Fundamentals of Semiconductor Devices
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Lecture - 43
III-nitrides

Welcome back. So, today is the concluding lecture for a compound semiconductors, if you recall in the last class we had finished up the concepts of MODFET HEMT and also discussed about gallium arsenide gas you know devices why they are used the band diagrams and other advantages and so on and so forth including HBTs where you can get a sufficiently high gain. I told you (Refer Time: 00:48) in the last lecture for compound semiconductor, we will discuss about 3 nitrides which is a very dominant semiconductor technology and you will see why.

People often say that 3 nitride or gallium nitride based technology is the second most important technologies in semiconductor after silicon even more important than gallium arsenide, because of the wide range of applications it has and the large market that it actually enables ok.

You will be surprised that gallium nitride white LED market is more than 14 billion dollars which is a huge market, all the white LED's that you can see off the shelf that you can buy in big bazaar I keep telling you is actually made of gallium nitride technology only. So, today we shall see what why gallium nitride is so important and what are the basic essential things of gallium nitride technology excuse me sorry ok. So, in gallium nitride technology when I say so we will come through whiteboard here.

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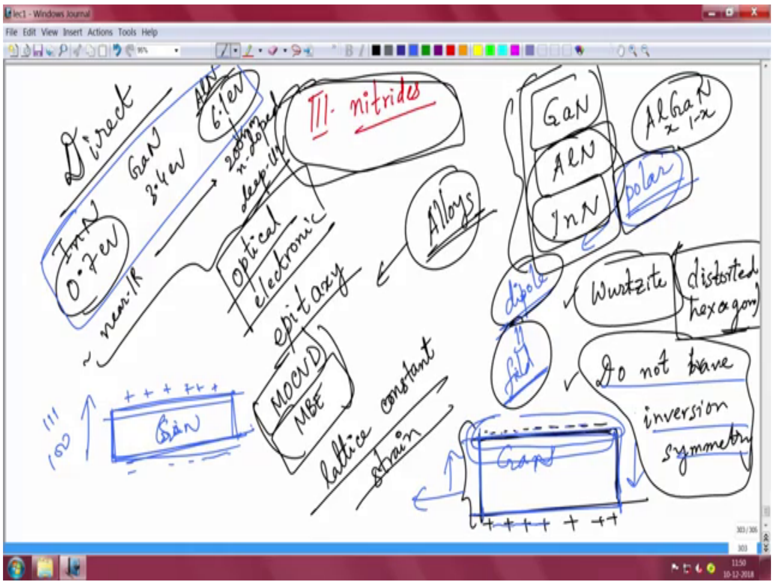

So, when I say 3 nitrides; when I say 3 nitrides it essentially means 3 compounds gallium Nitride Aluminium Nitride and indium Nitride and this binaries can combine to give you alloys as well. So for example, Aluminium gallium nitride or Aluminium indium nitride can be made or indium gallium nitride.

So, these alloys and these binaries together form the 3 nitride family of semiconductors and this 3 nitride family of semiconductor is completely direct band gap is completely direct band gap which means they can absorb and emit light and it it enables a huge range of band gap indium nitride for example, has a band gap of 0.7 ev, gallium nitride has a band gap of 3.4 ev and Aluminium nitride has a band gap of 6.1 ev which you can call to be like insulating. But this can be n type doped for example and so you can change the conductivity hence it is a semiconductor.

In a way you can span the band gap from 0.7 ev to 6.1 ev which is very it is almost like near IR to mid or this thing to this is 200 nanometer which is deep UV. So, you can span the entire optical up to UV and deep ultraviolet as well as near infrared almost on the borderline of mid infrared. So, this is a very you know unique kind of a property of this family of semiconductor that did it has a direct band gap and it has such a large range of band that you can actually enable by alloying and making heterostructures.

Of course, for optical devices it is a very big benefit, but also electronic devices can benefit from this kind of band gaps you will see why ok. All these materials have to be grown epitaxially which means either you have to do MBE or MOCVD to grow them layer by layer at a precision of an atomic thickness as I keep telling you and the beauty of this material system is that they are Polar materials.

What is polar material? Polar material is this these are polar materials and unlike silicon or gallium arsenide which are not polar or gallium nitride and it is family of compounds are polar material which means each unit cell has a dipole each unit cell has a dipole and that means you will see that if you take a slab of gallium nitride you know any thickness of here then each unit cell actually has a small dipole attached to it. So, there will be a sheet of negative charge at the top and a sheet of positive charge at the bottom. It can sustain electric field this kind of behavior and this is in spontaneousus in a spontaneous condition this is without any application of field without shining light nothing in equilibrium.

So, this is a very unique sort of a thing that you know you take a piece of gallium nitride and there is a charge at the top and the bottom, this is called you know this is because the unit cell it with unit cell of this actually the crystal structure of gallium nitride is Wurtzite and Wurtzite is essentially like a distorted hexagon and because of that it this material does not have a centre of inversion symmetry; what does it mean? What it means is that if you take a piece of silicon; if you take a piece of silicon for example if you take a piece of silicon or if you take a piece of gallium nitride gallium arsenide or anything right. If you take a piece of silicon if you flip it upside down, that means if this is the top surface and this is the bottom surface if you flip it upside down nothing will change because, this is the same plane whether it is 1 1 1 or 1 0 0 it will always remain the same unless you cut the crystal in some direction it the flipping upside down does not have any problem.

