High Speed Devices and Circuits

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Lecture - 3

Classification and Properties of Compound Semiconductors

We discussed last time, some of the important characteristics which are important for high speed devices and circuits. The most important thing that I have emerged is the mobility or the velocity of the carriers. When we say mobility, it is actually the low electric field mobility that we are talking of. One has to ultimately take a look at entire velocity field characteristics. That we will not take up right now. Right now, we are happy that there are materials which give better mobility than silicon. So, that is what we discussed last time and also we just take a quick look at various materials which are available. It was just a glance. It was a flavor that I gave you last time.

We get into bit more details on that today. So, that is why, we first classify what are these materials? In fact, we saw last time that it was the materials like gallium arsenide and indium phosphide etc., which are of importance. So, now we take a look at the classifications and properties of compound semiconductor or in general semiconductors. So, just see here, the slide straight away shows you.

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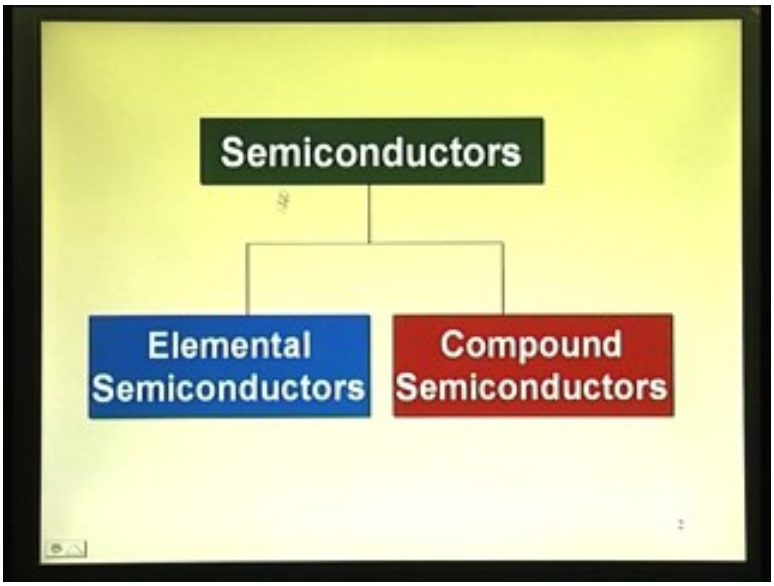

What generally, we say Semiconductors can be classified as Elemental Semiconductors and Compound Semiconductors.

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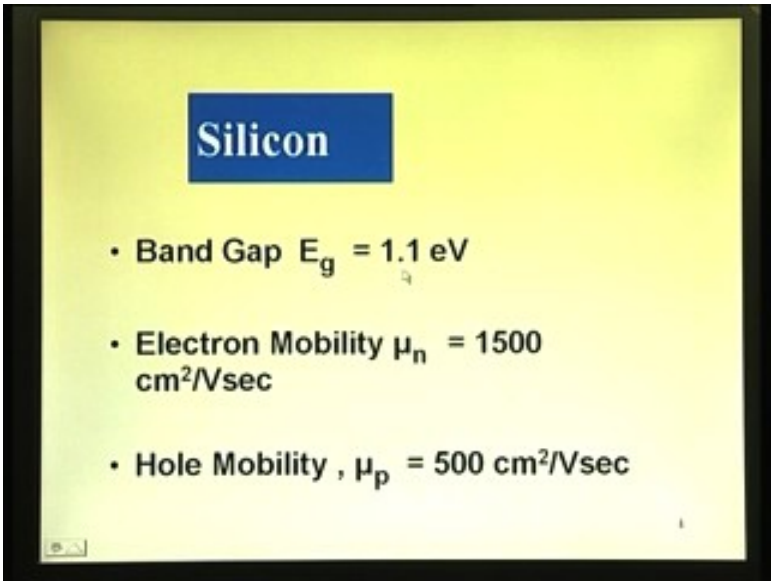

What is it? One is the elemental semiconductors that we have seen all of us are familiar. The moment you say semiconductor in 1950's, they would say it is germanium which belongs to the fourth group of the periodic table, germanium and it has a band gap of 0.72

electron volts. I am reiterating what we have said earlier, just for completing the discussion. Then, electron mobility of 3600 centimeter square per volt second which is very good. In fact, we will see it is better than silicon. So, if mobility where only the criterion, we would have used germanium although, but we have pointed out last time, why germanium got lost its way in the integrated circuits. The hole mobility, of course, is 1700 centimeter square per volt second. This is just for completness sake.

Now, if I take the more important fourth group semiconductor that is silicon. We also said why silicon is all pervasive or today, we can say it is only present. Now, it has a band gap of 1.1 electron volt and electron mobility of 1500 centimeter square per volt second. It has hole mobility of 500 centimeter square per volt second. Notice, these are lower than that of germanium but the scoring point is for silicon is the band gap is higher. So, you can make device which will go right up to 150-200 degree centigrade or a germanium will stop working when you reach about 70 degrees or 80 degrees, that is all hands up. Now that is about the elemental semiconductors belonging to the fourth group and mainly they are in fourth group and these have particular structure called diamond structures which I will take up may be tomorrow.

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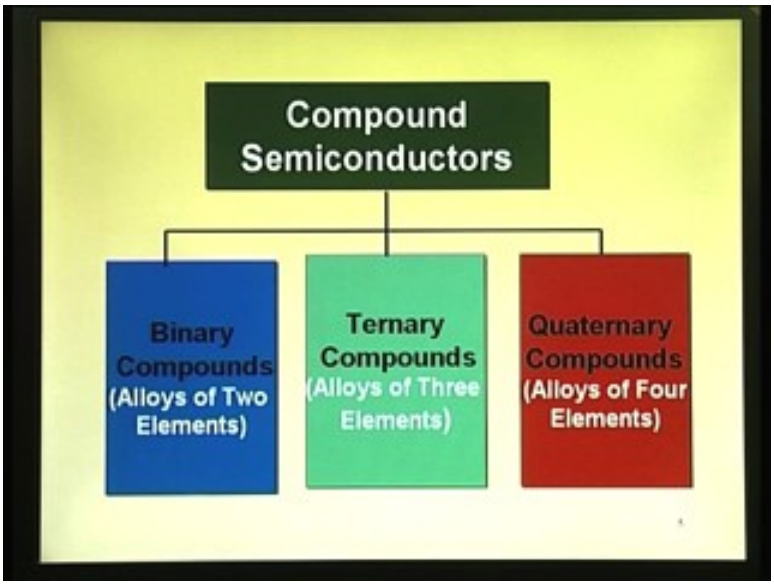

Compound Semiconductors, the moment we say compound semiconductor, we have

opened up a huge window through which you can see here. Mainly you can classify into three categories: one is the Binary Compounds which are compounds of two elements. It can be from any of the two groups from the periodic table and then other one is the Ternary Compounds. As the name indicates, it have got three elements which form the compound, which form the alloy. Then, you have got Quaternary saying that it has got four alloys, four elements which are constituents of the compound. so, we have Binary, Ternary, and Quaternary Compounds. Now, when you open further each of these windows, each of them will open up and there is in fact, you can say a huge galaxy of materials which show. So, let us see what are those things.

