High Speed Devices and Circuits

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Lecture – 8

Brief Overview of GaAs Technology for High Speed Devices

In the last lecture, we discussed the various p- type and n- type dopants with reference to gallium arsenide. We also said that in the case of indium phosphide also almost the same dopants hold good. After all, it is three-five in general not gallium arsenide, not indium phosphide, or gallium nitrate. Now, we will go further onto some of the other impurities which are present, either present or you deliberately introduce to modify to suit to your requirements. We will start seeing or discussing a brief overview of gallium arsenide technology or high speed devices.

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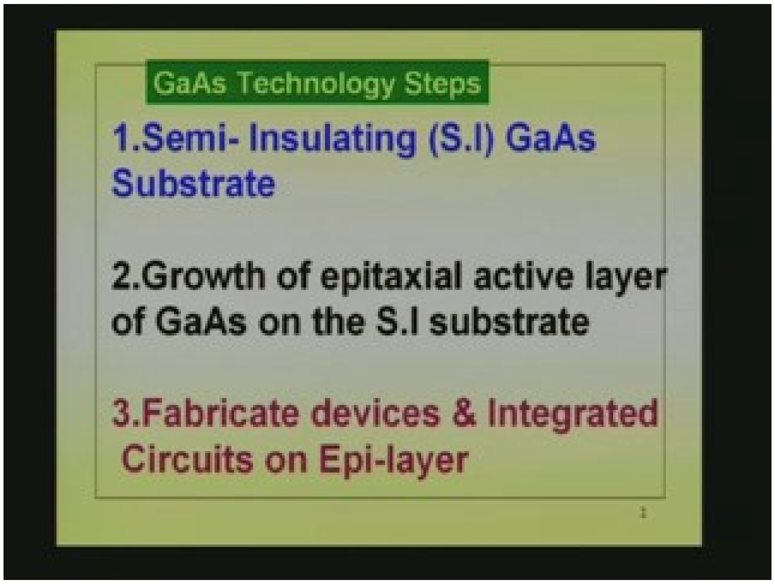

GaAs Technology Steps

1.Semi- Insulating (S.I) GaAs Substrate

2.Growth of epitaxial active layer of GaAs on the S.I substrate

3.Fabricate devices & Integrated Circuits on Epi-layer

Now, when you see the gallium arsenide technology what we would like to see is first some aspects of semi-insulating (S.I) gallium arsenide substrate. In fact that will be the starting substrate. Why should we have that etcetra, we will see soon. Now, on the top of that substrate, you will have an epitaxial active layer. In fact, this is the epitaxial active layer of gallium arsenide on semi-insulating substrate. On that, we will make the devices. So, what we are taking a look at is these three aspects one by one; this itself will take sometime then we will go into the next lecture on these. There onwards, we will not look back into materials, we look into devices.

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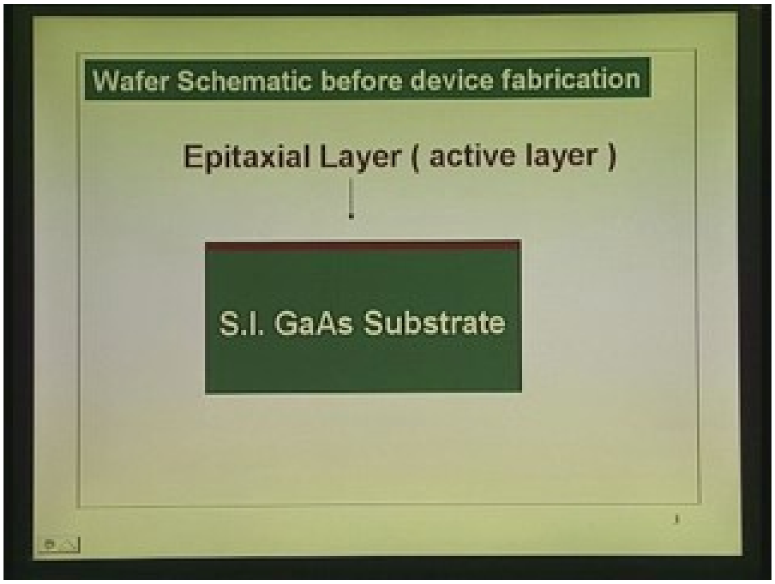

Wafer Schematic before device fabrication

Epitaxial Layer (active layer)

S.I. GaAs Substrate

Just watch the slides, what happens? I will go back if you have missed it. Semi-insulating substrate is starting. On the top of that you see the layer grows that layer is epitaxial layer. So, the starting substrate is a semi-insulating gallium arsenic substrate and on the top of that you will have epitaxial layer which will be the active layer. Now, before we go any further what we have to see is I will just go to the board and explain some of these things. Why do we need this semi-insulating substrate or why do we need an insulator at all? we cannot have the entire layer as active layer? For example, I want to make n channel MOSFET, what we do? We take a p- type substrate grow internal devices that is what we do. we cannot do a similar thing? Now notice, when you have a semiconductor material like this (Refer Slide Time: 04:40) whether it is n- type or p- type semiconductor, ultimately you do not use the full wafer. What is active is only a top layer that is the active layer. Whether you talk of MOSFET, JFET, and bipolar transistor, the active layer is very thin. Rest of this layer what does is it do? It provides only the mechanical support. In the process of providing mechanical support to that active layer, it does lot of harmful things. The harmful thing that it does are some of the capacitance of which come from the device to the substrate and also the capacitance for the interconnected devices. The capacitance of the interconnection layer or routing capacitance. The capacitance when are interconnected that capacitance is with respect of state that also comes up here. So, that is why when you want to go to high speed you want to cut down all capacitances as you have seen in flight at the beginning. How to cut down the capacitance? Replace this particular layer, entire bottom layer by means of an insulating layer. An insulating layer, so that the junctions, capacitance etcetera can be reduced. We will see how it happens. Also; when you have a thick insulating layer, when you have an interconnecting wire going through one device to other device, the capacitance of the layer with respect to substrate that is the capacitance for this layer that can be reduced because it can be made thick. For example, with respect to that up to this point if you have, I remove this layer let us say. By interconnecting layer, I can remove this layer. So, the interconnection goes through this like this that is the capacitance. Thick layer capacitance is very small. So this is one of the key things in high speed devices and high speed circuits made out of circuit devices. This is why people are looking more and more into substrates which are insulating.

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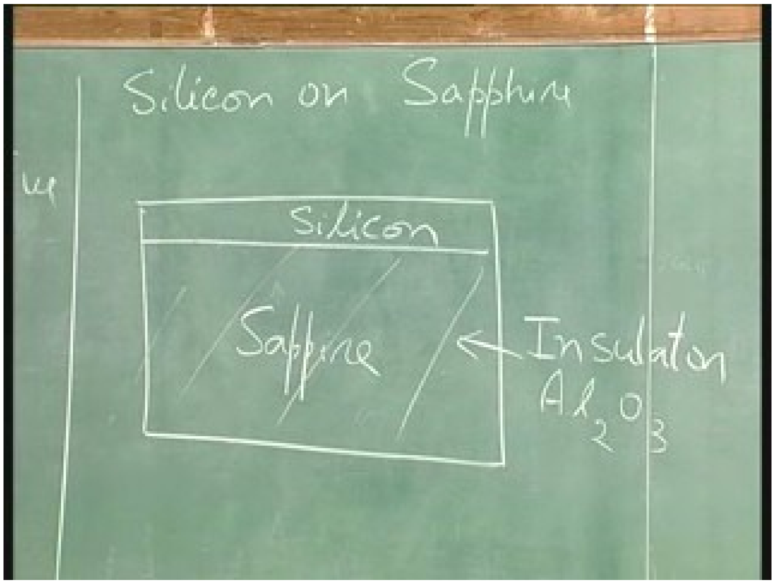

In the case of MOSFET way back twenty years back, people have spent their energy on like this, silicon on sapphire. Sapphire is Al_2O_3. It is an insulator, very costly material. But, still if you want high speed what they have done in silicon technology for high speed it is not as if the high speed is prohibitory of the compound semiconductors. In silicon itself people have been trying that is like this on sapphire you grow silicon. This is insulator. This entire thing is an insulator, because it is Al_2O_3 is an oxide. In fact, for defense applications when high speeds are required they were using that. Today also for some of the very secret defense applications high speed they use this. But, for other commercial mainstream ICs they do not use it, because it turns out to be very expensive. Instead what they have done is do not provide the whole thing as insulator. Within your technology what you can do is silicon can be put on an insulator which is put on the silicon substrate that is called SOI, silicon on insulator. So, we may have an occasion to come back to that later, but today since you are dealing with this I just brought out this. The substrate is insulator because that is the mechanical support and this is single crystal. On single crystal you can grow single crystal that is the nice thing. That is why you are looking for material, which are of high resistivity or if possible insulator which are single crystal and not only that materials will be insulator and single crystal, you must be able to grow the layer without any defects. That means the layer that we grow must have the same crystal orientation structure as this. Now these are two different materials all together. Still silicon matches lattice with sapphire when the sapphire has a particular orientation. So, that is why they were able to manage but still they are getting lot of defects here. So, thin layers are rather difficult still they were able to manage and get good performance. You can get (10:21) wafer in fact the person who is handling it I have seen they are so nervous because it is so expensive. I do not want to drop it and I say I do not want to drop it, you will drop it.

