High Speed Devices and Circuits

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Lecture 36

Indium Phosphide based HEMT

We have been discussing the high electron mobility transistor based on gallium arsenide substrate. Now, the question that we have to ask is is there a possibility of getting better performance in terms of mobility, in terms of higher velocities – is it possible? In fact, if you recall, indium arsenide is one of the materials that has got very high electron mobility (Refer Slide Time: 02:10) electron mobility of about 30,000 centimeter square per Volt second. Can we make use of that? We cannot make use of indium arsenide straightaway because the bandgap is low, but we can mix with gallium arsenide and we can get gallium indium arsenide or indium gallium arsenide, whatever way you want to call it, and we can jack up the bandgap and that material should have mobilities better than gallium arsenide.

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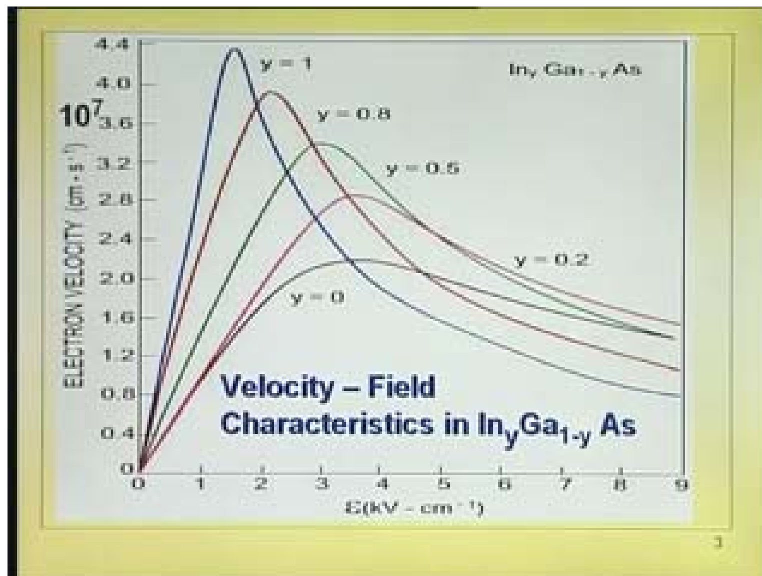

For example, I just go into this diagram. We can see this is the velocity feed characteristics of indium gallium arsenide; y = 0 is gallium arsenide. Instead of putting gallium indium arsenide, we can put it the other way also. It all depends which one we are focusing upon. I am just focusing… y = 0 is gallium arsenide. We can see the velocity field characteristics, it is like this, peaking around 2 into 10 to the power of 7 centimeter per second around 3 kV – 3 or 3.2 kV per centimeter (Refer Slide Time: 03:32) taking place. Then it saturates (Refer Slide Time: 03:34), goes down to about 10 to the power of 7.

If we take indium arsenide, you can see the fantastic mobility – sloping very sharply and then going right up to about 4.4 into 10 to the power of 7 centimeter per second. Unfortunately, we cannot use it directly, because of the low bandgap. Now, we can keep on changing y from 0 to 1 to get different curves. The other thing that I want you to note here is that indium arsenide will have higher mobility and higher peak velocity, but it will also have a lower saturation velocity. You can see it has gone down below 0.8 right away.

The saturation velocity is smaller but if we can operate in this region and make use of this high velocity and high velocity overshoot effects, then that is the material, but to make it useful, we must have a bandgap that is higher. So, take y equal to about 0.5, you can see here (Refer Slide Time: 04:36). (Refer Slide Time: 04:37) indium 0.5 and gallium 0.5 – 50:50. If you take that, you can see that the velocity is quite high 2.8 into 10 to the power of 7 and the saturation velocity is becoming comparable to that of gallium arsenide, tending towards gallium arsenide. So, you have a sort of mixture of the two.

The key thing now is the lattice match between gallium arsenide and indium arsenide or gallium arsenide and indium gallium arsenide. The whole problem is indium has a lattice constant of or the tetrahedral radius of 1.44 angstroms and that of gallium is something like 1.26 angstroms. That mismatch brings in lattice mismatch and so, we are not able to grow gallium indium arsenide or gallium arsenide without defects generated. But we will see later today, if possible, that such a thing is also possible if you take certain things into account. We will go (Refer Slide Time: 05:34). Right now, our understanding is we need

really lattice matching, we would definitely need that. You can have a material that has a y of about 0.5 or around that. Let us go back and see now. That has better performance than gallium arsenide in terms of mobility, in terms of peak velocity, etc.

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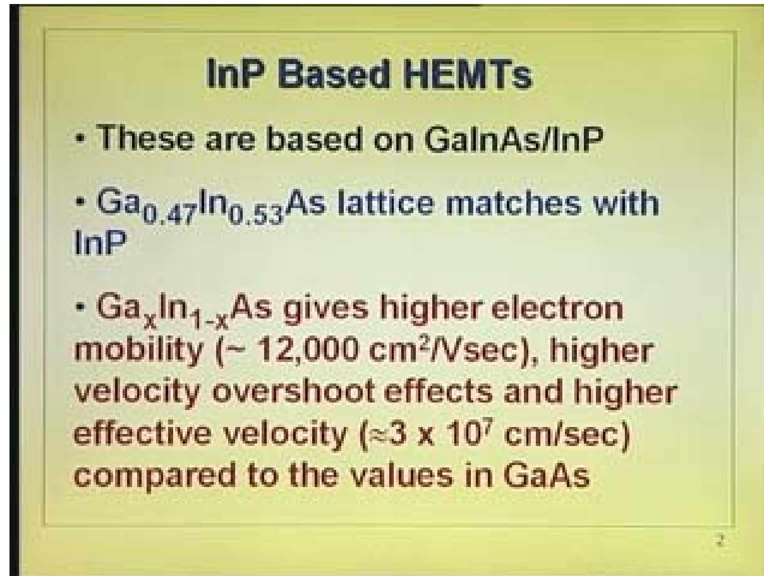

Let us go back and see that now. We have already seen that if you take gallium indium arsenide, where indium is 0.53, gallium is 0.47, it has a lattice match in the indium phosphide. If you go back to the old curve that we have plotted (Refer Slide Time: 06:14), gallium indium arsenide lattice (Refer Slide Time: 06:16) indium phosphide. In fact, we discussed the detector where the gallium indium arsenide with indium equal to 0.53 on indium phosphide, we have discussed (Refer Slide Time: 06:26) like that.

That shows that the mismatch is there. That means if you want to make use of gallium indium arsenide, which has better mobility, better velocity overshoot effects, etc., or better peak velocity, then we must go on to indium phosphide. A different device altogether based on indium phosphide substrate emerged with gallium indium arsenide as a channel material. Gallium indium arsenide gives actually electron mobility of 12,000 and in fact, even about 15,000 centimeter square per Volt-second. So, we have got that much mobility, which is much higher than that of gallium arsenide. Higher effective

velocity is close to 3, we just now saw that we get with gallium indium arsenide. Compared to gallium arsenide, it is much better.