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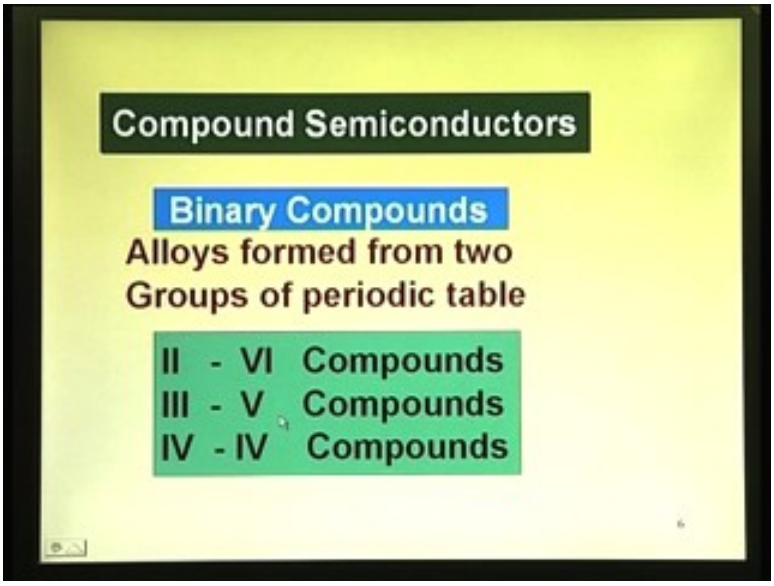

Binary compounds, let us take the first one. If you take the binary compound, as I said two elements form the compound and you can see here II - VI Compounds, III - V Compounds, and IV - IV Compounds. These are formed from the two groups of the periodic table depending upon which group are chosen. You call it as II – VI, III – V, and IV - IV. II - VI meaning, we have got the elements from the second group and the sixth group forming the compounds. III - V means you have got the elements from the third group and fifth group which formed the compound, and when I say group, it is a periodic table that we are talking of, then you have got IV - IV, and rush through the some of these things last time, just to give a flavor. This time is getting down to get more details.

So that is the thing.

Now let us see what are these II - VI compounds first and then we will see III - V and then we will take IV - IV. IV, you can see one of them you know already familiar silicon, other one is germanium and you can see other materials like carbon are there. II - VI compounds, groups and compounds formed by second group and fifth group element from periodic table, those are II - VI compounds.

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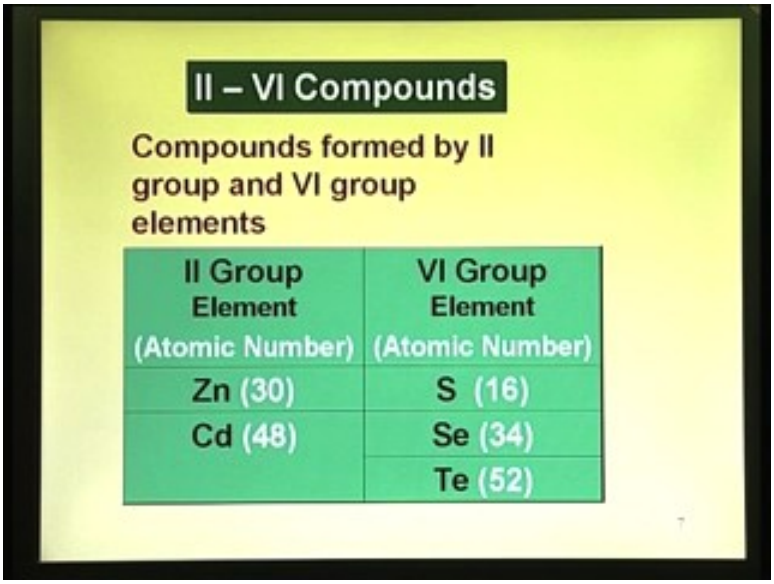

Now, you can see I listed out very popular semiconductors which people work on or people had been working on for over two to three decades. The second group, you can see there is zinc, cadmium within bracket I have written with this numbers that is atomic numbers. So, 30 is the atomic number of zinc. I just put it to give an idea of the atomic weight. Larger the atomic number, larger the atomic weight. It has some consequences on the performance of the properties of the compound. That why, I just put those numbers there

You have got cadmium which is heavier, the atomic number 48; sixth row we have got sulphur 16, atomic number; selenium 34; and tellurium 52. So, we have got heavy elements like zinc and cadmium etc. with large atomic numbers. In fact, atomic weight will be about 2.5 times that, anyway that does not matter. What matters is this atomic

number.

So, you can pick up zinc, you can form II - VI compound with anyone of them from sixth group. You can have zinc sulphide, zinc selanide, and zinc telluride. I hope you are able to see there? So, any way zinc sulphide, zinc selanide, and zinc telluride. Similarly, you can have cadmium sulphide, cadmium selanide, and cadmium telluride. Notice, all these have atomic number which are rather large. So I just whatever I have said now put it in the form of VI compound forms.

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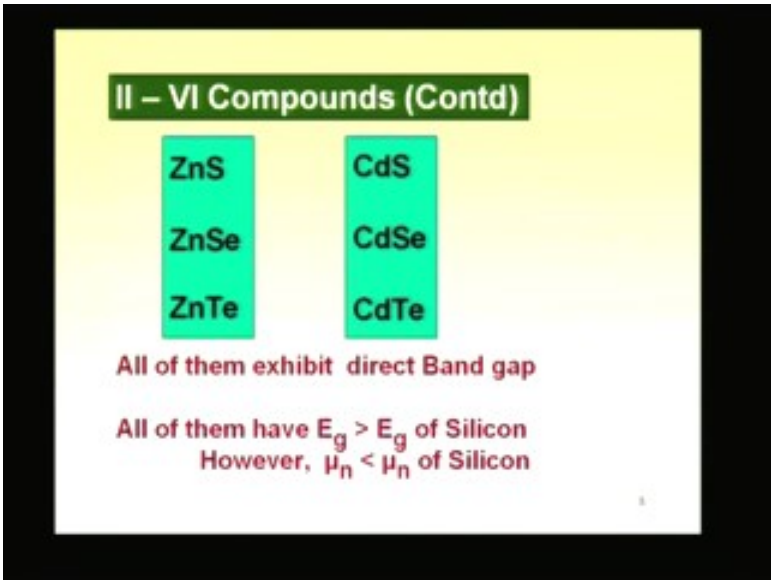

With zinc sulphide, zinc selanide, and zinc telluride, with cadmium sulphide, cadmium selanide, and cadmium telluride. Now, all these semiconductors which are formed by accommodation of the elements whose atomic numbers are rather large and they seemed to form direct band gap materials. I mentioned to you last time, what is direct band gap material? To recapitulate once again, I just draw the diagram on the board.

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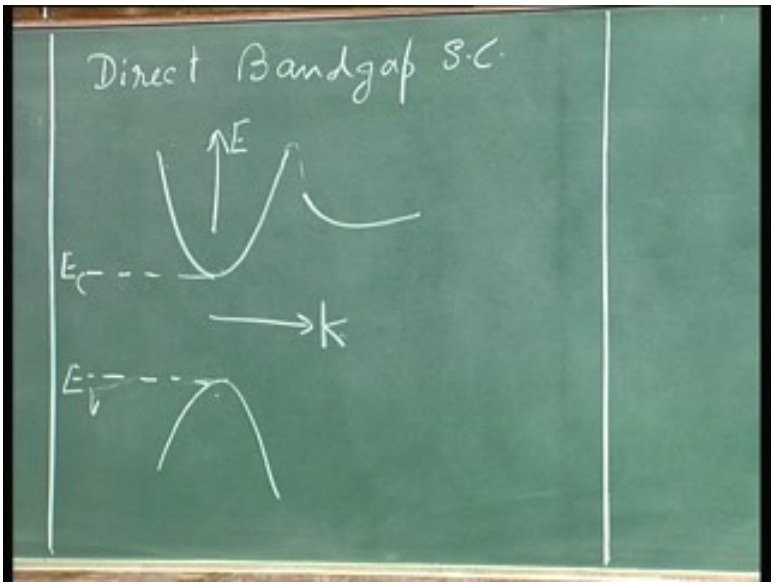

So, the direct band gap semiconductor S.C. is standing for semiconductor. There is just a simple diagram which will be like this. This is a continuous thing which comes out like this. I have shown just as broken, so this is the energy and this is the momentum EK diagram and this will be the bottom of the conduction band E_c and this is the top of the valence band. These are the two which matter because the transitions takes place from the lowest point in the conduction band and the highest point in the valence band and here the transition can take place just by interaction of electron from here, from here to here but interaction of electron is photon. In the sense, just the energy they have dropped by a photon that is sufficient, a direct transition is possible and all the materials like all these materials have that band structure, II - VI compounds where the atomic numbers are rather high. Why it is? Let us not question that, just is the observation, but when you have high atomic number, they turn out to be direct band gap.

