Solid State Devices
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Lecture - 4
Equilibrium and Carrier Concentration (Contd…)

This is the 4th lecture of this course and the 2nd lecture on the topic Equilibrium Carrier Concentration.

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Let us recapitulate what we did in the last class. In the last class we mentioned that we are considering the carrier concentration in the bulk region of a semiconductor under equilibrium conditions. We mentioned what is meant by equilibrium or thermal equilibrium conditions. And we distinguished thermal equilibrium from steady state. These are the ideas we considered previously and we also saw some of the variations of the concentrations of electrons and holes in semiconductors, in pure semiconductors, and in dope semiconductors. We also distinguished between pure and intrinsic semiconductors. We saw the difference between simple or elemental semiconductors, and compound semiconductors. Today we will proceed further and to begin with we will consider the topic of Wave-Particle Duality.

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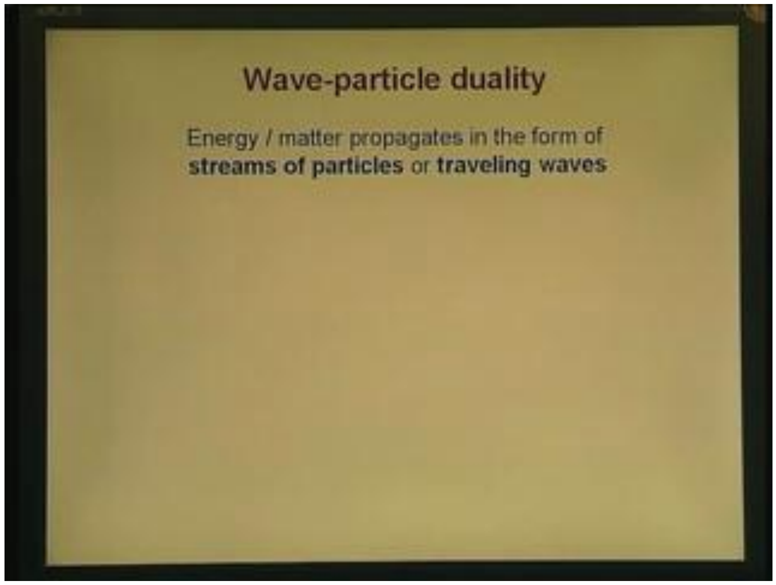

The important principle or the important concept of wave-particle duality, what does it mean? It says that the energy or matter propagates in the form of streams of particles or as traveling waves. So energy or matter travels, you can regard the energy or matter when it is propagating as propagating either as streams of particles or as traveling waves. Let us look at how some of the traveling waves are generated, and so on.

Now here, I would also like to show you in this context how Internet can be used as a very good reference material for understanding a subject. In this particular context, it is semiconductor devices. For instance, in large number of animations of various ideas and concepts are available on the internet. Let me show you some of the animations that are related to the waves. So all I do is I go to Internet and do a Google search. I can put the word “waves” and then I could add another word may be “animation or applets” and then I will get a number of options to choose from. Now here I could pick anyone from here and then see what is there. Let us look at this - electromagnetic waves. I am playing this applet with the permission of the people who have developed it.

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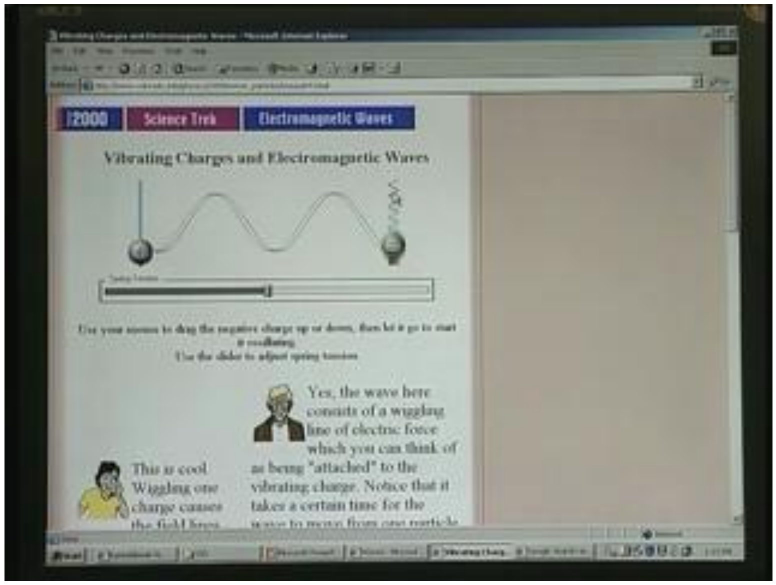

So although this is about electromagnetic waves you can also understand how, for example elastic waves are generated in ropes. So imagine that this is like a rope, this green line is like a rope, and then one end is flexed and then released. So what you have is a traveling wave generated from that end. So you are constantly flexing one end of the rope, periodically, and what is emanating from there is a traveling wave. So that is the kind of waves we are talking about. Let us look at some of the other waves.

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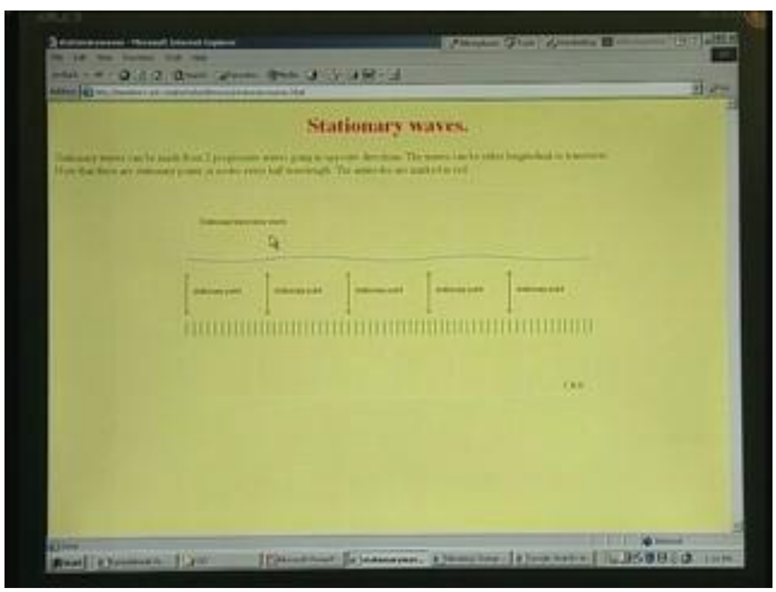