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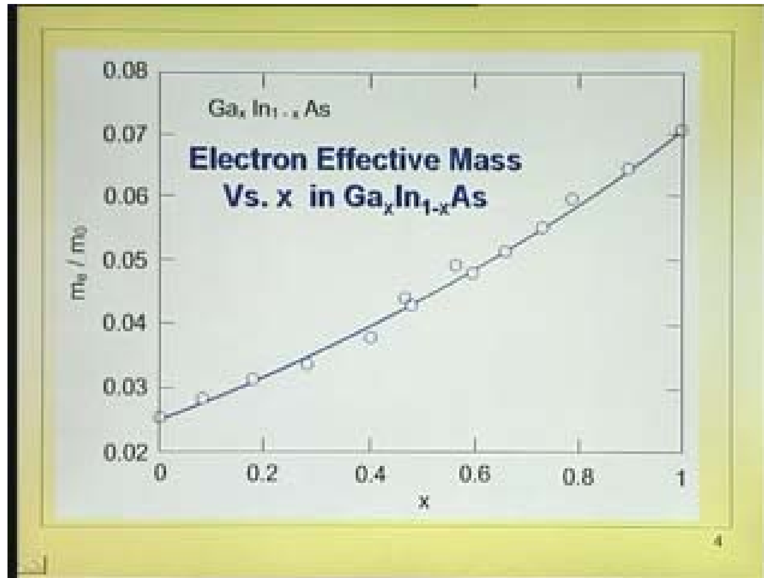

What we are now looking for is the gallium indium arsenide based or indium phosphide based HEMT with indium phosphide semi-insulating material. On top of that, you grow gallium indium arsenide. On the top of that, you must put a material with a wide bandgap and that material must also match with the gallium indium arsenide. In fact, it so turns out that it is… we will see what those materials are (Refer Slide Time: 07:45) indium arsenide.

This is just out of interest, just to see what sort of effective masses gallium indium arsenide has got compared to gallium arsenide. Obviously, the mobility is high and obviously, because the mobility is high, the effective mass must be much lower. We can see that indium arsenide has got very low effective mobility 0.025 ratio of effective mass by actual mass. Compared to about 0.07 or 0.067 actually for gallium arsenide, it is much low. It is just information that I am just putting across to you that as you vary x, that is, x in the gallium indium arsenide, you get better and better effective masses; lower effective mass, higher mobility.

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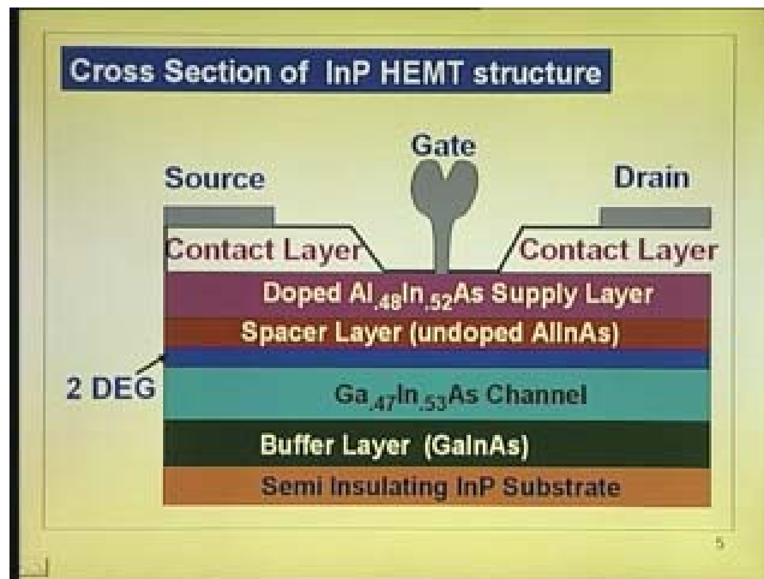

That is the structure, cross section of indium phosphide HEMT structure. Nothing new here. All that you have to see is the semi-insulating indium phosphide substrate. There is a buffer layer; we can grow gallium indium arsenide on semi-insulating indium phosphide; that mismatch is there. The buffer layer is actually grown before you actually grow the real channel material. As I mentioned earlier, this buffer layer absorbs any of the defects that are present in the substrate. If you grow the channel material on the semi-insulating gallium indium phosphide, there are chances that whatever defects are present in the semi-insulating substrate, impurities, defects etc., can get absorbed by the channel layer and we do not want that.

We want a buffer layer that will absorb all those defects or impurities so that this layer is very clean. You see that you have gallium 0.47, indium 0.53, arsenic channel with quite high mobility. This is of course what you get when you put that two-dimensional electron gap. This is not the layer. It is actually (Refer Slide Time: 09:51) put here. It is actually a thin layer, two-dimensional electron gas and structurally, you have gallium indium arsenide on that undoped aluminum indium arsenide. (Refer Slide Time: 10:01) indium arsenide you see it is a wider bandgap material compared to this gallium indium arsenide. In fact, the bandgap of aluminum arsenide is about 1.46 electron Volts, close to that of gallium arsenide. The nice thing is that layer has lattice match with this gallium indium

arsenide layer. Notice here aluminum 0.48, 0.52 and on top of that…. This is the spacer layer that is 20 to 40 angstroms undoped and the doped layer must be there. If we look at the philosophy or the principle of HEMT, there is an undoped lower bandgap material and on top of that, a doped high bandgap material separated by a spacer layer; that is the principle. We add more layers to bring in better performance like this buffer layer etc. So, undoped layer, lower bandgap, 0.75 electron Volts is the bandgap for gallium indium arsenide, spacer layer undoped 1.46 is the bandgap in electron volts. For the doped layer, how much doping we can put?

Of course, it now depends on the Schottky barrier 1.46 electron Volts bandgap. Then on top of that, you see here: one more material layer is added, which we call as contact layer. The whole idea is to put a layer above a wide bandgap material – a lower bandgap material. This can be a material that is even gallium indium arsenide, which has much lower bandgap. What is the idea of putting that? So that this Ohmic contact is a good Ohmic contact. You can make very good Ohmic contact with a material that has a bandgap that is low – that is the idea. In almost all the high electron mobility transistors, you will have a top layer, which is a lower bandgap material; that is the contact material. You can choose your materials that will have a good match with this particular layer (Refer Slide Time: 12:15). You do not care if it is defective there. In fact, if we want to make an Ohmic contact, it is better if you have a defective layer. When you alloy (Refer Slide Time: 12:25) germanium into gallium arsenide, you have a defective layer, highly defective layer actually (Refer Slide Time: 12:30) and it makes a good contact. That is the contact layer. This is the structure. Just a few things about the properties of these layers, just a quick glance of these things to get a better feel or to put a summary of the properties of these materials, I have put two, three tables.

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Electronic Material Properties of GaAs, $Ga_{0.47}In_{0.53}As$ and InP

	GaAs	$Ga_{.47}In_{.53}As$	InP
Bandgap (eV) 300k	1.43	0.75	1.35
Mobility (cm^2/V-s) 300K, pure	10,000	15,000	6,000
Mobility (cm^2/V-s) 300K, $10^{17}/cm^3$	5,000	8,000	3,000

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I could not accommodate in one table and so, I split it up into several. You can see some slight variations here and there (Refer Slide Time: 13:00). Bandgap of gallium arsenide is 1.43, gallium indium arsenide is 0.75, and indium phosphide is 1.35. In fact, aluminum indium arsenide that we put here (Refer Slide Time: 13:14), that also has a bandgap close to gallium arsenide. We do not try to put at this stage gallium arsenide on this, because there will be lattice mismatch but aluminum indium arsenide has got good lattice match. So you get a bandgap between (Refer Slide Time: 13:31); indium phosphide is of course 1.35.

