Fundamentals of Semiconductor Devices
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Lecture – 41
Heterojunctions (contd.)

Hello, welcome back again. So, today so, in last class we were discussing about Heterojunction. If you recall about how to draw the band diagrams for heterojunctions p-type, n-type and depending on the band alignment I told you different kinds of band alignments are possible straddling, staggered, broken and how to draw the band diagrams. I told you some of the rules, most of the text books and the classes do not focus much on how to draw heterojunction band diagram, but then so many devices depend on heterojunction. So, it is useful to understand how to draw heterojunction band diagrams, right.

I told you; today, we shall start with a graded heterojunction. Whatever we have done till now in terms of heterojunctions and heterostructures are actually abrupt heterojunction; that means, you have a gallium arsenide layer for example. And then you have an indium phosphide layer or indium gallium phosphide or something and you have an abrupt junction from one material to another material; within one atomic layer you abruptly change it, that is called an abrupt heterojunction what we have studied till now.

And, this is possible such kind of a sharp interphase and abrupt junctions are possible because of epitaxial techniques like MBE and MOCVD that I had discussed in last two last class, that allows you to control the thickness of the deposited layers up to a precision of one atomic layer. Thereby allowing in to grow very sharp interfaces and these are technological advancements in machineries, and you know the vacuum science. So, there is also a materials aspect to this.

I will tell you that instead of abrupt junction sometimes it is useful to gradually change the band gap of a material from one point to another point as you grow or deposit the material. So, for example, I have a wafer of gallium arsenide and I am gradually increasing the aluminium fraction. As I am increasing the aluminium fraction I am trying to grow aluminium gallium arsenide gradually over a certain thickness that is called grading. So, let us come through the whiteboard again.

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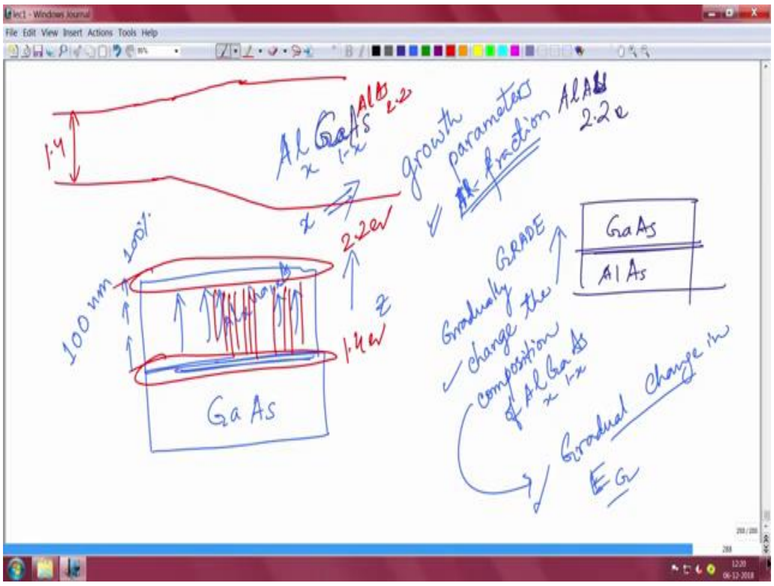

What I am trying to say here is that you have gallium arsenide which have band gap of 1.4 eV and you have suppose aluminium arsenide which I have sorry, aluminium arsenide with a band gap of 2.2 eV, if you make a heterojunction which is abrupt. It is abrupt heterojunction like gallium arsenide and aluminium gallium arsenide or aluminium. So, you can say aluminium arsenide, right. This in an abrupt heterojunction it is abruptly changing here.

But, over what we can do instead is that we can actually grade it. When I grade it I change the what do I mean by change is that, I gradually change the composition; I gradually change the composition ok. Instead of abruptly I gradually change the composition of say aluminium gallium arsenide ok. This is x, this is 1/x, I slowly change x and because of this what happens is that there is a gradual change in various properties like say band gap. Your band gap will gradually changed now.

Of course, the other things like maybe electron affinity, dielectric constant and other things also will change, but the most important thing is that your band gap will actually change gradually and this has huge implications in practical devices that are used for example, in white light LEDs, in your transistors that are going into your cell phones for RF transmission and receiving modules. Those are made of indium phosphide, gallium arsenide sort of a HEMT’s and HBTs that I will talk about. You use this gradual change in grading it is actually used in commercial devices. So, it is very important.

