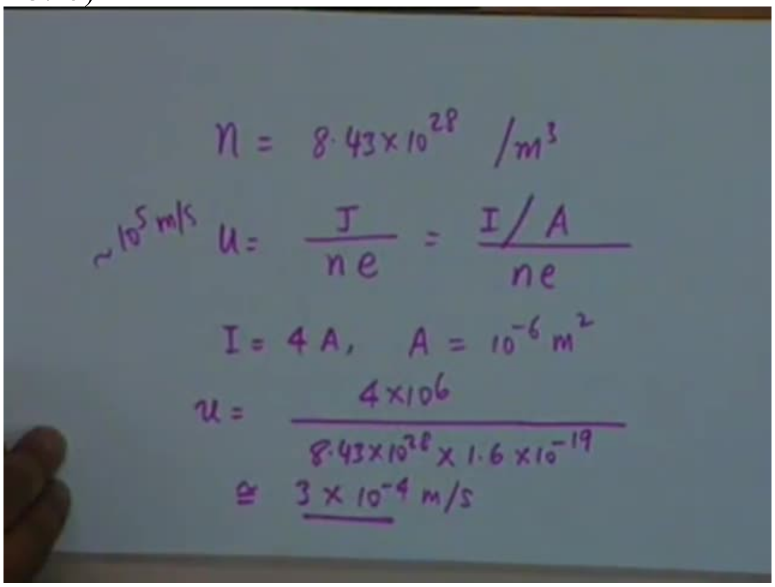
(Refer Slide Time: 21:16)



Let us look at a typical metal, let us say copper. Just to bring your, just to review some of the some of the concepts, let us take copper of which the atomic weight is 63.6 okay? What is the gram atom? Atomic weight expressed in grams alright? So the number of atoms number of atoms per unit volume of copper per metre cube shall be equal to the number in 1 gram atom, what is this number? This is the Avogadro number divided by the volume of 1 gram atom. Now this number is 6.022 times 10 to the 23 and the volume is mass divided by density.

The mass of 1 gram atom is atomic weight expressed in grams. Therefore this is 63.6 and at 20 degree C, the density of copper, dcu is 8.9 gram per cm cube, centimetre cube. This is how people still express the density. Well you can, you have to convert this to metre cube and the relationship is 63.6 divided by the density is 8.9 times how much shall this be? 10 to the 6 gram per metre cube and this number comes out as 8.43 times 10 to the 28. So this is the number of atoms in 1 cubic metre of copper.

(Refer Slide Time: 23:25)

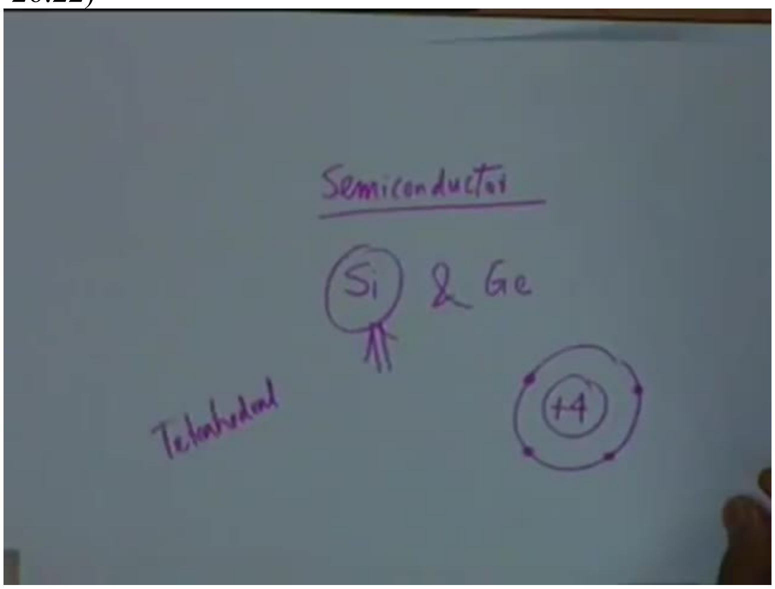


And suppose, every atom gives one free electron, then the number of electrons, number of electrons would be equal to 8.43 times 10 to the 28 number of electrons per metre cube in copper alright? Then the drift velocity u which is the current density divided by yes? n times the electronic charge. Current density is n e u alright? And current density is the current divided by the cross-sectional area divided by ne. Suppose in a copper conductor, let us say capital I is 4 Ampere and capital A, the cross-sectional area let us say this is 10 to the minus 6 meter square, then you can calculate by substituting these values, the drift velocity as 4 times 10 to the 6 alright divided by n which is 8.43 times 10 to the 28 multiplied by electronic charge 1.6 times 10 to the minus 19 coulombs alright. And this calculates out to approximately 3 times 10 to the minus 4 metre per second.

