Nanoelectronics: Devices and Materials
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Lecture - 28
Compound semiconductors and hetero junction FETs for high performance

So, we continue our discussion on the compound semiconductor with materials and devices which are useful when you go to nano scale particularly.

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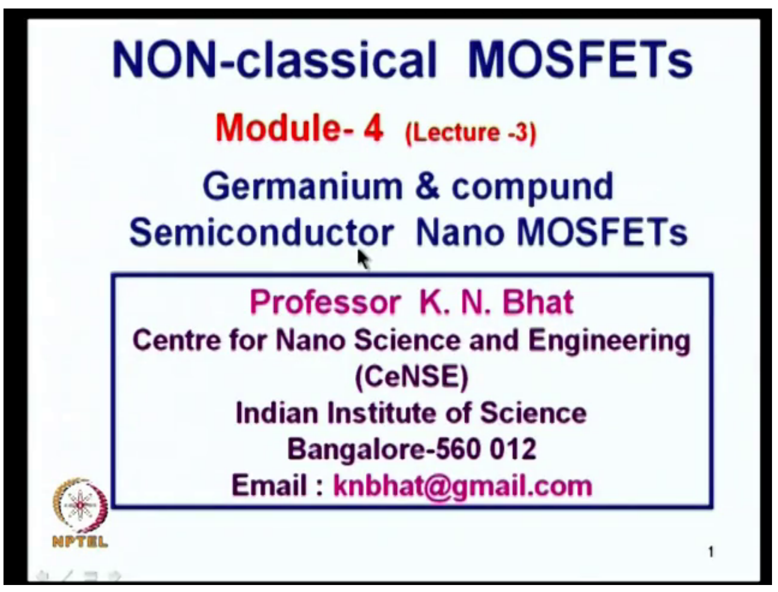

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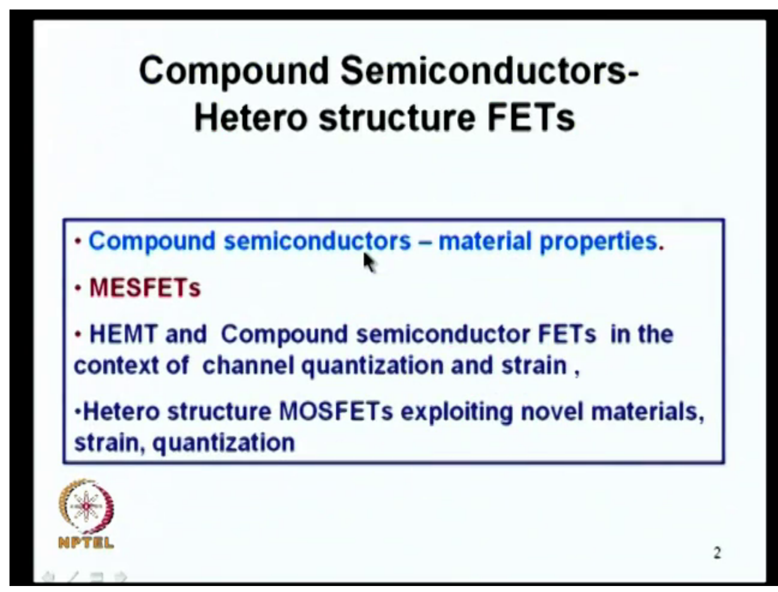

So, what we said is we will take up take a look at material properties, we have g1 through that in the last lecture and today we will see some more details about that and the properties, the velocity field characteristics and FETs using that what type of FETs are made popularly and then go on further.

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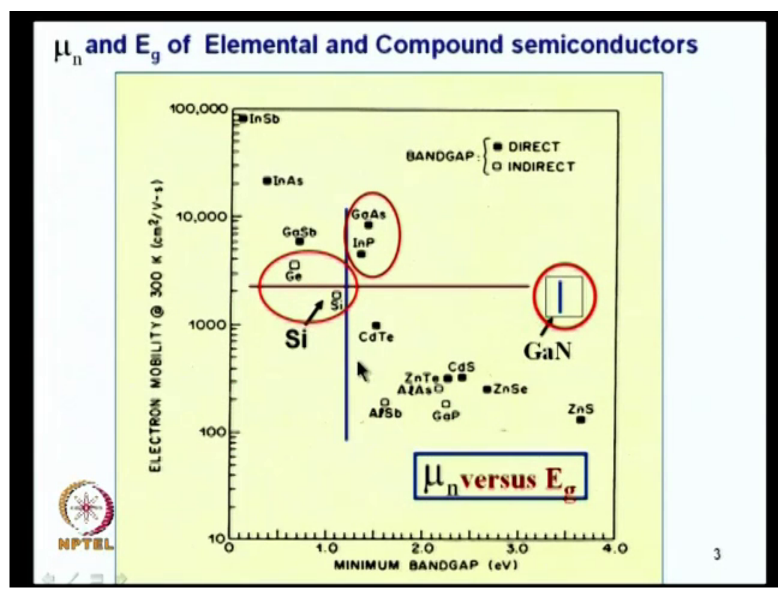

If the entire reason for taking a look at a non silicon materials is hidden or is described in this particular slide and you can see that on the y axis you have got the electron mobility. We are looking at deva materials which have got, electron mobility is higher than that of silicon which is the very popular material that is about 1500 centimeter square per volt second and the band gap is 1.1 electron volts at room temperature.

So, if you have to use or if you have to choose an alternate material which is superior to silicon, 1 of the thing that we look at is the materials which have mobility above this horizontal line that is above 1000 so 1500 or so. So, there are lot of materials the like that for example, indium antimonite, indium arsenide, gallium antimonite, germanium, gallium arsenide, indium phosphide including gallium nitride recently. Now, it is not enough if the mobility is high they should have also fairly decent band gap preferably higher than that of silicon or at least closer that of silicon. If you take a look at those ba materials which have band gap higher than that of silicon you have got a gallium nitride, but mobility is not much higher compared to silicon ideal value. Indium phosphide and gallium phos arsenide (Refer Time: 02:36) we pointed out last time we have got much higher mobilities or (Refer Time: 02:40) compared to silicon at least 5 to 6 times gap as that of silicon and gallium arsenide and at least 3 times than that of silicon and indium phosphide.

Gallium antimonite has got higher electron mobility, but band gap is smaller than that of gallium arsenide, germanium is the already that it is a potential material because of its high electron mobility as well as high whole mobility, but the drawback on the downside is that the band gap is lower, but due to when you do quantization confine make the thin layers, devices on thin layers than that mobility band gap can be improved.

So, you can also see here as I already pointed out gallium arsenide has got higher mobility, indium arsenide has got even much higher 220000 centimeter square per volt second mobility. But, if I can combine gallium arsenide and indium po gallium arsenide and indium arsenide make an alloy, which is a ternary alloy I can have the combined effect of these two that is higher mobilities and gallium arsenide can be obtained, but band gaps better than that of indium arsenide can be obtained. So, on takes look at material like indium gallium arsenide ok they are ternaries.

So, we can see that when you go into compound semiconductors you have got variety of

choices in terms of binaries, ternaries, quaternaries, quaternaries you have 4 elements gallium indium (Refer Time: 04:18) arsenide or materials like that.