So, essentially what is happening is that you are taking say for example, aluminium gallium arsenide where it is x and this is 1 - x and you are gradually changing x, practically when you are growing. So, suppose I have a layer of what is happening practical is that this is I have a layer of gallium arsenide. When I try to grow on top of this using a technique like MOCVD and MBE the growth parameters can be changed.

The growth parameters can be tuned or tailored such that I gradually start increasing the aluminium fraction. I gradually start increasing the aluminium fraction; maybe the aluminium source or aluminium precursor or whatever I am using I can gradually increase it up. Practically, what it means is that maybe I can use the increase the temperature of the aluminium cell in MBE, so, more aluminium will start gradually coming. So, slowly and slowly as I keep growing up thickness, this is thickness; z-axis is thickness by the way.

So, I will start increasing the aluminium compositions. Suppose this is 100 nanometre, suppose I am going 100 nanometre thick layer and I am here at this interface at this interface that is 0 percent aluminium, but I am gradually increasing the aluminium up to say 100 percent aluminium here. So, what is happening here is that throughout this I am aluminium percentage x is gradually increasing. The aluminium percentage x is gradually increasing and that gradually increasing is essentially making sure that at this point your band gap is gallium arsenide band gap, but at this point your band gap is aluminium arsenide band gap which is 2.2 eV this is 1.4 eV. So, over this your band gap is gradually increasing.

So, what is happening is that this is GaAs gallium arsenide which is 1.4 and suppose this is your aluminium gallium arsenide, aluminium arsenide which is 2.2 eV your band gap is gradually changing. So, it is changing like this there is no abrupt heterojunction like this ok. It is like changing like this ok. Let me use a different slide maybe.

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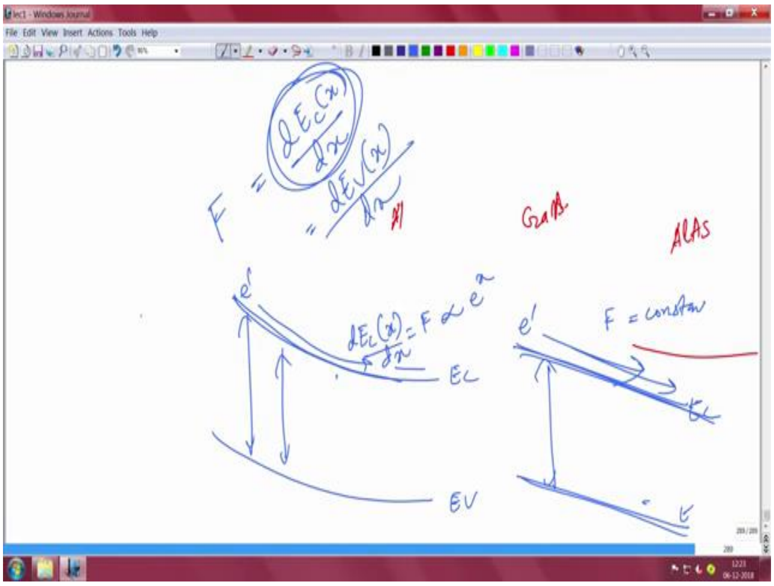

So, instead of having a band diagram like this, I mean practically of course, if you have doping then it will look something like maybe like that. It is a abrupt junction between say aluminium arsenide and gallium arsenide instead of that, I will grade the over some distance. So, what will happen is that this is gallium arsenide. Suppose, this is aluminium arsenide here ok, this is this band gap. So, I will increase it gradually like this ok. So, there is no abrupt heterojunction this is called graded layer. So, your composition is increasing this way.

So, aluminium composition is increasing and your band gap also is increasing. So, right this is your graded heterojunction and the when I say gradually when I say gradually you increase is gradually increasing, right. This gradual can be of many types you can grade it linearly this is linear grading you can grade it exponentially, you can grade it logarithmically, there are many grading scheme. So, this is a linear gradation in exponential gradation maybe you will have a band diagram that will look like this, right like this, right.

So, the way you grade can also be changed and that has a lot of implications because you know if you remember you have a electric field is defined as the slope of the conduction band, right; by the way this is for electrons actually, for holes it will be the slope of the valence band and we always only write conduction band because the band gap typically has always been the same. We always historically have been taking the band gap as the same. So, if the band gap is the same then you know if there is a slope in the conduction band, then the slope in the valence band also has to be the same because band gap is same.