But over in gallium nitride flipping upside down actually will have different properties, because of this polarization that there is a sheet negative charge at the top and sheet positive at the bottom. So, when you flip it upside down if you flip it upside down and this is gallium nitride then sheet positive will come at the top and sheet negative will come at the bottom and this is why it makes it you know it does not have any inversion symmetry, is not the same when you flip it upside down and where does this charge come from and what is this polarization that we will discuss of course. This is a very unique property I told you this is not present in many of the other common semiconductor like silicon and gallium arsenide and other things and apart from this polarization gallium nitride has a huge range of band gap as I told you.

So, this makes it very unique and it has a lot of properties of material which cannot be found in other systems and it you will see why heterostructure based on this are unique because now they are polar they have an inbuilt field, so even you are applying electric field outside you will see a very strange kind of a band diagram here.

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So, that is what I told you let us before I go to the unit crystal structure and the polarization, I will still revise a little bit here that you know gallium nitride and Aluminium nitride and indium nitride can enable a large range of you know band gap here. It and this is why it has been a it has been very promising it is enable the blue and the green LED’s and laser diodes are something that only gallium nitride technology has enabled efficiently. Before the advent of gallium nitride in 1990 people could not get blue emission and it is very very inefficient and green was also terribly inefficient because green is typically 500 to 550 nanometer blue is around 420 to 480 nanometer also almost bordering violet here.

But this kind of wavelengths require larger band gap and there was no semiconductor for example, 2.4 ev 2.9 to 3 ev these are required for green, this is these are required for blue there was no semiconductor that to operate in this that will have a band gap of such large band gap, people are investigating zinc oxide and some other materials but there has a lot of problem with p type doping. So finally, people have discuss you know (Refer Time: 06:50) made advances in gallium nitride technology and now this enables you to get this band gap. So, how do you get a band gap of say you want blue for example you need 2.9 ev and that is your Blue. How will you get this blue? The way you will get this blue is that you will have to mix indium nitride and gallium nitride.

You see gallium nitride has a band gap of 3.4 ev and indium nitride has a band gap of 0.7 ev, so I told you if you mix a little bit of this and little bit of the that. So for example, if you mix around 5 to 10 percent indium nitride and 90 to 95 percent of gallium nitride, for example you will get something like say indium 10 gallium 90 and the nitrogen, this will probably have a band gap of around 450 nanometer corresponding to a wavelength of 450 nanometer which will emit Blue.

So, this blue LED; this blue LED did you get if you cover it with a phosphor coating with a phosphor coating I will come to that may be in the LED lectures later on. If you cover with a phosphor coating this blue gets shifted to you know and it also emits yellow and the both of them mix the blue and yellow part will mix to give you a sensation of white, that is how white LED's are made mostly they are made.

So, if you look at a LED bulb if you stare it carefully you will see that it has a although it is white it has a slight bluish tinge you will look it today only ok, you will see a slight bluish tinge that is because it is a blue LED that has a phosphor coating to convert it into a white LED right. So, you have to mix and match indium you know around indium 10 percent gallium 90 percent for example. If you want to make a green LED which emits at say 540 nanometer that is green then maybe you have to have probably indium of around 0.25 percent gallium of around 0.70 indium 25 percent gallium 75 percent that will probably emit in somewhere around Green.

So, you know that you can tune the band gap of course you can argue that you can also mix aluminium nitride in indium nitride. But that is a little bit more difficult from the materials point of view, see these materials when I say you are mixing and matching to form alloys there is a lot of material science that goes behind it in terms of lattice mismatch and the difficulty in growing the material in the system.

Typically indium and aluminium nitride and indium nitride mixing them together has not been so widely studied, because it is little difficult to grow aluminium nitride it is also little difficult to go indium nitride. Gallium nitride has been more widely studied and gallium nitride based things can be more easily grown, so gallium nitride mixed with aluminium nitride and gallium nitride mixed with indium nitride are more widely studied. Rather in aluminium nitride mixed with indium nitride although that also can be done, it is the broad picture of 3 nitrides.

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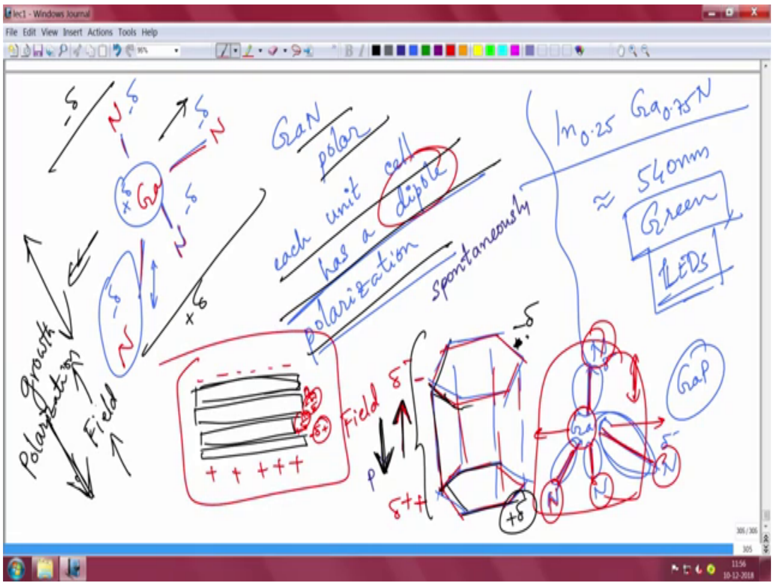