This is the central valley. In fact, we can call them valleys where it looks like a valley, central valley in the energy band momentum diagram. This is the satellite valley. In fact, if you give enough energy for the electron, they can go from right up to this point. The consequences of that, we will see when we will discuss the velocity field characteristics totally. That is very peculiar to the Direct Band gap Semiconductors.

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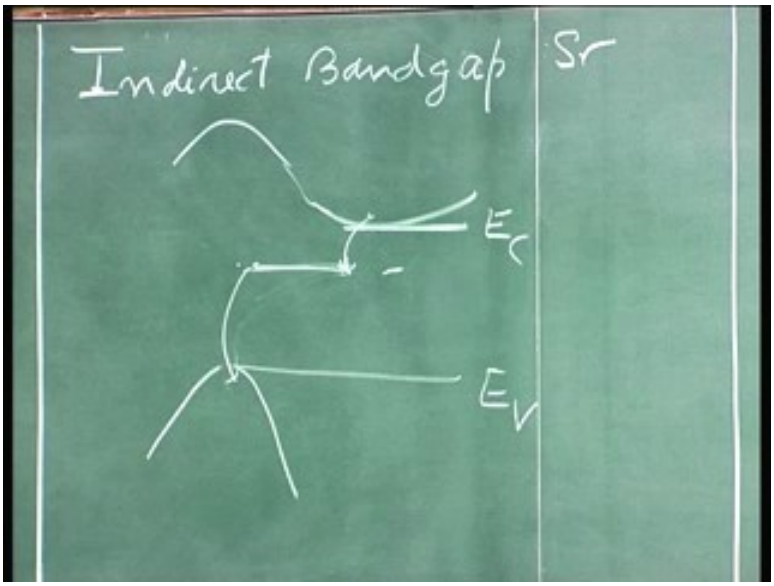

Now, you go back to this Indirect Bandgap Semiconductors. There, we saw last time itself. You will have the valence band like this and the conduction band may go like this. But, normally what they do is, they break up this and put this alone and may be like this. But, it is a continuous thing.

So, here this is the bottom of the conduction band E_c and this is the top of the valence band. Normally, when you plot the energy band gap diagram, you draw only these two lines because they are the one which are relevant for you. They are the ones which tell you where the electrons within a conduction band. They are the ones which will tell you where the holes are in the valence band. So, the transition from here to here, no it cannot take place directly with the help of photon _____. Because, the momentum of photons is small corresponding to that energy. So, result is, if a photon has to participate with the transition of electron from the conduction band to the valence band, it cannot conserve the momentum; it can conserve only the energy. Iit can absorb only the energy, it cannot absorb the momentum difference.

So, what we said last time is to reiterate, it will just make a transition to an intermediate level and from there it will come. In fact, intermediate level will come like this. It you make a transition to intermediate level. They are actually impurities which are present or

defects. What happened is, the electrons which are in the mobile in the conduction band, it will get trapped in those levels. The moment if trapped, its kinetic energy is lost rather its momentum is lost. The moment its momentum is lost, that momentum is zero here. It is brought down to this point and from there it will transit here. So, you have a two step phenomena taking place where the electrons are transferred from the conduction band to the trap level and from the trap level to the valence band. I think, in some other courses, it might have not touched upon _____ detail.

So this, because there it cannot be a direct transition from here to here. It has got to be through indirect some levels, it is called indirect band gap semiconductor. But the point to remember is when there is direct transition, it can emit light. When there is indirect transition like this, it can emit light corresponding to this energy.

Because, the momentum I have seen difference has been taken care of here. From here to here, whatever energy difference is there, can be absorbed by light. Because momentum has already been conserved transferred as heat into the lattice into these impurity and the rest is given out as light.

So, it is a combined effect of phonons and photons. In terms of, if you want to use that jargon phonons and photons. It is a layman language. In the layman's language it is that is absorption as heat and light. Ultimately that energy difference is as heat absorbed in the lattice. It is emitted as light to the outside. So, the wavelength depends upon the energy difference. This is just about what we have been telling about this particular material. These turn out to be a direct band gap materials. Most of them, noticed the atomic numbers are rather high 48, 35, 34, 52 etc.

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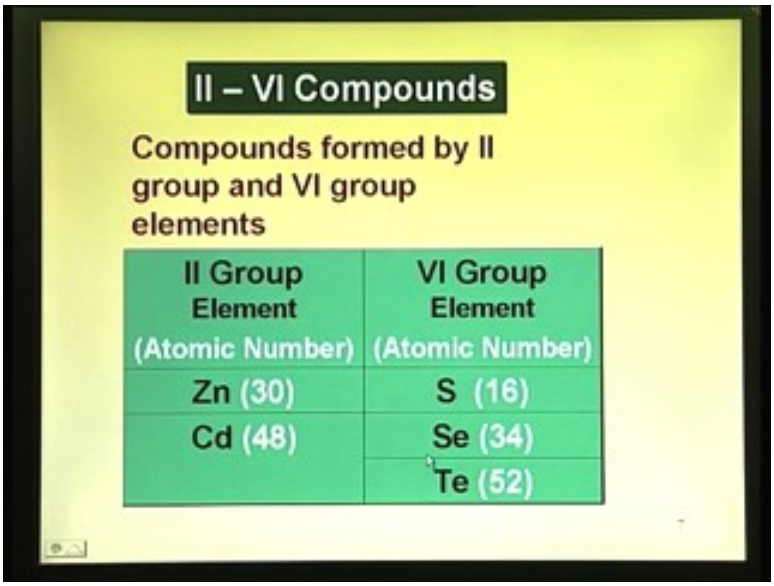

Notice their atomic numbers are rather high 48, 35, 34, 52 etc.

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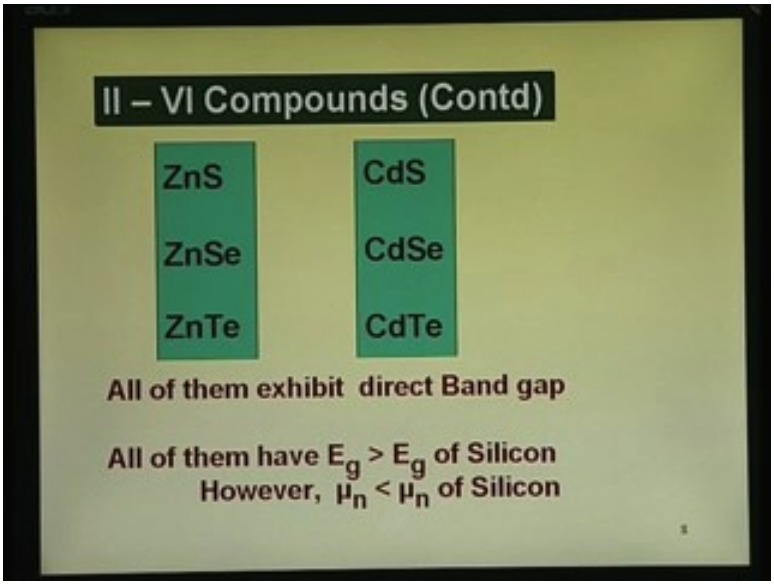

The other thing that we have to see here is as far as band gap is concerned, you will be happy about this. As for as, mobility is concerned, you will not be happy. Take a look at. I have just put the summary here; the band gap is higher than that of silicon for all these materials.