So, whether you take the slope here or you take slope there is the same. So, we take the slope of conduction and then I say that the slope the conduction band gives you the field. So, instead of this structure for example, if I have a structural like now in a same band gap, if I have something like that same band gap, same band gap E_C - E_V is the same then your field will be different and because the field is different your acceleration, your the mass effective mass will experience different kinds of acceleration and the time taken to for the electrons to move from one point to another point depends a lot on how you are grading because the electric field changes.

If you have a linear gradation like that then electric field is constant it will move this way, but and this is I am talking about the same material by the way, same material this is like silicon. Suppose, I have a band I have a electric field that goes like have a conduction band that goes like this is E_C, this is E_V. In this case, your conduction band is changing in a exponential way then your dE(x)/dx also the field also will go exponentially. Here the field is going linearly right the field is can constant here the field is constant because the slope is constant. Here the slope is exponential, so, the field is also exponential field is also exponential, right.

So, an electron will take a different amount of time to go from this point to this point compared to here. So, depending on the way you are grading, your field and hence your transport, your time taken everything the speed of the transistor everything is affected. And the way you practically grade this kind of thing is that when you increase the aluminium composition for; by the way, this is not graded ok. This is not graded, this is only constant material, but with heterojunction you can actually grade it and make it even more you have more flexibility.

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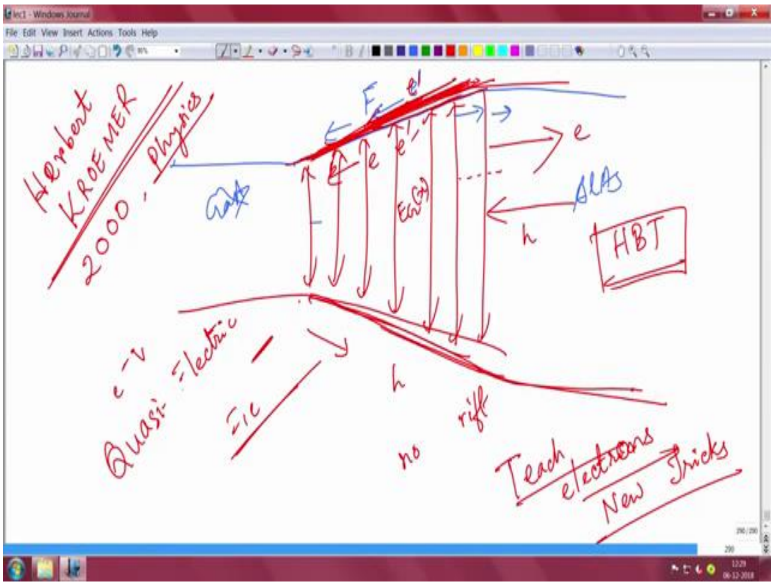

What I mean by that is that when you are grading linearly, suppose you have something like this you know right sorry. So, this is aluminium arsenide for example, this is gallium arsenide and this is your grading region. Now, you might have another where it is grading, this is a field here. This is a constant field; the field by the way you look very carefully in this region, you look very carefully. The field is the slope of the conduction band the conduction band has a different slope than the valence band. This was not possible in a silicon sort of a thing right here the slopes are different here opposite.

An electron on this part will try to roll down this way. So, the field is pointing in this direction for the conduction band. On the other hand, a hole here will try to roll down this side which means the field is in this direction. So, for electrons the field is in this direction and for holes the field is in this direction. So, the fields are pointing in opposite direction for electrons and holes this is something you will not see in a silicon or in a non heterojunction device, you see my point?

Electrons are also going to the left holes are also trying to the going to the left, that is not possible in normal heterojunction normal homojunction. Because if in a normal junction in normal semiconductor electrode silicon if you have something like that the slopes have to be same, electrons will go this way and holes will go that way, they always go opposite. They always go opposite because it is a same band gap, right. Here you actually can; here you actually can engineer the bands such that electrons go this way; holes go that way ok.

You can also do the grading and this grading is done practically by changing the aluminium temperature or the aluminium flow, flux like in the practical MBE tool you can do there actually. You can also have a grading such that the valence band is almost you know there is no field here, but all the things are dropping across the conduction band which means the slope here is zero which means the holes will not experience any field. That means, holes will not move in drift, will not drift because the valence band is flat, but I am increasing the conduction band this side. So, electrons will move try to move side.

So, I can selectively I can grade it such that I can selectively have drift of only one type of carrier; one type of carrier. I can make sure that grading is such that only the conduction band has the slope the valence band remains flat in which case in which case electrons will experience a force the holes will not experience a force. So, I can selectively have only electrons drift and holes not drift. I can selectively have only holes drift, but electrons not drift, I can selectively have such that electrons and holes drift in the same direction, I can also have a field such that electrons and holes drift in the opposite direction. This kind of flexibility gives enormous freedom to design new devices ok.