You see, the drift velocity is an extremely small quantity, 3 times 10 to the minus 4 metres per second. This compares very unfavourably with thermal velocity, that is if you if you if you elevate an electron to a certain temperature, capital T, then it gains energy and it moves because of kinetic energy and the thermal velocity is of the order of 10 to the 5 metres per second at room temperature, that is 300 degrees Kelvin. So the drift velocity compares very poorly with the thermal velocity and the point of this calculation is that if temperature rises, if temperature increases, what happens in a metal?

Resistance increases, conductivity decreases. Now why does this happen? It happens, when temperature increases, the electrons gain higher thermal velocity and therefore the time in between 2 collisions decreases alright? And the drift velocity then also decreases and therefore the conductivity decreases, therefore the resistance increases. And this is a property of almost all metals that the temperature, with temperature increase, the resistance increases.

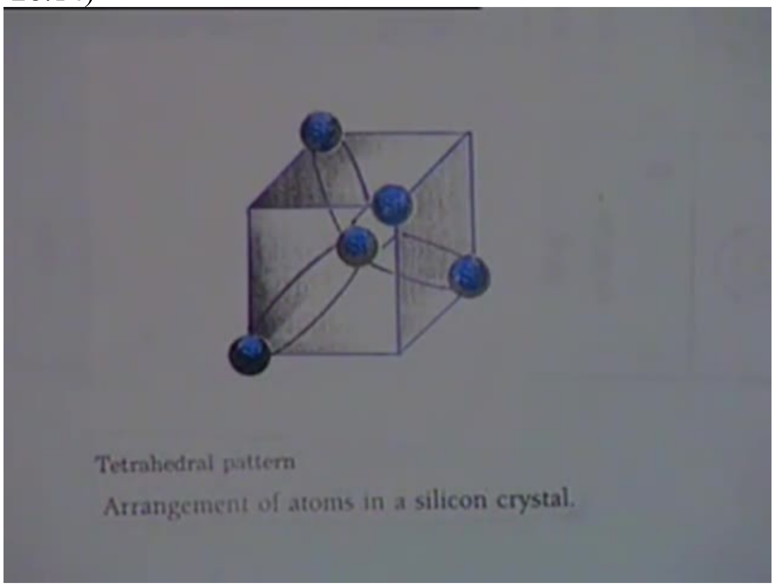
(Refer Slide Time: 26:22)



On the other hand, in a semiconductor, the opposite happens that is the temp as temperature increases, the resistance usually decreases. And to understand this phenomenon, we will have to understand how the charge carriers are affected by temperature and other physical parameters. How the charge carriers are affected because it is the charge carriers which contribute to the conduction of current. Without charge carriers, we cannot have any current. These semiconductor materials that we shall be mainly concerned with, are silicon and germanium and more of silicon than germanium.

So let us look at the silicon atomic structure. Silicon and germanium, both are 4th column elements of the periodic table. Then the number of the column denotes the number of electrons in the outermost shell. So silicon atom, typically shall be represented by 4 positive charges in the nucleus and a shell shown with 4 electrons like this. This is the silicon or germanium, they are both in the same periodic column, the 4th column of the periodic table. And the arrangement of the silicon atoms, the arrangement of the silicon atoms in space is the so-called tetrahedral arrangement, that is what we have is something like a queue.

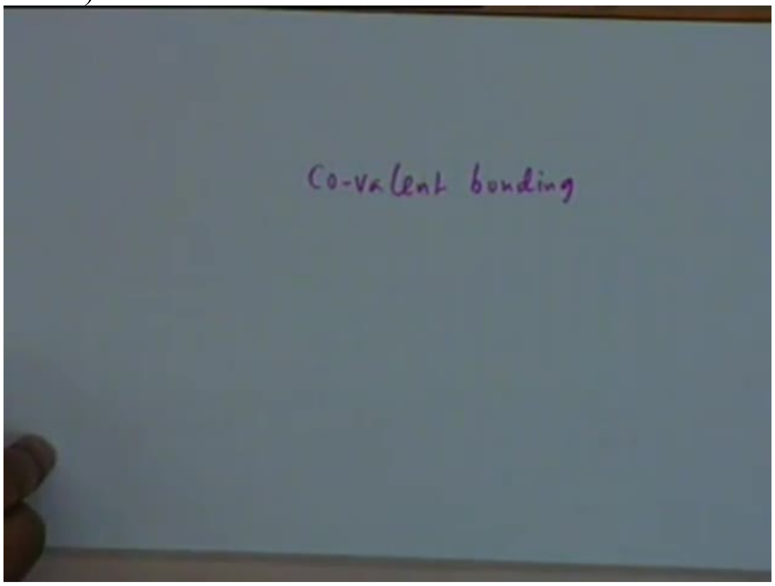
(Refer Slide Time: 28:14)