Mobility for gallium arsenide… this 10,000 is a very optimistic value. It may not be exactly that value that you get, but people have quoted these values that are from theoretical estimates. Then, for gallium indium arsenide, it is about 15,000, quite high mobility; 1.5 times that. For indium phosphide, generally people talk about 5,000 here in this particular table. So, 6000 is the optimistic value or some theoretical estimate. This is a pure material; how much mobility we can get depends upon how much is the purity. If we take 10 to the power of 17 doping, then we can see all the mobility is (Refer Slide Time: 14:17), but with the gallium indium arsenide even when the doping is 10 to the power of 17, we can get about 8000, but we are not bothered about that doping, we are bothered about this undoped layer, which is the channel layer.

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	GaAs	$Ga_{.47}In_{.53}As$	InP
Dielectric Constant	13	13.5	12.4
Effective Mass	0.067	0.041	0.077
Gunn Threshold (KV/cm)	3.2	2.8	10.5
$E_L - E_\Gamma$ (eV)	≈0.31	≈0.55	≈0.60

Dielectric constant is important (Refer Slide Time: 14:35) this top doped layer. Otherwise, it is not so important. For completion sake, I have put all these values because in one place, you have got these materials. These are the materials that are very popular; 13, 13.5, 12.4, not much different. AlGaAs also, aluminum gallium arsenide also falls into the same range. Effective mass is 0.067. We can see here it is much smaller (Refer Slide Time: 15:03), indicating that the mobility is much higher. Indium phosphide is 0.077 – mobility is lower than gallium arsenide. The Gunn threshold is actually the voltage or the field at which you have the transfer (Refer Slide Time: 15:21) from the (Refer Slide Time: 15:23).

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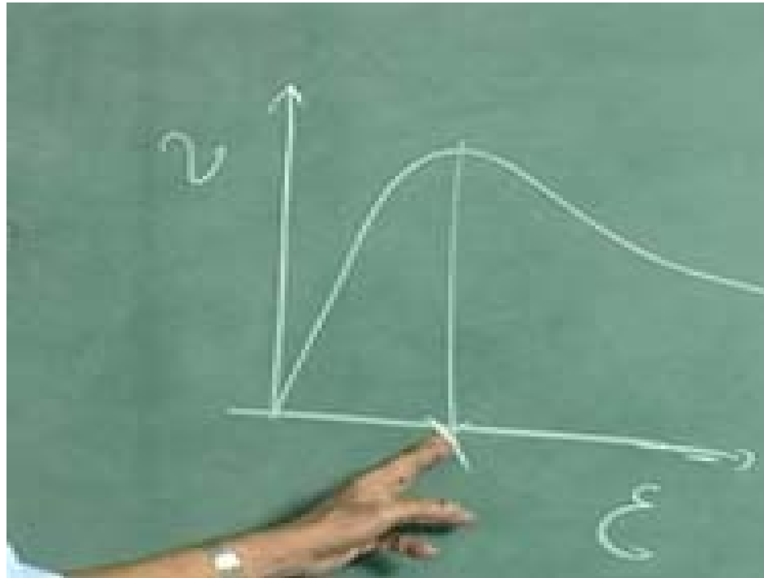

The Gunn threshold actually is…. If you have a velocity like that, that is the Gunn threshold (Refer Slide Time: 15:39). This is the field at which the electrons will be transferred from the central valley to the upper valley. That is called Gunn threshold because people made device called Gunn device (Refer Slide Time: 15:51); not the gun but it is Gunn, Gunn diode, so they say Gunn threshold. Actually, it is the electric field at which the scattering will take place from the central valley to the upper valley.

(Refer Slide Time: 16:07) you can see for gallium arsenide, it is about 3, 3.2. I also see slight ranges there, but it is around 3. If I quote sometimes 3, do not be taken aback by that; it is around that value – 3 or 3.2. I see also values (Refer Slide Time: 16:24) around that value, because after all, some of these things are simulated values. 2.8 for gallium indium arsenide is a slightly lower value (Refer Slide Time: 16:33); that is for (Refer Slide Time: 16:34).

If we see those curves that I have shown…. Let me go back to that. See here (Refer Slide Time: 16:39). Gallium arsenide is about 3, 3.2 and the peak of indium gallium arsenide is (Refer Slide Time: 16:47), that is about 2.8. More importantly, the velocity is higher compared to the gallium arsenide. This is again that E_L minus E_T. We used to call it as delta E there.

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If we have like that, that is the delta E that we are talking of and this is the bandgap corresponding to that L and tau. Just to distinguish between the indirect and direct, those terms are used. This is the bandgap that we are talking of there (Refer Slide Time: 17:33); it is 0.31. Even there, you see there are slight variations from values 0.31, 0.55 for indium gallium arsenide and for indium phosphide, we have put 0.55, around that point, more or less the same.

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	GaAs	$Ga_{.47}In_{.53}As$	InP
Mean Free Path (μm)	0.1 – 0.2	0.125 – 0.25	0.04 –0.80
Electron confinement material	$Al_xGa_{1-x}As$	$Al_{.48}In_{.52}As$	$Al_{.48}$- $In_{.52}As$
ΔE_C (eV)	0.24 at x= 0.3	≈ 0.52 InP ≈0.2	≈0.3

Then mean free path. Of course, we do not to have to worry. You we can see that (Refer Slide Time: 17:54) gallium indium arsenide, it is higher, which will actually give you better velocities and better mobilities. If the mean free path is smaller, scattering takes place easily and mobilities are smaller. Now, the most important parameter is the delta E_C. What is delta E_C?

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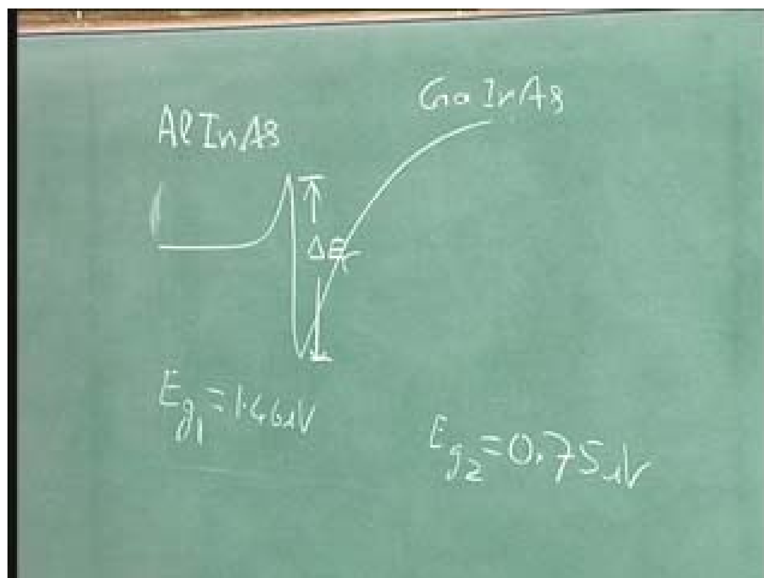

Suppose this is the aluminum indium arsenide and this is gallium indium arsenide with gallium 0.5, 0.47 here, indium 0.53; this is aluminum 0.48 (Refer Slide Time: 18:52), indium 0.53; this is 0.47 (Refer Slide Time: 18:56), this is 0.48, very close, but this material gives bandgap of 1.46 electron volts and E_{g2} here is 0.75. From your thumb rule, you can see what is delta E_C. That is delta E_C (Refer Slide Time: 19:33). We had a thumb rule that two-thirds of this… this minus this into two-thirds is approximately delta E_C.