Now, if you come to the unit cell I told you that gallium nitride has a little bit of an hexagon sort of a thing but it is it is a distorted hexagon. So, although it looks like a hexagon it is slightly distorted from hexagon and what happens is that because of that and because of another reason which is that you know this is the gallium nitride tetrahedral unit cell structure.

So, if one gallium atom will be bonded to 4 nitrogen it because of this sp hybridization and each of these gallium nitrogen bonds; each of this gallium nitrogen bonds here. Actually they have because of a large electronegativity difference they will the electron cloud will be shifted little bit asymmetrically, the electron cloud will be shifted little asymmetrically, the electron cloud will be more towards nitrogen and less towards gallium because of a large electronegativity difference.

So, you know there will be a resultant polarization along this bond because it is like a dipole now and with the in plane polarization the total in plane polarization will cancel each other, but the total the vertical polarization in the z direction this is the growth direction the in plane polarization will cancel each other. But the vertical in the direction the dipole will not cancel each other the dipole will not cancel each other. So, it will behave like there is a delta negative charge at the top and delta positive charge at the bottom.

So of course, you know unit positive charge will try to move this way so the field the Field will actually point in the upward direction which means and the convention pole they something called polarization in this material that is why the polarization will point in the opposite direction opposite to the field.

So, the electric field will be in this direction and the polarization will be in this direction. What is polarization? That ability of the material to you know to polarize basically it is a dipole they are right, so there is a negative sheet sorry, there is a negative sheets are there at top the positive like a delta charge at the bottom. So, this dipole results in polarization and you see the direction of the field is in towards the top and the direction of polarization is in the bottom.

So, this is this unit cell itself is polar, the unit cell itself is polar and that is why it has a dipole it has polarization [FL] and what happens is that if you take and of course one unit cell is nothing to get any layer you will have many many unit cells in many many layers of gallium nitride. So, you have 1 unit cell 1 layer then on top of that you have another layer you have another layer, you keep growing like this only then you will get a thick layer of gallium nitride know whatever 10 nanometer 100 nanometer one micron whatever.

So, every positive in every top interface you will have a negative charge at the bottom interface you will have positive charge negative then positive, so all this will cancel each other eventually the interfaces what remains is that at the bottom you will have one delta positive charge here you will have one delta negative charge here. So, that is called polarization and what will happen is that; what will happen here is that you will have to you know draw the band diagram taking that into consideration.

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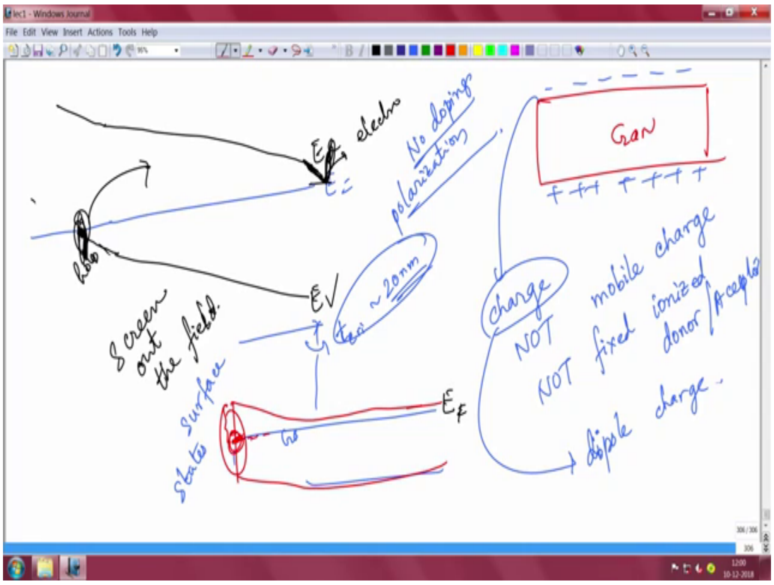

So, you know if you take a piece of gallium nitride like that there will be a sheet sorry there will be a sheet of charge here like that and there will a sheet of charge here like that, this charge actually this charge please remember this is not a mobile charge, it is not like a mobile electrons and holes that you can you know you can use to conduct electricity. It is not mobile charge it is also not you know like a fixed ionized donors or acceptors sort of a charge ok, it is not like a fixed ionized donor acceptor sort of a charge that you can get after doping a something, there is no doping here please remember there is no doping here.

But because of this polarization you will be able to get transistor even without doping which is not possible in other semiconductor right, you cannot have a transistor without doping right, but in gallium nitride you can have that because of this polarization it is an extra degree of freedom.