This is the key thing about that. If you are prepared to spend that much money and if you are not able to get as good performance as you looked forward to, you can as well switch over to another material like gallium arsenide. At gallium arsenide, we can get a semi-insulating substrate. That is why we were telling the answer for that with gallium arsenide is you have a semi-insulating gallium arsenide. If you are making indium phosphide as semi-insulating material indium phosphide, if you are using gallium nitrate we must look for an insulating substrate, may be silicon carbide. We look for high resistivity materials like that. Since we are focusing on this right now, let me focus on this material itself. So, first you must be able to get this semi-insulating gallium arsenide material, then you can think of putting the top layer on that and this can be single crystal gallium arsenide (1 0 0) oriented. On the top of that you can grow, that is what we were seeing there. On the top of that we can grow nicely that particular layer. It grows up as the time passes this that is the epitaxial layer. Epitaxy means arranged upon. You arrange the atoms on the top of a substrate and arrangement takes place exactly same way as the arrangement of the atoms in the substrate. Now, let us go into further details.

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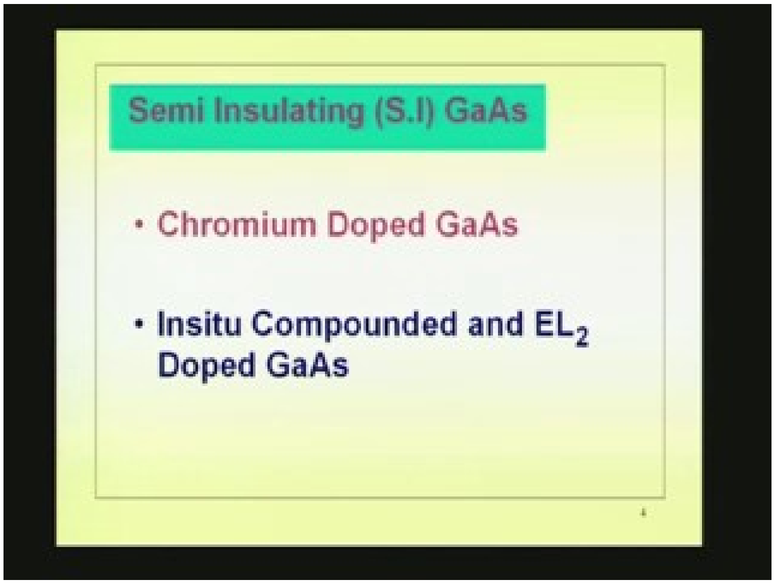

Semi Insulating (S.I) GaAs

- Chromium Doped GaAs
- Insitu Compounded and EL_2 Doped GaAs

So, first we will get into how to make this semi-insulating gallium arsenide. There are two approaches: One approach is chromium-doped gallium arsenide, other approach is Insitu compounded and EL_2 doped gallium arsenide. EL_2 is another impurity that comes in. We are not introducing it. It comes in and grows. What is the problem here? Why should you have chromium-doped gallium arsenide? You cannot grow insulating gallium arsenide? Un-doped 10 to the power of 6 carrier concentration which is very-very high resistivity, you cannot get that? We can never get it, because there are the impurities present. So, one of the major impurities which are present in gallium arsenide with people we are facing was silicon. Silicon itself was coming from the crucible and silicon you know in gallium arsenide it is n- type dopant. So, you get when you grow by Czochralski technique usually when you from melt prepared from a polycrystalline gallium arsenide. First you prepare a polycrystalline material and then use it as a melt, pull the crystal that turns out to be n- type because of the silicon and you will say un-doped gallium arsenide carrier concentration 10 to power of 15 that sounds funny, because if they are doped put carrier concentration 10 to the power of 15. The meaning is intentionally no doping done. Whatever has happened is unintentional. But, you want to bring back to the device. We want to make it insulating or high resistivity that is of the order of 10 to the power of 9 that is about the intrinsic concentration of 10 to the power of 9 ohm centimeter will be the resistivity of really un-doped gallium arsenide material.

10 power 9 to 10 power 10 in that range when the carrier concentration is that low, how we do that? That is done by compensating those dopants which have an entering unintentionally and the compensation is done by doping with chromium. We should discuss that why and what happens there. Other thing that they have done recently is do not let the silicon come in, somehow manage to grow the crystal by starting with high purity gallium and high purity arsenic, then make an compound that is Insitu compound and then grow. That turns out to be p- type. Due to some contaminants like carbon and contaminants like boron coming in that turns out to be p- type. So, we have no choice. In one way if you should already take polycrystalline gallium arsenide and then melt it and grow it which turns out to be n- type from the crucible and from the contaminants, other way it is p- type. So, if it is n- type we use chromium for compensation, if it is p- type you use that EL_2 that EL_2 is a particular name which no response with EL_2 is what it is called. So, what we said is to get there one route that you chose is chrome doped (Refer Slide Time: 15:55) or chromium doped both are same. This introduces why? To compensate for the shallow donor. Obviously, chromium which you said is an acceptor level. Now, why should it be chromium? We can put zinc.

Zinc is p- type impurity. While growing gallium arsenide you know silicon comes unintentionally, you can add zinc p- type, what is the problem? The problem is this. Can compensation be done with shallow acceptor? The meaning of shallow acceptor means shallow level. See, for example, what you have the problem is like this. Let me draw the conduction band and valence band like this E_C and E_V. You have unintentional silicon which comes up like this. Shallow donor which makes the carrier concentration about 10 to the power of 15 n- type. If that were absent you would have got may be 10 to the power of 9 ohm centimeter resistivity. Now you get very low resistivity.

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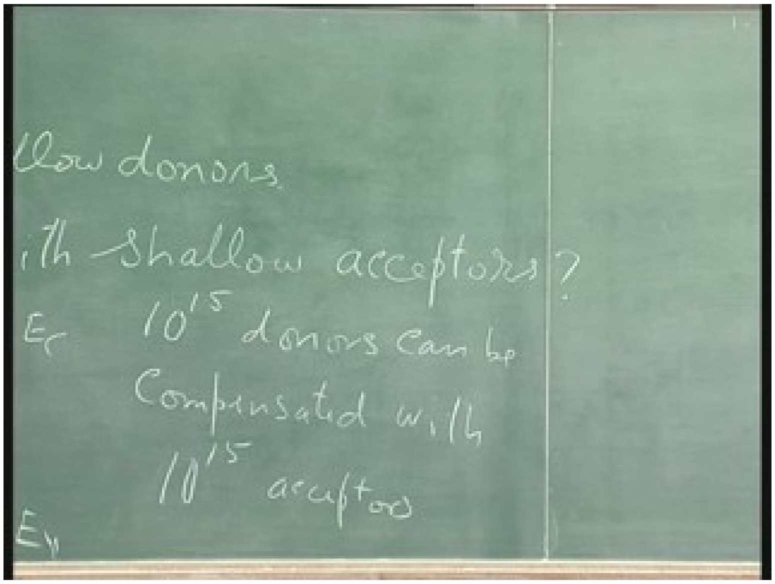

llow donors.

ith Shallow acceptors?

E_C 10^{15} donors can be

Compensated with

10^{15} acceptors

E_V

Suppose, I put acceptors here that is the meaning of that, shallow acceptor I put here 10 to the power of 15 donors can be compensated with 10 to the power of 15 per centimeter cube of course acceptor like this shallow. Now, it is very difficult to control that 10 to the power of 15. Supposing it becomes 10 percent off here, you will say okay it is 1.1 into 10 to the power of 15, so 10 to the power 15. It is not all right because if it is 1.1 into 10 to the power 15 what happens? 10 the power 14 is p- type, so you cannot compensate that. So, instead of going down to 10 to the power of 6 you add 10 to the power of 14 p- type whatever n- type has become p- type, very difficult to control this is difficult. So, what you need is introduce an impurity which will even if you change a little bit beyond certain level it is going to clamp or pin itself into intrinsic material that is the property that gives chromium.