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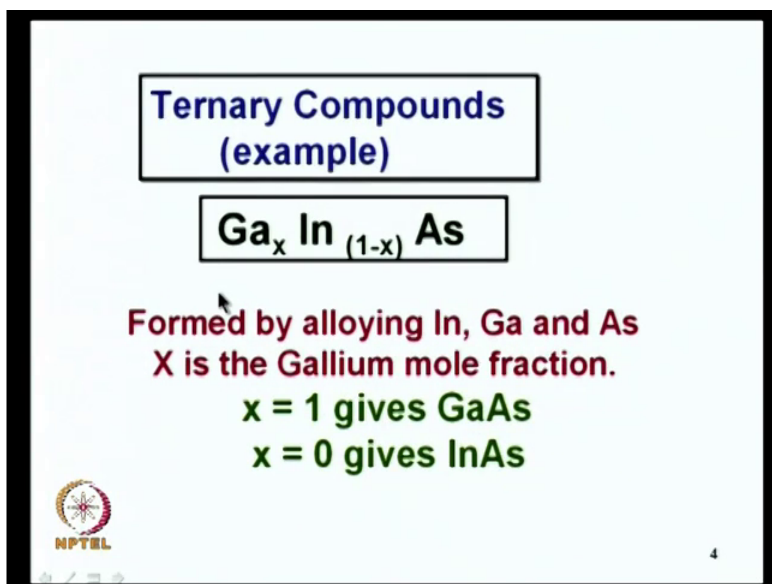

So, the ternary we are just talking of a material like gallium indium arsenide where you mix indium arsenide and gallium arsenide, already pointed is out last time you can see 1 x equal to 1 gives gallium molecule is 1, gallium atom 1 gallium atom for 1 arsenic atom and x equal to 1 means indium atom is 0 that is gallium arsenide. The x tells you the mole fraction of gallium in gallium indium arsenide; usually stoichiometric gallium arsenide will have x 1 gallium atom will have 1 arsenic atom.

But if you replace gallium with the indium atoms for example, if I replace for 2 arsenic atoms 1 gallium atom and 1 indium atom that we gallium 0.5 indium 0.5 and arsenic 1 that the gallium indium arsenide, let us just understand the symbol. So, here I can have gallium indium arsenide which will give you anywhere the band gap between the two and mobility anywhere between the two both will be direct band gap semiconductors.

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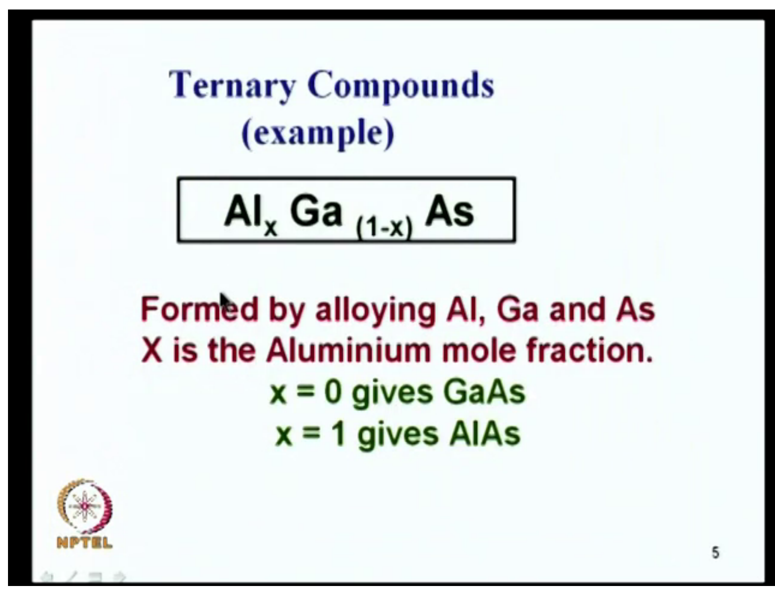

Now, other ternary compounds semiconductor which is popular is aluminum gallium arsenide Al Ga As, x equal to 0 gives gallium 1 and arsenic 1 that is gallium arsenide x equal to 1 gives gallium equal to 1 minus x is 1 minus 1 0 and aluminum is 1 that is aluminum arsenide you can change. In fact, the band gap of gallium arsenide by moving from by keeping on changing the g concentration or in replacing gallium with aluminum atoms Al Ga As or aluminum gallium arsenide.

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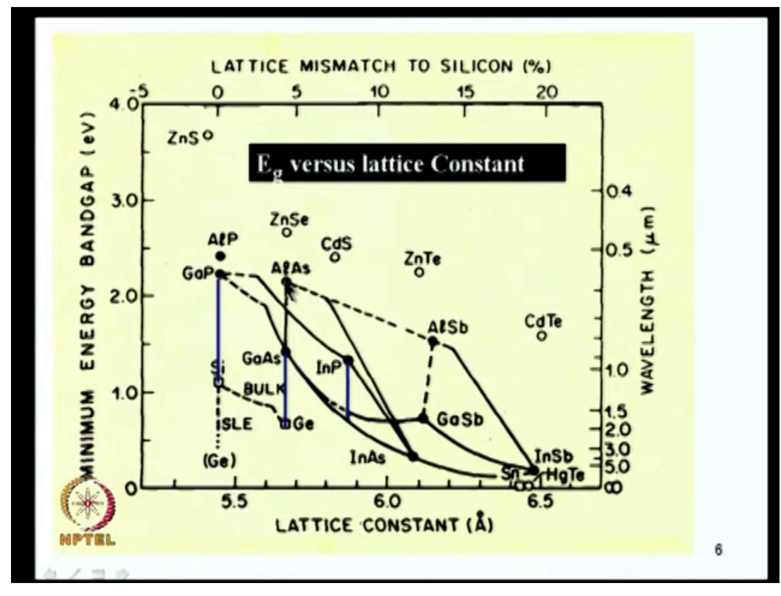

So in fact, I had just began some of these the discussions on these. So, what is happening is here is you can mix for example, I can have gallium arsenide and indium arsenide is here I can mix them together to get gallium indium arsenide. I can have gallium arsenide grown on aluminum arsenide or grow aluminum arsenide on gallium arsenide. So, when you want to make hetero structures that is d materials or devices based on 2 different materials like gallium arsenide and aluminum arsenide you can do that provided you are able to grow one layer over the other without introducing defects. So, if you take look at this chart which is very popular one the y axis gives you the band gap, minimum band gap means the gap between the conductional band edge and the valance band edge if you take gallium arsenide is about 1.43 aluminum arsenide is 2.1 or so.

Now if you take the lattice constant germanium, gallium arsenide, aluminum arsenide all of them have about 5.65 angstroms lattice constant; that means, you can grow gallium arsenide on germanium without having defects or the interface or minimum defects you can grow aluminum arsenide on gallium arsenide or you see from gallium arsenide if you keep on adding aluminum in place of gallium you move in this direction comp and when x equal to completely 1 its aluminum arsenide. So, you can see this solid line indicates that it is direct band gap, the dotted line indicates that beyond that point if you add more aluminum it becomes indirect band gap aluminum arsenide. So, never the less you can grow aluminum gallium arsenide on gallium arsenide. In fact, there are hetero structures fabricated using Al Ga As on gas aluminum gallium arsenide on gallium arsenide.

Now, very good lattice match similarly you can grow gallium arsenide on germanium, this has been 1 of the popular starting material for gallium arsenide solar cells because you can collect the entire solar spectrum with just about couple of microns of gallium arsenide, but gallium arsenide if it is you are using the full thick layer of gallium arsenide therefore, it is very expensive. So, you can use a cheaper substrate like germanium on that you can grow gallium arsenide and make device pn junctions or hetero type of junctions on gallium arsenide make this ourselves. So, that in gallium arsenide base devices, if I what use indium phosphide base devices or gallium indium arsenide, you can see gallium arsenide is here that is constant 5.65 indium arsenide is bigger lattice. So, it is about 6.6.1 close 6.1 angstroms that is constant.

Now, if you mix them gallium arsenide and indium arsenide at a particular ratio you can

get the lattice constant which is about 5. 5.85 or so which would match with indium phosphide you can grow therefore, gallium indium arsenide on indium phosphide indium phosphide. So, starting with indium phosphide substrate you can make layers of gallium indium arsenide with a very good lattice match. So, this is just I so wanted show you that if you want to make hetero structures you can have gallium indium arsenide on indium phosphide or gallium arsenide on germanium or Al Ga As on gas aluminum gallium arsenide on gallium arsenide. So, this is the very popular diagram it is a people take a look at (Refer Time: 10:27) matches with which 1 see, you can grow gallium phosphide if you want on silicon very good lattice point 5.45 or so and above that.

Where (Refer Time: 10:39) band gap material the, if you take a look at the mobility the mobility is low in the case of gallium phosphide. So, you can use it only for some optical applications like leds etcetera you can mix them together also.