This polarization gives you an extra degree of freedom, so this what is charge is essentially is that it is a dipole charge it is like a dipole charge [FL]. So now, if you draw a band diagram of this of course, in equilibrium your Fermi level has to be constant, but what will happen is that because of this you know negative and positive the field will look the band diagram will look like this it will look like this.

But of course, if you keep growing it thicker and thicker then eventually your this is the valance band know this is the conduction band, this valence band will approach the

Fermi level right and it cannot cross this because then you will get what will happen is that you as soon as you approach this and purchase this you will generate holes and you will of course this will also touch here because this the same slope you will also touch electrons here.

And these electrons and holes will essentially screen out they will screen out the field they will screen out the inbuilt field. So, you cannot keep growing it will cannot this valence band cannot go like this it cannot go like that that is not possible it will get pined here, because you will get very large density of holes and very large density of electrons that will essentially screened out the field.

So, what will eventually look like this is that this is your Fermi level and you will after that it will go like this ok. If the entire band gap will drop here and after that so only upto certain thickness you will have that field that is a critical thickness critical and for gallium nitride probably that is around 20 nanometer or so if I recall correctly or may be even less. But again this assumes that in the in the surface there is no impurities of state, but in gallium nitride technology typically there is always surface states.

The surface states are essentially like on the surface you have traps and donor sector acceptor kind of levels which will have different kinds of effects, one of the effect is that because of the surface states or traps they will pin the Fermi level which means they will fix the Fermi level at one point and not allow it to go to much you know the entire band gap.

So, what will happen is that if this is a Fermi level then you know it will get pined at some value here. So, instead of the whole band gap drawing here dropping you will drop only some part of band gap because, this traps are pining the Fermi level the Fermi level is not allowed to move physically what it means is that there is a large number of electrons or holes that this traps can donate and Fermi level will like to move be around that.

Because if the Fermi level tries to move this extra charge then this traps will essentially either donate or take electrons away from the Fermi level to make sure that the Fermi level is at this position this is called Fermi pinning. Anyways this is not so important from this course point of view, I just told you that you should be aware of now how to do this material enable technology. So, one of the important thing is that one of the very big thing is that.

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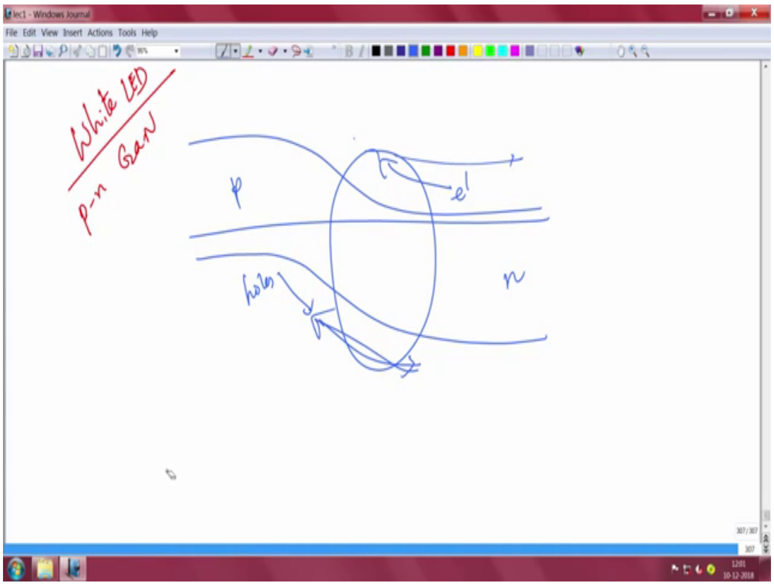

It makes the white LED ok, white LED essentially is a p n junction of gallium nitride and in between you will have quantum well when we discuss LED's we will come to that you know your active layer. If you have a p n junction like that of gallium nitride it will look like this, but I write this is p this is n.

But I told you the when you are injecting sorry when you are injecting holes from here and you are injecting electrons from here they are expected to recombine. But the diffusion their diffusion line might be more which means they will have to diffuse a long before even one electron and one hole recombines also they may move fast, so then they will not get much time.

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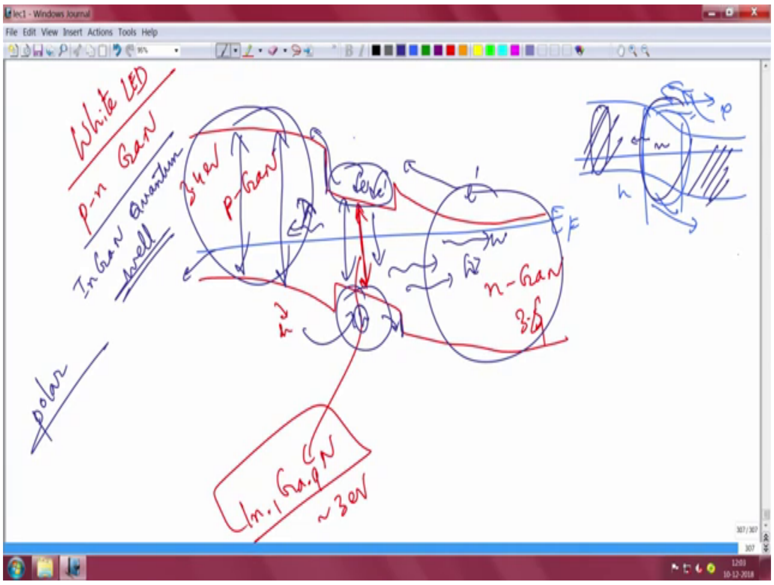

So, one of the approaches in LED designs is that you do not have this kind of thing, what you do is that you enable them to recombine even more efficiently. So, you have a smaller band gap material there like that I am not drawing it well so let me draw it again. So, if you understand right if there is a p n junction just like a p n junction like this, the holes that go this side and electrons that come this side to this side have to recombine in the depletion region.