In fact, when you form the compounds with higher elements, it not only will turn out to be indirect. The atomic number is higher; it turns out to be also higher bandgap and it is not get into the phases of that.

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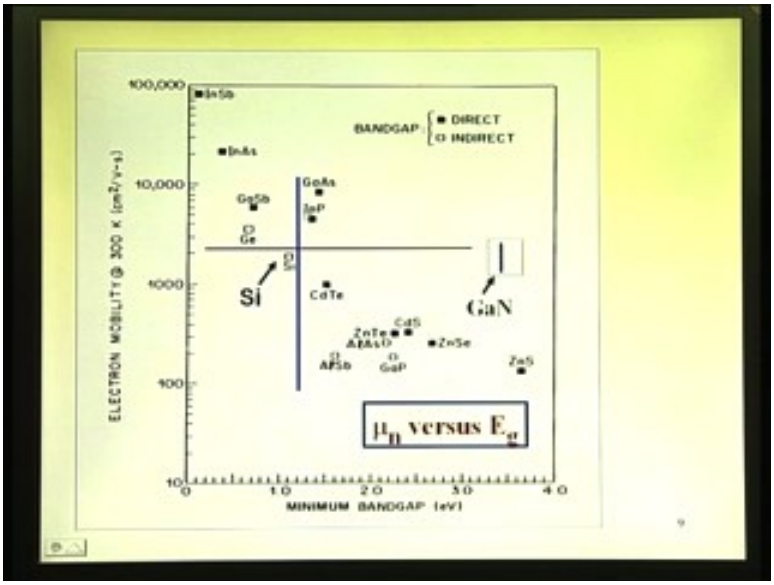

So, mobility is smaller. This is the diagram which I have put last time. It also, but now, what I have done is I just added few things into this. The whole thing out of compounds I have put there to look in this particular previous slide was II - VI compounds. See, what those are: This blue line is telling you a line which divides between all the materials on the right hand side have got band gap higher than that of silicon and to the left hand side all these materials have got band gap less than silicon; and the red line, all those materials which are above this line have mobility higher than that of silicon. So, we would like to take a look at high mobility materials and also at the same time we would like to take a look at materials whose band gap is higher than that.

So, let us see this particular II - VI materials. Are they any good for microelectronic devices? Are they any good for high speed devices or devices at all, just microelectronic devices? See Cadmium telluride. Cadmium telluride is there. Wider band gap larger than that of silicon and mobility is lower than that of silicon. Cadmium sulphide band gap larger than that of silicon, it is about 2.5 electron volt and mobility much smaller.

Electron mobility we are talking of, it is just about 300 or 350. Zinc telluride band gap of about 2.3, a pointer shows there and the mobilities comes around 300 to 350 which is much smaller than that of silicon. You do not like to take a look at those materials whose mobility is much smaller than that of silicon though the band gap is very good and you can send us going one by one so that we get a complete field for that thing. Zinc selanide again 2.8 electron volts band gap. Mobility, very poor, there are 300. Zinc sulphide, we are worried about only band gap fantastic something like 3.8 or so mobility, you can see it is way down something like about 100 to 150 centimeter square per volt second, no good. So, none of these materials will be suitable for microelectronics in spite of the fact that band gap is higher, but interesting part of that is, they are all direct band gap materials. The moment you said direct band gap semiconductor, it will be useful for optical applications. Because, if it is a direct band gap materials, direct transition can takes place with electron transition light emission. Light emiting diodes and even in some solar applications, they will be useful. The transition from here to here or here to here can be managed by means of light. If you _____ light, the transition can be from there to here. If you allow inject carriers, they can fall from here to here emitting light. So, reverse processes in both directions, light emission or light absorption can be easily done. Some of the photooptical or optonics, optonic devices which also are some of the high speed devices today that means not for microelectronics.

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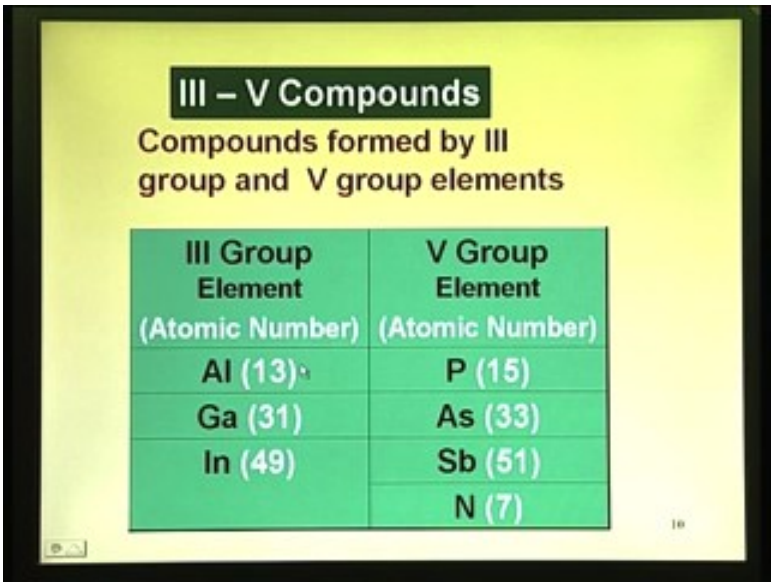

Let us now go back to the next one, the most committed thing that is the once, III - V semiconductors; third group and fifth group. These are compounds formed by third group elements with fifth group elements.

Third group are listed here, the popular third group elements. Aluminum, gallium, and indium. Notice it have an order in order of increasing atomic numbers 13, 31, and 49 atomic numbers and heavier and heavier elements. On the right hand side, similarly, I have got phosphorus, arsenic, and antimony. It is interesting to note that these are 13, 15, 31, and 33. That is 13 aluminium, phosphorus 15, 31 gallium, atomic number of arsenic 33, germanium is actually inbetween 32 fourth group element. So _____ there is some other fourth group element is there. Very interesting to remember. I think you have to go back to your physics periodic table: third group, fourth group, and fifth group. Third group is 49; fourth group is missing there, and fifth group is 51. So, increasing atomic number, correspondingly increasing atomic number, and there once last one nitrogen. This I have added recently that is why it is not coming in order. I have added recently because it is a material which has cloned attention in the recent years.

Why, we will see that. So, now let us see you can make the compounds of aluminum with anyone of them; aluminum phosphide, aluminum arsenide, aluminum antimonide, and aluminum nitride. Now, you can expect that most of these materials are of indirect bandgap because the atomic number is small.