And whenever you grade the band gap like this you grade the band gap either linearly, exponentially, logarithmically does not matter. You have this graded band gap like this. This slope that is that comes up because of the change in band gap you see at every point at every point the band gap is changing and that change in band gap is because the aluminium composition is changing of course, when I say AlGaAs I can also talk about indium gallium phosphide, indium gallium nitride, some oxides, some antimonides it is everywhere I am just giving an example of AlGaAs ok. It is just an example.

So, when I grade the band gap keeps changing; any point the band gap is x and the band gap keeps changing, right. This gives a slope here as you know now know and that gives us a field either electron or whole it gives a field and that is called a Quasi-electric field. A Quasi-electric field because this field has come from the grading of the band gap and as you know this person you should Google up. Everybody has a smart phone you can immediately Google up of this person Herbert Kroemer; Herbert Kroemer he got he is one of the pioneers or the fathers of this heterojunction and many of these concepts of grading and heterojunction and how it will benefit the devices in semiconductor laser or heterojunction bipolar transistors that are used in your cell phones now.

He had done the theory and he had predicted he has proposed this long before MBE and MOCVD instruments where advanced enough to enable practical demonstration of this devices much before that in 1960s and 70s. He predicted all those based on theory and only in 1990s for example, MBE and MOCVD machines have come become very advanced to allow this kind of grading. Practically, it is very difficult to do all this thing, it is not very easy and you cannot just do band diagram on paper practically someone has to do it.

So, Herbert Kroemer he got the noble prize in 2000 in the year 2000 in physics. He is a still a professor at USA, Santa Barbara. He was one of the pioneers of this and he used the term Quasi electric field and by doing this Quasi electric field because you can do it in any direction he called it you know you are able to teach the electrons he used to call this in his noble lecture teach electrons sorry teach electrons new tricks.

So, you are essentially playing with electrons you are able to teach the electrons new tricks. You can make the electrons and holes behave in a different way you know like they can go in different direction they can go in the same direction. This kind of beautiful things are possible at heterojunction that has enabled this devices.

So, this is a grading of the heterojunction that you should be careful of. There is a lot of maths here of course; that I have skipped here very conveniently there is a lot of maths in terms of how you can actually do this you know when you are changing here suppose you have a doping here, right.

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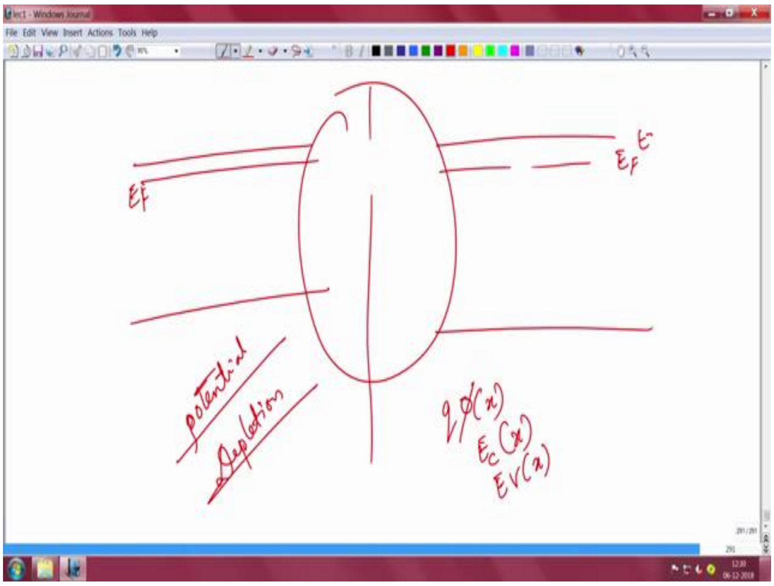

For example, you also have a this is suppose E_F one semiconductor and this suppose you have another semiconductor. This is also n-type, this is also n-type, but you are grading this part you are grading. Then in grading you are changing the band gap, but there is a potential that will change because of this band gap change, but potential also will change because of the depletion and other things. So, those two things you know mathematically you have to take into account.

So, at any point x you can define the potential for example, you can define the; you can define the band gap the band the conduction band the valence band. So, the mathematics behind it which we are skipping here, but in general the qualitative picture should be clear to you now, right.