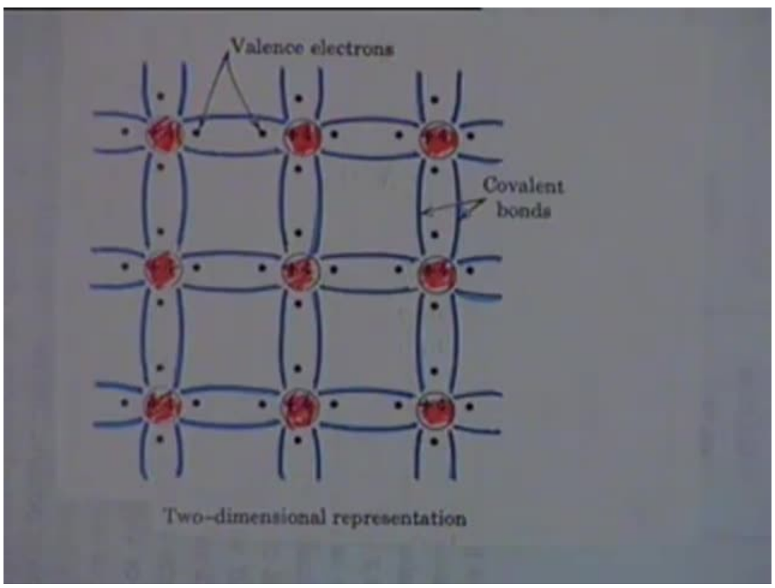


If you consider a queue if you consider space to be just a position of cubes like this, well another cube here, another cube on this side, one cube up, one cube down and so on, if you consider space to be occupied by cubes like this, then silicon atoms placed themselves 1 at the centre of the queue, 2 at the upper face, opposite corners, that is diagonal positions and 2 on the lower face again at opposite corners. Well, the corner corresponding to this is unoccupied, the corner corresponding to this is unoccupied.

And these silicon atoms are bound together by a kind of bonding which is called covalent bonding, covalent, C O V A L E N T. Is this arrangement clear? If you take a piece of dice and put a dot at the centre, 2 dot on the upper face at diagonal positions, 2 dots on the lower face at the other diagonal position then this describes the arrangement of a silicon atom. And then you have you have number of them repeated on the right, number of them repeated on the left, number of them repeated on the top and bottom alright? This makes a bulk silicon.

(Refer Slide Time: 29:37)



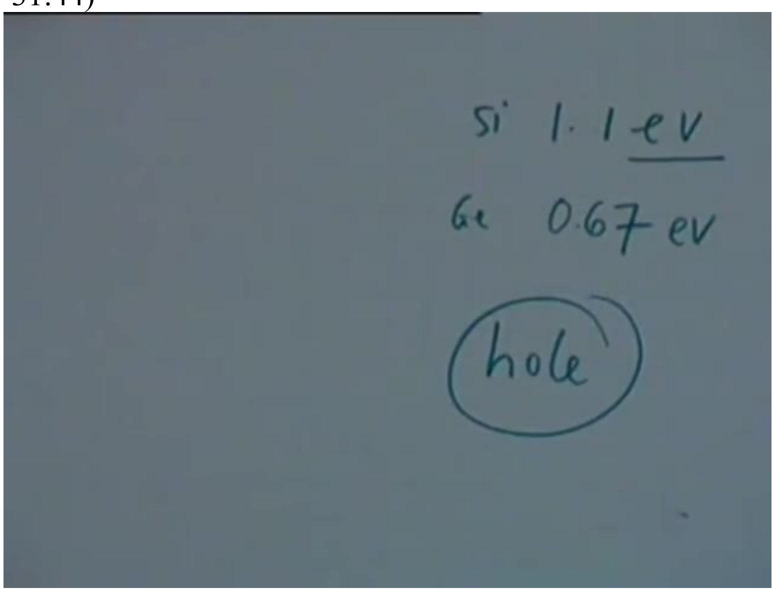


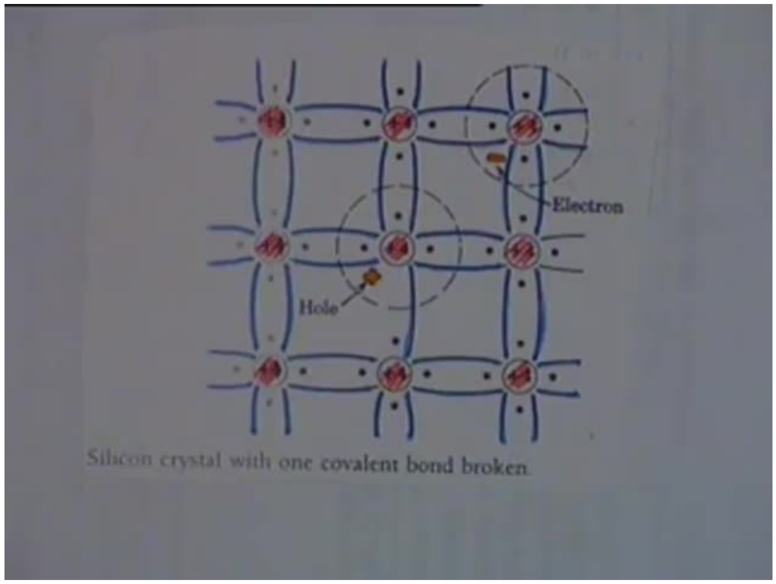
Now the bonding that exists between silicon atoms is the so-called covalent bonding. There can be many other kinds of bonding but for our purpose, for silicon and germanium, the bonding is covalent and it is, it occurs due to the sharing of electrons between atoms. A typical two-dimensional picture I cannot show in 2 dimensions, a three-dimensional picture but a typical two-dimensional representative incher, representation would be like this. If you look at, these are the positive charges plus 4 and 1, 2, 3, 4, these are the outermost shell electrons.