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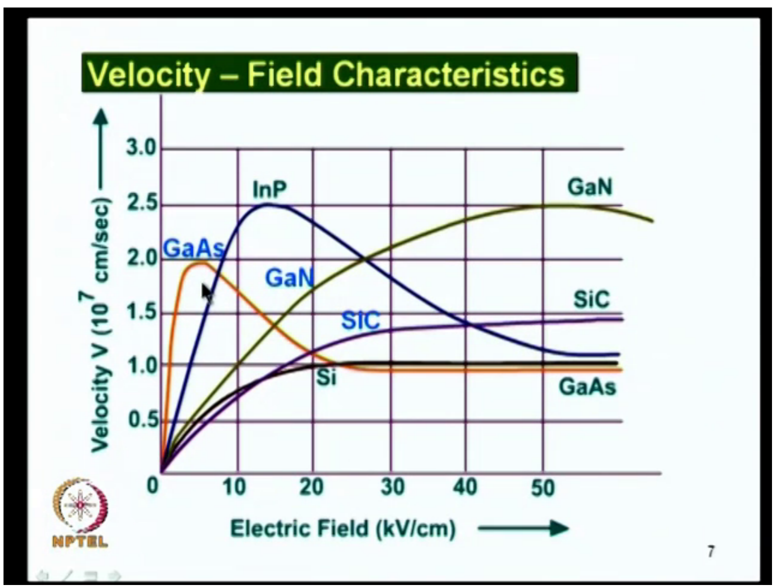

Now we take a look at the velocity field characteristics of the different materials, the very popular material that we have in use in industry is silicon, silicon they have discussed this velocity versus electric field, increases linearly initially then saturates catering limited velocity 10 to the power of 7, 1 into 10 to the power of 7 centi meter per second that is the velocity saturation velocity and mobility of electrons is much (Refer Time: 11:43) that you going to get is about 1500 centimeter square per volt second.

Now, if it is silicon carbide which is also an alternate material, mobility is not very high about 700 centimeter square per volt second, but it is a wider band gap material and used for high power high temperatures that has got a (Refer Time: 12:05) characteristics like this, notice the saturation velocity in this case is much higher compared to that of silicon which would imply that you can use it for higher voltages, high fields, high break downs.

So, power devices people tend to take a look at it at silicon carbide, but it is a more difficult material to work with. So, the there are some restricted applications on that people are looking to that both for microelectronics as well as for micro electro mechanical systems because it is a much tougher material compared to silicon. Now, they are both behaving almost identically, but if you take a look at gallium arsenide the velocity field characteristics are totally different because of the difference in the band structure of the gallium arsenide and silicon.

Silicon is a indirect band gap semiconductor we have discussed that gallium arsenide is a direct band gap semiconductor we will discuss more details in the next few slides. So, because of this direct band gap material property the you will see soon that in the next slides the gallium arsenide velocity field characteristics increases practically linearly where low fields, you can see it is much deeper compared to the silicon velocity field characteristics. Indicating the mobility size the low field region velocity is proportional electric field linear it is deep, mobility is high about 8500 centimeter square per volt second and velocity it keeps increasing, but after some electric field something happens with what we will discuss soon and the mode of transport of the electrons changes and the effective mass of electrons becomes higher. As a result velocity falls and it falls and ultimately falls down through the almost equal to the saturation velocity of silicon. So, it goes up down, but most important thing to notice gallium arsenide has got very high mobility plus if you are operating in this region of electric field anywhere here.

You can see the velocities of carriers are then go as high as twice that of saturation velocity. So, one can visualize that you can have devices which have got which have got high velocities. So, at that is what we are looking for high mobility high velocity, if you take look at indium phosphide which is slightly lower band gap that of gallium arsenide and slightly lower mobility it has got similar characteristics like that, goes up down. Take a look at gallium arsenide which is again direct band gap semiconductor mobility is lower

than that of gallium arsenide lower than that of indium phosphide. So, its slope is lot smaller goes up peak field reaches at fields like 50 kilo volts per centimeter; that means, you can see that this can be used for very high fields or high voltages. So, power device people more than nano device people, power device people take a look at this gallium nitride (Refer Time: 15:35) alternate material or making high power devices, high voltage devices.

Lot of work is going on that we can see the peak field peak velocities is about 2.5 into 10 to the power of 7 mobility may be lower, but the peak field is high all these amplifications on the carrier transport in these type of materials let us take a look at what why such a thing happens gallium arsenide.

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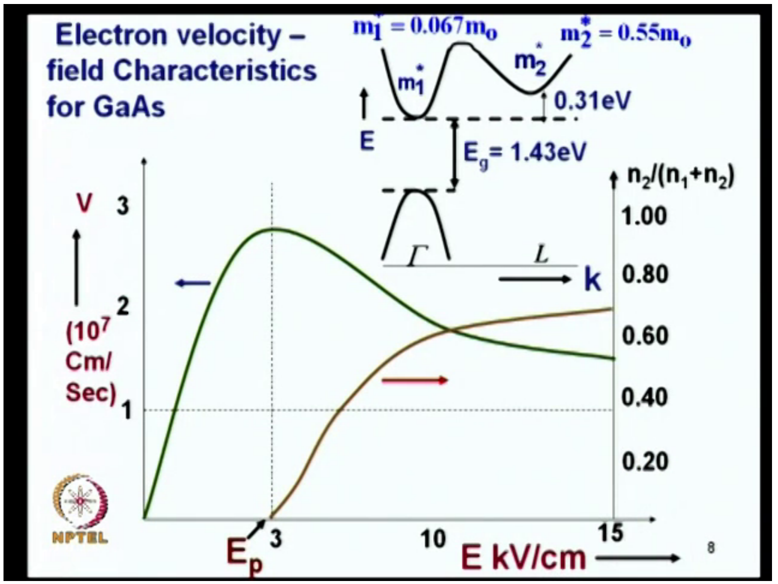

If you take a look at gallium arsenide we have said the velocity field characteristics is like this 2 slighlty more than 2 sometimes people quote, the energy band diagram if you look at the allowed states in a conduction band, the energy on a y axis and x axis if you (Refer Time: 16:37) the momentum that is E k diagram we call E k diagram, usually when we plot energy band diagram.

We plot the energy band diagram by this dotted line that is the conduction band edge and

this dotted line that is a valence band edge. So, we talk of transition between the top of the valence band and the bottom of the conduction band. Now, if you take look at gallium arsenide the energy versus momentum diagram follows this rule, I am not going to more details of that there is too much of physics in there, but what we have to understand is these are the allowed energy conditions, we see the minimum energy position in the conduction band these are the allowed states in the conduction band, energy conditions. So, if the electron is here the minimum in this conduction band edge coincides with the maximum in the valence band edge; that means, if an electron has to transit from conduction band edge here.

See, if you take a look at this conduction band if in thermal equilibrium all the electrons in the conduction band edge will be located around this minimum, electrons tend to occupy the minimum energy position and the whole tend to occupy the maximum energy position because that is the minimum energy position for holes, holes would be here velocity will be here. So, electrons all of them are located here thermal equilibrium condition which would mean if an electron transit from the conduction band edge here to the valence band edge that can happen just by loosing that energy and that difference in the energy can be absorbed by a particle like photon light, it can be emitted as light because of it is large wavelength the momentum is small.

So, there is no momentum difference between the electron here and here therefore, the conservation of energy 1 is required, suppose in this if you talk of silicon it is not a direct band gap it is a band, it is a band gap is slightly different for example, if I take a look at, oh sorry if I take a look at the, if you take a look at silicon the conduction band is the valence band edge will be like that.