We have two examples; one is of a stationary transverse wave and the other is a longitudinal wave. So let us look at the stationary transverse wave. What is this? This is an example of a traveling wave generated from one end, and another traveling wave generated from the other end and the two interfering so as to give rise to a standing wave. So this is a standing wave pattern. So it is an interference of two traveling waves. The standing wave is a consequence of two traveling waves. So when do you say a wave is traveling? When some quantity of the wave is varying both as a function of space and as the function of time; which means at any point in space if I look at that parameter of the wave it will be varying as the function of time. Or at any instant of time if I look at the wave in that space that parameter will vary with distance. That is the traveling wave. Let us look at another traveling wave.

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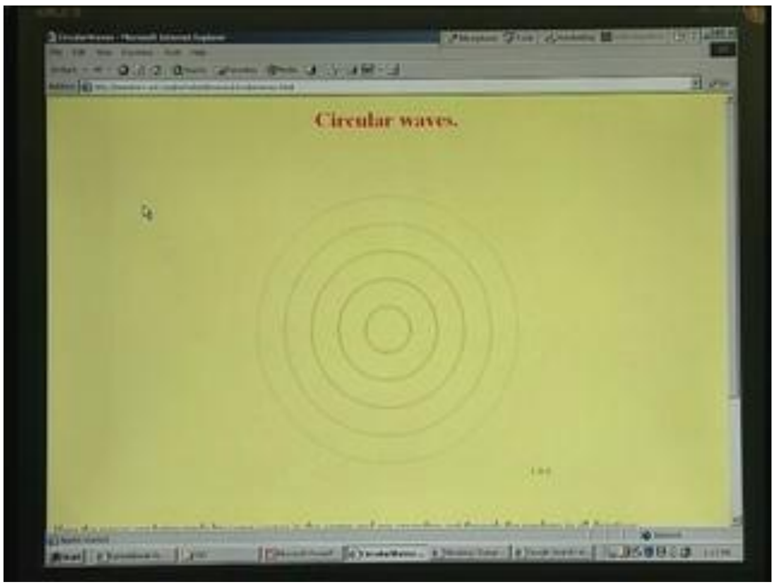

If you drop a stone in water you will have ripples generated. This is another traveling wave. This is an elastic wave because it is a wave generated in a medium wherein atoms are displaced with respect to time and distance. Now you can have interference of such circular waves. So you have a circular wave emanating from one point, and then it is going and hitting a surface from where reflection is taking place. In other words, another wave is generated and the two interfere. These are some of the examples of traveling waves and this will give you a feel of how parameters of the wave vary with distance as well as time. This visualization of the wave is important to understand further the idea of wave-particle duality.

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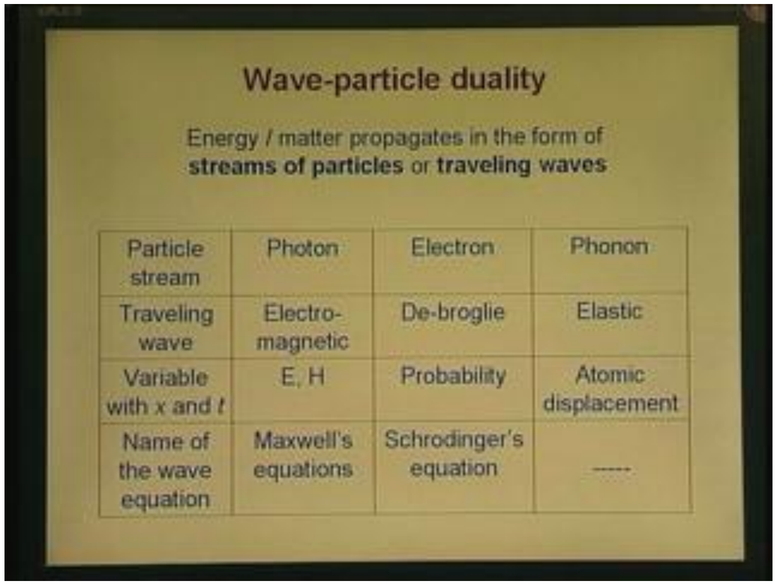

Let us look at some of the examples of wave-particle duality. In this table I have listed here streams of particles such as photons, electrons and phonons. You are familiar with photons and electrons; you may not be so familiar with phonons so we will discuss about them now. Photon is a particle. Its equivalent wave, traveling wave is an electromagnetic wave. Now, what is it that varies for an electromagnetic wave with distance and time? It is electric field and magnetic field. These are the two parameters which vary with x and t.

What are the equations that describe this wave?
These equations are named after Maxwell, The Maxwell's Equations. Similarly, you can take the electron, streams of electrons, the traveling wave that is associated with electrons is the De Broglie wave. De Broglie was a Scientist who showed that matter can also travel as waves. Now on a De Broglie wave, what is it that is varying with time and distance. It is the probability wave. So probability varies with distance as well as with time. And the equation governing this particular wave was given by Schrödinger equation. As against this let us take the phonons. I will come to the particle aspect of phonon a little later.

Let us start with the wave aspect of this particular particle that is an elastic wave. We have just now seen some elastic waves, the traveling wave in a rope, or the ripples in water when a stone drops on the surface are all examples of elastic waves.