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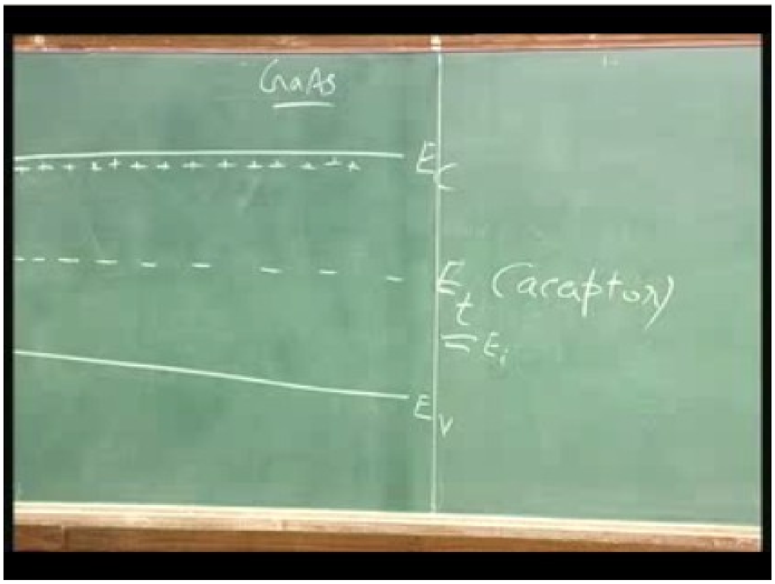

Let us see what it is. Once you see some of these things, we can flip through those slides, because those are the things it gives. This is very difficult with shallow. I have not written that but you can just note down yourself. This is difficult to exactly compensate with shallow acceptor. Now, let us see what chromium does. This is gallium arsenide of course (Refer Slide Time: 20:10). Chromium introduces a level. It introduces an acceptor level. We can call it as a trap level. It is an acceptor level which is E_t just to distinguish it from the convention shallow donor is an acceptor I call it trap level. It is actually deep level, deep level meaning lying deep from the conduction band or valence band. Please understand deep level does not mean the impurity is lying deep. Deep level means as far as energy band is concerned it is actually away from the conduction band or the valence band closer to the center of forbidden gap. So, acceptor E_t that is chromium gives rise to this level. I can rewrite that chromium level. Now you have got unintentionally doped silicon. Let us see how this works out. This is E_D unintentionally doped with silicon n-type. Now, let us see what happens. I start with no chromium, electron concentration is 10 to the power of 15. I start adding chromium, you are adding acceptors. When this was absent where is the fermi level in n- type material? Above the intrinsic level. This is almost equal to E_i. E_t in this case is almost equal to E_i. In fact, you will see in the next slide there.

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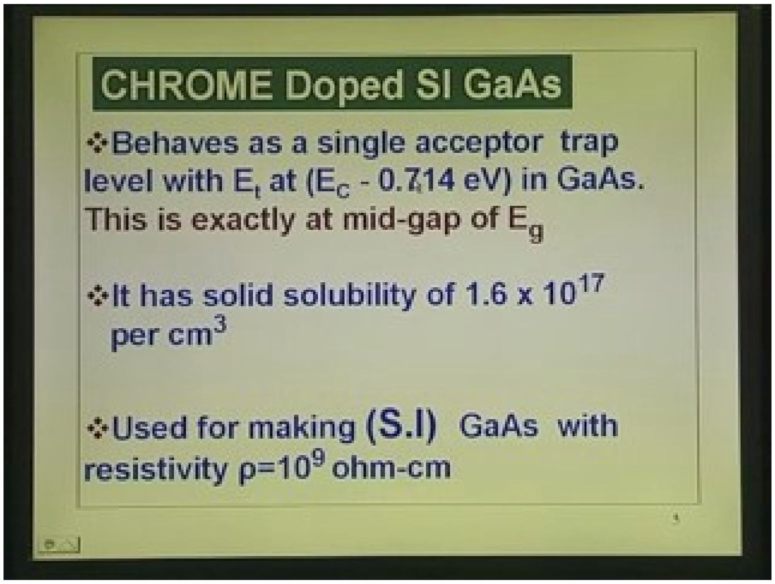

CHROME Doped SI GaAs

- Behaves as a single acceptor trap level with E_t at (E_C - 0.714 eV) in GaAs. This is exactly at mid-gap of E_g
- It has solid solubility of 1.6×10^{17} per cm^3
- Used for making **(S.I)** GaAs with resistivity $\rho=10^9$ ohm-cm

That introduces behaves like a single acceptor trap level with E_t at E_c minus 0.714 electron volts which is exactly at the mid gap of E_g. The key thing is you have introduced an acceptor at the mid gap of the forbidden level. So now, we will see as we go on adding chromium concentration from 10, 100, 1000, etcetera we keep on increasing what happens? Nothing will happen if we go to 10 to the power of 13 or 15 like that. But, once you go to that level this acceptor, what is the status for that? If the fermi level is here all of you know the concept of fermi level that is n- type. As I keep on adding this fermi level is above the acceptor level. So, the level is below. See the concept of fermi level is all the levels below that are mostly occupied. All the levels above that are mostly unoccupied. This is unoccupied means what? It has given an electron, donated for that level is unoccupied; that is the meaning of that. It can go up or go down whatever. So, if you add here, fermi level is here initially. This is not occupied that is donated electrons. This is occupied. So, if there are 10 to the power of 15 electrons here due to donors when this is 10 to the power of 12 out of those 10 to the power of 15, 10 to the power of 12 will go down here to occupy that. That is where it gets the electron from, it is occupied. So, conduction band electrons are 10 to the power of 15 minus 10 to the power 12, 10 to the power of 15, keep on adding. As you keep on adding it becomes more and more p- type. Because we are adding a p- type impurity so it becomes more and more p- type in it because the electron concentration comes down. Why does it come down? It has to satisfy this. These are ionized because that is below the fermi level. Now, so as you keep on increasing that chromium concentration it becomes less n- type, fermi level keeps on moving towards the center okay and when it reaches this point, it will reach this point what happens? Half of them will be ionized. It begins all of them will not be ionized. Supposing it is 10 to the power of 15, only half of them will be ionized when it comes down to that point. Now, increase it further what happens is it has to become p- type if all of them are getting ionized but if the fermi level comes down. If you add more, if it is ionized it will become less n- type and become more p- type and if it becomes more p- type fermi level will come below that. Now you came to catch if the fermi level comes below that, what is the ionized state of this? It is not occupied, so what happens is the fermi level will actually go down. It cannot go down because then it becomes ionized. If it is not ionized it is not becoming more p- type. Now dynamically we can see keep on adding when it reaches certain level the fermi level will go, get stuck up to the middle. It will not go below that is the thing. So, we can see that the nice thing about this particular impurity at the center of the forbidden gap is it can precisely compensate for this 10 to the power of 15.

Once there are 10 power 15 ionized impurities if you add more those chromium atoms will not be ionized and if it is not ionized it is lying there that is all. It may affect the mobility. The maximum solid solubility of chromium and silicon is something like gallium arsenide is something like (Refer Slide Time: 27:39) 1.6 into 10 to the power of 17. So, you will not have silicon contamination beyond that. So you can completely compensate. That is why people are able to get making use of this process. When you grow from the melt add a bit of chromium. The maximum solid solubility is that. Even if there is 10 to the power of 17 chromium which is solid solubility as the temperature, how many will be ionized? The number ionized will be corresponding to whatever donor impurities are present. Because by that time it becomes intrinsic, once it is intrinsic the additional chromium is just lying there. Probably it gets interstitial sites, physically that could be what is happening. You added much more it goes into an interstitial site that is what just I could see physically. But from the point of view of this ionizations that are very clearly see that.