Now the atoms place themselves in such a manner that two neighbouring atoms, they share their electrons. That is, this atom shares one electron with this, similarly it also shares one electron with this. So there is this these blue lines which are kind of hands, it is a kind of a handshaking, 8 hands of the central atom which extend in 4 different directions, orthogonal with respect to each other, 2 adjacent directions being orthogonal with respect to each other and they share these electrons.

From the theory of quantum mechanics, it can be shown that this is a very stable structure. This gives silicon and germanium the stability of the atomic structure that it is reputed for. At absolute 0 of temperature, that is absolutely no energy anywhere and the silicon or the germanium atom acts like an insulator. The amount of energy it can be calculated from the quantum mechanics that the amount of energy required to knock out one of these electrons from silicon is approximately 1.1 electron volt, 1.1 electron volt.

(Refer Slide Time: 31:44)





Silicon crystal with one covalent bond broken

You know the unit electron volts energy unit? Okay. Whereas if it is germanium, then it is 0.67, approximately taken as 0.7 alright? Now this energy can be given to an electron in various ways. You can shine light on silicon. Then some of the electrons will will get a quantum of energy h nyu which if it exceeds 1.1 electron volt then it will say, hell with you, you are binding, goodbye to you. So it goes out alright. When it goes out, now it becomes a free electron, it has a lot of space to play around. It is not bound to any particular atom alright?

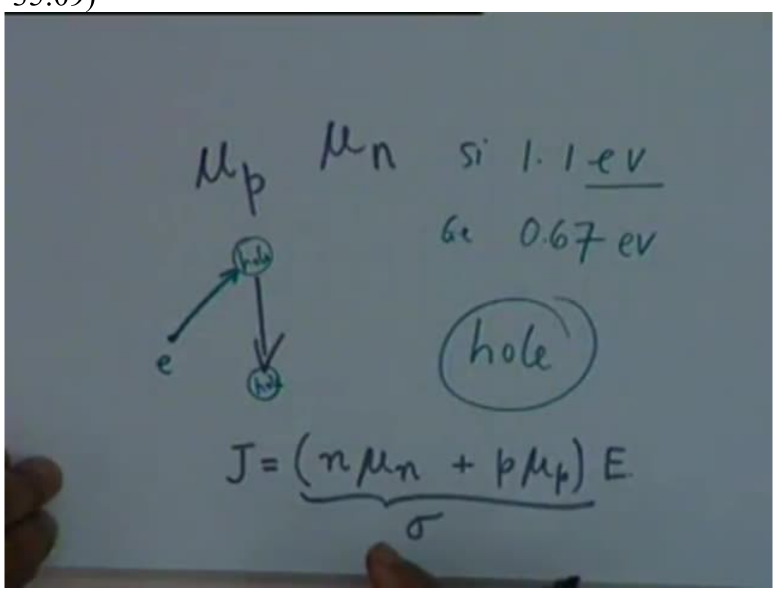
And it leaves the mother atom, the atom from which it has dissociated, what kind of charge? Obviously, positively charge this positive charge is obviously a fixed charge alright? It is a fixed charge, that is the mother atom remains positively charged, the infant electron, it goes out alright? The vacancy that is created, the vacancy that is created is called a hole, H O L E. All right? Let us take a picture. Hole, H O L E. Let us take a picture. Here we show this central atom of silicon.

An electron has been knocked out of this, either by thermal energy or light energy or some other kind of energy. The electron has been excited enough to move from here to some other position. Let us say somewhere here alright? Then if you consider this region, before this electron, this free electron had entered this region, the region was electrically neutral. But now this region is negatively charged. Similarly, this region where there is an absence of an electron, an absence of an electron means this hand has now been broken.

This hand of covalent bond, there are 8 such hands. 7 of them remain, one of the hands has been broken and therefore, this region has become positively charged and the vacancy that is created, is called a hole alright. Now it it can be shown from quantum mechanics that current conduction, current condition will now occur because there are free electrons but surprisingly, current is also conducted by holes and it happens like this. Suppose in the structure another electron may be knocked out from some other atom, comes in the neighbourhood of this positively charged region.

Then there is no reason why this electron should not feel inclined or obligated to go to this and fill up this vacant position. That means, it brings back, it brings back the broken hand. So it makes the structure stable.