Similarly to make gallium, gallium you can make gallium phosphide, gallium arsenide, gallium antimonide, and gallium nitride; that is the material people boast of so much these days or _____ or varieties of applications including microelectronics and optoelectronics

There is a jackpot in which people have hit recently and lot of work is going on in that. Then, you can expect here, combination of gallium and phosphor, gallium phosphide could be indirect. Because atomic numbers of both are small and other two; gallium arsenide, gallium antimonide etc., could be direct because atomic numbers are high. But for any law, you know there is some exception. Gallium nitride, it does not fall into the category somehow that is a direct band gap semiconductor though the atomic number is

small there. Indium, 49 is the atomic number. You can immediately say that the compounds which are formed with other fifth group are direct band gap. So most of the indium compounds are direct band gap. Gallium compounds except gallium phosphide are direct band gap. Aluminum compounds, all of them are indirect band gap

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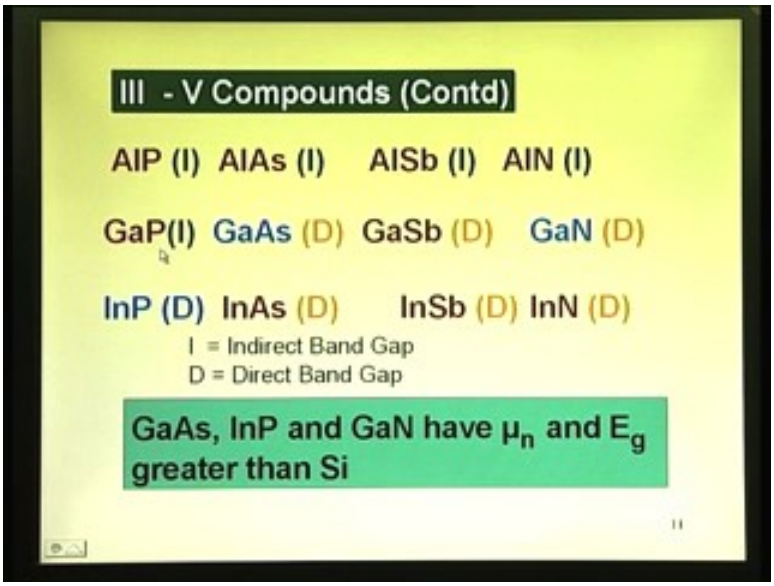

So, these the list which I just now mentioned which is formed. That is, the I inside the bracket is indirect. The D inside the bracket tells you it is a direct band gap. I have written down here. So, you have got aluminum phosphide, aluminum arsenide, aluminum antimonide and aluminum nitride, all indirect band gap semiconductors because the smaller the atomic number 30 of aluminum. Then gallium phosphide, that is indirect because even though gallium is 31, phosphorus is 50.

So, that is why the total atomic number is rather small so that is indirect. Gallium arsenide, antimonide, and gallium nitride all of them formed direct band gap as I have just now pointed out to you. Indium phosphide, you can see all, whole lot of them the indium atomic number is 49, big atom. In fact, its _____ radius is 1.44 angstroms compared to 1.18 angstroms of silicon, huge. You can say 1 angstrom, 1.44 angstroms, but looking into atomic scale, you go down stand with atom 1.11 or 1.18 of silicon and 1.44 for indium, this is huge difference. So, they are formed the direct band

semiconductors.

So, now what we are telling is, if we go back to the table, a big diagram where you have got the y axis the mobility and x axis the band gap. If you go back, you will see the gallium arsenide, gallium phosphide, and gallium nitride have band gap larger than that of silicon. Gallium arsenide and gallium phosphide have mobilities larger than silicon definitely.

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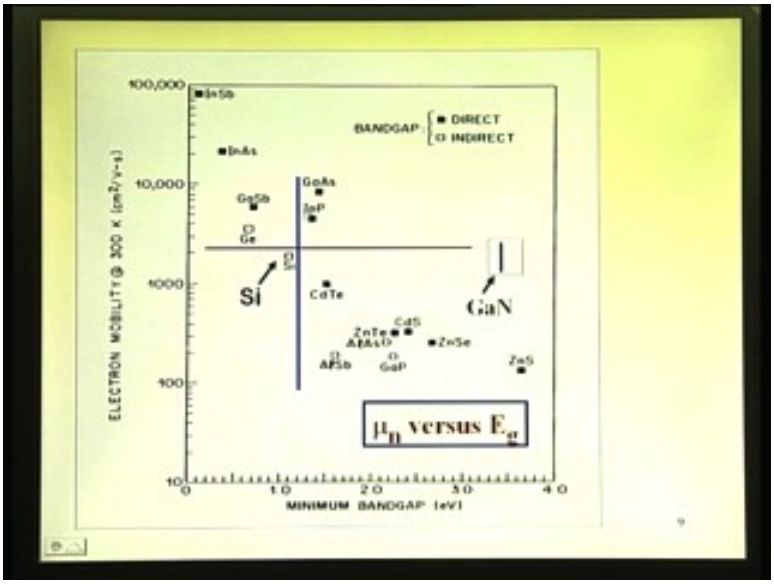

Gallium nitride slight question mark. We will go back to it. If you have just finished by seeing this, we will go two slides backward here. You can see here what we are looking for is above this line and to the right and there are only these two materials: That is gallium arsenide and indium phosphide. Silicon for example is here. SO, among these materials, all these materials, indium antimonide, indium arsenide, and gallium antimonide, they are all direct band gap semiconductors. I am telling you that they could be used to optical applications dealing with light, but for microelectronics, there is no use because their band gap is much smaller than that of silicon.

For example, indium antimonide is something like 0.18 or something like that. Indium arsenide is about 0.3 electron volts. It is very difficult to make a junction which works at room temperature. Because, lot of carriers are present, and lot of carriers are present,

leakage current is large. Supposing, you are carrying intrinsic concentration is 10 to the power of 18; how will you make it as extrinsic? Make a pn junction at room temperature. See, silicon intrinsic carrying concentration know, it is 1.5 into 10 to the power of 10 per centimeter cube electrons and holes. Now, if you put dopants like 10 to the power 12, donors that becomes n type, it is very easy to make n type material 10 to 12, 13, 14 and 15 at room temperature. If you take for example, a material like gallium arsenide; its band gap is 1.43. There the band gap is higher than that of silicon which would mean the intrinsic carrier concentration at room temperature is much lower about 10 to the power of 6 for a centimeter cube.

So very easily, you can dope. At the same time, you must be concerned about the impurities that come in also. The impurities in trace of 10 to the power 8 will show first some sought of dopants. Whereas silicon, if the impurities at the level of 10 to the power of 8; you would not care about. So, these are some of the classic things each one has to remember. Very important things one must remember.

Now, the point that we have to make out was a material like indium arsenide whose mobility is something like 20000. You just do not look at it for microelectronics. Reason, its band gap is some 0.33. So, its carrier concentration, intrinsic carrier concentration is up above 10 to the power of 15 or 10 to the power of 17 per centimeter cube. So, if you dopants of the order of 10 to the power of 15, what will happen? Intrinsic carrier concentration is 10 to power of 17; dopants are 10 to the power of 15. If the dopants are buried in that or submerged in these electrons which are already present. It is like pouring few drops of water into ocean. It is not sea. So it is exactly that is the thing that is happening 10 to the power of 17 or 10 to the power of 15. If you have to so that means, you add 10 to the power of 15 p type dopants and 10 to the power 16 n type dopants, it does not make a junction because you have a high concentration of electrons and holes. How can you make this device work as the pn junction? These devices, if you want to make it as pn junction; how can you make it? You have to reduce the intrinsic carrier concentration. How can I reduce the intrinsic carrier concentration? Lower the temperature; you have to cool them down below the room temperature and bring down the carrier concentration 10 to the power of 13 and 10 to the power of 12.

Then, if you have dopants up the order of 10 to the power of 15, it will act as the pn junction. That is what I strict pointing out last time that it is difficult to make devices which work at room temperature junctions. So, those devices are invariably cool. IR detectors which are made some of the devices are cool much below the room temperature.

So, that these intrinsic carrier concentration which is actually behave like noise in those devices with the lowered. So that is the key thing here. So, that is why, we are not able to choose these materials. In spite of its excellent mobility, we are are not able to choose it for microelectronics and the very reason, these two materials are suitable for microelectronics because of the better band gap and better mobility.