So, whenever you want to compensate, we can compensate with an acceptor impurity. In fact, about 30-35 years back in silicon they were using this trick. If you want a very high resistivity material 10,000 ohm centimeter resistivity silicon material, you have to _______ to get that material because some impurities will be there which will be giving it n- type or p- type. What they were doing was they were adding gold. Sacrifice some gold put gold into that and gold can compensate. It can act as an acceptor. It introduces gold in silicon, introduces a deep level at the center of the forbidden gap that will compensate, if it is n- type. So, that is what people are trying to make it n- type, add gold. Center of the forbidden gap whatever gold you add all that you have done is you have wasted your gold, but beyond that point it will become intrinsic. They were selling like that. But once you use that wafer for making devices disaster. You have bought the wafer which has 10,000 ohms centimeter resistivity, but once used at a hole it will move all around. It will get inside even into your furnace. So, you do not get good results in that. People are struggling with that. Now today, if you want to buy 10,000 ohm centimeter resistivity silicon wafer what you will say is uncompensated you must say, so that the vendor does not cheat you. You should say I want uncompensated 10,000 ohm centimeter p- type or n- type resistivity material we can buy. Then, he will grow very pure crystal and give you and ______. So, this is about it. This is one way of getting the semi-insulating gallium arsenide by chromium doping.

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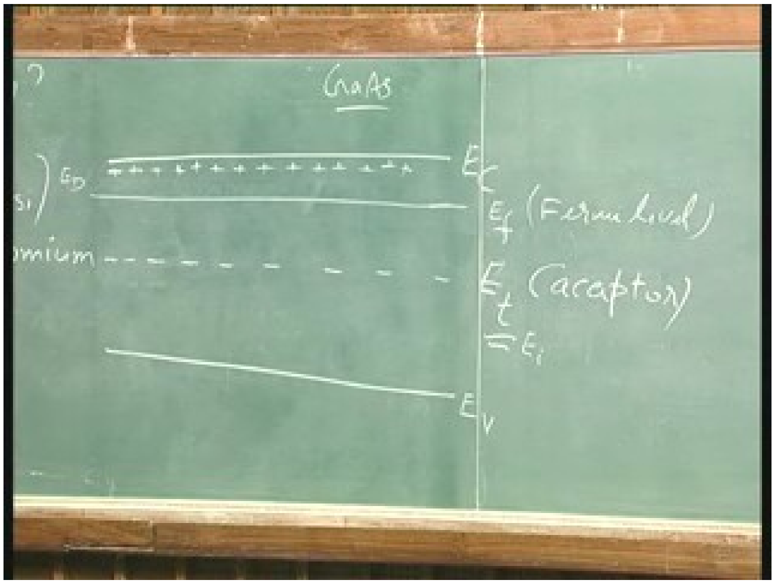

So, the trick is if I have donor impurities as shallow introduce an acceptor at the middle of the forbidden gap. Similarly, alternately, if you have a shallow acceptor impurity if you want to compensate, introduce a donor impurity at the center of the forbidden gap that will do the trick. We will get exactly very high resistivity obtain your ohm centimeter which you can use as substrate.

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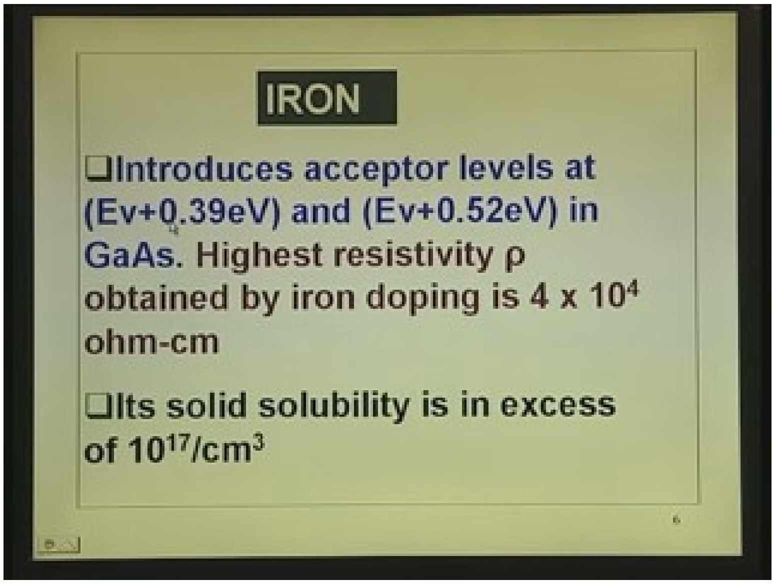

IRON

- ❑Introduces acceptor levels at (Ev+0.39eV) and (Ev+0.52eV) in GaAs. Highest resistivity ρ obtained by iron doping is 4×10^4 ohm-cm
- ❑Its solid solubility is in excess of $10^{17}/cm^3$

Let us go further. Now as a matter of curiosity I am just putting other materials to see what we are telling is true or not. If you introduce iron as compensation it has an acceptor level at Ev plus 0.39. What will happen? Supposing I have iron if I take gallium arsenide E_C and E_V I have donors (Refer Slide Time: 31:38) gallium arsenide unintentionally doped. I introduce an acceptor somewhere here. This is iron. This is how much? 0.39 electrons. So, you can see ultimately as you know you do not have much control on that including that you are adding. It will be decided by the solid solubility limit at that temperature. So, it will actually come down from here. Fermi level will ultimately come and merge with this. Till it comes; we will keep on increasing. So that is what you get a doping concentration of iron doping. You get 4 into 10 to the power 4 ohm centimeter. If you have 10 to the power of 9 you get p- type 10 to the power of 4 that is because it lets the fermi level come down here. It lets all of these things ionize that is one point that I wanted to mention it here.

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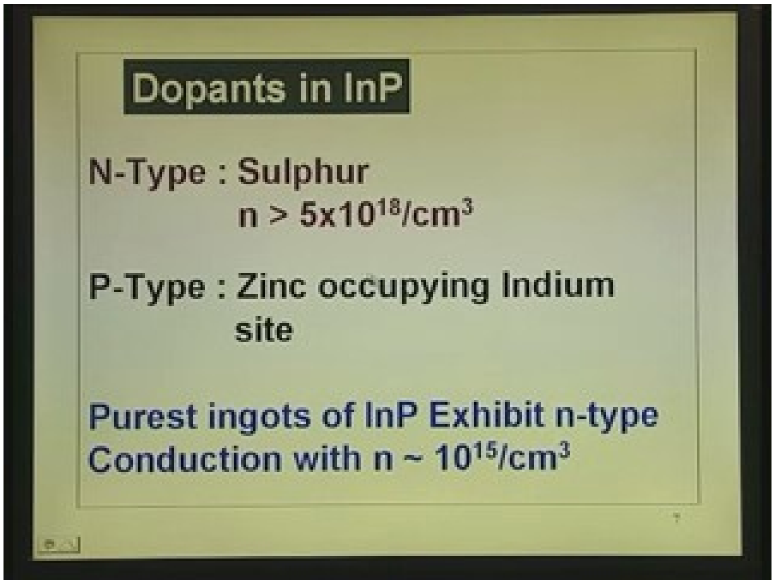

Dopants in InP

N-Type : Sulphur
$n > 5 \times 10^{18}/cm^3$

P-Type : Zinc occupying Indium site

Purest ingots of InP Exhibit n-type Conduction with $n \sim 10^{15}/cm^3$

Just let us not ignore indium phosphide all the time; let us give it a chance to this also. Here you see dopants in indium phosphide yesterday itself I mentioned. This is just reproduced zinc on that that is you can make it n- type not compensation by intentionally doping sulphur, intentionally doping it with silicon. We can make p- type with zinc. Purest ingots of indium phosphide exhibit n- type conduction with 10 to the power 15 per centimeter cube, just like what we saw in gallium arsenide.