(Refer Slide Time: 35:09)

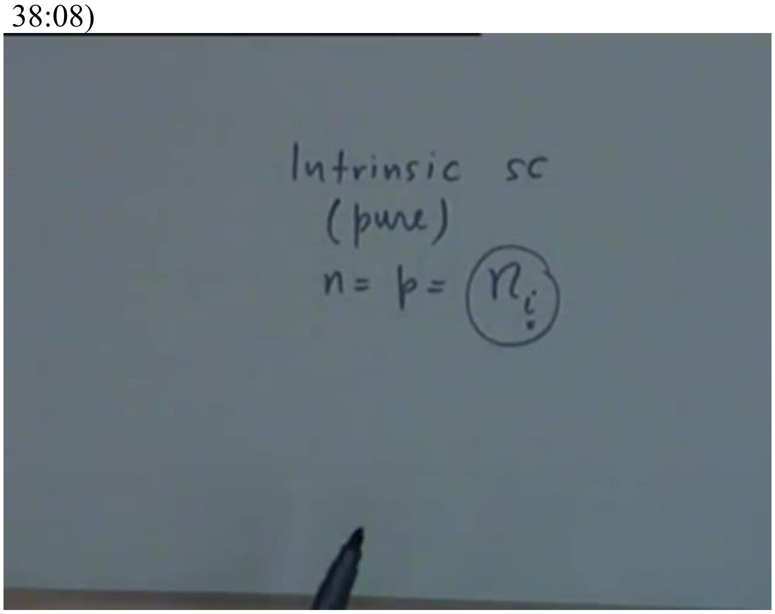


Now if I look at the picture, there was an electron here, electron and there was a role here. So this electron has gone to the hole and made it neutral. As a result, if this electron had belonged to another atom, what would have happened? A hole would have been created here. If initially, this was a neutral region, a hole would have been created here. So it is as of this hole which was in this position it is as if this hole has moved one new position and by sophisticated calculations of quantum mechanics, it can be shown that the hole moment is exactly like that of an electron. That is the hole which is a vacancy now behaves as a positive charge positive charge with a charge equal to that of the electron and a mass which is different from that of the electron.

In other words, in a semiconductor, we have to talk of 2 kinds of mobilities. There are 2 kinds of charge carriers. There are holes, there are electrons, 2 kinds of charge carriers and therefore we shall have to talk about the mobility of holes. Instead of H, we write P, P for positive because holes are positively charged and instead of electrons, we write N, that is the negative charge alright. And therefore the current density if we take the same equation as we derived in the case of a metal, the current density shall now depend on electrons as well as holes and therefore current density shall be n times mew n, this is due to the electrons times the electric field plus p times, p is a concentration of holes or the number of holes per unit volume. p times mew p and both shall be multiplied by E.

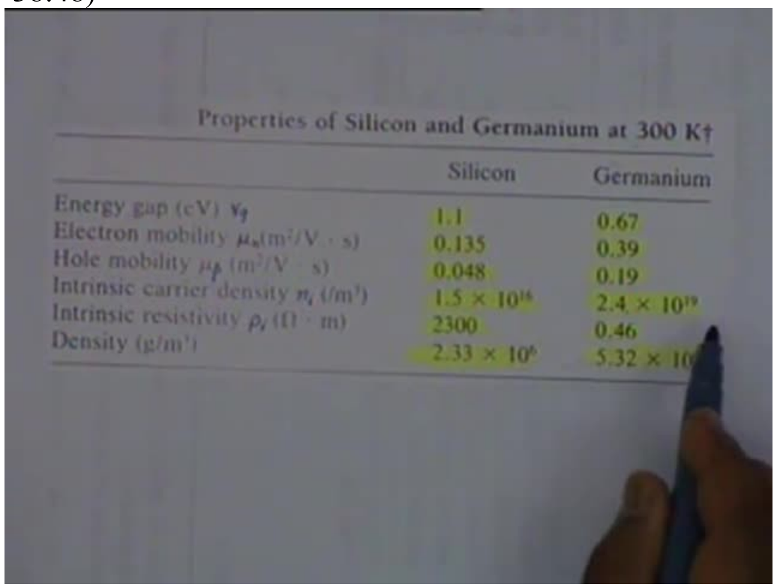
And therefore, the conductivity in a semiconductor shall consist of 2 terms. One is due to the electrons and one is due to the holes alright? You should appreciate at this point that in an intrinsic semiconductor at any temperature, the number of electrons and holes should be the same. Is not that right? Because every time you create a hole, you have knocked out one electron. So one negative charge, one positive charge. All right? This is the story in a pure semiconductor. If it is impure, then the situation is quite different which we shall come to.

(Refer Slide Time: 38:08)



But you understand that in a pure semiconductor which is also called intrinsic and the meaning of the word intrinsic shall be clear a little later but in an intrinsic semiconductor, n is equal to p is equal to ni, this i stands for intrinsic. In an intrinsic semiconductor, germanium or silicon, electron concentration is the same as the hole concentration and this is usually denoted by ni alright?