Mobility is at least five times larger for gallium arsenide, at least three times larger for indium phosphide. Electron mobility, we are talking of. It is enough if we are able to get the electron mobility. We do not have to worry about other one, which you can talk of devices which depend upon electron transport alone.

Now, there is one thing that I put in box I have put here and you can see that I put a vertical line there. The vertical line tells you the reported mobility for gallium nitride varying from 1000 right up to about 2000. So, if I can get 2000, I am in business because that is better than the electron mobility of silicon, if at all depends. You know that is here we can see the band gap of gallium nitride GaN is something like 3.49 electron volts and you can imagine what will be the intrinsic carrier concentration is. See, when you went from silicon 1.1 electron volts to gallium arsenide which is 1.43 electron volts, 1.1 to 1.43, the carrier concentration fell down, intrinsic carrier concentration fell from 10 to the power of 10 to 10 to the power of 6 almost about 3 to 4 atoms _____. If I go to this gallium nitride which is 3.5, absolutely, practically _____ no electrons. Electron that you will get be from the impurities that you had. These impurities can intentional or unintentional. You want the devices to depend upon your intentional dopants, intentional donors, and intentional acceptors. So, there, those are the moments which actually affect this mobility. You get the range of mobility because of unwanted impurities, they can see the chart present, the chart has some sort of dopants.

So, if you get better and better material that means purer material, we get better mobility. That is by the range is telling you that this material is still a material that people are looking into it. See the whole thing in microelectronics, the way it goes is the demand comes from the system engineer and the system engineer puts the pressure on circuit engineer and a circuit engineer puts the pressure on device engineer and the device engineer finally says give me a better material. So, the ultimate pressure is taken by the materialist, material engineers. So, we can see that lot of people work on materials. In fact, in some of the conferences that we see on, for example, international workshop on physics of semiconductor devices, you saw huge number of papers published on materials. That is the starting point.

This is the thing about these types of materials. That is the story about the III - V materials and ultimately we have gone into gallium arsenide and indium phosphide are the ones. Of course to some extent taking a look at gallium nitride and indium nitride. Indium nitride if at I look at, the band gap that the people talk of a wide range. Recently, they have started talking of band gap of about 0.7 electron volts. It was much smaller earlier.

So, the whole range you can just get there in the sense whole range has been has been reported, that means still people are working purifying those materials. What it is may be? We may have a chance to just have a glance through it. I do not intend to convert these series of lectures on high speed devices and circuits into materials but ultimately, materials required. In fact those who work on VLSI design will be comfortable if they know about devices, if they know about something about materials also, so that they have the pack up. Those who do not know about both devices and circuits both only know the layout portions of that computer type of algorithms and they feel bit helpless.

I hope there are no computer engineers here who will not agree with me. So that is the fact. Students were gone abroad from with the electronics background with devices and circuits found that it is very comfortable. We could have join our industries here. We also found that it is comfortable knowledge of devices and circuits and also materials.

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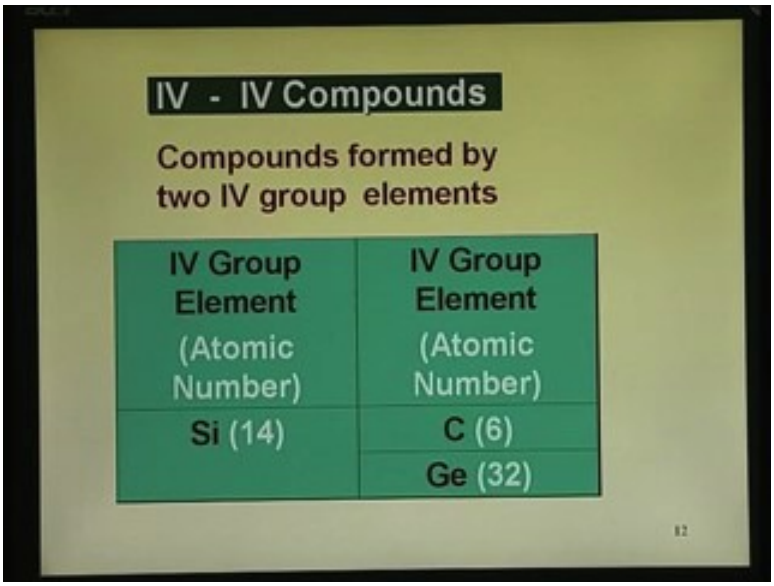

Now, let us take a look at the IV - IV compounds. So, we have finished and we are still on binary II - VI, III – V, and IV - IV. Silicon fourth group, carbon fourth group. Silicon itself is indirect band gap semiconductor. So all the more, if you make compound of silicon and carbon silicon carbide, it will be indirect band gap. If it is heavy atoms, it turns out to be a direct band gap. If it is lighter atomic number small it turns out to be indirect and there is silicon germanium, alloy of silicon and germanium both are semiconductors _____. Both are semiconductors and we mix them, both are indirect. But you will get only indirect band gap semiconductor. So you cannot use it for optical application, so take this as VI.

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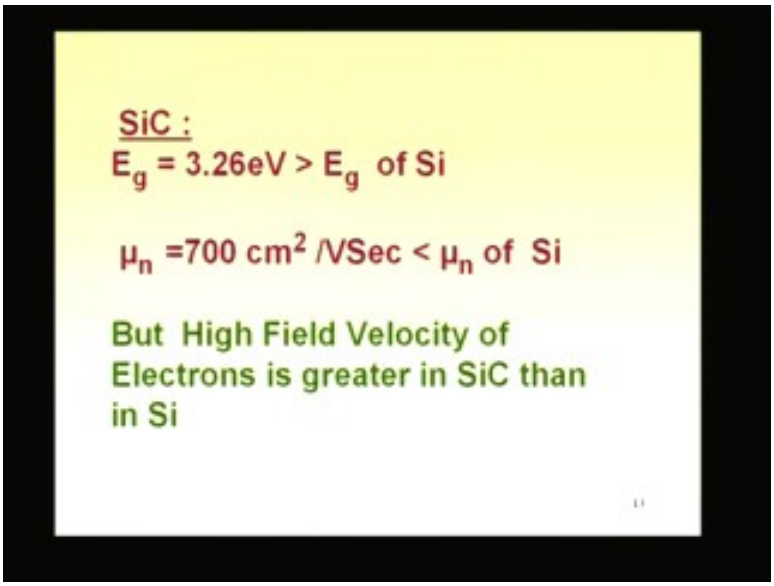

Now silicon germanium, we will touch upon little later, but silicon carbide is a material which looked into very vigorously looked into, very vigorously looked into because its band gap is larger than that of silicon. It does not get our nod today because, because of this dopants mobility.

It is smaller than that of silicon, but the interesting part is ultimately what you would like to take a look at it is, this will tell you about the low field velocity. As increase of electric field, how the velocity is changing? That will be smaller and that will decide of course the ON resistance. We discussed about ON resistance which is inversely proportional to the mobility and directly proportional to the channel length.

So this particular case, you will have problem with ON resistance, but we will have occasion to discuss this in slightly in more detail, the total velocity you should take. You take velocity at higher field and those velocities of electrons are greater in silicon carbide than in silicon.

Now, you can see, if you are talking of smaller and smaller devices for a given voltage, it drops across a smaller length, the fields are high. Those high fields that is a saturation velocity if you can call it; the high field velocity in silicon carbide, it so turns out that it is higher than that of silicon. I am not projected it right now, just briefing you right at this

moment, why I have put this slide? That is because it is a material in which also a lot of work is going on. So it is not mainly III-V, it is II - VI also here. Silicon germanium also for some Heterojunction Bipolar Transistors, they are used.

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Now, let us put the summary of these properties of the III - V semiconductors which are suitable for microelectronics.