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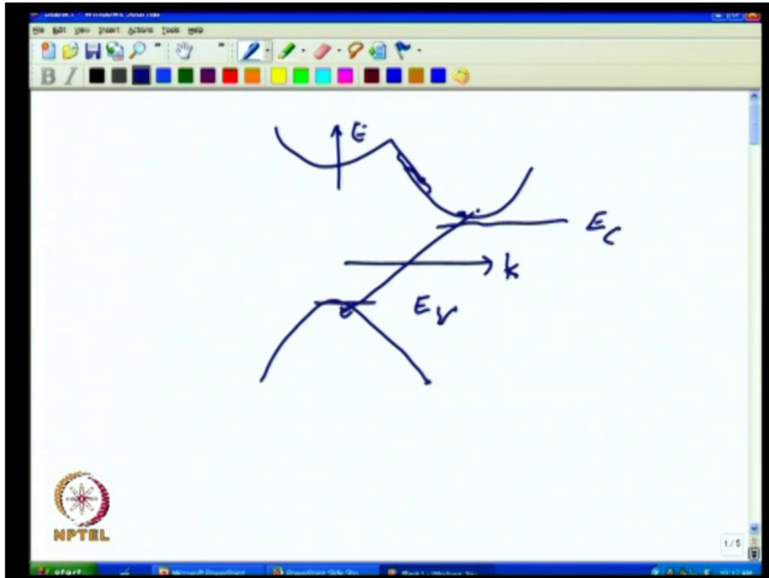

The conduction band edge minimum with somewhere here and this point will be something like something like that. So, this is the conduction band edge, this will be the valence band edge that is Ec Ev. So, you can see that this is a minimum of the conduction band edge position this (Refer Time: 19:56) have to transmit from here to here.

This is the energy and this is the momentum k this transition will have to can be accommodated by a particle which can absorb the energy difference and also the momentum difference. The photon can cannot do that it have to take place through some intermediate levels or the phonons. So, this transition is called indirect gap band transition or the material is called indirect band semiconductor. So, always this electrons will be remaining here and transition will be from here to here by with the help of phonons, now if you go back to the gallium arsenide or in a phosphide you will see the direct band gap the transition can take place with the help of photons. So, that is a direct band gap material.

Now, what you are trying to see is what happens if I apply electric field to the gallium arsenide material, if I have a contact and if I apply electric field between the two the energy of the electron here goes up. So, between the 2 omhic contacts when I apply voltage current will flow because with a velocity v decided by this curve. As we increase the electric field velocity will increase linearly initially and during all this portion all this

electric field the energy of the electrons is much smaller than the energy required to move to the transition this point, the difference between this valley the central valley and the satellite valleys if the electron is here next we will borrow the result the effective mass of the electrons here is small that if 0.067 times the response of electrons the ma mass of electrons in vacuum ok.

So, 0.067 effective mass times the mass of electron if the electron is here the effective mass is much higher than that. So, long as electron is remains in this particular region which is happen till it goes on acquiring energy from electric field the electron will remain in this region. So, till go with the velocity decided by the small effective mass, effective mass small means the mobility is higher. If we remember we have derived it earlier shown that mobility is inversely proportional to the effective mass mass is smaller mobility is higher. So, velocity is higher, but once it goes higher and higher velocity the energy of the electrons is goes up.

So, high that it finds it can get scattered to this level, if the energy is comparable to that because by about 0.31 electron volts it can just move from here to here, it can get transition can go from this valley to this valley. So, the electron moves from here to here see it has gone to this particular position I have electric field equal to about in this case for gallium arsenide 3 kilo volts, up to that point it will go the electron energy is or velocity is sufficient or the energy is sufficient for the transition takes place from here to here. So, once it moves into that point with that energy there suddenly it finds itself to be heavy, half m v square it is energy here half m 1 v square (Refer Time: 23:43) when it is transferred here it is half m 2 v square m 2 is larger than m 1 so velocity start falling immediately.

So, it is not as if all the electrons will get transferred immediately it is begin transition from here. So, many of the electrons will start moving from here to here as you go to higher and higher field. So, what is plotted here is I am not showing the calculation, ratio of electrons m 2 here divided by total number of electrons m 1 plus m 2 if n is a total number n 2 divided by n that is n 1 plus n 2 is was already plotted here for example, here it is n 2 is equal to 0, but at that point good fraction of electrons have started transporting on to the satellite valley as a result number of electrons in a satellite valley goes up number of electrons which have higher effective mass goes up. So, number of electrons

which have got lower velocity goes up. So, the average velocity begins to fall if begins to fall, ultimately it approaches this 1 into 10 to the power of 7. So, you have got these regions. So, called negative differential mobility region is obtained here ok.

So, you have got transition from this central valley to the satellite valley which results in the reduction the velocity, but notice in between the region they have got the velocity much higher than this 10 to the power of 7. So, please remember that there is a region where you can get very high velocity, suppose you have the electron here this is actually what we are plotting is the steady state velocity gradually increases the electric field. So, that give time enough for them electrons required thermal equilibrium and transferred on to that, but suppose you have electrons just near that source inject straight away into the channel where there is very high field. The electron just gets injected into this region it finds itself in the very high field region, if it is very high field region ideally if it is very high field region velocity field characteristics here supposing its field is here it is straight away find itself into launched on to that high field.

So, it will just keep to go into that velocity so long as it is in this region. So, in the steady state by the time it was acquired gone to this region it has begun transfer transition to this, but if it is transition suddenly when you apply about the transition to take place from here to here it does not take place immediately, it takes a finite time. So, for a finite time it experiences that high electric field with that high mobility. So, velocity can shoot up here much higher than even this velocity. So, long as it remains here that is what is known as velocity or shoot effect in the transit conditions that we will see subsequently. Now, let us see how it will happen in the case of indium phosphide, indium phosphide has got similar structure except the band gap is instead of 1.43 it is 1.35 and this difference in this energy instead of 0.31 is 0.53.

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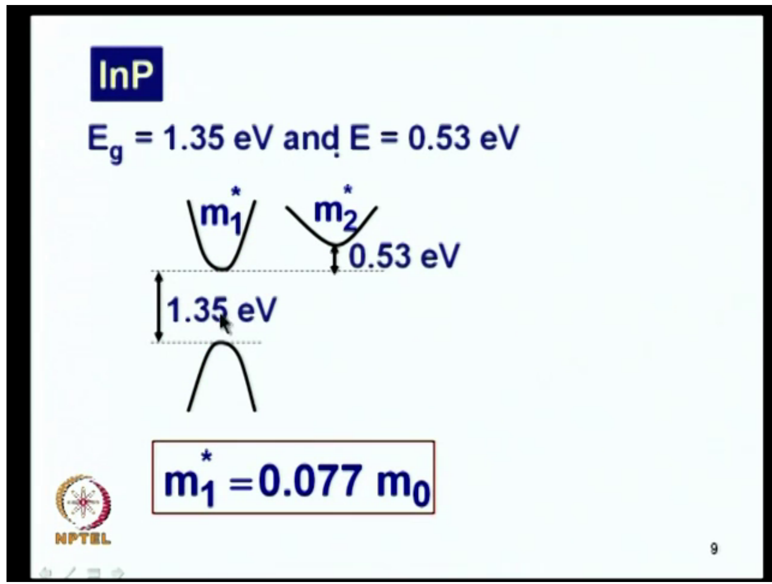

That means if I keep on applying the electric field for the electrons to move from here to here I must go to higher electric field. So, the transition from the central valley to the upper valley will take place at higher fields here supposing for example, here the transition begins at 3 kv because it is enough if it acquires 0.31 electron volt energy, but if this gap is 0.51, the transition will take place at a much higher electric field, that is what you see here.

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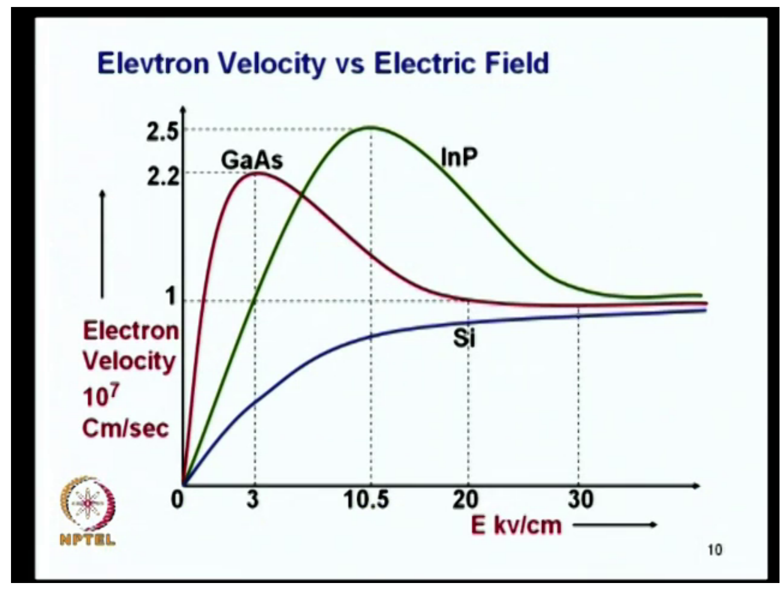

See for example, gallium arsenide the velocity field characteristic is in this fashion, the transition from the lower valley to upper valley takes place at 3 kv per centimeter, indium phosphide the mobility is low this slope is smaller and it takes more electric field require more electric field to acquire enough energy to transfer from here to here. Therefore, it remains in the lower valley for longer extent of electric field and by that time it goes to much higher electric field see it has to go to much higher electric field to go to transition to the next region.