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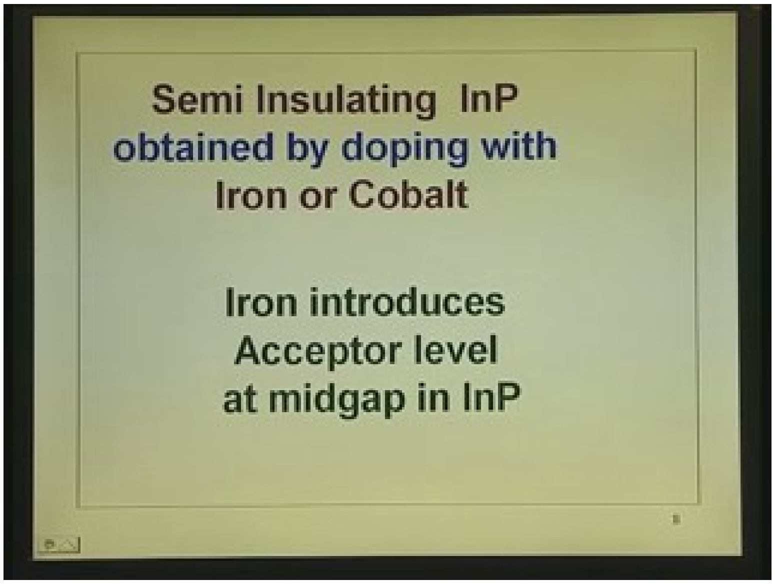

Semi Insulating InP
obtained by doping with
Iron or Cobalt

Iron introduces
Acceptor level
at midgap in InP

Here, if you want semi-insulating indium phosphide we cannot use chrome. You cannot say chrome will be introducing a level at the center of the forbidden gap for all materials. It does so for gallium arsenide. For indium phosphide iron introduces an acceptor level at the mid gap. So, you can get semi-insulating indium phosphide by doping with iron. You can be ______ that if you do not take care with the usual crucibles which you use, silica crucible if you use that will be silicon that will be doped on that. So that is why comfortably they use compensation like that.

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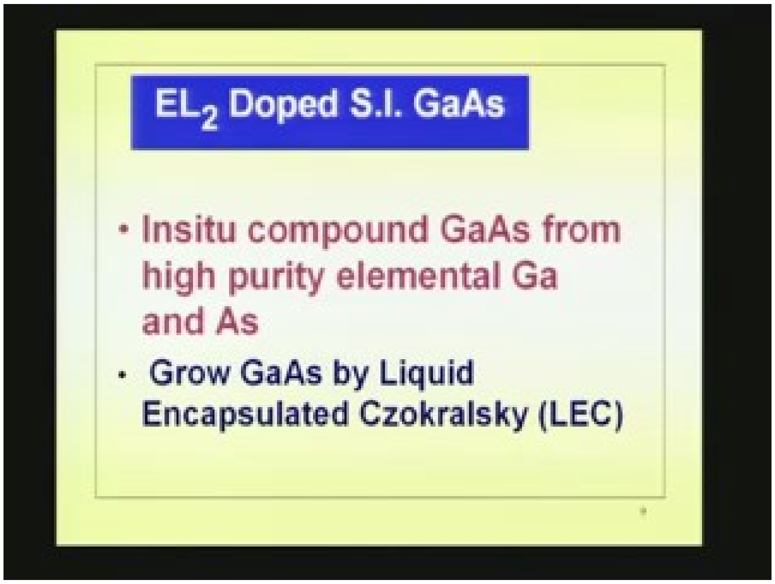

EL$_2$ Doped S.I. GaAs

- Insitu compound GaAs from high purity elemental Ga and As
- Grow GaAs by Liquid Encapsulated Czokralsky (LEC)

Now, let us take a look at this other doping thing for gallium arsenide. You get n- type gallium arsenide when you do conventional doping melt polycrystalline gallium arsenide then grow you will get n- type. That you can compensate with chromium acceptor level, but when you use Insitu compounded, you make a compound of gallium arsenide in a melt. Do not bring a melt bring gallium 99.9999 purity, six nine purity that is called. Bring arsenic again six nine purity. Six nine means there are six 9s, you bring the mix up. From there you start growing. It looks very easy. Why did we not think of it before? You have thought about that, but you are not able to do it. You bring gallium and arsenic keep them together like this heat them because after all first you have to make gallium arsenide melt from there you must grow the crystal. When you heat them you go to the melting point of gallium arsenide, you heat. The vapor percent of arsenic is 60 atmospheres at

1238 degree centigrade that is very high. So, what will happen when they start heating. What is the vapor pressure remaining? Let us just take a look at that. What is the meaning of vapor pressure? When I say I put arsenic here and I heat it, the vapor pressure is so much means the implication is if I put in a vacuum chamber I keep arsenic and heat. It will start losing arsenic. Arsenic will start evaporating till the pressure of arsenic vapor is sufficient to prevent the loss of arsenic. See for example, if I say one atmosphere is the vapor pressure of arsenic at five hundred degree centigradethat means if I heat it to five hundred degree centigrade in a vacuum the solid arsenic will start evaporating collecting in the vacuum till the pressure is one atmosphere. You evacuate it will start heating till it is one atmosphere. Then it will stop evaporation. So, we maintain an over pressure of one atmosphere for arsenic you will not lose it. Now here your problem where you have to go the melting point of gallium arsenide 60 atmospheres arsenic over pressure. God forbid you cannot do it unless you have that arsenic pressure melting or some other gas pressure must be used. That means you must have crystal pullers which can bear the pressure of 60 atmospheres. Can you imagine what will be a 60 atmosphere pressure? Just imagine 10 atmospheres even that is terrifying. Why is it terrifying? It is like a bomb. It is really like a bomb with so much pressure. 60 atmospheres is so much. So, if you have a chamber it must withstand that much pressure.Those were the difficulties people hadbut today as we go on we will see that we will have to overcome some of those difficulties and they are able to grow that,but when you do that you get that material p- type.

Fortunately, there is a deep impurity which comes up and that deep impurity is El_2 that is name given. It is actually a defect. When you grow the gallium arsenide a slight over pressure of arsenic; you increase the pressure of arsenic somewhere so that you do not lose it. So, the over pressure of arsenic when you grow you get arsenic sitting on the gallium site and arsenic sitting on the gallium site turns out to be n- type, it is a donor. So, a defect of arsenic anti-site if you are fitting in this site in the fifth group lattice site, it is occupying the gallium site that is called anti-site defect that is what you will do. So, that defect is the deep donor at the center of the forbidden gap which can compensate all the p- type impurities. We will see more about that. So, El_2 is run by ElC_2 compounded gallium arsenide, but we will see now how to do that. You first compound it and then when you do that you must have a cap being put to prevent the loss of arsenic, if you put a protection cap to prevent loss of arsenic. So, I just do not go into the chromium dope now because chromium dope is once you have the crystal from a polycrystalline material you add to the melted chromium that is rather simple. You do not have to worry about other things. Here this El_2 doped semi-insulating gallium arsenide is very popular today because you can get without intentionally adding materials like chromium then that is the technology, why?

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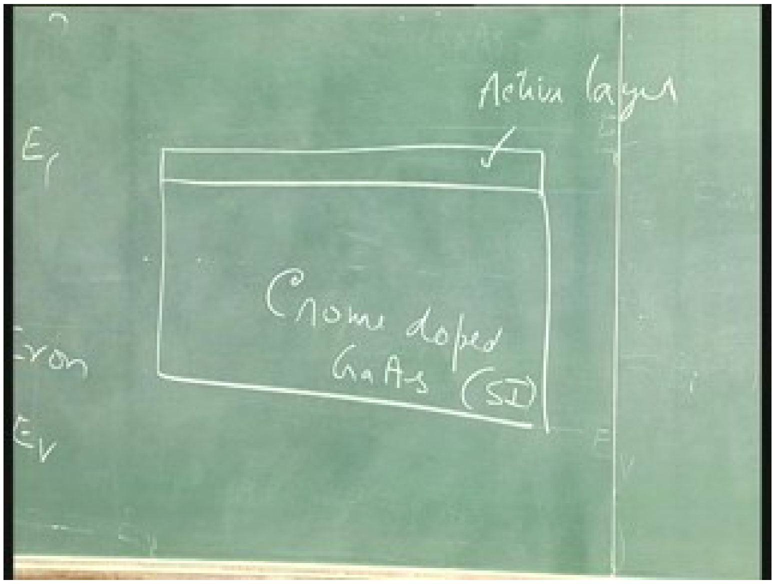

If you have a substrate which is chromium doped, if I have chromium doped gallium arsenide which is semi-insulated, on that you grow an active layer. You do it at air temperature afterwards. This has chromium. This one you want to grow at the doping of 10 to the power of 14, 15, and 16 that is active layer n- type. Now, when you grow that at higher temperature and do any processing that chromium gets inside that layer. All these deep impurities which are added deliberately it gets into this. Once it gets into this, the properties of the layer which you are growing changes. That is due to one of the major problems people had when they were making the gallium arsenide devices in 1980's, but after that the problem has been sorted out without adding chromium. So, in this case what they were doing was do not put the active layer right here. What you do? put a buffer.