Now, notice what has happened between the AlGaAs/GaAs system and this. In the AlGaAs/gallium arsenide system, this bandgap was 1.9 or so – 1.93 if it is 0.4, but it as less than that. Even if it is 1.93 and if it is 1.43, you have got about 0.5, but here, the difference is 0.7. Therefore, this delta E_C is higher in this case. We can see that delta E_C is higher is shown here, 0.52 (Refer Slide Time: 20:27). It is not exactly two-thirds of that, but it is around that point, because after all, the delta E_C is decided by neutral levels, the alignment. Let me not go back to those discussions because we have just said that the delta E_C is decided not by chi_1 minus chi 2, but by the alignment of the neutral levels. So, aluminum gallium arsenide is the confinement layer.

This layer is aluminum gallium arsenide and if this is gallium arsenide, this is 0.3 electron Volts (Refer Slide Time: 21:07) for a particular x. We do not go into too much of x there because we are worried about aluminum contamination there. Here, this is 0.3 for AlGaAs/gallium arsenide system, whereas if you take this particular system (Refer Slide Time: 21:30), gallium indium arsenide and the top layer, doped layer is aluminum indium arsenide, we get delta E_C is about 0.52. With the indium phosphide, this layer gives 0.2. I can make (Refer Slide Time: 21:45) indium phosphide and gallium arsenide 0.2, just for information.

These two numbers that are put here are the delta E_C between aluminum indium arsenide and gallium indium arsenide. This is the delta E_C between indium phosphide and gallium indium arsenide. If aluminum indium arsenide and indium phosphide is used at the confinement layer, top layer and indium phosphide as the undoped layer, then we will get 0.3. These are numbers that we should note, in the sense that this gives us further motivation to go in for gallium indium arsenide. One of the motivations is… the first one

was better mobility, better velocities – peak velocities. The other thing is because this bandgap is lower than that of gallium arsenide, we can have wide bandgap materials on the top and have delta E_C higher. What do you gain by having higher delta E_C? You get better confinement of electrons in the notch. See, if this is higher (Refer Slide Time: 22:50), the quantum well is deeper and more electrons are held there. They are locked up there more; that means the maximum current that we get, maximum transconductance that we get as result will be higher if delta E_C is higher, particularly the maximum current because how many electrons we can hold here without opening up this (Refer Slide Time: 23:10), without conduction in this region that is what is implied by that. We discussed this in the previous lecture.

So, delta E_C determines what sort of number of electrons at the maximum current. If you go to maximum current, then actually, the signal level is high, that is, the DC current is high. So, the implication is you can make devices with low noise, signal to noise ratio high. That is one of the improvements that you get with gallium indium arsenide based devices with aluminum indium arsenide; low noise devices, because you can go to higher currents because, for two-dimensional electron, gas concentration will be higher in this case – more electrons, which is referring to you signal.

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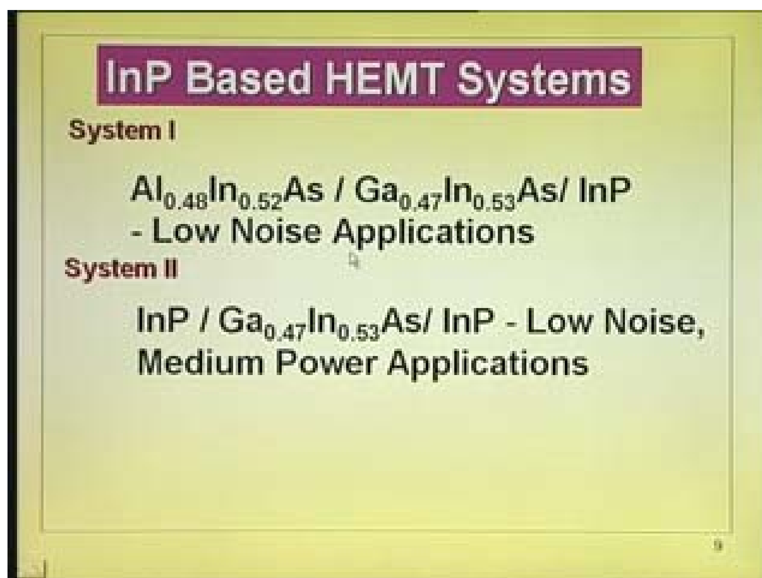

Let us take a look at what are the different types of devices that we can make with indium phosphide based HEMT. Evidently, this is what we have just now projected – aluminum indium arsenide, gallium indium arsenide, indium phosphide. Low noise applications (Refer Slide Time: 24:20) delta E_C is large and the electron concentration is large. I am just projecting another type of HEMT to you because we have opened up a wide variety of devices that we can get when you use this type of materials. If you make a slight change and make changes in the arrangement, you get different performance; depending upon your requirement, you can actually choose those types of devices. Low noise is this one but we will see that this type of device gives low breakdown voltage (Refer Slide Time: 24:58) about 5 Volts. We gain certain benefits and we lose some. You may not be able to go to higher power.

What they did was remove this particular layer, put indium phosphide, gallium indium arsenide, indium phosphide. 1.46 is the bandgap there and 1.35 is the bandgap there. We get delta E_C. Actually, it is (Refer Slide Time: 25:26) but we must be very careful here. Do not plan to use the two-thirds formula. The delta E_C will (Refer Slide Time: 25:33) as high as that. I think we should work it out and see. The neutral level indium phosphide is not at two-thirds below the conduction band; it is about one-third below the conduction band. The neutral level here is about one-third below the conduction band. In fact, it is a tremendous disadvantage for making Schottky barrier on indium phosphide.