But the diffusion lengths are longer so they have to diffuse much longer much more than this depletion region to even enable recombination. So, it leads to inefficient recombination also they can move very fast and might not get time recombine. So, what you do is that this is the Fermi level you have a quantum while in between a narrow band gap material in between.

So, this is your n type gallium nitride, this is your p type gallium nitride in between a in you have a narrow band gap material which can be say indium 10 percent gallium 90 percent because this is ingan and this will band gap will be say for example 3 e v I am just telling you this will be 3.4 e v this is 3.4 e v and this is inside is 3 e v.

So, what will happen is that when holes come, when holes come they will fall back here and they will not be able to go out because there is a barrier here. Similarly when electrons go this side they if they fallback here the electrons will be here they will not be able to come out easily because there is a barrier here. So, electrons will spend more time in the well holes will spend more time in the well they will get more time to recombine and then they will emit light h nu.

Then they will emit light radiatively they have to recombine of course and because this layer is a wider band gap material than this, the wavelength of light emitted; the wavelength of light emitted will be such that the energy of the photon will be less than the energy here. So, the photons will not be absorbed here or absorbed here.

If you have the same band gap material like this then the photon that comes out here has the same energy as this, so this part will absorb and kill the photon this part will absorb and kill the photon, so that reduces efficiency so you have to get something like that. So, essentially a wide a LED is made of a p n junction of GaN with indium gallium nitride quantum well that is your that is your a white LED, but of course I told you because this materials are polar and there is a field, so this ingan you know this ingan has a huge field and that is not good for the device right.

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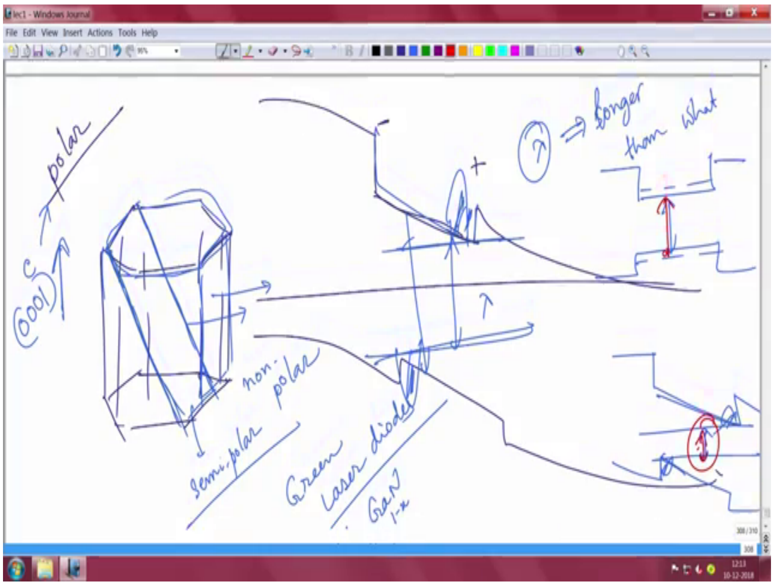

So for example, your you will have a huge field actually like something like this maybe even in equilibrium, even in equilibrium you will have something like this, you do not want this field you what you want is that you do not want the extremely high field in ingan because there will be a sheet of negative and sheet of positive charge.

So, this polar materials are not the best materials for making LED's but people use them, but nowadays they are going to you know if you have a gallium nitride crystal like this right, I am not drawing it very well I am just telling you it just a unit cell. You have a gallium nitride crystal like this then the thing is this is a c direction this is the growth direction which is called c and this is a (Refer Time: 19:31), so the direction convention is 0 0 0 1 that is this direction and this is polar direction and so you have a high field.

So, what people do is that they take other planes they look at this kind of plane. So, instead of looking at this plane the top you are looking at this plane for example, that is called non polar, it is not it does not have polarization because, we are looking at this direction you will you will make an LED and this direction it might be little difficult for you understand, but you do not worry about it. But there might be also planes that go like this you know you might slice the crystal such that this is your plane on which make devices those are called semi polar.

They also have very negligible polarization almost no polarization this is semi polar there is a lot of research on semi polar green LED's and so on, you essentially slice the crystal in this direction and make the device there instead of making the devices on this top.