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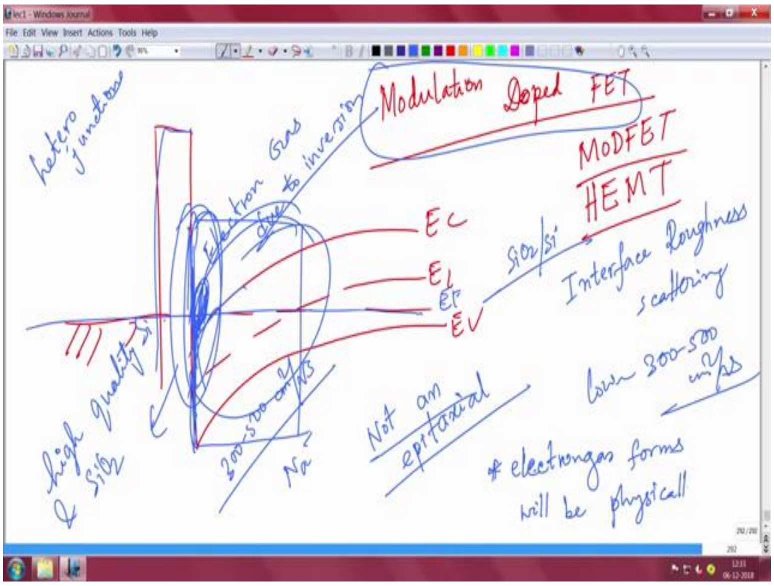

So, let us talk about one of the most important or you know very useful devices that has exploited this heterojunction is called a modulation doped; a modulation doped field effect transistor, it is called MODFET Modulation Doped Field Effect Transistor or also the mobility is high in this kind of devices as we will see now. Therefore, it is called high electron mobility transistor. These are very widely used in many high speed RF applications.

You remember the silicon band diagram the silicon MOSFET that we have studied few classes back? Remember silicon MOSFET? You have the you know this is E_i, this is E_c, this is E_v and then this is your Fermi level. The Fermi level is like this, right. You create a very high density of electron gas here by inversion there is an electron gas that forms here due to inversion you remember that, right. There is an electron gas that forms here due inversion this is very high density in electron gas.

But, in the case of mobility only of 300 to 500 per centimetre square by volt second and that is a low end of mobility. Do you know why? Because this electron gas coexists with this p-type material, this is a p-type material by the way it is a p-type material that is inverted, right. But, this is a p-type material that is there and this interface this interface is between a very high quality silicon which is you know a very high quality silicon that is wafer and an oxide which is silicon dioxide. This is not an epitaxial this is not an epitaxial interface; that means, the silicon oxide is not going epitaxial, it is going by thermal oxidation or other kind of approaches like LPCVD and all.

So, this interface roughness scattering. This interface this interface of silicon, silicon dioxide; silicon dioxide and silicon interface. That is not a very very that is not an epitaxial interface, that is not done in vacuum it is a thermal oxidation I mean the silicon wafer that there is a gap between the silicon wafer being grown bulk. So, Czochralski method or something and also the silicon oxide being deposited.

You have a huge interface roughness scattering interface roughness scattering at this interface. Besides, this is a background doping of p-type. There is always acceptor impurities are there N_A^- those also affecting the mobility here, that is why the mobility is low. It is around 300 to 500 cm^2/V-s this is band.

So, modulation doped field effect transistor uses heterojunction. It uses heterojunction to make sure that number -1 the main important thing is that the electron gas that forms this is this will not form by inversion by the way ok; electron gas that forms that forms will be physically separated from the impurity, physically let me use a different slide.

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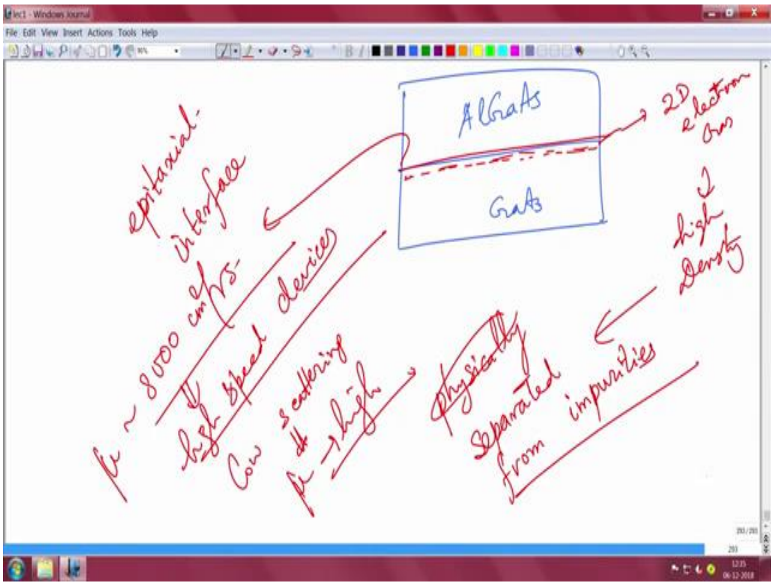