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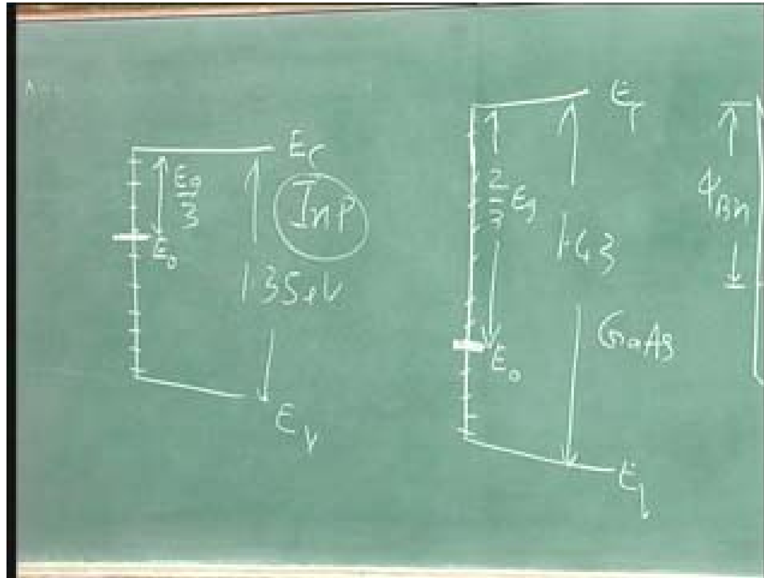

If I say indium phosphide, we have got all those levels: conduction band, valence band, this being 1.35, around that point. In gallium arsenide, the neutral level was here (Refer Slide Time: 26:24). In gallium arsenide, you have the neutral level here, then E_C and E_V. These are all the levels. This is 1.43. This is gallium arsenide and this is indium phosphide. Suppose the neutral level is here (Refer Slide Time: 26:56), two-thirds of E_g that is E_0. What is the barrier rate that you get when we make a Schottky barrier? It is that. When the (Refer Slide Time: 27:14) density is high, the Fermi level gets locked onto that and we get a (Refer Slide Time: 27:20). I will just draw that diagram here on this side.

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We get a (Refer Slide Time: 27:30) like this. In the Schottky barrier, we get it corresponding to that. That is the Fermi level and that is two-thirds, this is phi B_n. We are very happy with the Schottky barrier. Suppose that particular layer… suppose you have got the bandgap 1.35 and if the neutral level is here (Refer Slide Time: 28:09), this is E_0 and it is almost E_g by 3; 1.35 and E_g by 3 is about 1.353, 1.35 by 3 and about 0.4, 0.45. If I make the Schottky barrier here, what will be the Schottky barrier rate? Let me remove this and draw that now.

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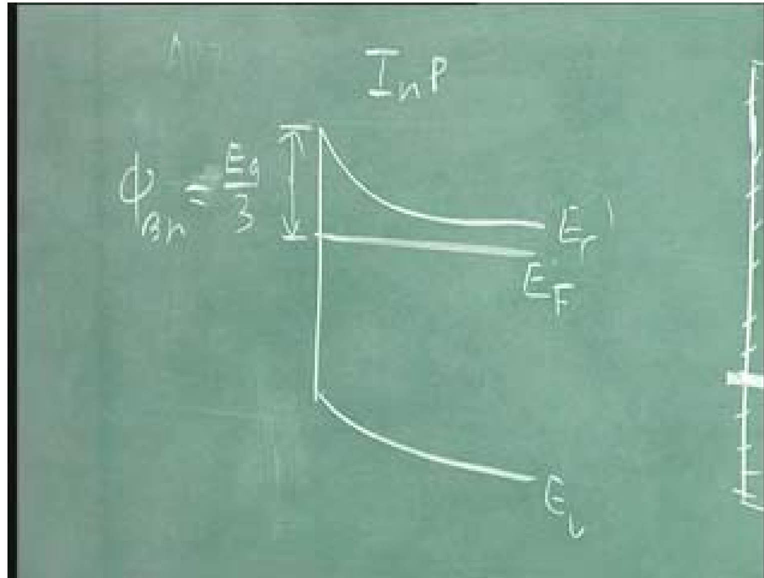

I will make an n-type material. This is roughly E_g by 3 for indium phosphide. That is actually equal to phi B_n. What will we say about this now? This is E_c, E_v, and E_F. The barrier rate is now 0.4 – very difficult to make Schottky barrier with indium phosphide. That is one of more difficulty people have faced when they made this particular thing. The only thing is that you have to make modifications on the surface to improve this barrier rate. You we have to work hard to improve this barrier rate.

In fact, you will not see in literature the MESFET made with indium phosphide. We do not see reports about indium phosphide MESFET. We see reports and devices fabricated with gallium arsenide, MESFETs fabricated with gallium arsenide. That is because we get high barrier rate here. Here, we do not get. It is not an Ohmic contact, but it is a very poor junction. If we talk of indium phosphide, you talk of MIOS field effect transistor, MISFET; put an oxide layer on the top of that to make those devices.

But all the same, I just put this across as another device that people think of (Refer Slide Time: 30:26), where system II is there – indium phosphide to improve the breakdown voltage of the devices. The breakdown voltage is low because of the presence of layer that has a lot of aluminum; they replaced it with this. If you can replace this with gallium arsenide, (Refer Slide Time: 30:48). Instead of replacing with indium phosphide, replace

this top layer with gallium arsenide. What is the benefit? No aluminum there, bandgap is 1.43, two-thirds of E_g minus two-thirds of E_g (Refer Slide Time: 31:01), whereas here, one-third of E_g minus two-thirds of E_g. It is (Refer Slide Time: 31:08). That is why….

Just go back to the table and see the barrier rate (Refer Slide Time: 31:15). Delta E_c is 0.2. If we go by the thumb rule two-thirds of E_{g1} minus E_{g2}, you will get close to this, close to 0.5 because aluminum indium arsenide is 1.46 and indium phosphide is 1.35. Even though the bandgaps are the same, because neutral level of indium phosphide is closer to the conduction band, we get the delta E_C width between gallium indium arsenide and indium phosphide is 0.2. (Refer Slide Time: 31:47)

I use these formulae for finding out the delta E_C. Do not choose blindly two-thirds of E_{g1} minus E_{g2}. Ask yourself what is the neutral level? If the neutral level location is known, we can immediately pin it down and say how much is delta E_C, because finally, the two neutral levels align with each other – that is the key. The system II is that we put our money on gallium arsenide, replacing aluminum arsenide (Refer Slide Time: 32:22) indium phosphide.

People have done these devices and said that we can get better built-in power applications, but still low noise is open to question. I just put it because people have reported that type of thing. delta E_C is 2.2, the number of electrons that you can have is not as much as that. You get higher (Refer Slide Time: 32:43), about 10 Volts or something like that.

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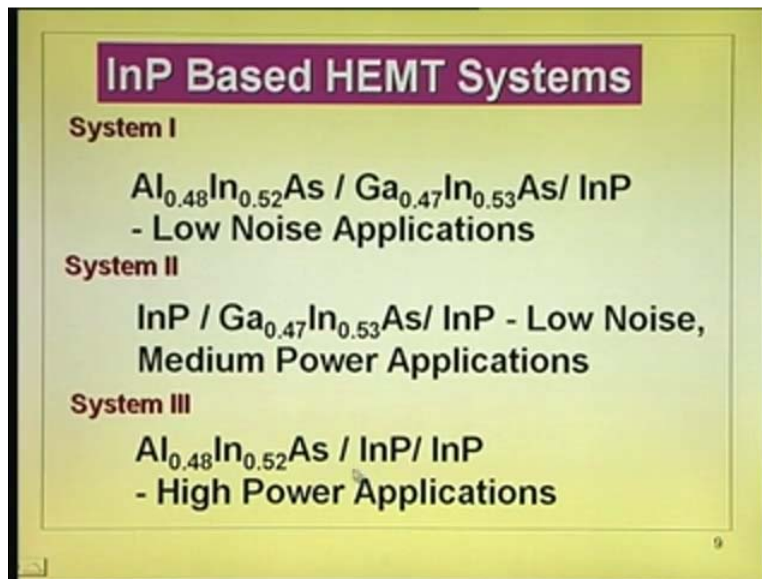

System 3: throw away indium gallium arsenide. It is only for high power applications, that is, do not use indium gallium arsenide, keep that top layer, put this indium phosphide layer. This material has wider bandgap compared to aluminum gallium arsenide – 1.35. Now, you can see you still get delta E_C between these two, about 0.3 because it is not seen. This is 1.46 E_g and this is 1.35. If we use your formula blindly, you will get 1.46 minus 1.35, 0.1 divided by… (Refer Slide Time: 33.29), but you get about 0.3. This is because the neutral level of indium phosphide is one-third below the given conduction band. (Refer Slide Time: 33:39) for you to think and work out these numbers.