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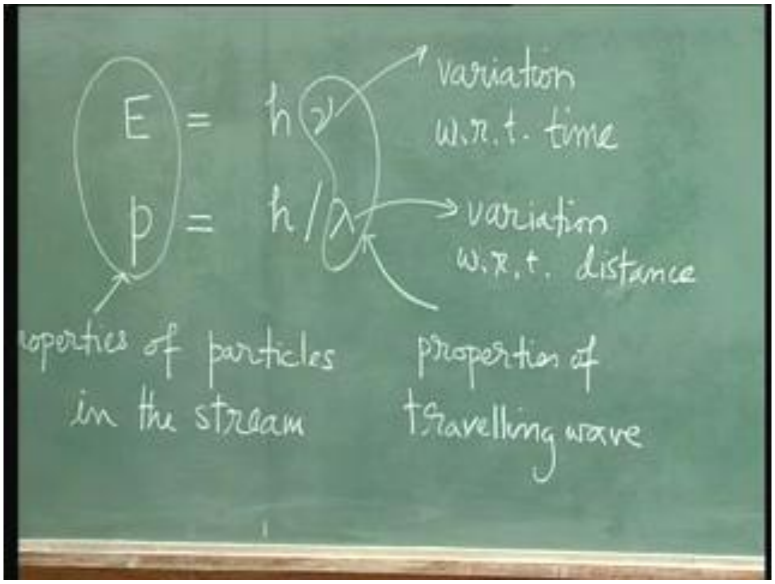

Here what is it that is varying with distance and time?
It is the atomic displacement that varies with distance and time. The particle equivalent of this wave is called the phonon. Why is it called the phonon? The name phonon is related to sound. So when sound is traveling in solid, it is an elastic wave that is created in the solid; and the particle equivalent of sound; “phono” stands for sound. So a particle equivalent of that is phonon. So although strictly speaking it is associated with propagation of sound in a solid medium, in general it is used as a particle equivalent of an elastic wave that may be generated in the solid. Now it is because there are number of elastic waves you cannot associate any single Scientist with this elastic wave. That is why this particular column in this table slot is left blank. It does not mean that there is no equation. It only means that there is no single scientist or single equation that you can identify with this particular form of wave-particle duality. Now, let us understand the advantage of using this concept because any concept is introduced to simplify the understanding of some situation. Let us try to see the equations which relate the particle and wave aspects.

For example, you know the equations:
Plus E (that is energy) is equal to Plank’s constant h into frequency of the wave. Another parameter is p the momentum which is related to the wave aspect as h divided by lambda. Here E and p, these two parameters represent the properties of particles in the stream. On the other hand, these parameters namely nu and lambda represent the particle of properties of waves associated with the streams of particles. Note that as the word “traveling” in the phase “traveling wave” indicates the wave involves propagation. So here, for example nu is a parameter representing variation with respect to time. On the other hand, lambda, the wave length is a parameter that is related to variation with respect to distance. This energy E and the momentum p written in these equations also represent the minimum quantum of energy that can propagate.

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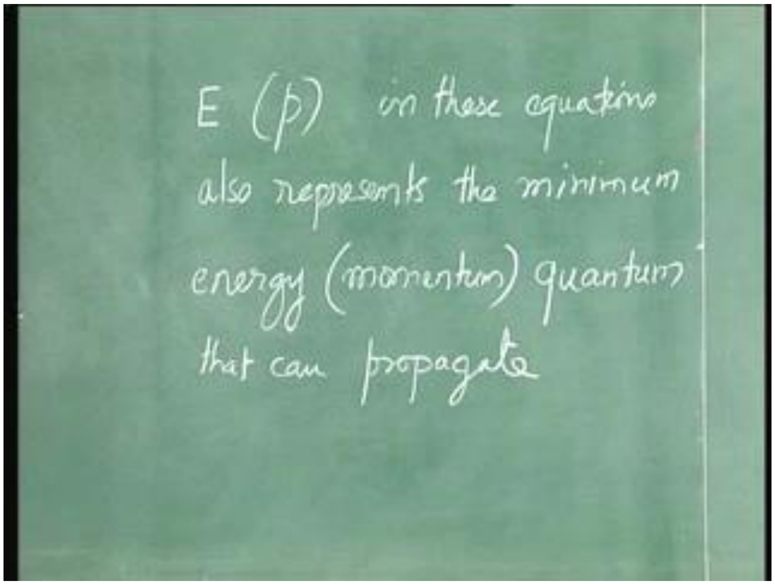

Not exactly energy because E is energy, so we will keep (p) in brackets. So E represents minimum energy and (p) represents (momentum) quantum that can propagate. As you know the important thing in quantum mechanics is things do not vary continuously but they vary in discrete sizes. The minimum amount involved in this variation is the amount E or (p) as given by the equation E is equal to h into nu and p is equal to h divided by lambda. Let us consider an example to see what kinds of wavelengths are associated with energies.

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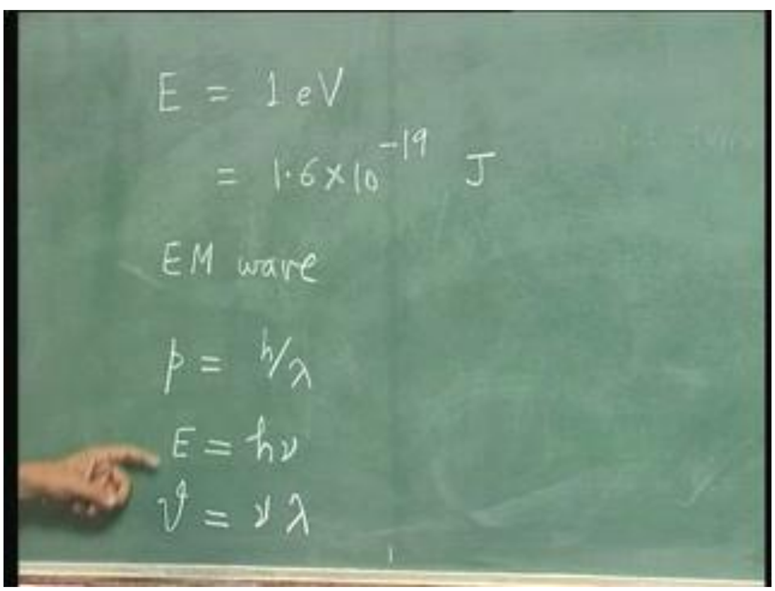