Because see compared to this case 0.31 electron volt energy this case 0.35 electron volt energy. So, it requires more energy to transfer from the lower valley to upper valley. So, you go to higher electric field and higher velocities are required. So, you can see that the peak velocity in the in the phosphide is much higher than that of gallium arsenide, silicon you can see that is hardly scene, you do not have that transient you do not have that peaking of the velocity field. Now, let us take a look at the transient condition, I am sorry just I will just go into the transient condition come back to this after of the transient condition right in the (Refer Time: 29:26) ok.

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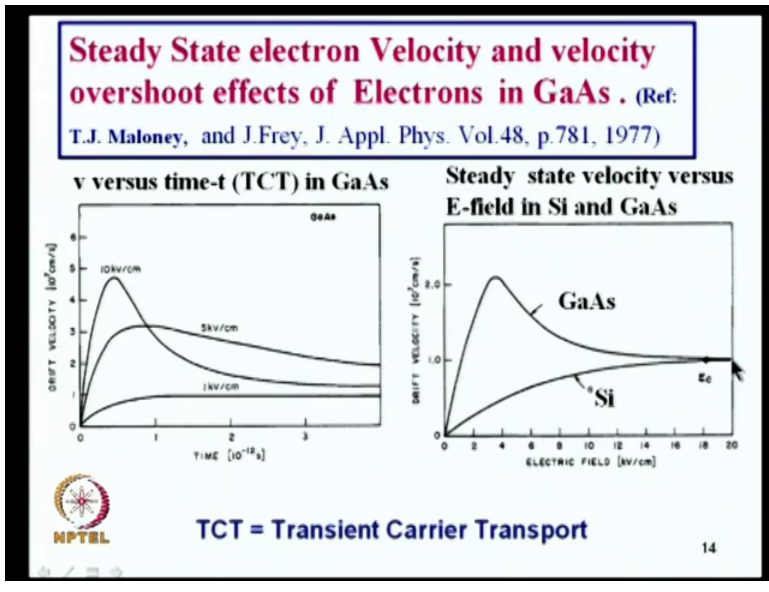

I should have add this slide before I will take on this first steady state electron velocity and the transient velocity, what I have plotted here on the right hand side is the let us take a look at the gallium arsenide. Since just I menti1d about the transient velocity I will take

a look at this slide itself, steady state conditions drift velocity versus electric field silicon is like this y axis 1 into 10 to the power of 7.

Here gallium arsenide slightly more than 2 into 10 to the power of 7 centimeter per second it over shoots there then comes down. Now, if I have that transient condition have which a I have just pointed out supposing I have the electron in the lower valley that is middle valley and if I apply a voltage electric field suddenly for example, if I apply 1 kv suddenly transient steady state 1 kv velocity is almost close to 10 to the power of 7 here, scattering limited is also 10 to the power of 7 high field. So, if I apply 1 kv per centimeter it will go up to that point and remain there, it transitions from the from sorry from this valley to that valley does not take place because the energy is not sufficient.

Now, if I go to this particular electric field for example, if I apply 10 kv per centimeter suddenly in the sense electron is cold in the source it is injected into the channel where the it sees very high fields because of the voltage applied to the drain region. If it were in the steady state you can see that 10 kv per centimeter the velocity is here, but for the electron to see that 10 kv per to the see to go to the steady state value of something like about close to 10 to power of 7 centimeter per second. It cannot go suddenly to that upper valley, before it goes to the upper valley it remains in this lower valley experiencing the velocity if the electric field of 10 kv per centimeter. So, whatever mobilities there that is actually the mobility divided by the lower value central valley where the effective mass is low.

So, mobility is 8000 into that electric field 10 kv it is shoot up to that high value. So, and it will acquire energy and it will go much more than what it will go in the steady state and shoot up and by that time it has shoot up it has acquired, you can see it as acquired to acquire velocities even much more than that peak velocity of 2, 2 into 10 to the power of 7 it will go even, 5 into 10 to the power of 7 centimeter per second these are actually simulation results using Monte Carlo simulation which has reported way back in 1977. So, it will go to that higher velocity over shoot will be there over and above the steady state velocity once it goes that velocity it has acquired sufficient energy to get scattered to the upper valley where the effective mass is lower. So, one thing gets scatter to the upper valley its velocity falls down.

So, you can see that for a short period of time like about 10 to the power of minus 12 0 to 1 picoseconds this in x axis time, y axis velocity the (Refer Time: 33:11) a short time when it has remained in the lower valley and when it was experiencing high fields there be high velocity, but once it has acquired that high velocity its energy has gone sufficiently large that that has gone to the upper valley where the mass is higher. So, velocity falls starts falling. So, you can see in 1 microsecond, 1 pico second during that 0 and 1 pico second if there is high field in the channel the electrons can attain high fields. In the sense if you make short channel devices you have a chance that the electrons have got velocities even higher than the saturation velocity let us see what is the distance traveled during this time of 10, 1 pico second. So, what we have do is I can plot velocity versus distance along the channel, what do I do multiply velocity versus time and plot it like this.

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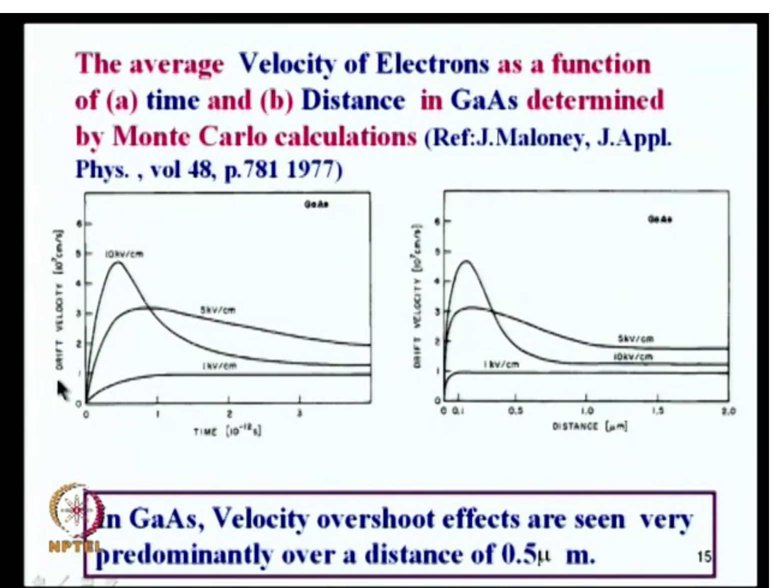

So, you can see for gallium arsenide these a same graph I have shown here, velocity versus time and you multiply velocity versus velocity into time and plot it as velocity into distance you can get velocity versus distance plot will be like this that 5 by the time it has reached peak it has gone beyond about 0.2 micro meters. So, you remember these scattering distance within 0.5 micro meters exist in the case of gallium arsenide you can see if the channel length is 0.5 micron when the electron has moved from 0 to the 0.5 micron its average the velocity has gone through 2, 3, 4, 5 into 10 to the power 7 centimeter per second and it falls. Average velocities much larger than the saturation

velocity of electrons here similarly if it is are in indium phosphide. In fact, you see even slightly better ok.