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System I - $Al_{0.48}In_{0.52}As$ / $Ga_{0.47}In_{0.53}As$/ InP

Most widely used HEMT
structure on InP substrates

$Al_yIn_{1-y}As$
E_g (300K) = 0.356 + 2.35 y + 0.24 y^2
= 1.46 eV for y = 0.48
$Ga_xIn_{1-x}As$
E_g (300K) = 0.356 + 0.7 x + 0.4 x^2
= 0.75 eV for x= 0.47

ΔE_g = 0.71 and ΔE_c = 0.52eV

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I am projecting these things and I will mention what are the merits and demerits. We know the structure. Now, we can run through the three types of devices just telling what is what. The first type is aluminum indium arsenide/gallium indium arsenide/indium phosphide is widely used, HEMT indium arsenide based. Here, I just wanted to give you some formulae, because I wanted to correct some of the concepts that we had earlier. All through, what we are telling is if you mix two materials, the bandgap varies linearly, actually not linear. In fact, when I showed you the x versus aluminum content in the aluminum gallium arsenide, it is not linear but is slightly nonlinear. This is actually the equation that was given; it is reported in literature. E_g for this system gallium indium arsenide is 0.356 plus 2.35 into y, where y is the aluminum content; that is about 1.46 for y = 0.48; 1.46 (Refer Slide Time: 35:07). That is how we get because if we try to put it linearly, you will not get it.

The same case is true in gallium indium arsenide; gallium indium arsenide is not exactly linear as (Refer Slide Time: 35:17), though we had plotted approximate curve fitting into that thing and said, but then, you will not get at x equal to… if you put linear at x = 0.47, you will not get 0.75. In fact, I had one of our friends here reporting that that formula does not fit in, (Refer Slide Time: 35:35). So, 0.75 because of the slight non-linearity. This is just for completion sake. We can see between these two systems, delta E_g is 0.71

and delta E_C is 0.52 – close to two-thirds, because for this, E_0 is two-thirds and for this, E_0 is at almost two-thirds. We get that. That is what gives you better confinement of electrons, more number of electrons in the notch.

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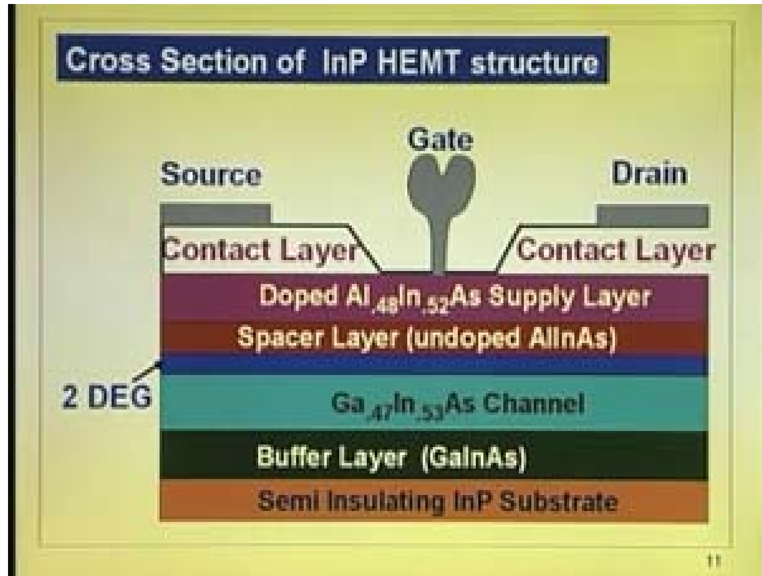

This is just a reproduction of the diagram that we have drawn right at the beginning, because at the end of those numbers, this is the structure. Indium phosphide, buffer layer, gallium indium arsenide, this layer, and this layer. This buffer layer can be made gallium arsenide or it can also be aluminum indium arsenide, or if we want to hear one more jargon, super lattice structure. What is super lattice structure? It is alternating wide bandgap, small bandgap, wide bandgap, small bandgap material. Some of these terms are familiar; these are coined.

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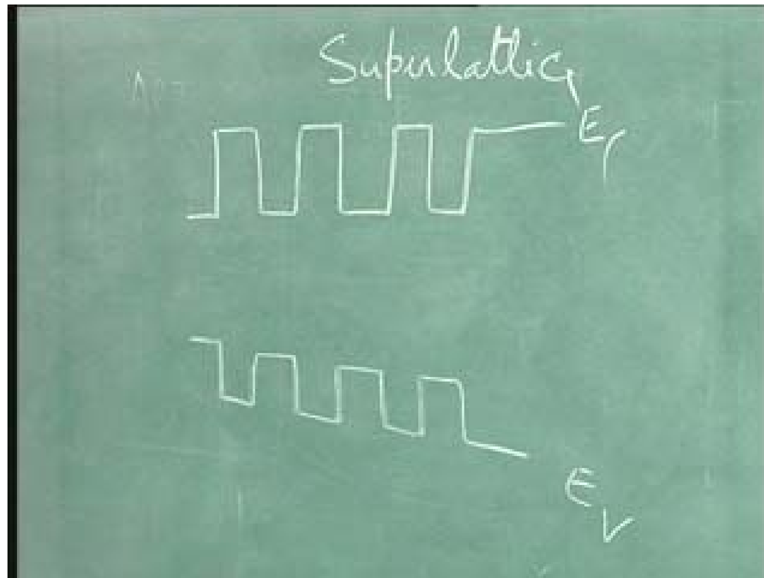

If I have a material… these are very thin layers – 5 angstroms or 10 angstroms, each one of them of that order or maybe 20 angstroms, thin layers of wider bandgap. That is E_C and that is E_v. This type of structure is called super lattice, where we have wide bandgap, narrow bandgap, wide bandgap, narrow bandgap. I have seen no explanation in literature why we call it super lattice, but is very clear if you have atoms nearby… in the lattice, what is the potential variation? If we take an atom, when you move from one atom to another atom, you have got the super lattice. You have got the potential variation. As you go near the atom, there is a dip in the potential. You have got the potential variation going like that (Refer Slide Time: 38:12).