(Refer Slide Time: 38:48)



The 2 the 2 elements before we go into the intrinsic semiconductor, we would like to have a look can you see what is, can you see this on the monitor, this figure? Clearly? Not clearly? I will zoom them out. Just let these numbers ring a bell when these numbers arise in a certain semiconductor situation. Energy gap we say 1.1 for silicon, 0.67 for germanium. Energy gap is the energy required to gap the valance band and the conduction band, that is to take out an electron from the valance band and move it to the conduction band alright?

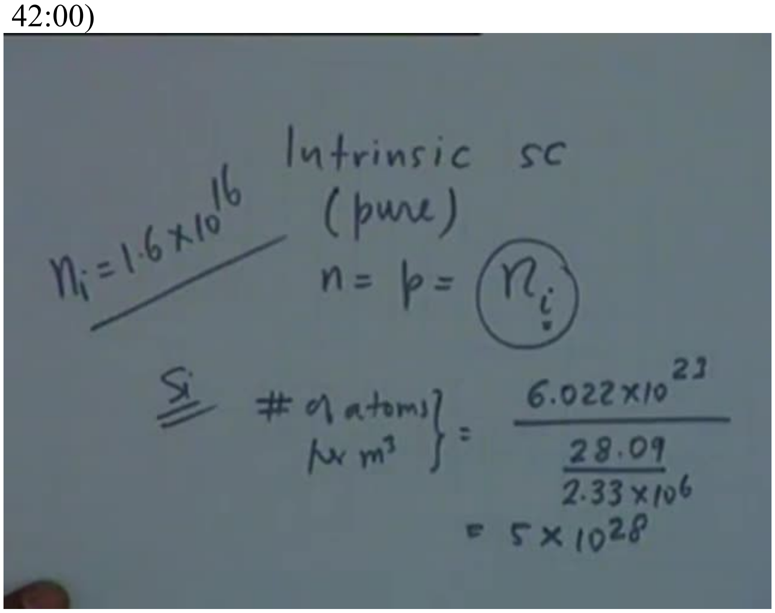
The electron mobility and hole mobility if you look at these 2 figures, you see that electron mobility is much higher than the hole mobility. Holes are less mobile than electrons. This is true in silicon as well as germanium. 0.39 and 0.19. The intrinsic carrier density which we have just define, ni that is if the semiconductor is pure, then you shall have 1.5 times 10 to the 16 electrons per metre cubed in silicon and 2.4 times 10 to the 19, 3 orders higher in germanium. Even then, germanium is not preferred. The reason shall be clear later.

But anyway Uhh what is the number of atoms per unit volume in silicon? Well, you can make a similar calculation as we did in the case of copper, Avogadro number divided by atomic weight divided by density and that comes of the order of 10 to the 21 which means that for every 10 to the 5 atoms of silicon, there is one hole or one electron. So they are very sparsely populated. It is not very dense, it is very sparse population. In copper, we assumed that there are, there is one electron per unit per atom which is not the case here.

Intrinsic carrier density is at room temperature, that is 300 K, is 10 to the 5 less than the intrinsic concentration of atoms. The intrinsic resistivity is 2300 which is a pretty large number, germanium is much less, only 0.46. And the density, density is the physical density that is grams per metre cube grams per metre cube not kg per metre cube for a very funny reasons. Uhh These mixture of units, centimetre, gram, kilogram, this continuing semiconductor electronics. I am not I will not change this. I am not authorised to change this. So I will not do that alright?

It is only IEEE or international bodies like that which can change but this is 2.33 10 to the 6. When you take this figure, you must remember that the unit is grams per metre cube, not kg per metre cube alright?

(Refer Slide Time: 42:00)



Okay, now if we take silicon for example, if we take silicon you can find out that the number of atoms per unit volume per metre cube is the Avogadro number, that is 6.022 times 10 to the how much? 23 divided by the atomic weight which for silicon is 28.09 divided by density at room temperature which is 2.33 times 10 to the 6 and this is simply equal to 5 times 10 to the 28. I am sorry, it was not 21, it is 28. And ni, that is the concentration of electrons in intrinsic semiconductor, intrinsic silicon is 1.6 times 10 to the 16. So for every 3.3 times 10 to the 12. What is 10 to the 12? Billion?

Student: Billion.