For example, let us take the energy of one electron volt. One electron volt represents the energy that is gained by a unit charge of value 1.6 into 10 to the power minus 19 J when it falls through 1 volt. So, if you want to write this energy in joules it would be 1.6 into 10 to the power minus 19 J. Let us assume that we are talking of an electromagnetic wave. In an electromagnetic wave, if energy is 1 electron volt what is the wave length? Now, we use the equation p is equal to h by lambda; so lambda is equal to h by p. Now how do you know p? You have the other equation E is equal to hnu. Wave speed is given by V is equal to nu into lambda. So we combine these equations, you can write instead of using lambda is equal to h by p let us express p in terms of E and V.

We can write p by E is equal to 1 by nu into lambda is equal to 1 by V. So p is equal to E by V. And now we can write lambda is equal to h by p is equal to h into V by E. So lambda is equal to h into V by E. Next, let us substitute the values. So the wave length lambda corresponding to 1 electron volt is equal to h V by E which is 6.626 into 10 to the power minus 34 J by sec. Note that I am putting the numerical value as well as the units. This is important; whenever you make a calculation of a physical quantity in terms of other physical quantities you must put the values as well as the units of all the quantities. Otherwise you are not sure whether you are using the right units and your numerical value is correct. Now V is a velocity of light that is 3 into 10 to the power 8 m by sec. Now, this is where I want to again emphasize the importance of units.

We might remember the velocity of light in terms of centimeter per second instead of meter per second. If I were to put this unit in centimeters per second that is 3 into 10 to the power 10 centimeters per second then my numerical value that I get will be different and that would actually not be correct because joule seconds is an MKS system whereas centimeters is not correct length unit for MKS system, it should be in meters. That is why we must write the velocity of light in meters per second when we are writing the Plank's constant in joules seconds or MKS system. Now the energy E, one electron volt is 1.6 into 10 to the power minus 19 J per second. So I put the joules here. Now the first thing is we must check the units, so this joule cancels with this joule, the second cancels with second, and you are left with meters. So the value that I get here will be in meters. The result is 1.24 into 10 to the power minus 6 meters which is same as 1.24 micrometers. Next, let us look at the specific advantages to be gained from this idea in the context of semiconductors which we are studying.

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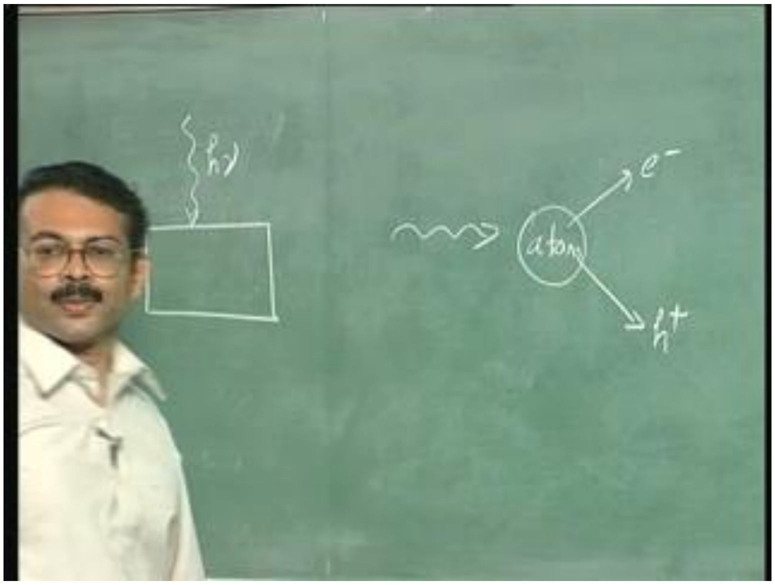

For example, if you want to know the effect of light falling on the semiconductor, this is equivalent to an electromagnetic wave falling on the semiconductor. Now this interaction between the electromagnetic wave and the semiconductor crystal or semiconductor atom can be represented by assuming the particle equivalent of the electromagnetic wave. And, in fact, if you recall in the first lecture we showed the generation of electron hole pairs form an electromagnetic wave or a photon. So this is a photon or a stream of photons falling on the semiconductor atom in this case, and then you have an electron hole pair generated.

Now this particular phenomenon can be regarded as a collision of a photon with an atom in the particle equivalent parlance. So, instead of regarding as a wave interacting with an atom where things look more complicated, if the wave is converted into its particle stream regarded as a particle stream, then it becomes a simple problem in collision. So it is a collision between a photon and an atom. Now you can treat this collision from the energy momentum conservation point of view and find out whether the photon can generate an electron hole pair. We have to find out whether it can break the bond, whether it can supply the energy that is required to make an electron free. Does it have the momentum and so on. In this way you can treat this particular interaction.

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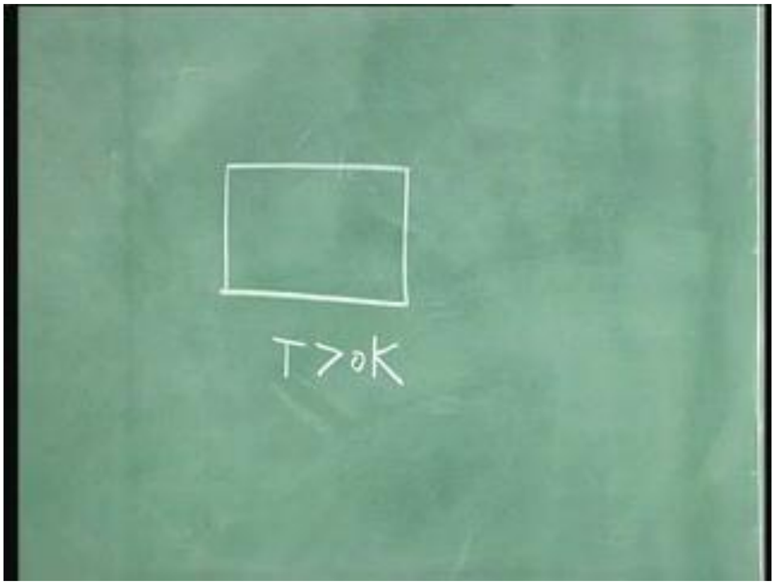