In the case of lattice, you have got the spacing between the lattice atoms, which are few angstroms. The same way, if you keep this layer very thin, it is equivalent of the lattice atoms. That is why it is called super lattice. Wide bandgap, narrow bandgap, wide bandgap, narrow bandgap; how many numbers you want is your choice. You may have 10 angstroms and you put 10 layers and you get 100 angstroms. In fact, this layer should be as thick as possible (Refer Slide Time: 38:46). This is the buffer layer that absorbs all the defects from here – at least 0.8 microns layer. If you want super lattice, it is very easy to grow in the case of MBE. How do we grow that?

Switch from AlGaAs to GaAs, AlGaAs to GaAs. GaAs is not gas, gallium arsenide. We have aluminum gallium arsenide, gallium arsenide, aluminum gallium arsenide, gallium arsenide. You have got the arsenic source all the time open and have the gallium sources also all the time open. We move from here, we have aluminum source also put. (Refer Slide Time: 39:27) aluminum, no aluminum, aluminum, no aluminum, gallium and arsenide is all the time present. This is such type of structure. I just deliberately brought it to you, because do not be flabbergasted if somebody says use super lattice. It is nothing but a heterostructure, a number of heterostructures that is present here; that is the most interesting part of that. This is the layer that is just protecting this channel layer from contaminants, defects etc., present in the lower layer.

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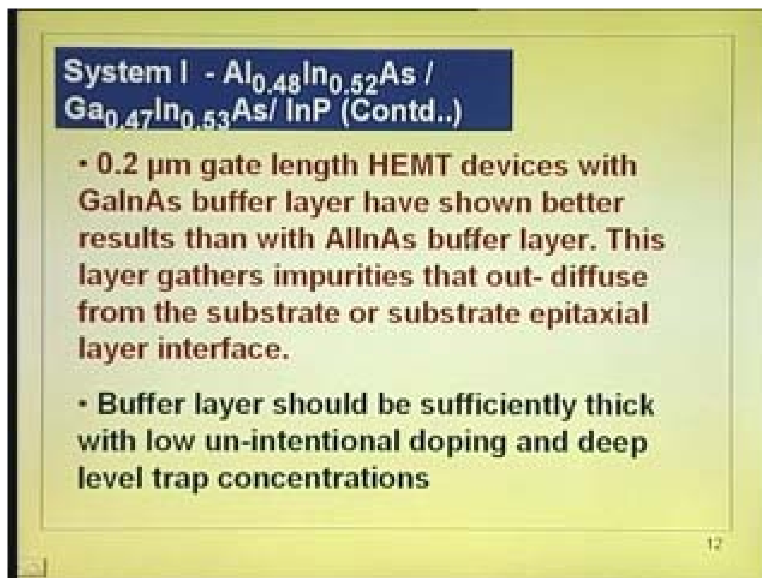

These are some of the performances. It is the AlGaAs/GaAs/indium phosphide system, that is, system I. 0.2 microns gate length HEMT devices with gallium indium arsenide. This is what I am trying to point out. People have fabricated this device with this buffer layer made up of gallium indium arsenide or aluminum gallium arsenide; they found that this is much better, probably because if we put aluminum indium arsenide, that (Refer Slide Time: 40:34) itself source of defects because of aluminum presence. I could say that may be the cause. That is what is said here. This layer shows better results than

aluminum indium arsenide buffer, that is, we use gallium indium arsenide buffer than aluminum indium arsenide.

Apparently, the super lattices have better performance, but is harder to grow because we have to switch from one layer to another layer within that structure. The buffer layer should be sufficiently thick – that particular layer between the semi-insulating layer and the channel layer has low doping. That is (Refer Slide Time: 41:16). If I have doping, there will be bending between these things. There is no bending here (Refer Slide Time: 41:22), just potential wells put in between, that is all. You will have an average bandgap corresponding to that average. If you have this like this, you can talk of a bandgap corresponding to that, on an average. That is the trick that they do. You can create wider bandgap material depending upon the thicknesses of those lattices, super lattices.

(Refer Slide Time: 41:43)

AlInAs/GaInAs/InP Transistor Performance

- Maximum Output conductance of 0.25 μm gate length devices are 98 ms/mm with p-type $Ga_{0.47}In_{0.53}As$ channel layer, which gives high effective electron velocity ($\approx 3\times10^{7}$ cm/sec) and high electron mobility (12,000 $cm^2/Vsec$)
- f_T (cut off frequency) is measured to be in excess of 175 GHz and g_m = 1000ms/mm with 0.1 μm gate length and W= 25 μm

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Transistor performance. Maximum output conductance of course is output (Refer Slide Time: 41:50) indicates. More than that, what you have to look at is effective velocity is 3 into 10 to the power of 7 and mobility of 12,000, the cut-off frequency is 175 GHz, which is really fantastic, and transconductance with 0.1 micron gate length. You should be careful of course about what sort of channel lengths you are using. I do not have both

things together – 0.1 microns indium phosphide based device and 0.1 microns gallium arsenide based device.

For this, it is about 1,000 milli-Siemens per millimeter, whereas what we saw in the previous lecture for gallium arsenide for a 1 micron device is about 400 at 77 degree Kelvin and room temperature about 225 milli-Siemens. All that we are telling is that this gives very good performance (Refer Slide Time: 42:35) because people working on indium phosphide shout from the rooftop that indium phosphide is the material, but people working on gallium arsenide project gallium arsenide based device. In fact, ultimately, I would think gallium arsenide based device has a better say in various aspects, because that is a better-known technology, cheaper than indium phosphide but easy to handle. On the same count, of course, the silicon guy will say that silicon is the best material, but we cannot get this sort of performance.

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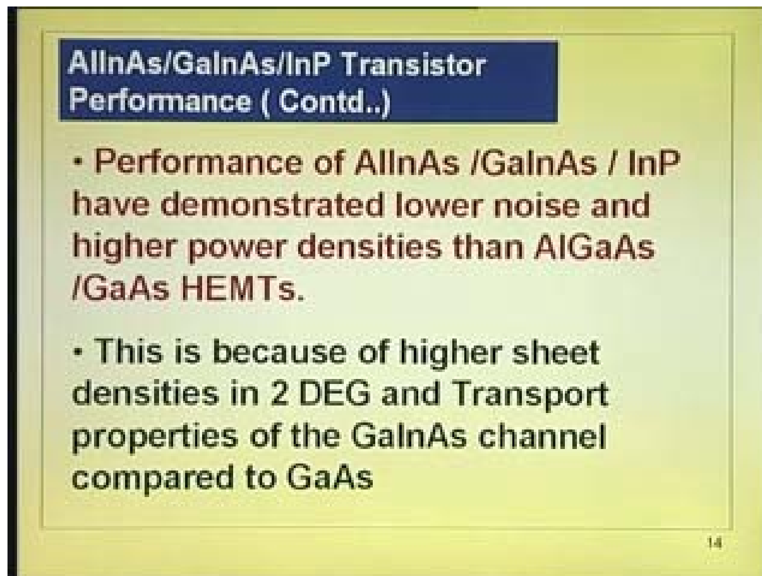

Of course, as I mentioned earlier, this AlGaAs/GaAs/indium phosphide system has lower noise performance, because of the higher sheet densities in the two-dimensional electron gas; higher sheet density because electron concentration is high because delta E_C is high. This is the aspect that one has to remember. (Refer Slide Time: 43:37) where it can be used. Do not choose just wherever you like, you can use it in those applications, but you

cannot go to higher voltages, 5 Volts upper limit; for low voltage, less noise, etc., you can use that.