So, these are called different planes and LED's and other things the optical devices work better when you have your devices on the non polar and semi polar planes [FL]. So, that is all about your LED's and you know you know gallium nitride base LED's, but of course a gallium nitride base has many other technologies apart from the white blue LED it can also make green LED as I told you and green laser dioded that are very useful and those are used and these are also ingan by the way ingan you can change the x here lot of materials and device researches keep going on in this in different parts of the world it is a lot of advanced research going on even now for green LED's and laser diodes and then there is you know there is also electronic devices.

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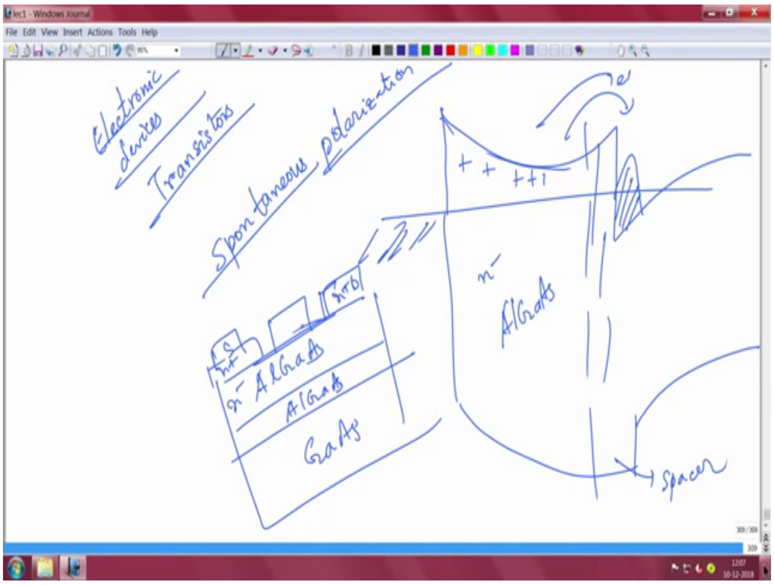

Based on this there is also electronic devices, which is essentially transistors electronic devices are transistors, it if you remember your gallium arsenide technology. You remember gallium arsenide technology? It looks like this no, if you remember this is your aluminium gallium arsenide layer which was sort of doped and then there was a special layer which was undoped and this the donor levels here will donate the electrons and this electrons will come here and form the electron gas you remember that.

Now the best thing about gallium nitride is you do not have to dope it because there is already polarization ok, there is already polarization. The polarization that exists on gallium nitride and it is sister compounds aluminium Nitride AlGaAs Ingan whatever without any application of bias without anything is called spontaneous polarization because it exist just like that right, it exists.

So, instead of disc kind of a structure and this was AlGaAs gas by the way right this was like AlGaAs which is n minus doped then AlGaAs that is undoped which is this layer and then there is a gallium arsenide. Of course, on top of that you have an n plus layer where you put source n plus layer where you put drain, but you have to you have to (Refer Time: 22:24) that away so the gate is here right. Now in case of AlGaN technology you do not have to do even a doping it is a very fantastic kind of a thing what you do is that you just have aluminium gallium nitride ok.

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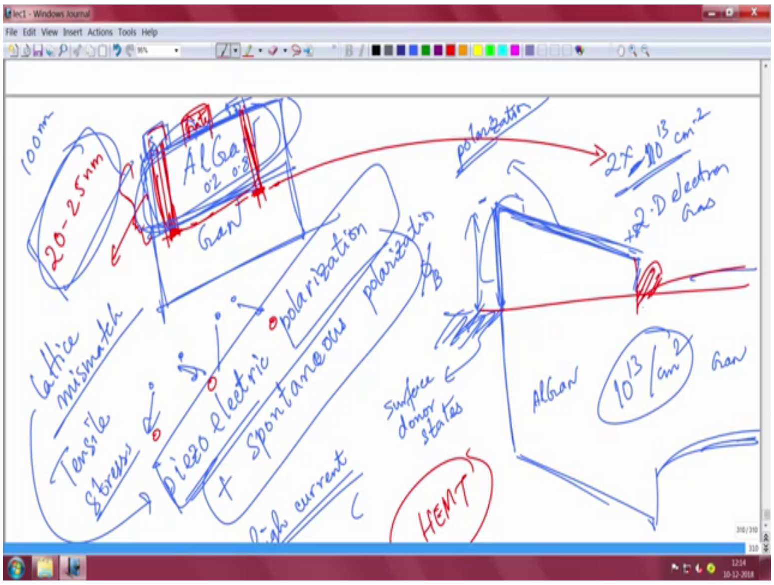

And this aluminium could be around say 20 percent gallium could be say 80 percent and then you have gallium nitride [FL] that is it that is it you Do not have to do anything no doping no n plus contact nothing. What will happen is that and if you draw a band diagram we will not go into the details of how to get this, but this is what happens because of the polarization you will get an electric field like this. Of course, this is delta ec and it will go like that it will go like that ok.

So, this is your AlGaN, this is your GaN and there will be huge 2 D electron gas here, this 2 D electron gas is very very high density this could be at least 10 to the power 13 centimeter square which is not possible with silicone based MOSFET or gallium arsenide based devices equilibrium. It can be even depending on the design it could be even 2 into 10 to the power 13 which is insane very high very very high so they can carry very high current. Because this is very high current very high density they can carry much higher current than gallium arsenide or silicon and that is also has it is own advantage you can operate the device that to get much higher current.