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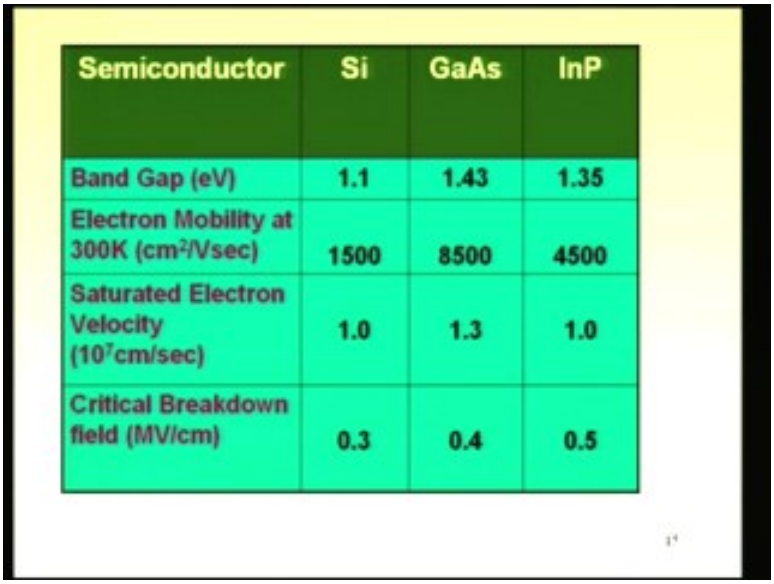

Semiconductor	Si	GaAs	InP
Band Gap (eV)	1.1	1.43	1.35
Electron Mobility at 300K (cm^2/Vsec)	1500	8500	4500
Saturated Electron Velocity (10^7cm/sec)	1.0	1.3	1.0
Critical Breakdown field (MV/cm)	0.3	0.4	0.5

So, what you have said is; today, it is silicon elemental compound used everywhere for microelectronics and computing the compound materials like gallium arsenide and indium phosphide. You can see, this is the table which summarizes most of the thing like band gap is 1.1 electron volt for silicon; 1.43 for gallium arsenide; and 1.35 for indium phosphide. Electron mobility; 1500 for silicon centimeter square per volt second of course, 8500 for gallium arsenide assuming that there are no contaminants. If there are unwanted impurities that may come down. That is true even in silicon. If there are too many impurities are present that can come down. Indium phosphide 4500 centimeter square per volt second. Then saturated electron velocity, somewhat that is what I mean is when I go to high fields, maximum velocity that electron get; you know that velocity is proportional to electric field at low phase. As you keep on increasing the electric field, the velocity keeps on increasing, it cannot go beyond the certain limit. There is a limit saturation. That velocity in silicon is about 10 to the power of 7 centimeter per second into 1. Gallium arsenide is slightly higher. This is again that number 1.3, I put it is the more recent number which people are quoting. In fact, if you see some of those graphs, velocity field characteristics, _____ book which it returns way back or even some of the books which copy them; to tell you that I have put down one slide like that which will tell you that saturate velocity is slightly lower than silicon. But today, we will accept that saturation velocity is slightly higher than that of silicon which is good. So, that gives an added attraction for gallium arsenide; whereas, indium phosphide it is about 1 into 10 to the power 7. Then, other thing that we concerned will be the break down strength which you may not worry for VLSI because we are talking of lower voltages, but when you are talking of power devices, there you will talk of higher fields and breakdown voltages etc. Even here, you will worry about the breakdown voltage if your doping concentrations are large because fields will be high.

So in this case, the silicon has about 0.3 million electron volts per centimeter or 30 volts per micron; 1 micron gap can withstand 30 volts maximum. Generally, it depends also doping around 20 to 30 in that range. Gallium arsenide is 0.4 millionvolts or megavolts per centimeter which is 40 volts per micron. Then here, you have got indium phosphide which is about 50 volts per micron. Generally, it depends upon a band gap. Higher band gap should give you better breakdown strength. But here it seems the indium phosphide

eventhough it is slightly smaller band gap, it has got the better breakdown strength. These are measured values which we will have reverted.

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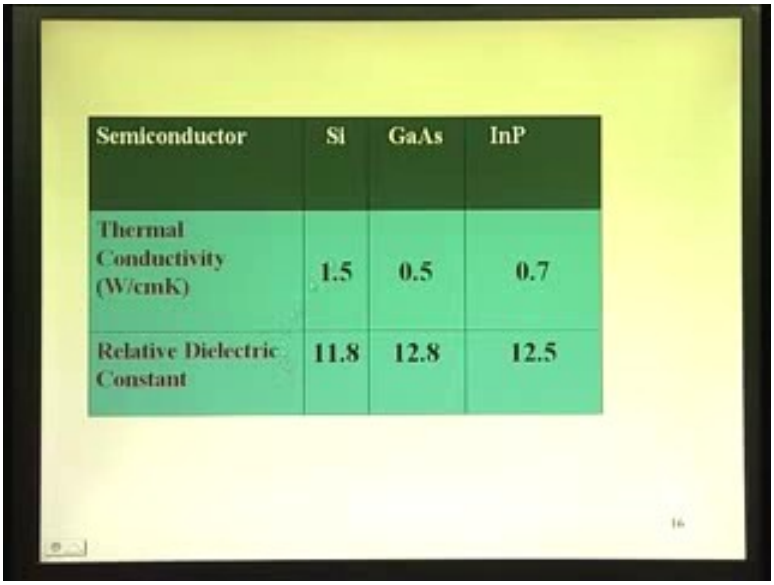

Now, other properties which people want to look into is thermal conductivity. Thermal conductivity of silicon watts per centimeter degree Kelvin is 1.5. Thermal conductivity of gallium arsenide is 0.5 and indium phosphide is 0.7. It may not matter for current transport thermal conductivity, but it matter for power dissipation. The way the power is taken away from the junction depends upon thermal conductivity. If the junction is somewhere on the top and on the other side you will have the contact to ambient.

Now, the heat generated at the junction should flow to the ambient, that flow is like conduction. How much flow is the conduction depends upon thermal conductivity. Higher the conductivity, is better. That is why silicon is scoring over other materials. You will see silicon carbide if you examine that has got even better thermal conductivity than silicon. So, that is why people look for silicon carbide for power devices not for high speed devices. Better thermal conductivity, mobility is not bad, but it is not good either but if you are not interested in higher speed but power, than silicon carbide is a good candidate.

But gallium arsenide, you can see it has that problem of the thermal conductivity being

the slightly smaller. Relative dielectric constant. That is not much difference 11.8; 12.8 and 12.5. Almost around that. These are almost comparable. It is smaller than that of germanium. Germanium, if you recall, it is 16, relative dielectric constant. It is a material. It may matter for some capacitor coupling etc., but otherwise it is that value. When we want to use for calculation, these are the things.

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Ternary compounds, we are finished yet. Binary, we have finished and in binary we had II - VI, III – V, and IV - IV and out of them, after all the searching, we found the III – V. Among them; gallium arsenide, indium phosphide, gallium nitride may be the once which we can use ternary. Ternary is actually formed by alloying three elements.