Take another example, when you have a semiconductor crystal at T greater than 0K, at T greater than 0K the atoms are in agitation and each agitating atom give rise to a traveling wave. Now you can take it as a fact that each vibrating atom because this atom is bonded to the next atom, and next atom is bonded to the next atom, the series of atoms which are bonded together can be regarded as a kind of continuous solid medium as an analogy. And therefore if any one atom vibrates since it is bonded to other atoms, the other atoms are also set into vibrations and what is generated is a traveling wave. So, in a semiconductor for T greater than 0K you have atoms agitating and giving rise to traveling waves in which atoms are displaced as a function of time and distance.

Now, what is the effect of these elastic waves?
The traveling waves are elastic waves. What is the effect of these atomic vibrations or these elastic waves because of the atomic vibrations on electrons? If you want to know, it is a rather complicated picture when you look at this way. But now if you regard the elastic waves as streams of particles called phonons this becomes a collision between phonons and electrons. So now you can regard this collision between phonons and electrons. We can treat this collision from the energy momentum conservation point of view, and then we can see how this collision affects, for example, the mobility of electrons. How is it that traveling waves, elastic waves present in semiconductor solid affect the movement of electrons? This can be easily treated as collision between phonons and electrons. In all these collisions between particles we assume the energy and momentum conservation loss and treat this collision.

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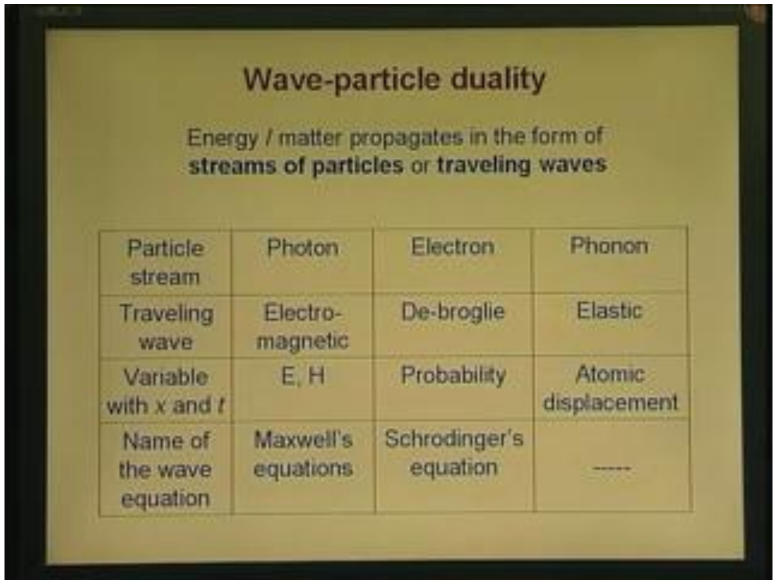

Now, we have discussed the basic concepts namely the thermal equilibrium, steady state and then wave-particle duality. Now, with these ideas we can proceed to see in detail what is happening within a semiconductor and how do you get the electrons and holes.

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We will start with what is called the, Bond model of an intrinsic semiconductor: First, we take up the intrinsic semiconductor and then we will go to the extrinsic semiconductor which is more complicated. When I use the word “intrinsic” for our discussion we will be considering a pure semiconductor without any defects or impurities and that is what we are going to assume. The model we are going to develop is for such a semiconductor.

Now in any such modeling you must understand there is an important approach and that is, first you discuss the model in a qualitative fashion and then only you write the equations corresponding to the model phenomenon.

In other words, you must always discuss the qualitative theory first and then the quantitative aspects. This qualitative theory is very important because this is what gives you the insight; this is what tells you whether you have understood what is happening within the semiconductor. So, one must not think that when you say a model it is the equation, and it is not correct. The word model actually includes the qualitative understanding and later on its translation into an equation. So let us first discuss this model of an intrinsic semiconductor in a qualitative fashion. That is, the so called Bond model.

As we will see, a qualitative model of the semiconductor is the Energy Band model. This model will not help you to make accurate calculations of concentration of electrons or holes as a function of temperature. But what it will help you to do is, it will show you why there are electrons and holes, why is it that you have electrons, the negatively charged particles which can carry current, and holes the positively charged particles which can carry current in a semiconductor and why substances are not there in a metal. It can also explain to you, why is it that the temperature coefficient of resistivity of semiconductors is negative. That is, when the temperature increases in some range the resistivity falls. In other words, it will explain why the concentration of carriers should increase with temperature in an intrinsic semiconductor. Then it can also give you rough idea of the concentration of the semiconductors as what kinds of order or magnitude are involved. The first step in this model is to look at the crystal structure.