So, even a smaller area can give you higher current you can reduce the size of the area of the device and you can also get higher current [FL] you can also do get a higher RF output power. For example, all this things advantages come, smaller device footprint higher power and so on. But you see there is no doping here this bending of this field that is happening is they do polarization, you can think because there is a negative charge here there is a positive charge here and this is thick gallium nitride, so that you know dipole is skinned out mostly. So, this is that because of this field you get this very high density of electron gas it is not because of doping, there is no doping and the physically the electrons come from the surface states.

So, on this here this is a short key by you hide by the way, there are surface states here, this surface donor like states actually they are called donor states they can donate electron. So, this surface donor states donate the electrons and they are actually accumulating here, so there is no doping and the polarization is not the source of the electrons here please remember, polarization assists or enables the electrons to be here polarization assists.

So, you do not have to dope, physically the electrons come from the surface states and you Do not have to do any n plus layer here for contact. Because if you put a metal here like a source and you put a drain here you anneal at very high temperature like 850 or 900 depends on the method, of course. Then this metal will and you see this electron is here know this electron gas which is essentially this, this is this very high electron density gas ok.

So, if you annealed a very high this metals at very high temperature anneal they will spike they will metals will spike below. So, will basically touch this and touch this so you will have a current between source and drain. Now you put the gate like this you do not even have to put a dielectric that is it, this your gallium nitride transistor.

Now this aluminium gallium nitride I told you is around 20 percent aluminum 80 percent gallium typically the thickness you can vary it is around say 20 25 nanometer and when you grow aluminium gallium nitrate on gallium nitrate if you recall aluminium gallium nitride has a lower lattice constant smaller lattice constant. So, if gallium nitride is like this spacing of the atoms then aluminium nitride is actually a smaller.

So, when you go aluminium gallium nitride on gallium nitride it tries the mimic, so there is a stress it is called a tensile stress because your aluminium gallium nitride atoms of this layer are pulled out side to accommodate to the gallium nitride below and because of this stress if there is a stress because, there is a strain know that is called because of the lattice mismatch.

Because of the lattice mismatch there is a strain and because of that there is an extra polarization that comes out it is a strain related polarization or stress related polarization we call it piezoelectric polarization. You might have heard this word piezoelectric electricity it is called piezoelectric polarization because it arises from the strain in the top AlGaN layer.

And this strain in the top AlGaN later happens because the lattice constants of AlGaN and GaN are different, so the AlGaN layer is tensile stressed to gallium nitride below when you grow. If you grow to take if you grow like 100 manometer then this AlGaN layer will crack because the tension will release will be relieved. So, it will crack and your device will not work so that you Do not want to go to thick, even 30 nanometer and 40 nanometer is risky it will crack. So, we keep the thickness lower than the critical limit at which it will crack it will crack, because it is a high stress it will develop you want to keep the stress reasonably within the critical limit.

So, because of that the AlGaN layer will have a piezoelectric component of polarization that exist along with the spontaneous polarization and both of them will point in the same direction or will reinforce each other magnitude. The spontaneous polarization always exist there and piezoelectric polarization comes because of strain and this piezoelectric polarization of course does not exist in gallium nitride here because, the gallium nitride is not strained as such I am assuming just the freestanding substrate. So, this piezoelectric polarization will make sure that this electron gas density is extremely high and that is the reason you are able to get 10 to the power 13 per centimeter square or more than that ok.

This piezoelectric polarization will make sure that you get very high density, so your AlGaN has been stressed here [FL] and this polarization is actually enabling you to form this electron gas without doping which is beneficial to electric devices. But as you might have seen in the ingan this is not beneficial to a polar optical device because of this extremely high field your electron will be here accumulating here your holes will be accumulating here. So the emission of the wavelength will correspond to only this gap instead of this gap here.

So, what will happen is that the actual wavelength that you emit is short is actually a longer wavelength it is a red shifted then what you actually expect. You see my point? It is like you have this quantum well you have this quantum well this is the band gap you expect to emit between 2 layers here. But if this quantum well becomes something like this then electrons will be here holes will be predominantly here because the field will push it here and here so what you emit here is only this much; can you see that? Is only this much which is much smaller than this.

So, you will get a longer wavelength is the red shift you do not want that is why in optical devices polarization is bad you go for semi polar and non polar. But in electron devices like HEMT high electron mobility transistor you actually love the polarization here, because it enables you from a high density of gas here.

Now I will not go into the details of working of this device, it is a transistor you see that there is a source there is a drain and there is a gate and this is the electron gas that you essentially modulate here, right; this is the electron gas that you modulate here ok, it is very high density I will just tell you the applications.