So, what we are telling from here is you can get you are making you some this velocity more (Refer Time: 35:30) effects you can go to channel length which are 0.3, 0.2 microns length and acquire high velocities therefore, very short transient times can be acquired and you can get much higher speeds. So, that is what I just wanted to point out here. In fact, I have skipped a few slides ill go back to those slides after this. So, here velocity overshoot occurs when the carrier velocity in transient condition exceeds steady state drift velocity that is steady state is something much more than the steady state velocity here, steady state velocity for that region is much smaller, but it is much higher than that.

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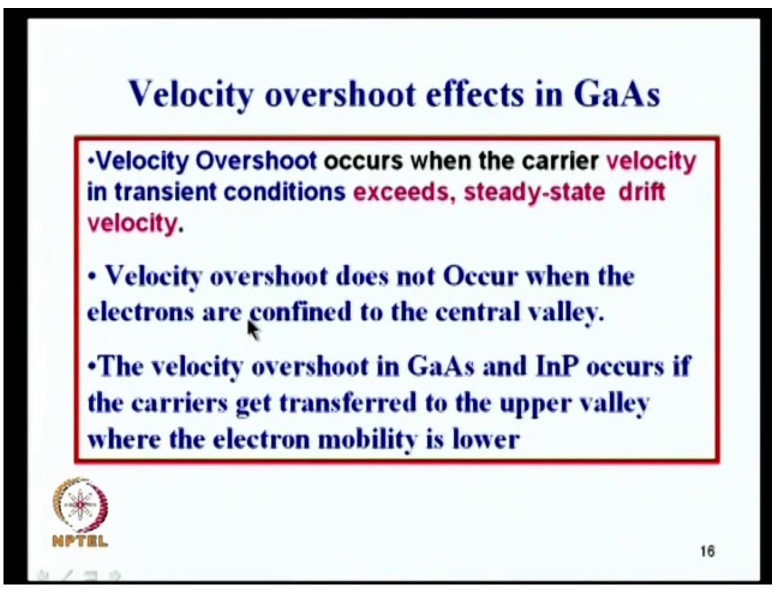

Velocity overshoot does not occur when the electrons are confined to the central valley.

For example if the electric field is 1 kv per centimeter, 1 kv per centimeter they will trans do not have the energy to go to upper valley. So, they are right through their confined to the lower valley you do not see their velocity overshoot effect the velocity overshoot in gallium arsenide and indium phosphide occurs if the carriers get transferred to the upper valley where the electron mobility is lower.

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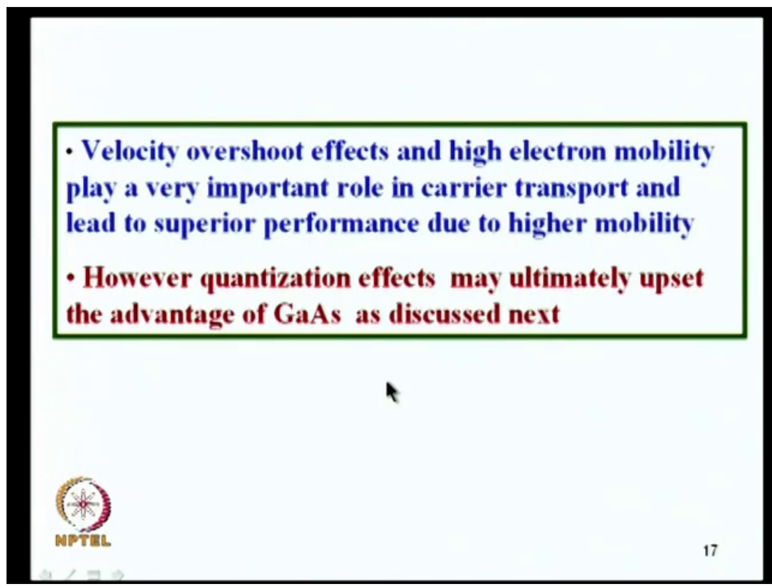

So, velocity overshoot effects and high electron mobility these are the ones which encourage the people to take a look at more and more into gallium arsenide and short channel devices and they lead to superior performance due to higher mobility, but one will actually see that quantization effects may ultimately upset the advantage of gallium arsenide as we discussed next what is this quantization effect.

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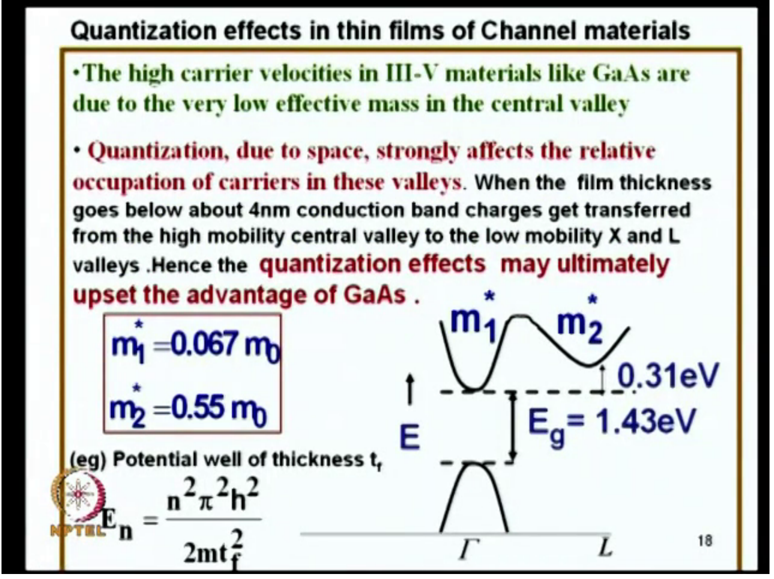

See gallium arsenide the front the main advantage is the mobility of electrons is high the low field mobility is high and because of that you are able to get the direct band gap effect and because of that you are able to get the velocity overshoot effects etcetera. Now, if I use very thin layer of material as we have seen in the SOI, the due to the quantum confinement effect the band gap increases in the case of silicon it is a indirect band gap material, in the case of germanium it is indirect band gap material and the band gap goes on increasing. This can be used as advantage in the case of germanium, because higher band gap it enables you to overcome the poor performance due to the lower band gap in germanium, in gallium arsenide we have the direct band gap ok.

Now, if I make thinner layer of gallium arsenide surrounded by wider band gap materials you will have conf quantum confinement effects and this effects the relative occupants occupation of careers in these valleys for example, if you recall the quantum effects, quantum well potential well problem the energy level would affect the distance between the energy levels will be increasing if the width of the quantum well is reduced, thinner the quantum well more will be the distance between the energy gaps. So, if I have a particular energy gap material E 1 Eg the energy gap will keep on increasing and the how much is the splitting of the energy level depends upon how much is the thickness of the material, thinner the material more is the splitting it also depends upon the mobility, mobility or the effective mass the mass m, smaller the mass more will be the splitting.

Now take a look at the two these two you know valleys central valley of gallium arsenide and the satellite valley, here the effective mass is smaller. So, when the confinement effect comes in this energy levels here will move faster and faster with the electric field and increase the and not electric field when you reduce the thickness the energy level split will become more and more much faster here compared to here because here the effective mass is 0.55 times m naught, here it is 0.067. So, they this you can actually visualize this situation where this gap this gap keeps on increasing much faster than this gap. So, what you one can imagine a situation where you will have where you will have see for example, right now I have the energy band I cannot like that that is the satellite valley this is the I am sorry that is a satellite valley.