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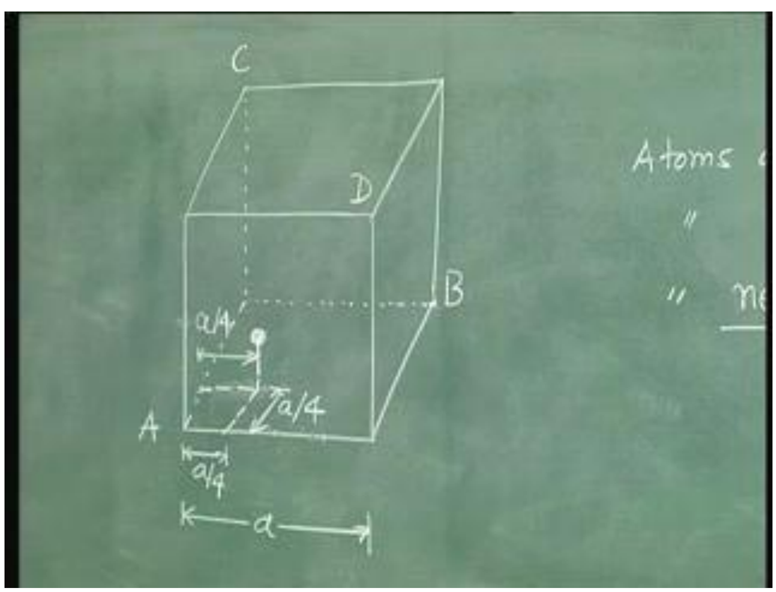

You know that any crystal has regular arrangement of atoms. It involves the repetition of what is called a unit cell or a unit cube. Let us draw the unit cube of silicon. The length “a” of this cube is normally called the Lattice constant. Where are the atoms located in a unit cube of silicon? You have one atom at each of the eight corners. You have one atom at the centre of each of the six faces, and four atoms located near four corners: A, B, C and D. If A and D are located at these two corners at the bottom, then the C and D are located in such a way that diagonal CD is at 90 degrees to this diagonal AB. From the top you see the four corners: A, B and C, D.

There are atoms near the corners A, B, C and D. We will consider what is meant by the exact location of an atom near a particular corner. Take the atom that is located near the corner A. It is at a distance a by 4 in this direction, a by 4 in the perpendicular direction, and a by 4 in the vertical direction so it will be a by 4 on all corners so X, Y, Z in these directions. You can similarly locate atoms at corners B, C and D. C and D are within the cube so it would be a by 4 in vertical direction, a by 4 in the perpendicular direction and a by 4 down.

I am not showing you all the atoms because then the picture may or may not be clear. I insist you all to take a look at the Internet in this context. There are a number of applets and animations available of the crystal structure where you can rotate this particular unit cell and see how it looks from different angles. The important thing we need to know is that there are eight atoms at eight corners and six atoms at each of the six face centers.

Example: if you take one face the atom you will be located at centre of the face. Similarly there is one atom at each of these six faces. And then there are four atoms within the cube located near the corners A, B, C and D.

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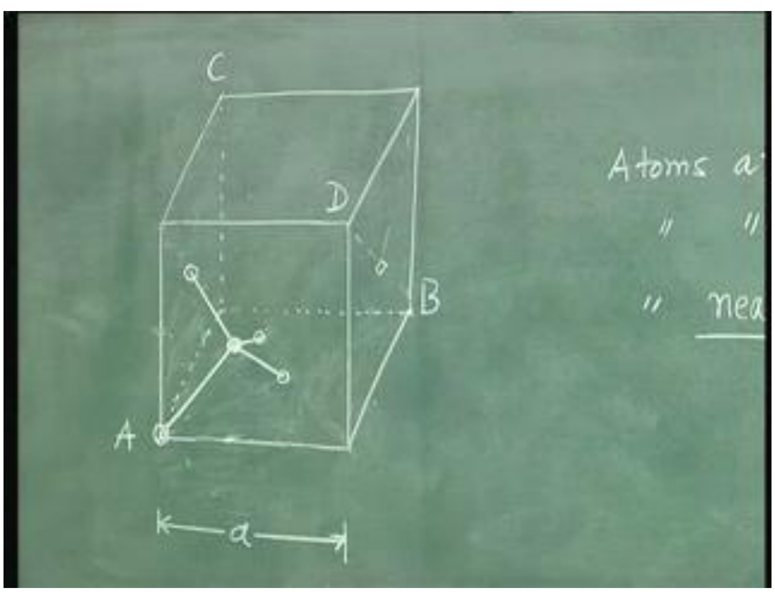

What is important to note is that each atom in this particular arrangement is bonded to four neighboring atoms. Let me show you this with the help of this particular atom as to which four nearest neighbor is this bonded. So this atom is bonded to this corner and it is also bonded to the center of this face. Then it is bonded to the face center of the bottom face and it is bonded to the face center of this side face.

Like this, the atom at the corner B will also be bonded to four neighboring atoms; atom at corner C and atom at corner D will also be bonded to four neighboring atoms. And if you see all the bonds you repeat this arrangement. And if you see the various bonds and the arrangement of atoms what emerges is that it is a regular arrangement in which each silicon atom is bonded to four neighbors. Since it is difficult to work with this three dimensional arrangement and what is of interest to us is these two aspects; a regular arrangement of atoms and each atom bonded to four neighbors. We can always use a two dimensional representation of the three dimensional arrangement for purposes of understanding. So that two dimensional arrangements would be as follows:

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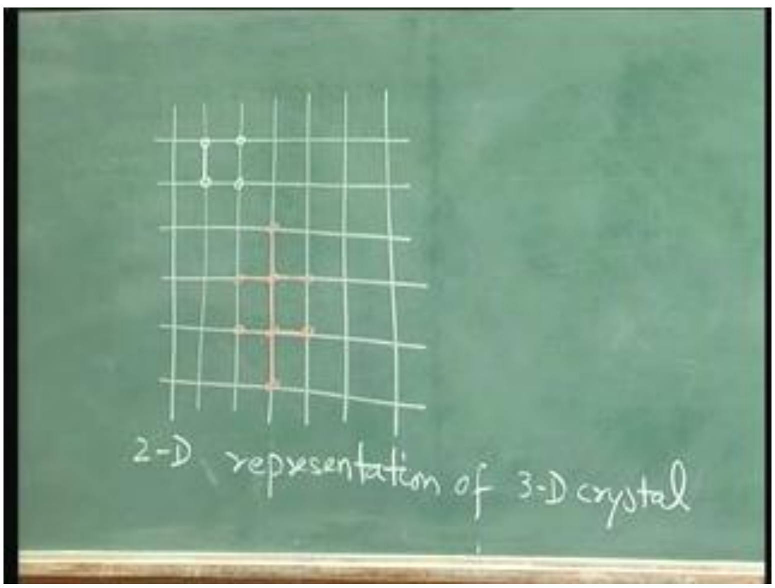

Like a matrix for a network, each intersection between two lines indicates the presence an atom and each line between two such intersections, this line represents the bond between the two atoms. In this arrangement, every atom is bonded to four neighbors. So, for silicon every atom is bonded to four neighbors and we can conveniently use a two dimensional representation showing this particular arrangement.