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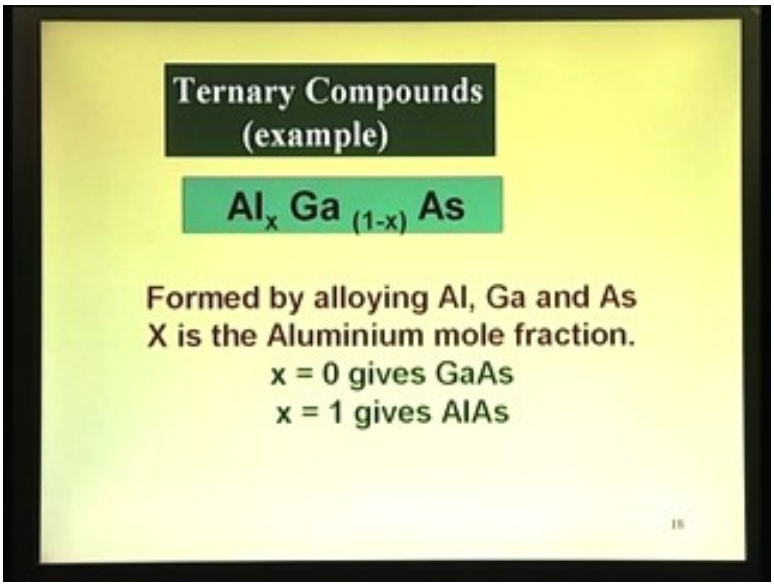

A very popular example is aluminum gallium arsenide. That is, you know these gallium arsenide if you want short form, we call it as GaAs. Aluminum gallium arsenide we call it as AlGaAs. If you take too much effort with the aluminum gallium arsenide, AlGaAs and InGaAs for indium gallium arsenide. So these are the shortcuts used like we use shortcut in the computer. We use shortcut while telling also and it becomes a jargon, AlGaAs.

So, makes life difficult for others and use jargons, but hence understand AlGaAs is aluminum gallium arsenide. You understand what it means. It is a compound made or formed by aluminum gallium and arsenide. Please remember and here also, x tells you what is the mole fraction of aluminum. If x equal to 0 use 0 aluminum and x equal to 0 means 1 minus x is 1, that means, gallium is 1. If x equal to 0, that compound becomes gallium arsenide and you can see here, it is stochiometry. For 1 gallium atom, there is 1 arsenic atom; 100 gallium atoms, 100 arsenic atoms that is gallium arsenide. Aluminum arsenide; 1 aluminum atom, 1 arsenic atom. Now, aluminum gallium arsenide is AlGaAs; if there are 100 arsenic atoms and 50 gallium atom and 50 aluminum atoms, x equal to half. If x is half, 100 here arsenic and 50 here, 50 here. So that is the meaning of x, mole fraction. Stochiometry is maintained. Total number of arsenic atoms is equal to total number of aluminum and gallium. What is happening is where gallium is supposed to sitting, the aluminum is sitting there. It is faking for gallium. It gives a totally different

property.

You can understand gallium arsenic arsenide has certain properties of mobility and band gap. Aluminum arsenide has got different mobility. The combination should have a combined effect. A band gap in between the gallium arsenide and aluminum arsenide, mobility in between that. Another example which is very popularly used why and how; that we will see subsequently is ternary compound is gallium indium arsenide. X equal to 1 gives gallium arsenide and x equals to 0 gives indium arsenide. This is formed by alloying gallium indium and arsenide. Stochiometry 1, that is gallium arsenide 1 gallium atom has 1 arsenide atom. Gallium indium arsenide 100, if there are 100 atoms of arsenic and if exceeds 0.5, they have 50-50. X is 0.6, they have 60 40 and x is 0.6, 60 gallium atoms and 40 indium atoms. If you have 60 gallium atoms then the property is closer to gallium arsenide. If you have 60 indium atoms, the property is closer to indium atoms. Indium arsenide band gap is closer to indium arsenide. So, these are the things.

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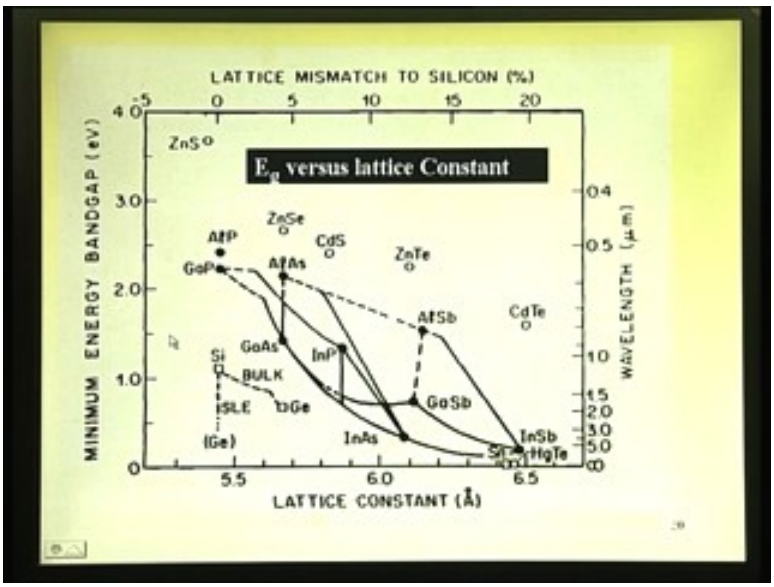

Now, this thing I think, you can see it here, but otherwise it is a very popular thing which is available. Literature, this gives entire structure, entire range of the materials with which you can form binaries with which you can form ternaries and with which you can form quaternaries. Now, notice here and let us start one by one.

We will continue on this tomorrow but today some of the things I will point out to you. You take for example, all these top notched devices here whose band gaps are high. As I said, they are all atoms with atomic numbers which are high that is bigger size atoms, their lattice is big. Now, you can see all these materials have got higher E_g all of them. Also you can see, when you move from zinc sulphide to zinc selanide, we will see that atomic number goes up and the lattice constant also goes up and zinc telluride; if you look back into your table, I have put sulphur, selenium, telluride in the increasing order of atomic number. So, lattice constant also when you mix with zinc, it goes on increasing.

Same way, cadmium sulphide and cadmium telluride is bigger lattice constant because larger atom size and same way you have got gallium phosphide phosphorus 15 atomic number; gallium arsenide arsenic atomic number is 33 and gallium antimonide atomic number is 51. So, it become bigger and bigger. So, what you are trying to point out is, you can actually have gallium phosphide, you can have gallium arsenide. You can mix them together, you can have gallium arsenic phosphide. See examples that I gave, two examples that I gave are changing gallium with aluminum or gallium with indium. Let us take look at that.

See for example here, gallium arsenide, I changed by adding aluminum that is aluminum arsenide. I mix them together depending upon how much x is present. I keep on increasing aluminum content here and moves towards aluminum and the entire thing, the energy gap actually changes from 1.43 ultimately it goes right upto about 2.2.

Notice also, here this is solid line. I have drawn that solid line because gallium arsenide is a direct band gap semiconductor. To recall back, aluminum arsenide is a indirect band gap semiconductor. So, if it is rich in gallium; when you make aluminum gallium arsenide, if it is rich in gallium, it has the property which goes to gallium arsenide. It is a direct band gap semiconductor. A solid line tells you that it is direct band gap but you see close to this edge here, the aluminum gallium arsenide here will be indirect because it has more leaning towards aluminum arsenide. So, the nice thing about this is, you can mix gallium and aluminum with arsenic and vary the band gap from 1.43 to 2.2. We can vary the band gap from the direct band gap to indirect band gap that is total engineering, band

gap engineering people call it as; always people love to use new terminologies. This engineering, band gap can be engineered by mixing the materials. More about these things, I will discuss. The entire picture will bring back. We will discuss there are lot of things said to be seen because this is the very popular picture everybody projects to see. Now so to sum up, we have seen the III - V compounds, II - VI compounds and IV - IV compounds. So, those varieties are there plus the elemental semiconductors and among all of them, you can choose any one of them. If you want microelectronics, gallium arsenide and indium phosphide. If you want other applications, you can opt for electronic. You can use other materials.

Thank you very much and we will see tomorrow, next class.