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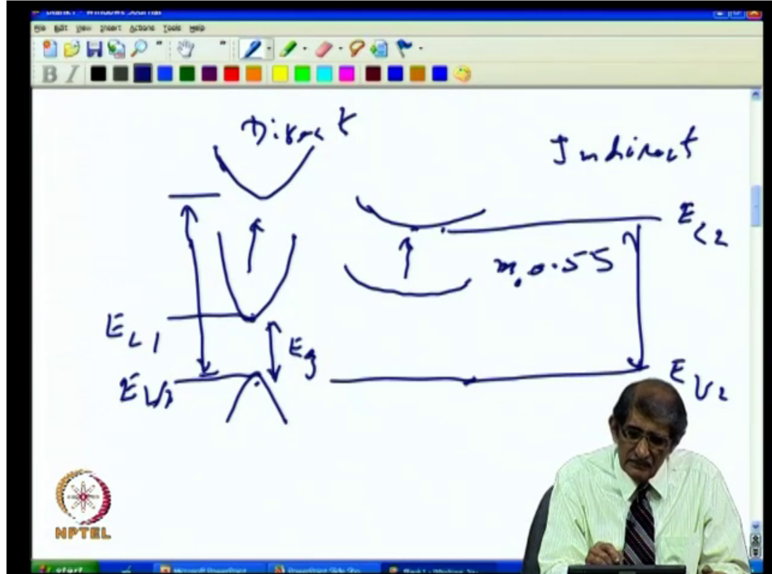

So, the electrons are here, now the energy levels here itself is split what will happen will be this band gap which is actually the band gap of gallium arsenide direct band gap that will increase much faster and will move in that direction and you will have that is a I exaggerate it and so it is like this it will move to that because of these smaller effective mass the split will be more what was direct band gap here can become indirect band gap.

It is remained direct band gap if this also moves same way, but the effective mass here is smaller m naught into 0.55 here it is 0.067 times m naught this way also will move, but this will move somewhere here like this, what will happen now this has moved here. So, the this is the direct band gap from there to here and the actual band gap will be from here to this point because that is smaller compared to that.

So, what happens is what I am trying to point out is this particular whatever was directed band gap that band gap increases, much more than whatever was this white indirect band gap. So, if I in effect what would happen will be this goes off and you will end up with this the transition is between this and this because this is the Ec and this is the ev initially it was Ec was here and Ev was here, Ev 1 this is Ec 2 and Ev 2 due to the quantization Ec 1 has become Ec 2, Ev 1 has become Ev 2 and that eg whatever was there had become this 1 whatever was direct the material is no longer direct band band gap material it becomes indirect you may ask so.

So, what if it is indirect band gap it will be form it will not use it up to up to optical transfer applications, but you see what you have done electron has high mobility here because of this sharp nature of the ek diagram whereas, the electron here has got lower mobility higher effective mass. So, the electrons when it remains here the mobility of the electrons is smaller. So, whatever effect. In fact, you had on gallium arsenide when it was direct band gap high electron mobility all that is lost all velocity overshoot effect high velocities all will be lost when you go to quantization.

So, the moral of the story is when you go to very thin layer of gallium arsenide you may lose when you go to thickness of like 2 or 3 nanometer thickness of gallium arsenide you will encounter this effect, but still if you are using say a 10 nanometer, 15 nanometer you will still have the benefit of gallium arsenide. So, you can still use with the advantage for those thicknesses you can still use gallium arsenide for so nanoscale devices. So, that is how would I stand point out here. So, it is not all that dangerous, but you have to worry about that effect the direct becoming indirect when you go to thicknesses below about 4 nanometers ok.

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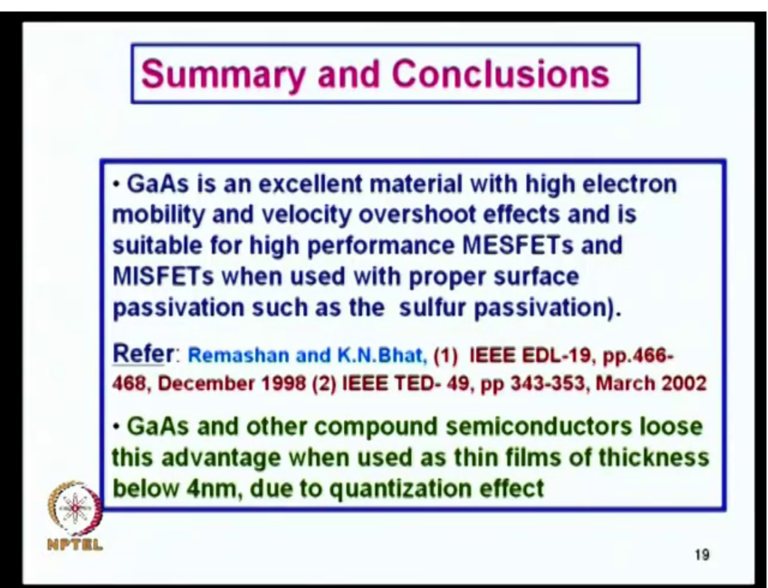

So, gallium arsenide is an excellent material, I will come back to these discussions later it is a excellent material the high electron mobility and the high electron mobility and all that you have discussed now, but they also we have seen the use loose advantage when used in

thin soft thickness below 4 nanometers due to quantization effect. Now, let me go back to that slides which has skipped where what type of devices can you make with gallium arsenide. So, what we have seen is.

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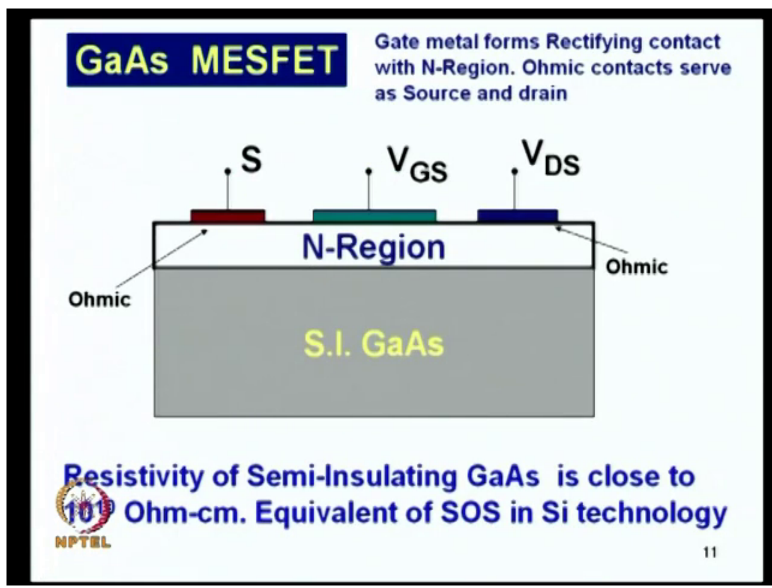

Gallium arsenide has got high electron mobility and it has got chances of having velocity overshoot effects, velocities in excess of saturation velocity and we have seen that saturation velocity effects come into picture when you go to short channel effects; that means, when you go to short channel effects you can make use of the velocity overshoot effects.

In fact, they have made channel device channel which are shorter say of the order of 0.5 micro meters or even smaller than that seen that the effective velocities as high as 2 into 10 to the power of 7 can be seen with gallium arsenide with devices. Now, one of the very popular devices which are used for gallium arsenide is the MESFET, now why not MOSFET you can use MOSFET that is you can use metal oxide then gallium arsenide layer, but the interface state density in gallium arsenide is very high the problem that you have with the germanium which you have we have explained a was seen in gallium arsenide as early as in 1980's. People have spent lot of effort lot of research effort has been put in gallium arsenide for surface (Refer Time: 47:31).

So, that you can deposit a dielectric and make a MOSFET's, but that was great success with some success I will tell you that aspect after discuss this particular device that is a MOSFET. Since initially there was not much success with these MOSFET the alternate device that they thought is suitable is make a MESFET, take n type gallium arsenide we make devices on n channel need n channel devices using n type gallium arsenide. So, what is done is just like what you did in the SOI you can have gallium arsenide layer on SOI, but if you grow gallium arsenide on SOI that will be not a single crystal. Instead of SOI what you do is whenever you want to use materials like gallium arsenide in a phosphide or gallium nitride you will use a high resistivity material at the substrate see for example, in silicon technology we had silicon on sapphire SOS, sapphire has is high resistivity material single crystal very costly you can grow silicon on that take make devices on SOS alternate was SOI.