So, essentially what will happen is that you have a structure here. You have suppose aluminium gallium arsenide and there is a fixed type of band diagram you have to use. A fixed type of structure you cannot arbitrarily use indium phosphide on top of gallium arsenide or something. It has to follow it is rule there has to be a proper band diagram there has to be proper stack you will not get otherwise.

In this interface this is gallium arsenide by the way, you would be able to get with proper band engineering, a very high density of electron gas very close to the interface. This is again the 2D electron gas. The 2D electron gas which is of very high density this is of high density 2D electron gas and that will be the best thing about here is that is physically; that is physically separated that is physically separated from impurities.

The doping that you use will not be coexisting with the electron gas here that is why this scattering will be low, no scattering almost by the impurity and hence your mobility will be; mobility will be high ok. And besides this interface that interface is not an oxide semiconductor interface; it is a semiconductor-semiconductor interface, that is an epitaxial interface that is grown in purely in vacuum and so, the mobility the room temperature mobility could be up to 8000 cm^2/V-s , which is very high.

And this gives rise to very high speed devices which is not possible with silicon, right very high speed devices that is not possible with silicon. There are many variations over here, but please be advised that you know it just cannot be any other heterostructure, it has to be some fixed type of heterostructures. So, what happens in the structure is there I will show you.

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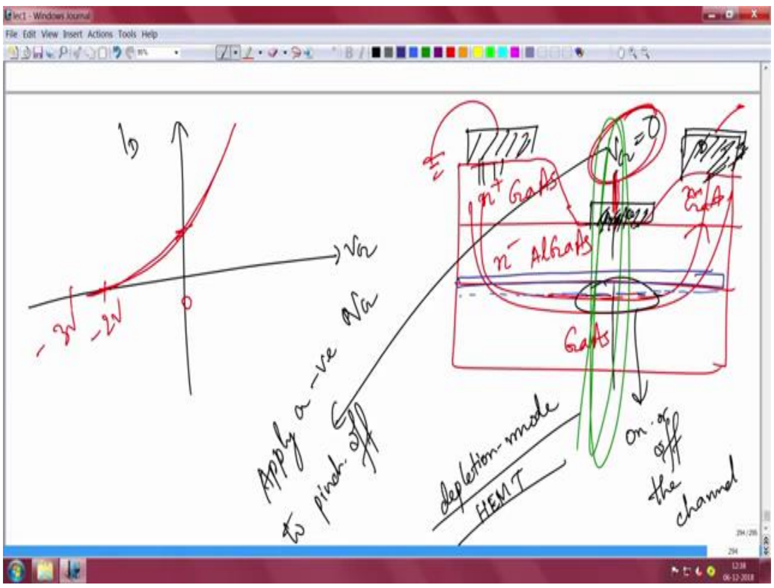

It is not just AlGaAs GaAs- you know you will have to have what will happen is that the structure will look something like this. Actually I will draw a structure here. So, the top will have n-plus highly n-plus doped gallium arsenide this is actually for making contact ohmic source and then contact; then you might have a doped n doped aluminium gallium arsenide layer and then you have undoped gallium arsenide layer and your 2D electron gas will from here, actually a very high density very close to the interface very very close like 2 – 3 nanometre from the interface.

What you do is that you put your source here, so that it forms a very good contact with the n plus, right it is n plus doped know. You put your drain here, very good contact and now you have to modulate the channel. You cannot put the gate here by the way because they get will leak. In a field effect transistor the gate should not leak, right. You have to apply a gate you know. So, what you do is that you etch away that region. So, what I mean is that you from the source then you etch away this part.

Again, you have this part this is gallium arsenide which is n plus and then your source and drain are here of course and your gate is here your gate is here and this is n minus this is not so highly doped. So, your gate metal will not be able it will not leak. So, much, but this is n minus doped here. So, below the gate; below the gate you will be able to turn on and off the channel by modulating ok; on or off the channel by applying and appropriate gate voltage.