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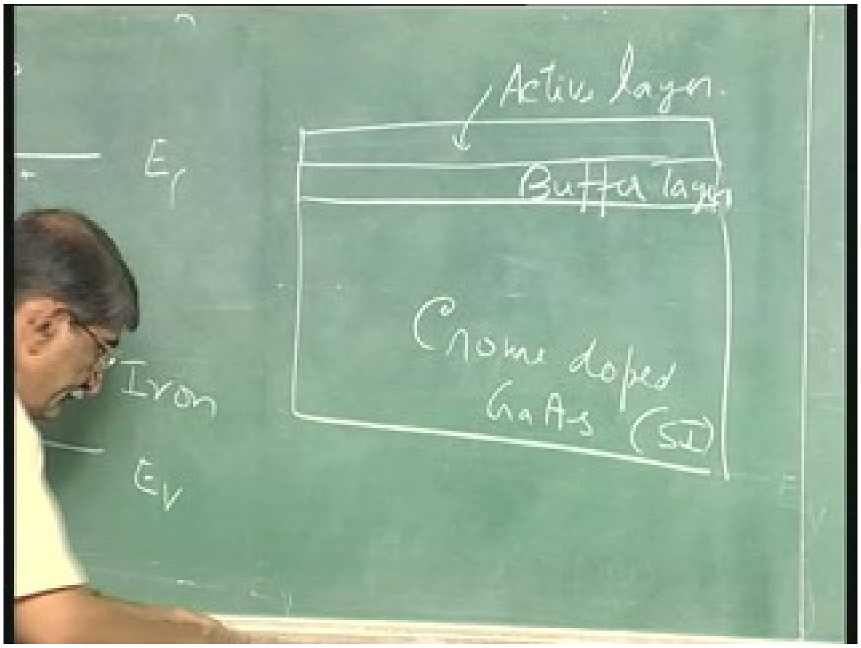

The solution is put a buffer layer. On the top of that you grow your active layer that is what they were doing. So in case when you see in the publications if you see a buffer layer put that is mainly because it is a chromium doped. When we use semi-insulated substance there you have not deliberately added impurities like chromium you do not need buffer layer, straight you can grow other layers. Let us go back into this now. The approach now is you can just quickly see we understand what is needed; we need gallium arsenide made with a pure mixing of pure gallium and arsenic.

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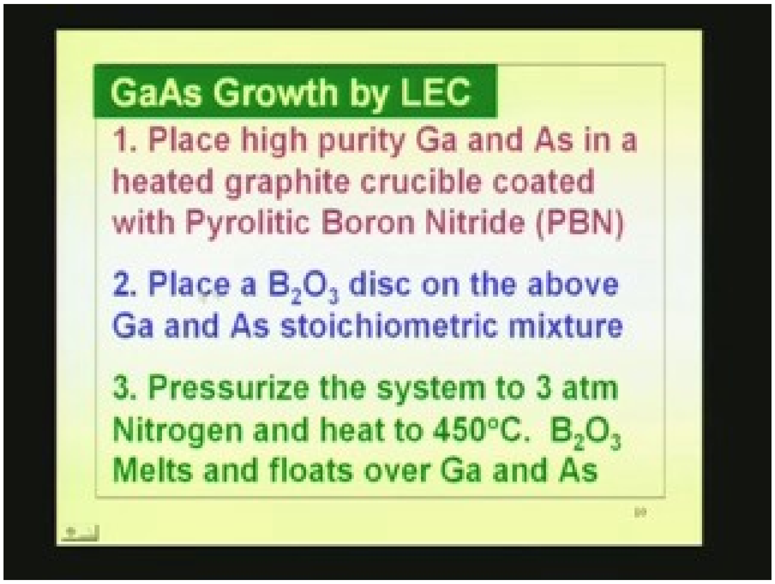

GaAs Growth by LEC

1. Place high purity Ga and As in a heated graphite crucible coated with Pyrolitic Boron Nitride (PBN)

2. Place a B_2O_3 disc on the above Ga and As stoichiometric mixture

3. Pressurize the system to 3 atm Nitrogen and heat to 450°C. B_2O_3 Melts and floats over Ga and As

So, place high purity gallium that is the six nine purity and high purity arsenic in a heated graphite crucible coated with pyrolitic boron nitrite. It was that takes care of any of those silicon contaminations etcetera are coming up. Some of the contaminants graphite crucible also is prevented by using some coating of boron nitrite. So, that is what is done there.

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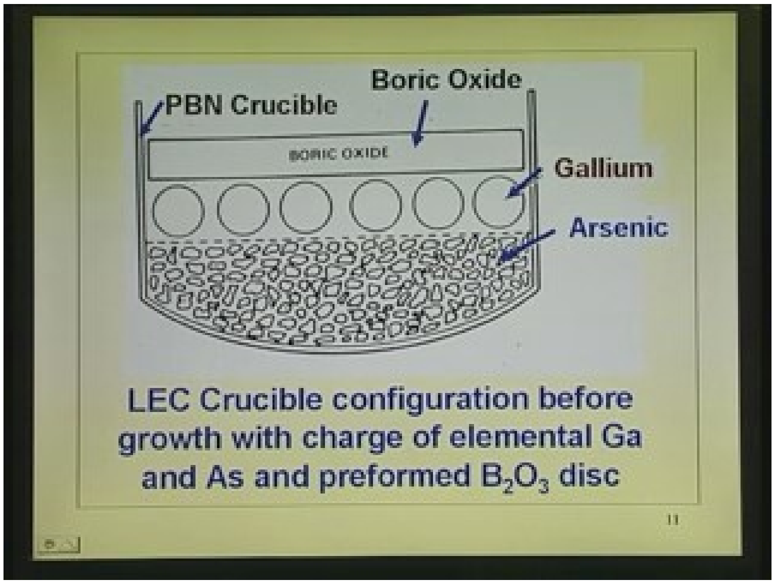

LEC Crucible configuration before growth with charge of elemental Ga and As and preformed B_2O_3 disc

Right now put it in a crucible there as you go the picture so that it is visible to you. What exactly happens is you see the crucible, pyrolitic boron nitrite coated crucible, arsenic gallium you put them together now that you have put your gallium above that. How is it? Gallium is above that. Arsenic is solid, gallium is liquid even at 29.5 degree centigrade that is why you put it on top of it. On the top of that, you put boric oxide B_2O_3 and B_2O_3 actually is you know it is a cap that you provide. It will melt at about 450 degree centigrade. So what you have to do is you put this disc of B_2O_3 which has undergone all baking etcetera, put it on the top of it, now heat it. Let me go back to that. So, place B_2O_3 disc on the above gallium and arsenic stoichiometric mixture 50% by weight of gallium and arsenic 50, 50. You put that and then put this cap and here we see it as a disc actually. It is not yet melted. So the system this whole thing is a system (Refer Slide Time: 43:38) you have to pressurize the system to about three atmospheres. So that is where the catch is you must have crystal growing system which can go to high pressure three atmospheres of nitrogen. You do not have to have arsenic. You have the nitrogen pressure to prevent the loss of arsenic as you heat up. So, heat to about 450 degree centigrade. At 450 what happens is your B_2O_3 melts and it floats over gallium and arsenic. You have chosen B_2O_3 because it should not react with that gallium arsenide. It should be lighter than this gallium arsenide. So, it floats. It is not at the bottom. It should remain on the top a well thought out cap not the ordinary cap. It is a well-thought out cap. It melts and floats on gallium arsenide that is to prevent any loss of arsenic when you pressurize on the top. So once you do that, once it melts what you do is this is the time 450 centigrade, arsenic and gallium have not reacted. All that you have done is you have melted that you have molten B_2O_3 which is protecting with the three atmospheric pressure. Now, you want to jack up that to higher level where gallium and arsenic will react but you cannot do that without increasing the pressure.