For example here, if I take this atom its four nearest neighbors would be this, this, this and this and these are the bonds. For this atom the four nearest neighbors are this, this, this and this and so on. So this is a two dimensional arrangement or representation of a three dimensional crystal. Now let us look at some of the numbers associated with the crystal structure.

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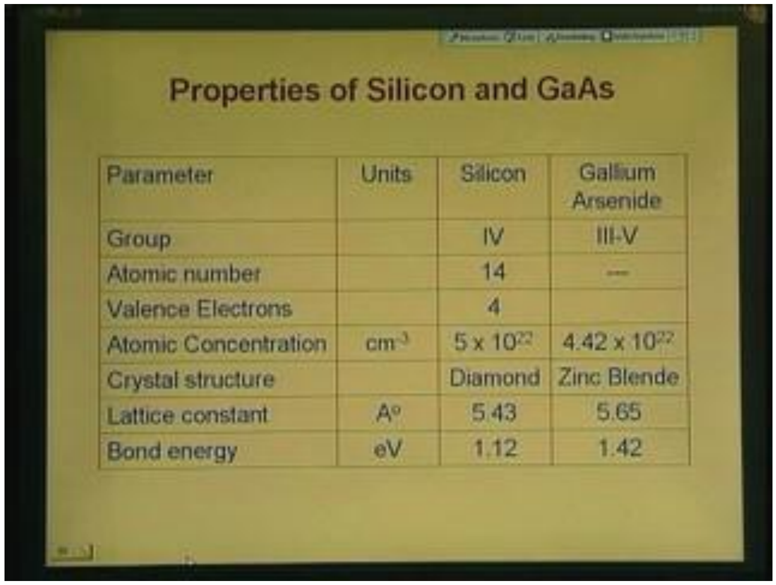

On this slide we have shown some parameters that you must know for silicon, and gallium arsenide which is a compound semiconductor. Silicon is a group four element, since it is a group four element it has four valence electrons.

We will first take the various parameters for silicon and then we will go to gallium arsenide. So atomic number of silicon is 14 so it has 14 electrons surrounding the nucleus out of which 4 are the electrons in the outermost orbits and they are the valence electrons because they participate in bonding. Then comes atomic concentration, what is the concentration of atoms in a silicon crystal, the concentration is 5(10)22 unit by cm cube.

The crystal structure of silicon is called diamond; it is also called the tetrahedral structure. The Lattice constant that is a length of the unit cube which is this particular parameter "a", this length of the unit cube has a constant value of 5.43 Angstroms. One must become familiar with units associated with very small dimensions. One unit that we came across was micron. Many of the device surges are in microns. For example, if you are asked to tell the dimensions of this room, you are probably likely to tell the dimensions in meters or feet and just by looking at the room one can get a feel.

For example, you can look at the black board and tell the dimensions in feet or meters. How does one get a feel for micron? Human hair is 50 microns thick. So one micron is 1 by 50th of that thickness. An Angstrom in terms of microns is, 1 Angstrom is equal to 10 to the power minus 10m, or if you want to remember in terms of centimeters it is 10 to the power minus 8. To remember in terms of microns, it is 10 to the power minus 4 microns.

In other words, 1 micron is equal to 10,000 Angstroms. So in terms of this dimension the Lattice constant is 5.43 Angstroms. And finally you have the bond energy on the slide. The bond energy is 1.12 electron volts for silicon. So energy is represented in terms of electron volts which is the energy required to break the bond between two silicon atoms (covalent bond). The analogous values of the various parameters are given here for gallium arsenide. Gallium is group three, arsenic is group five, so gallium arsenide is three five semiconductor. You can find out the other three semiconductors. Atomic concentration is 4.42 into 10 power 22 cm cube. Atomic concentration in various materials are similar, the order is 10 power 22. It is very important to remember that the order of concentration of atoms in solids is around 10 power 22. The name of the crystal structure for gallium arsenide is zinc blend and the Lattice constant is 5.65 Angstroms and bond energy is 1.42 electron volts.

Next step is, we will look at how the electrons and holes are created when you raise the temperature of a semiconductor beyond T is equal to 0k. We will always consider silicon as an example unless stated otherwise.

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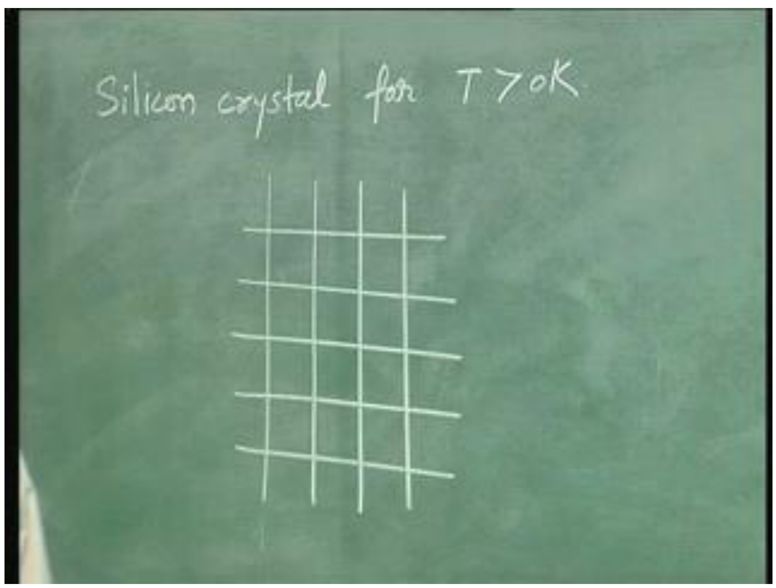

So silicon crystal for T greater than 0k. Let us start with the picture for T is equal to 0k and for T is equal to 0k there is no thermal agitation and so your picture is something like this. All atoms are bonded to four nearest neighbors, no bond is broken. When you raise the temperature beyond 0k what happens is that each atom starts vibrating about its mean position. Whenever an atom vibrates it generates an elastic wave. You can regard this picture as analogous to what happens in a pond when rain drops fall. If there is no rain the top surface of the pond is calm. Once the rain starts falling, wherever a rain drop falls from there a ripple is generated - circular waves.