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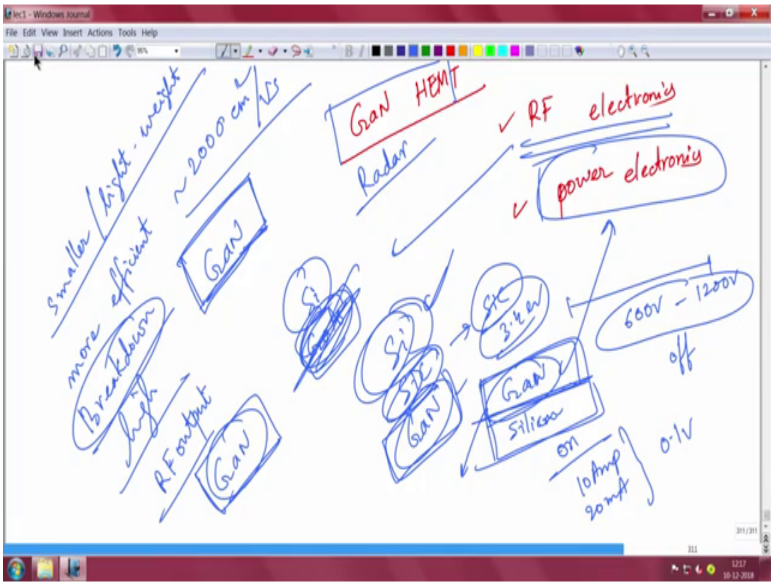

This gallium nitride based HEMT are now increasingly entering the market and giving a tough competition to silicon in 2 areas one is called RF electronics and one is called power switching electronics or power electronics.

So in these areas there are see in this area of RF electronics you also have silicon and you also have a you know gallium arsenide technology, gallium arsenide is for super high speed very high frequency, but the power output it can give is much lower of course silicon because of it is cost advantage it is there but the performance is not up to the mark as gallium arsenide definitely.

Now, gallium nitride is coming there and it can work at very high speed because and it is a wide band gap I mean material. So, it can go to much higher temperature because you know it is a wide band gap material so high temperature electronics is possible, it also has very high charge density so and the 2 (Refer Time: 30:16).

So, it is mobility also is high around you know 2000, not as high as gallium arsenide but it is it has also high velocity. So, you can make a very high density current can go, so you can make smaller devices; you can make smaller devices which are lightweight it can also take much you know high current it can take much high current it has polarization. So, you do not need to dope. You can take much higher current, so you can make smaller footprint devices which are more efficient also. It has a one of the advantages that because it is a wider band gap material it is breakdown field is very high, it is breakdown field is very high which means you can operate the device at much higher voltage, that means you can also get much higher RF output power and these has much better than in gallium arsenide.

Of course, gallium arsenide has a little advantage of speed still gallium nitride is now widely used in strategic sector like radars and missiles and all in the advanced countries in US and Japan and all they are technology is used. Power electronics is another area where you have to essentially block a very high voltage, we will come to all this little bit you know we have a couple of lectures on different kinds of transistors and their applications I will tell you. You essentially have to block very high voltage say 600 volt or you know 1200 volt and you block you have to allow very small current to pass and then in this is the off state and in the on state you want very high current to flow like 10 ampere or 20 ampere current to flow at very little voltage like 0.1 volt or so.

In that kind of power electronics gallium arsenide does not exist there is silicon of course and there is something called silicon carbide I did not go to that and then there is gallium nitride. So, this technologies compete with each other silicon competes because of the cost performance may not be as good as GaN ok, GaN can actually switch faster, it can also go to much higher breakdown voltage. So, it you can block higher voltage you can switch fast because mobility is better in gallium nitride then in silicon or silicon carbide so it can switch faster.

So, these are some areas where gallium nitride based device technologies are entering the market, of course there are other technologies like silicon carbide which is also a compound semiconductor technology it is band gap is 3.4 e v that is exactly a set of gallium nitride. But gallium nitride has more of material properties problems you know gallium nitride freestanding substance like silicon wafer you can buy a pure GaN for is difficult to grow. So, it is also very expensive you cannot make large scale devices you know commercialization you grow gallium nitride on something which is very cheap and so the gallium nitride as to be grown on top of silicon.

For this power devices mostly and this makes it very cheap but the problem is silicon is the different material and gallium nitride is different material. So, the materials growth has enormous challenges that people have been trying to address for a really long time, there has been sufficient advancement, you can get good quality of gallium nitride on silicon, but nowhere near the quality of gallium arsenide wafer or you know other things. So, that is why it is a lot of material challenges it is still a very hot area of research just in case you are interested.

So, with that we will wind up today's lecture, so we are done with compound semiconductor technologies, we will finish here your compound semiconductor technologies gallium arsenide gallium nitride the 2 major technologies I have touched base. It is a wide variety of things oxides are there peroxides there is antimonides mercury cadmium tellurides and so on. It is not possible to cover everything within one single course for that we need a separate course on compound semiconductors there is a lot of applications in optical devices and other areas sensors and other things.

I kept it only brief here in the overview of this course, [FL] introduce you to gallium arsenide and gallium nitride technologies the very basics, even in gallium arsenide devices or gallium nitride LED's and HEMT. There is enormous amount of content that you can just Google up and try to see you can always e mail me ask me if you have any questions, these are not actively a part of your curriculum for gate exam or other exams if you are looking at.

But these are important for your own understanding for your curiosity and for general awareness in the subject if you want to take up higher studies or you want to do in some government research labs and so on ok. So, with that we will conclude our compound semiconductor class, from the next class we shall begin optical devices starting with solar cells.

Thank you.