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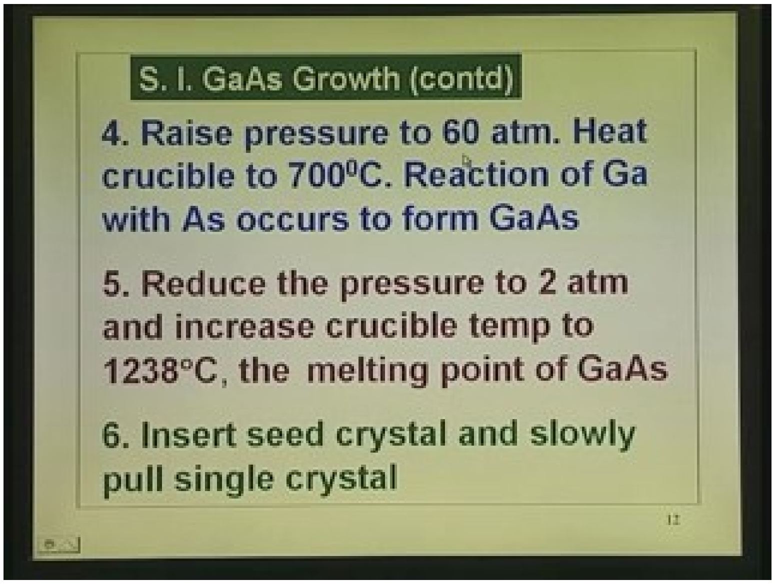

S. I. GaAs Growth (contd)

4. Raise pressure to 60 atm. Heat crucible to 700^{0}C. Reaction of Ga with As occurs to form GaAs

5. Reduce the pressure to 2 atm and increase crucible temp to 1238°C, the melting point of GaAs

6. Insert seed crystal and slowly pull single crystal

So, raise the pressure to 60 atmospheres that chamber can withstand that was the catch earlier. Now, we have those crystal pullers which can withstand those temperatures and then heat the crucible to 700 degree centigrade. Reaction of gallium and arsenic occurs to form gallium arsenide. Once it has melted, you have the compound form gallium and arsenic at lower temperature. Now, you do not need 60 atmospheres, because this is a very important thing that you should note. Vapor pressure of arsenic, if you go to 1200 degree centigrade that is 60 atmospheres, that is why we are using this 60 atmosphere layer. But once you have gallium arsenide, if you heat the gallium arsenide to the melting point of gallium arsenide, the vapor pressure of arsenic on gallium arsenide is one atmosphere that is the nice thing. The vapor pressure of arsenic over arsenic itself is 60 atmospheres at that temperature but vapor pressure of arsenic over gallium arsenide is very low. So, that is why once a compound is formed reduce the pressure to 2 atmospheres that is sufficient to prevent the loss of arsenic with that cap of B_2O_3 increase the crucible temperature to 1238 that is the melting point. 1234 plus 4 melting point of gallium arsenide then insert the seed crystal with (1 0 0) orientation pull rotate and pull that is the Czochralski technique.

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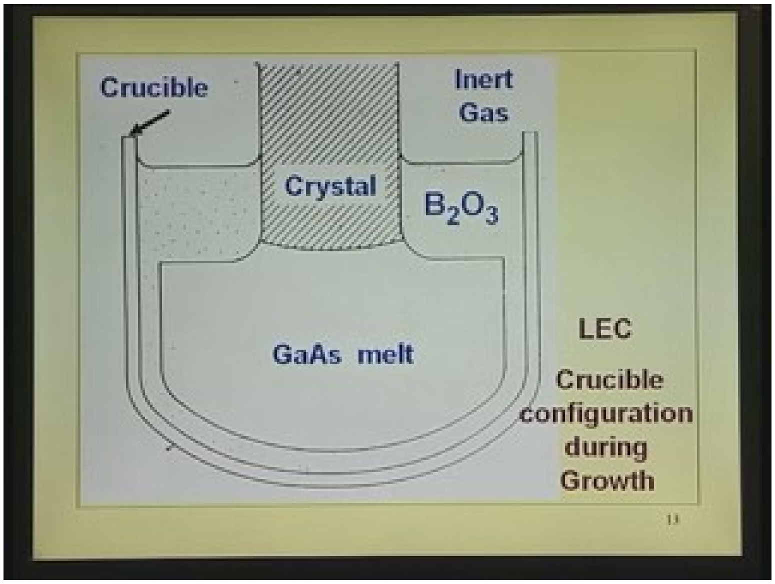

LEC

Crucible configuration during Growth

This is what you see here. Gallium arsenide melt and the seed crystal dipping into that thing and then pulled gradually rotated. Today, we can grow three inch to four inch rods of gallium arsenide that means we can have wafers of three or four inch diameter comfortably which are semi-insulating and you can see there all through this B_2O_3 is the protector. That is lighter than this gallium arsenide and density is lower. Therefore it is the cap all through and you make a coating of that on this wafer crystal as separate. So, this is called the L E C technique liquid encapsulated Czochralski. Normally, for silicon we use the same technique that is Czochralski where you do not put this layers rotating layers. You do not have to go to high pressures. You just grow it very easily because of the pressure of silicon at the melting point is very, very small. You do not have to worry about the loss of silicon. Even if you lose silicon what happens, you lose that that is all. You still have silicon. If you have gallium arsenide if you lose arsenic what happens you have gallium arsenide which is rich in gallium and if you lose too much you will be left with only gallium.

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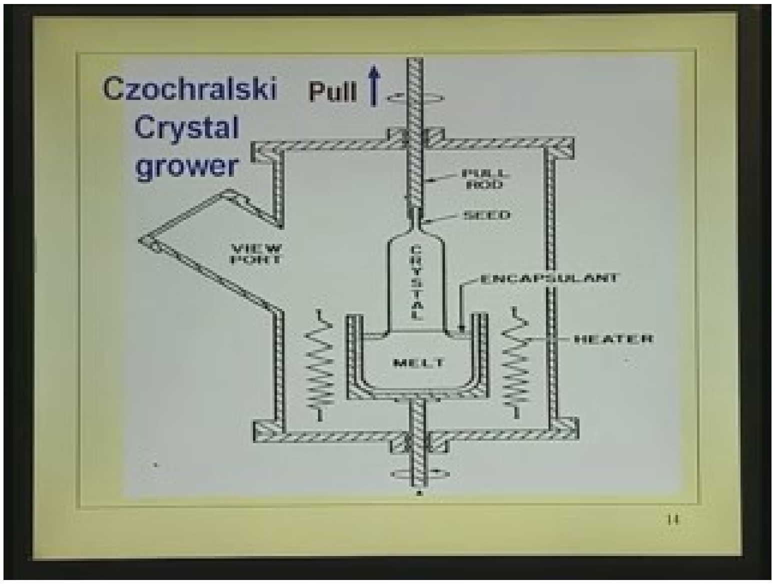

Czochralski Crystal grower

This is the puller crystal puller. What we are seeing like that and all that portion that is here, that is the crucible, this is the melt I think you can see that thing clearly and this is the crystal which is being pulled and you can see that is rotated and pulled rotation pull speed everything governs your diameter. So, this is where the crystal grower is used. How the hell is growing? Is it growing alright? Are you having in a twinning and twisting etc. taking place. So, this all should be done in a very vibration free table because any slightest tap there will ________ defects in the crystal the twist. So, that is actually the growing of the melt, from the melt gallium arsenide and this system is to withstand high pressure and you see this is the heater which can be _________ either way you can use it.

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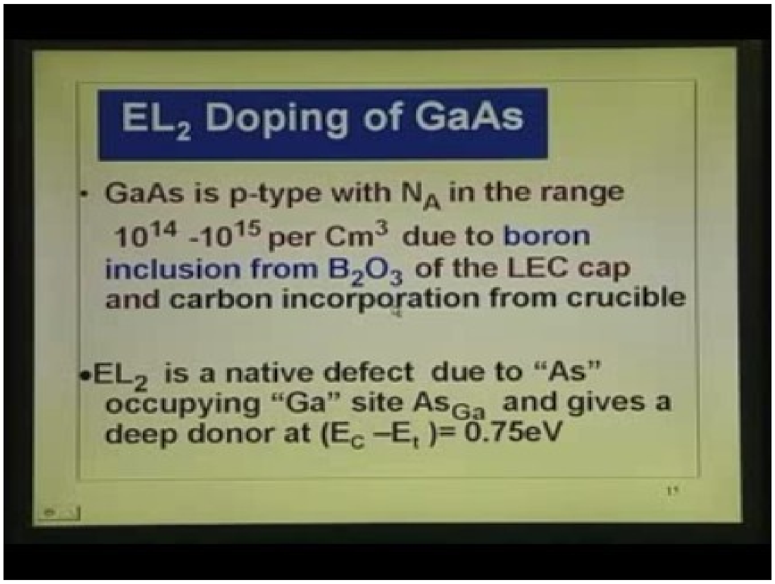

EL_2 Doping of GaAs

- GaAs is p-type with N_A in the range 10^{14} -10^{15} per Cm^3 due to boron inclusion from B_2O_3 of the LEC cap and carbon incorporation from crucible

- EL_2 is a native defect due to “As” occupying “Ga” site As_{Ga} and gives a deep donor at $(E_C - E_t) = 0.75eV$

Now El_2 doping of gallium arsenide comes into picture. I have already mentioned to you that gallium arsenide is p- type when you grow like this if that El_2 is not present. So, it is about 10 to the power of 14 to 10 to the power of 15 centimeter cube. This is due to contamination of the boron from B_2O_3. That seems to be repeated once and also it is also carbon incorporation from crucible little bit to some extent. These two things make it p-type gallium arsenide, but that shallow dopant can be compensated by the native defect which is due to arsenic occupying which I said already. We put here gallium black and white color gallium site, arsenic occupying gallium site. It is sometimes written like this wherever gallium is supposed to be there it has pushed the gallium and arsenic sitting there that is the idea of that. So, that is the symbol that is used ant- site and gives a donor level at E_c minus E_t equal to 0.75 that is almost close to central forbidden gap.