Professor: Billion. All right

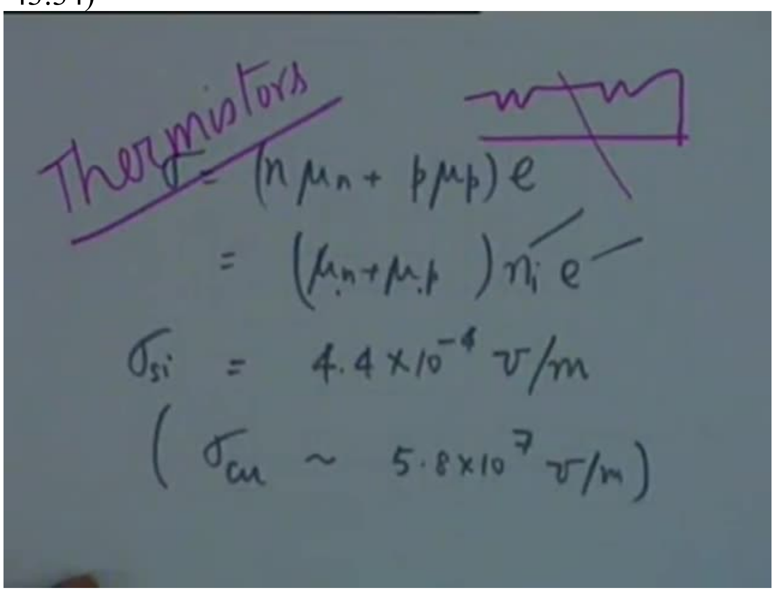
Student: Billion.

Student: Billion.

Student: Billion.

For every 3.3 times 10 to the 12 silicon atoms, you have 1 electron or 1 hole which is really indeed very sparsely populated.

(Refer Slide Time: 43:34)

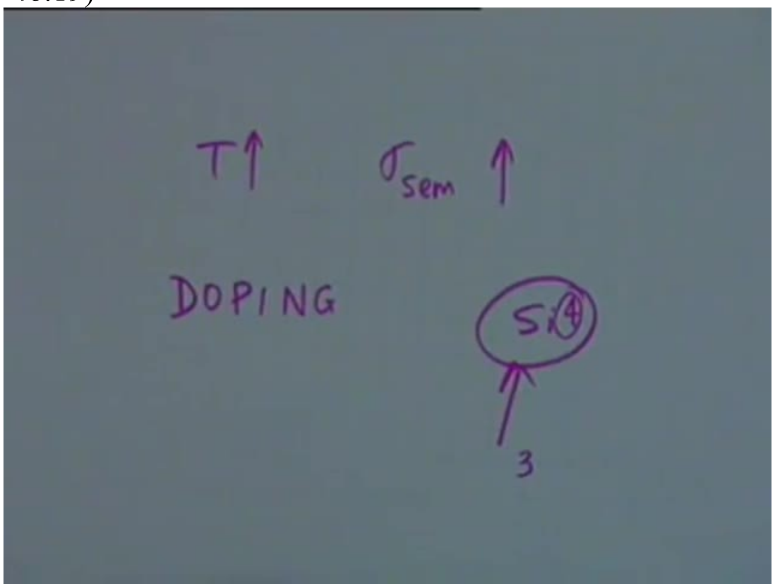


And if we calculate the Sigma, the conductivity, it is n mew n plus p mew p times times electronic charge yes and n and p are equal. They are equal to ni in intrinsic silicon. So it would be mew n plus mew p times this. If you substitute the values, 1.6 times 10 to the 16 for this, 1.6 times 10 to the minus 19 mew n and mew p then it calculates out to only 4.4 times 10 to the minus 4 mho per metre. Is the is the unit correct? You compare this with copper. What did we calculate? Calculate is 5.8 times 10 to the 7 mho per metre.

You see how poor the conductor is. Sigma silicon is much less than Sigma copper and therefore at normal room temperature, silicon is an extremely poor conductor of electricity. Question now is why have silicon at all, why consider silicon at all for electronic devices? There are 2 reasons. One is more one minor reason is that semiconductors are materials in which the resistance usually goes down with temperature and therefore whenever you want to make temperature compensation, for temperature compensation, you require positive temperature coefficient and negative temperature coefficient.

If you have 2 resistors in which one is a PTC, positive temperature coefficient, other is NTC, negative temperature coefficient then you can you can cancel the temperature dependence. That is one thing. Number 2, you can use either of these 2 resistors as a sensor for temperature. Right? if the if the resistance changes with temperature. And semiconductor materials are very useful in this context. Many of the instrumentation and control situations sense temperature through semiconductors and in this application, they are not they are known as thermistors, that is thermal resistors or heat sensing resistors, thermistors. This as I said is a minor reason.

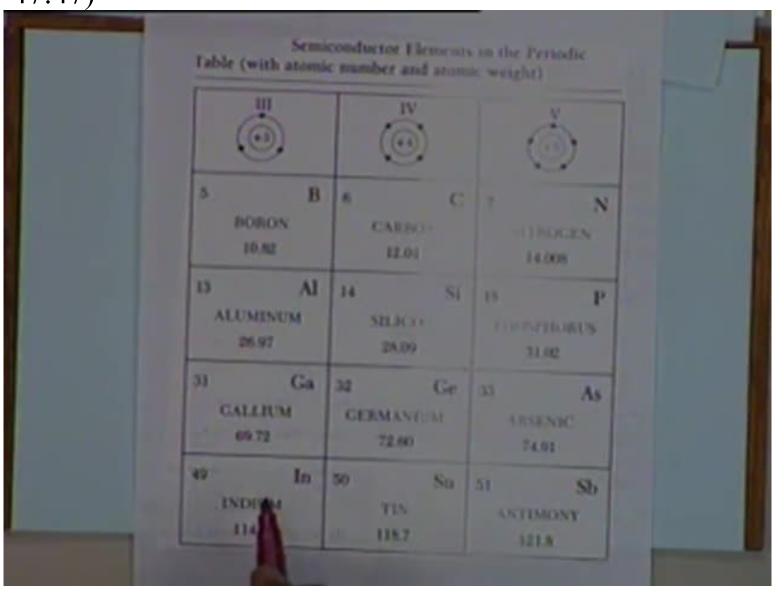
(Refer Slide Time: 46:19)