Now these ripples will emanate from each of the drops and they will interfere. Similarly in each of atoms that is vibrating a traveling wave is emanating and interfering with traveling waves generated from the other atoms. So you have elastic waves within the crystal. Looking at a wave-particle analogy we can therefore say that for T greater than

0k you have phonons moving about in the crystal. So there are elastic waves of atoms created which can be regarded as streams of phonons.

First set of particles that we get are the phonons. At T greater than 0k you have phonons. We can show that you will also have photons. How do you show that you have photons? Photons are analogous to electromagnetic waves. How can we show that a vibrating atom in a silicon crystal is going to give raise to electromagnetic waves? It is very important to understand and it can be explained with the help of animation.

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Now what is shown on this slide is a positively charged nucleus which is dark blue and surrounding it is a negative electron cloud corresponding to the electrons. When an atom is vibrating how does this charge picture look like? You have the electron cloud not moving along with the nucleus, it does not move along with the nucleus. There is a relative displacement between the center of the electron cloud and the positively charged nucleus.

Now if you regard the center of the electron cloud as representing a negative point charge and the center of the nucleus as a point charge which is positive, then you can see that between the positive charge of the nucleus and the negative charge of the electron cloud there is a dipole created because these two are displaced with respect to each other. The black dot here and the horizontal line of the black dot represent the negative charge. It is represented by a negative sign whereas the positive charge is shown here in the nucleus. This relative displacement of the positive and the negative charges creates an oscillating dipole.

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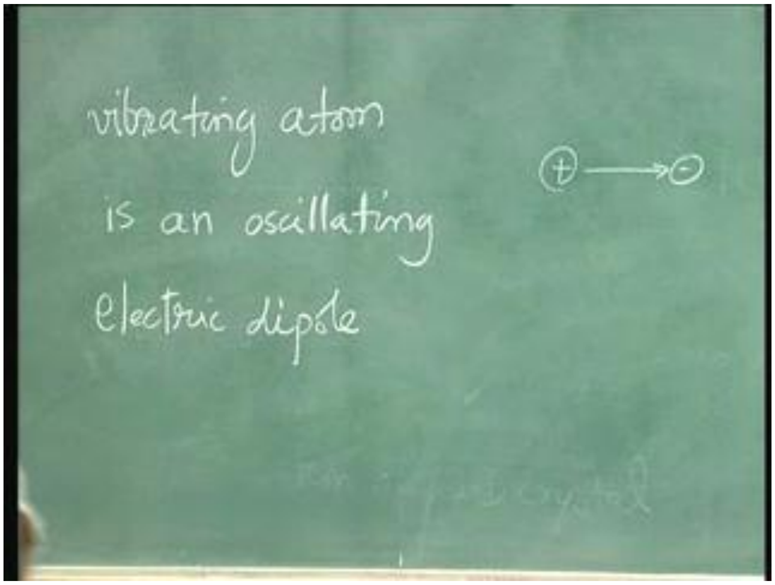

A vibrating atom is an oscillating electric dipole. Whenever there is an oscillating charge, oscillating dipole as per Maxwell's equations the charge must radiate an electromagnetic wave. So an oscillating dipole is the source of electromagnetic wave. If the distance between them is changing the dipole oscillates.

When oscillation takes place an electromagnetic wave is radiated. That is how every vibrating atom in the silicon crystal is also a source of electromagnetic wave; a source of elastic wave - that is phonons. It is also a source of traveling wave that is electromagnetic waves therefore you have photons moving about in the crystal. So you have phonons and the photons. And as we said these waves emanating from different atoms will interfere.

In the particle equivalent parlance we can say: many particles can converge on to a point, there is interference from waves emanating from different atoms, and they interfere at a point is equivalent to many particles converging on to a point. And if this happens, if the total energy of these particles is more than the bond energy between two atoms, that is, 1.1 electron volt in the case of silicon then it is possible to break the bond.

What is the consequence of breaking the bond? It is after all a bond is created between the two valence electrons between two atoms. One of the electrons is set free and there is a free electron. This is how a large number of particles converging on to an atom can give raise to a broken bond, and in other words it can give raise to a free electron.

The electron jumps out of the bond as shown in this diagram as a broken bond and an electron being set free. An electron being set free means that is no more localized to any atom. There is no sufficient freedom for it to be outside the crystal, it is only free of the particular atom which was holding it; but it must move about within the crystal. So it does not belong to any single atom, in that sense it is free to move about only within the confines of a crystal. There is a vacancy left behind by the free electron.

Since absence of a negative charge the neutral region will be acting like a positively charged place. In the presence of the electron everything is neutral, so in the absence of the electron it becomes positively charged. The vacancy created is called the hole since it is devoid of a negative charge and is neutral with the electron or with the negative charge the vacancy is positively charged.

What we gather from this description is that for T greater than 0k within a semiconductor crystal there will be four types of particles moving about. These four types of particles are: phonons which are elastic waves emanating from atoms, photons which are electromagnetic waves emanating from atoms, free electrons also regarded as De Broglie waves; free electrons created because a large number of photons and phonons can converge on to a silicon atom and if the total energy exceeds the bond energy they can break a bond, so you have free electrons. And an electron that has left a vacancy – the vacancy itself can move about and is positively charged. It can respond to electric fields, it can move in the responds to electric field therefore can be treated as a carrier of current and this is the hole. So electrons, holes, phonons and photons are four types of particles which are present.