At 0 gate voltage by the way you will always have some charge here. So, unlike silicon MOSFET typically this is called depletion mode transistor. This is called depletion mode transistor because you have to apply this is called depletion mode transistor this is because you have to apply; you have to apply a negative voltage to pinch of the channel; negative gate bias to pinch of the channel or to turn the channel off to turn the transistor off. What I mean to say is that if you draw the I_D and V_G, then you have to apply a negative voltage here to turn off the channel, maybe minus 2 volt or minus 3 volt or whatever, depends on a charge.

You have to apply negative voltage to turn off the channel which means at 0 voltage you actually have charge here by the way and that charge will conduct. If you keep this flow thing or if you apply 0 voltage or if you keep this flow thing if you ground this and if you apply some voltage on the drain, there will be large amount of current that will flow this way there will be large amount of current the gate is not off. You have to apply a negative voltage to turn off the channel.

And the way you actually looking at the band diagram if you look at the band diagram along; if you look at the band diagram along this direction along this if you look at the band diagram then what you have is that I will take a new slide may be here.

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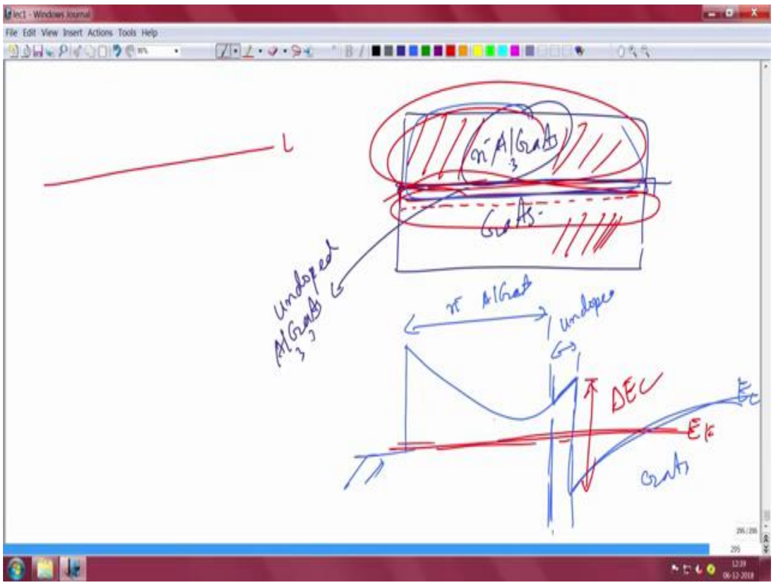

You know you have essentially if you look under a gate not and the contact is fine that you only look on to the gate this is n minus AlGaAs and this is typically say 20 – 30 percent maybe aluminium, 70 percent gallium and so on and this is undoped gallium. Typically there will be a actually I did not draw in the previous slide there will be a thin layer here of aluminium gallium arsenide that is undoped very thin layer it is called spacer layer ok.

What I mean to say is that there will be a thin layer of undoped aluminium gallium arsenide of the same composition as this if it is 30 percent, this also will be 30 percent, ok. This is aluminium gallium arsenide undoped and 2D electron gas is actually formed at this interface of undoped aluminium arsenide and gallium arsenide. This doped gallium arsenide and this doped aluminium arsenide, sorry and is undoped gallium arsenide between them there is a thin layer of undoped aluminium gallium arsenide so that this background impurity of this will not be physically coexisting with the channel here.

So, the band diagram if you draw the band diagram it will look like this is a Fermi level, this is a Fermi level ok. So, what will it will happen is that it will look like this ok. This is the conduction band only. The valance band also will have a mimic there. So, essentially this is the doped n minus aluminium gallium arsenide, this layer on the top. This layer is the undoped layer, this part to very few nanometre may be 5 – 10 nanometre this is the undoped aluminium gallium arsenide and this is gallium arsenide layer. Of course, this is your delta Ec which is a conduction band discontinuity. So, in a way if you have the.