Major reason is that as temperature increases, capital T increases, Sigma of a semiconductor increases. And this increases almost exponentially. It might cause an avalanche of conductivity. And this is why we have devices like the avalanche diode or the zener diode. As temperature increases, Sigma increases almost exponentially and more surprising thing is that if you introduce a very small amount of impurity in the semiconductor and this process technically is known as doping doping, that is you dope a semiconductor, let us say silicon with some amount of impurity.

This impurity has to be a special kind of impurity. It has to be an element from a neighbouring column of the periodic table, that is Silicon is has 4 outermost shell electrons, you must inject in silicon a very small quantity of either a trivalent or pentavalent impurity. So the impurity can be of valency either 3 or 5.

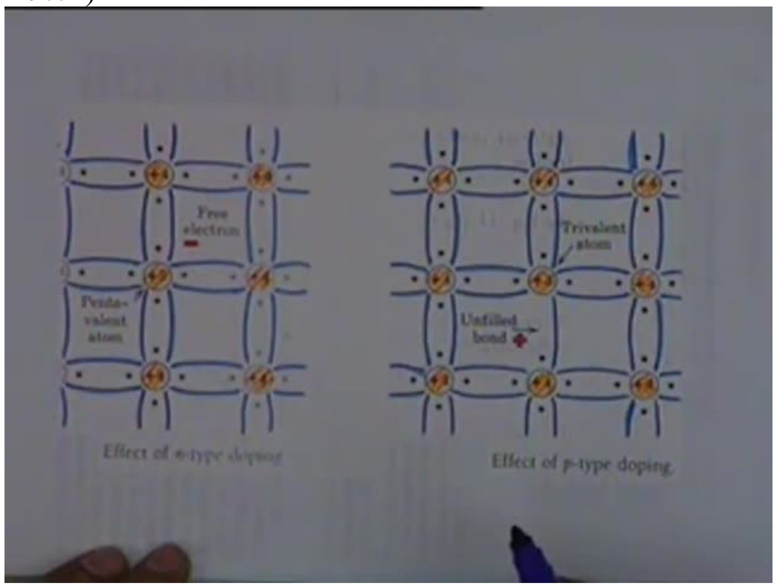
(Refer Slide Time: 47:47)



Then you can see, what are the possible candidates? Can you see this? This is the 4th column and silicon silicon is here, germanium is here. There are other candidates. Carbon, tin, both of them can act as a semiconductor. Now the trivalent impurities are boron, aluminium, galiam, indium whereas pentavalent impurities candidates are nitrogen, phosphorus, arsenic and antimony. There are semiconductors which neither which use neither silicon, nor germanium. They use a combination of 3rd and 5th group elements.

These are called three five semiconductors and the most exciting semiconductor of today is the gallium arsenide, that is the combination of gallium and arsenic, gallium arsenide but we are not going into this. We are considering what happens when a pure silicon crystal is doped with a small amount of trivalent or pentavalent impurity.

(Refer Slide Time: 49:02)



And this picture tells us what happens. Well what happens in the following? Suppose you have a pentavalent priority. For example, pentavalent example phosphorus or arsenic alright. Suppose it is arsenic. Arsenic pentavalent means there are 5 positive charges and there are 5 electrons in the outermost shell. So what it does is, once it enters the bulk of silicon, well it takes up a position where normally a silicon atom should be and when it takes up a position, this, the neighbouring silicon atom do not know that it is arsenic.

So they they extend their hands and 8 such hands are filled up, 1 electron extra is knocked out of this because 8 electrons make a stable configuration alright? The 9^{th} one, the 5^{th} one that this arsenic atom had extra is knocked out. So it becomes a free electron all right? This arrangement, in this arrangement therefore the impurity impurity donates electron and therefore this is called a donor impurity or it creates negative charge, so it is called n type of impurity. Small n, small n for negative charge.

On the other hand, if you inject a trivalent atom, if you inject a trivalent impurity like boron, well boron has only 3 electrons to give. So it is a beggar. It is a beggar. It accepts another electron all right? If it takes a position of silicon, well it one of its hands cannot be satisfied by the neighbouring, one of its one of the hands of a neighbouring silicon cannot be satisfied by this and therefore there is an unfilled bond or a hole all right? Therefore it is able to accept an electron knocked out thermally or otherwise from another atom. So it is called an acceptable atom or since it creates a positive charge, it is also called a p type doping and this is the point we shall start from next time.