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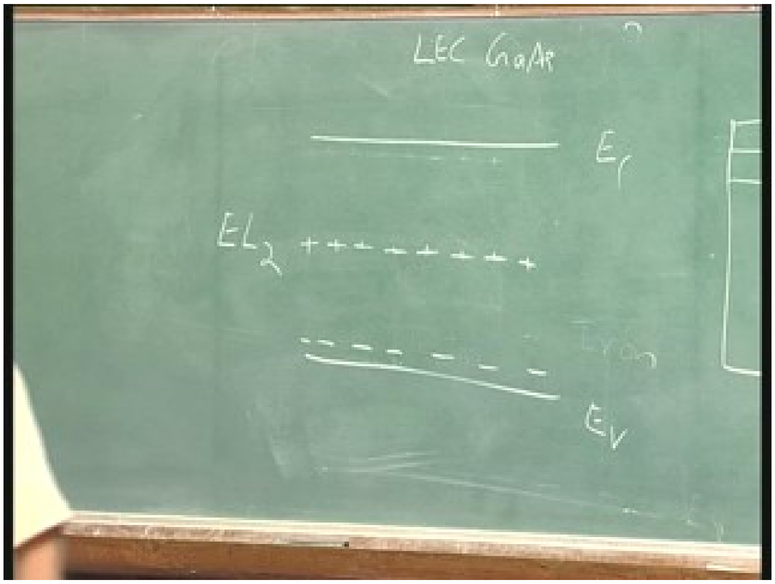

So, that is where we have got L E C gallium arsenide. It does not have the donor. It has the acceptor and then you get El_2 filter which is anti-defect. So, this is the result of the defect which you normally may not like but you like it here. You do not have to worry about this particular defect moving into the next layer. You may not like the impurity to run so that does not move into that unless you go to the liquid melting point of the gallium arsenide.

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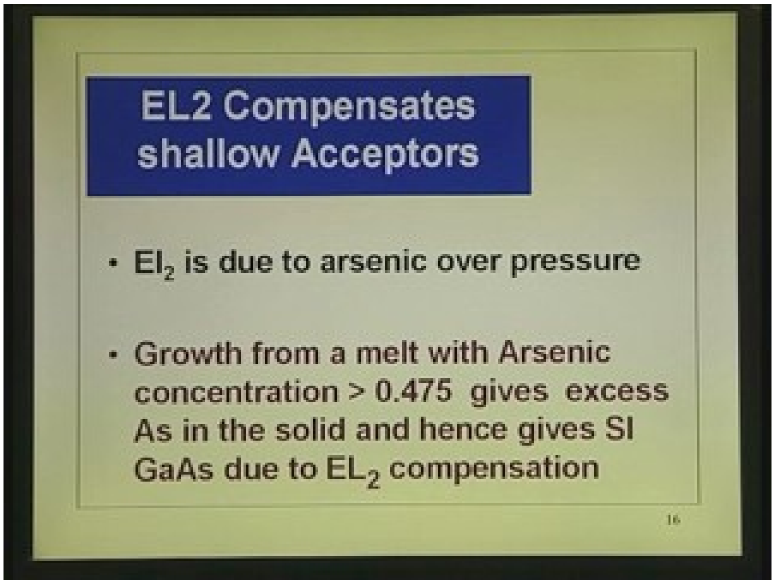

EL2 Compensates shallow Acceptors

- El_2 is due to arsenic over pressure
- Growth from a melt with Arsenic concentration > 0.475 gives excess As in the solid and hence gives SI GaAs due to EL_2 compensation

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El_2 is due to growth arsenic over pressure. Growth from the melt with arsenic concentration greater than 0.475 gives excess arsenic in the solid. I just put that diagram here. The statement you can just note even if you do not have to grow from the stoichiometric melt, even if it is slightly on the left hand side that is less arsenic not 0.5, slightly less 0.475 then also when you freeze it, pull it, it has excess arsenic and that sits in the gallium site. So, people have found that we can get 10 to the power of 9 ohm centimeter. If you have this stoichiometric and above or slightly below that I just draw the diagram here now. What we draw is what I drew yesterday again because that is relevant here. We remove all these things here. You remember gallium arsenic and what we drew (Refer Slide Time: 53:13) yesterday was 29.5 first diagram and then here 0.5 which actually is a solid line which actually represents a region like that. When you see the whole thing, you get like this. Then you have got like that above that line is liquid and here you have got liquid plus solid liquid plus solid. If I expand this again what I showed you yesterday because that is relevant here.

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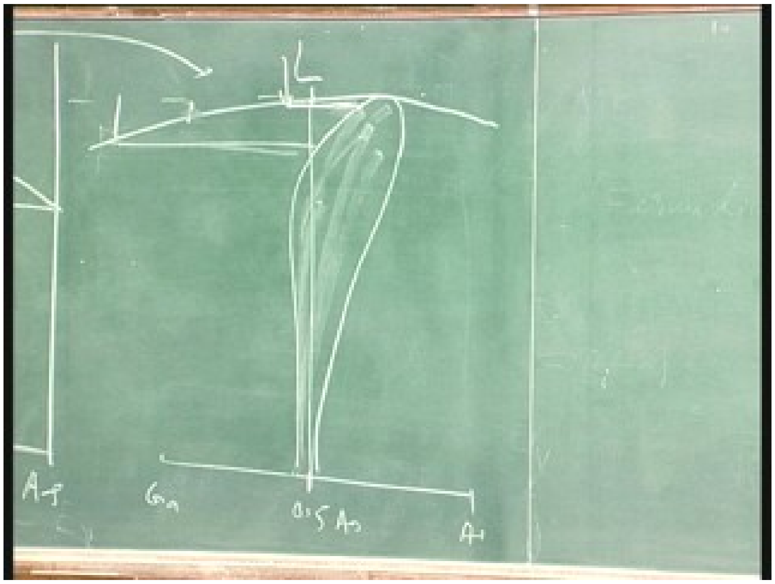

We wonder why that is happening. I have 0.5 arsenic, 0.5 gallium and this is gallium and this is arsenic 100%. Now, if I draw a line like this that is one you expand this line alone. I import only this portion then what you get yesterday what we saw was something like this. I am not able to draw it very neatly. This is a ________ view of this and on the top of that we have got ________. So, now you can see when I freeze from here or here the solid that freezes where does it go? It goes into this. It freezes from here which is less than 0.5, 0.475 when I freeze the freezing solid is, this is liquid plus solid. This is liquid plus solid. The solid will be there. The freezing solid is at that composition that is the meaning of the phase diagram. So, if I have the composition corresponding to this here that is arsenic rich slightly arsenic rich. So, you have x arsenic and also gallium vacancies those excess arsenic and also gallium vacancies. Those excess arsenic atoms go and fit in the gallium site which is anti-site and which actually becomes beneficial for you to compensate for those carbon or boron impurities. So, if I go on to that side till all the time you will get this. But, if you go on to this side, you may not have these anti-site defects, because if I come down from here it may come here just about stoichiometric. The melt is actually non-stoichiometric, but composite to that you get is arsenic that is what we are looking for. So, that is why you get this high resistivity material when it is more than 0.475 arsenics. So, to sum up what we can get now is semi-insulating gallium arsenide material we can get with this technique, with the help of the El$_2$ center. You do not have to do comb grouping. These are material which is used these days for making integrated circuits at the starting material. We will continue on this tomorrow because next we will see the top layer of this epitaxial layer. That part we will discuss in next class.