In gallium arsenide take a semi insulating gallium arsenide, what is semi insulating? It is not insulating, insulating material will have resistivity in the of the order of 10 to the power 13 to 10 to the power of 14 ohm centimeters. Whereas gallium arsenide band gap is 1.43 intrinsic carrier concentration is of the order of 10 to the power of 6 centimeter square centimeter 6 per centimeter cube, 10 to the power of 6 cent per centimeter cube pairs per centimeter whole (Refer Time: 49:34) silicon it is about 10 to the power 10 per centimeter cube gallium arsenide about 10 to the power 6. So, we can see about 4 orders of magnitude lower carrier concentration in intrinsic gallium arsenide that would mean you can have about 4 orders of magnitude higher resistivity for gallium arsenide. So, un doped gallium arsenide pure gallium arsenide, intrinsic gallium arsenide, intrinsic pure that can show about 10 to the power of 10 ohm centimeters close to about 10 to the power of 10, 10 ohm centimeters.

You do not call it as insulating you call it as semi insulating gallium arsenides, si gallium arsenide you will see all these terms in compound semiconductors semi insulatings gallium arsenide semi insulating indium phosphide. So, take that material, grow gallium arsenide on that, thickness of this layer you can choose, how to choose that we will see that depends upon just like the SOI layer what would be the threshold voltage that you require that will be the criterion for choosing that, what is the channeling that you want to choose see for example, if I want to short the channel in a (Refer Time: 50:53) si you have to use thinner layers. Similarly if I want to short the channel in more and more effective the

avoid shorter channel effects you must go to thinner and thinner layers of active layer. So, the device that we talk of here is not MOSFET it is metal semiconductor contact ok.

How this work out, a this has a rectifying contact at the center I have not put this contact heavy it it in ideally it would be as close to this contact as possible like in the case of MOSFET this will be a n plus region when very close contact to the gate region you are able to isolate it because of the oxide layer. Now, I have shown this electrically separated, but as close as possible to this gate metal I cannot keep it very close to this and a self align with a respect to that because then there will be shorting between the source and the gate or between the drain and the gate ok. So, you can see these 2 contacts are the ohmic contacts. So, you have a n type semiconductor to which you have made a ohmic contacts at the edges. So, if I do not have anything here contact this electrode is if it is absent what you will get will be take a bar of semiconductor, make contact to the edges of that apply voltage and like a resistor.

You will get a I v characteristics for the like let our resistor and the fields are small when you go to high fields because of velocity saturates current also will saturates. So, you get a characteristics similar to transistor there, now here that is how no use for us. So, what you do here is you get put a gate metal here by which you can control the depletion layer below that, below this region you know that a metal semiconductor contact if it is rectifying contact there is a depletion layer below that. So, I let us go to the next diagram gate material forms rectifying contact with the n region ohmic contact serve as source and drain regions because this can directly supply the electrons to this channel ok.

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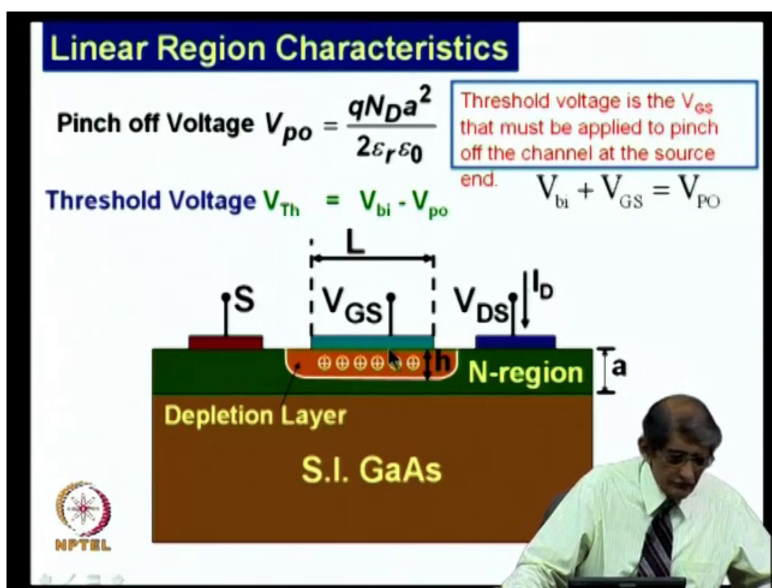

Now, let us see what happens here if I have a gate here metal semiconductor contact what I have drawn here is the depleted region.

Initially first let us talk of the case where I do not apply any voltage to the drain, just apply the gate voltage with respect to the source, it is as good it is a ohmic contact is as good as put in a contact below that somewhere. So, when I do not apply any voltage anywhere metal semiconductor contact, if it is rectifying contact there if the there will be depletion layer below this metal and what I have put here plus is the depleted donors depleted of the electrons plus here represents a donor atom which has which is depleted of its electrons. So, this is the depletion layer edge that I have plotted. So, due to the built in voltage Vbi we have seen when we discuss Scotty ky barrier device we have seen that there will be depletion layer h.

How much is the depletion layer a width h depends upon, what is the built in voltage, what is the built in voltage depends upon the doping level and the and at the barrier height (Refer Time: 54:43) b n this is also we have seen I am just recap recalling your memory. So, here if you just go back to the some analysis supposing I have built in potential v Vbi, if I instead of a I will call it as h if I have Vbi I replace a by h. So, Vbi Vb equal to q N D nd is a doping concentration into h squared by twice epsilon repsilon 0. So, the built in potential which is decided by the work function difference of this metal and

semiconductor or the barrier height as well as the doping concentration mostly by the wow 5 ms or the barrier height this built in potential decides what is the depletion layer width is.

Now, you can see if I have a depleted layer here, what has happened is the channel thickness is reduced by this quantity I can draw that in a separate diagram, see if you take a bar if semiconductor just to get some clarity on that if I take a bar of semiconductor.

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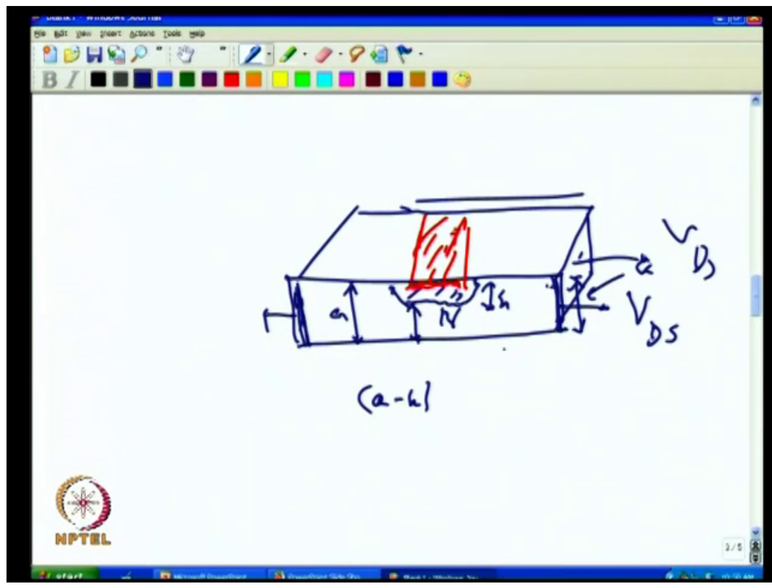

That is a ohmic contact, in the picture there I have shown the contact on the top equivalently I have a voltage applied here vds, now if this is n type if there is no metal the full h8 a is available for conduction. So, the current flow will be when I apply V D I can take this as V D by rs r total resistance this will like this that is the bar going like this there is a contact here.

So, the entire region is available for current flow, now if I put a metal on the top of that what happens is I can draw the diagram here I just draw it right here that is a metal. Now, underneath that part of that will be depleted because of the because this acts as a retrained contact. So, let us see that how that will be there will be depletion layer below this, it is a 2 dimensional effect normally when we will the plot this we plot only this portion. So, just

let me remove that this thing I have to put that. So, I will have the depletion layer you will have the depletion layer like this going. So, this much width is now not available for or current flow. So, if this is a and if this is h what is available for the current flow is only this portion that is a minus h.

So, the effective area for cross section is reduced now so; that means, by using this gate I can control the thickness of this channel which is available for current flow. I can apply a reverse bias to this a gate and the depletion layer width is widened and this a minus h what is available will reduce. So, I can control the current flow through this drain and source by change gate apply the voltage to the gate. So, I will discuss this more details about that in my next presentation how this actually works like a transistor. So, what you have to see is by applying the voltage I control the area of this channel.