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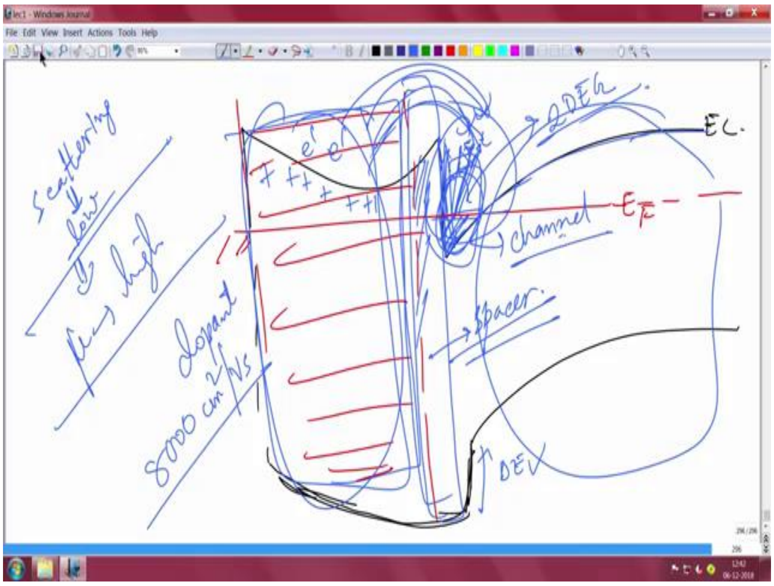

So, if I draw a next slide here so, essentially what will happen is that this is your conduction this is your Fermi level. What will happen is that this is your conduction band. Valance band will also look like that, sorry. It will exactly look like that like that ok. This is your Fermi level ok. This is this part; this part is your n minus doped AlGaAs which means there is a moderate doping of AlGaAs here AlGaAs here.

So, here AlGaAs this part few nanometre this is undoped this is delta Ev, this is delta Ec conduction band and this is your; this is your conduction of gallium arsenide. The Fermi level is actually above the conduction band here. So, this part has a high density of 2D electron gas ok. 2D electron gas that has formed physically because from this layer they are donors now they are donors here because we have dropped.

Those donors will donate electrons, those electrons will essentially fall here those electrons will fall here and create this electron gas here. And that is what a Fermi level has gone below the conduction band or above the conduction band electrons are falling here, but there is this layer this is called the spacer layer few nanometre.

The spacer layer makes sure that this electron gas this channel that is the channel by the way that carries current between source and drain the 2D electron gas, this channel is physically separated from this dopant layer; this is the dopant layer, right. It is physically separated from the dopant layer. So, that in spacer will make sure that this will be separate from the donor the spacer layer. So, the scattering will be low. The scattering will be low which means the mobility will be very high ok.

The mobility will be very high and so, you call it high electro mobility transistor. As I told you at room temperature you can possibly get 8000 volts centimetre square by volt second in a gallium arsenide AlGaAs HEMT or a MODFET. This is a beauty because you are actually having an epitaxial interface there is no interface roughness scattering, where negligible of that and your doping that is actually giving you the electrons they are physically away separated by a few nanometre spacer layer.

So, they will donate give electrons here. And a few nanometre spacer layer will make sure that the scattering that the channel charge is not coexisting with the dopant because this gallium arsenide is not doped, right. So, this is the basic structure of a gallium arsenide AlGaAs high electron mobility transistor.

What we will do is that, we will end up the class here today for today. We have introduced many of the things that are being essential in compound semiconductor. We have discussed about heterojunction band diagram the greater heterojunction. I have introduced the concept of modulation doped FET how is superior to the silicon MOSFET in that the scattering is low and you get very high mobility. This is the band diagram that I have shown you in the previous slide the band diagram of a AlGaAs gas modulation doped transistor.

I will tell you why it is used in the next class. I will also tell you about few other types of this transistors that are used maybe other material system like aluminium gallium nitrite gallium nitrite. So, you will have a broad picture of this transistors that are there and when you are talking about heterojunction transistors I might as well introduce you to in the next class or not introduce sorry recap HBT or Heterojunction Bipolar Transistor which is the superior version of by BJTs. In that the emitter is a wide band gain material I told you.

During the BJT classes that with HBT when you have a wideband gain emitter you are going to get much higher gain. You overcome there are many drawbacks of BJT by using HBT either an HBT or an HEMT. HEMT of gallium arsenide indium phospide systems are there in each of the smart phone that people used in the world today that helps to receive and transmit RF signals because all your information all your internet everything comes in RF and you have to process those, right. So, those transistors are used for that.

If you do not use gallium arsenide indium phosphide transistor in your cell phone then you are smart phones batteries will be the size of a huge brick ok. It saves power actually; so, those are very essential in the present day electronics. And also in the next class we will discuss about few optical devices how heterojunctions are used and from there we will transition to optical devices in the next two next lecture ok.

So, thank you for the time, I will look forth to see you again.