(Refer Slide Time: 43:52)

System II : InP/ $Ga_{0.47}In_{0.53}As$ /InP

•$Al_{0.48}In_{0.52}As$ / $Ga_{0.47}In_{0.53}As$/ InP HEMTs have relatively poor gate to drain and drain to source breakdown characteristics.

•Typically drain to source BV < 5 V, associated with traps in AlInAs

•InP/ $Ga_{0.47}In_{0.53}As$ /InP system overcomes the above problem.

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Let us just quickly go through system II. In system II, instead of aluminum indium arsenide, (Refer Slide Time: 44:05) indium phosphide. It is not (Refer Slide Time: 44:08) so much but people have projected it, tried various things; it gives… because this layer, the first type aluminum indium arsenide or gallium indium arsenide gives breakdown voltage less than 5 Volts. They said let us try putting indium phosphide in that place, because this is containing lot of aluminum. This overcomes the above problem and you get over 10 Volts or so.

(Refer Slide Time: 44:31)

InP/ $Ga_{0.47}In_{0.53}As$ /InP System

- Main problem in this system is the low schottky barrier height associated with n-type InP
- 150 Å GaInP with 18 % Ga with barrier height of 0.64 eV has been used to cap the InP layer for enhancing the schottky barrier height

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The main problem in the indium phosphide system II…. Please remember that the difference in system I and system II is that in the top layer, instead of aluminum indium arsenide, we put indium phosphide, but the moment you put that, it has the problem of low Schottky barrier height (Refer Slide Time: 44:50). What they did is they put on the top of that 150 angstroms of it. The moment there is a problem, there are people to play games on that, try all sorts of tricks to overcome the problem; they put gallium indium phosphide with 18 percent gallium, which gives barrier height of 0.64, better than 0.4, you get a Schottky (Refer Slide Time: 45:15) indium phosphide layer, put gallium indium phosphide layer, which has lattice match.

(Refer Slide Time: 45:22)

System III - $Al_{0.48}In_{0.52}As$ / InP/ InP

- InP channel layer improves the breakdown voltage of the device
- ΔE_c for the notch is 0.35 – 0.4 eV

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System III. We are running through because after all, we understand what is required and aluminum indium arsenide over gallium indium arsenide is the most popular device in indium phosphide based but people have been taking a look at other materials. In system III, keep the top layer as aluminum indium arsenide, replace the gallium indium arsenide layer by indium phosphide to improve the breakdown voltage. That will give you a definitely better… because indium phosphide is a wide bandgap material compared to gallium indium arsenide. I think you still get the delta E_C about 0.3, because it is not two-thirds; the neutral level is at one-third below the conduction band – please understand that. delta E_C is 0.35 to 0.4, not exactly 0.3.

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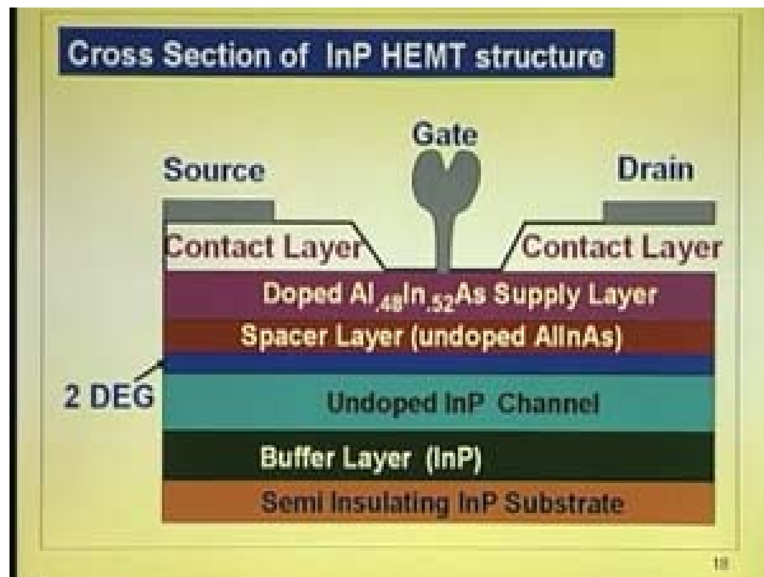

This is the cross section of that particular device. It is the same device: semi-insulating layer, buffer layer – indium phosphide, undoped indium phosphide layer, which is a channel, then undoped aluminum indium arsenide, and aluminum indium arsenide. All that you have done is instead of indium gallium arsenide, you put indium phosphide. People expect this to give better performance than gallium arsenide, because of high velocity overshoot effects.

(Refer Slide Time: 46:46)

Performance of $Al_{0.48}In_{0.52}As$ / InP/ InP

Devices with L_g = 0.3 μm resulted in

g_m (extrinsic)= 610 mS/mm)

Gate to drain breakdown = 10 Volts

f_T = 76 GHz

f_{max} = 140 GHz

Disadvantage : significantly lower value of low – field electron mobility. As a result, shows high ON resistance

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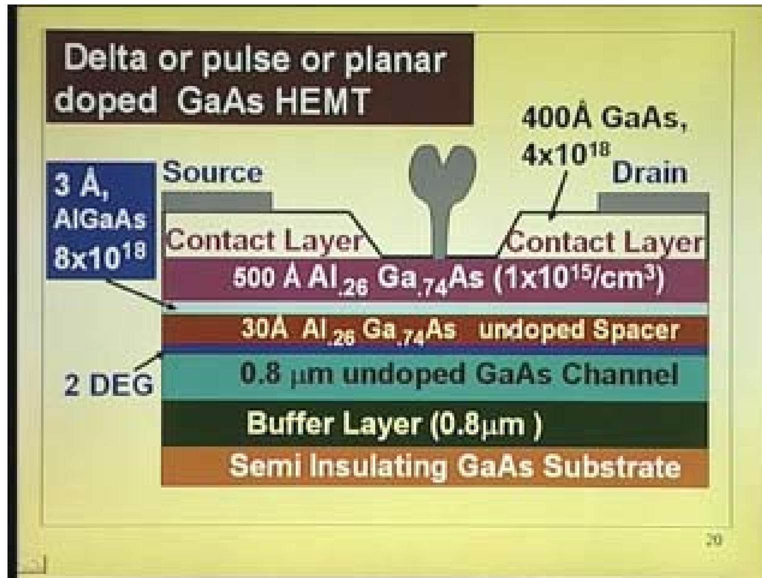
Devices with 0.3. Now, you can see the comparison is not existing, 0.3 micron device gate length. g_m is 610 milli-Siemens per millimeter – quite good, f_T is 76 GHz – not as good as indium gallium arsenide; that was 750 GHz, but 0.1 micron channel length. We can see the comparison (Refer Slide Time: 47:05). Maximum frequency of operation is that for unity power gain. That is the (Refer Slide Time: 47:09) power gain unity, 140 GHz. The disadvantage in indium phosphide, the mobility is low compared to gallium arsenide, gallium indium arsenide. It is about 5,000; bandgap is poor material; (Refer Slide Time: 47:34) high ON resistance because of that. That is the (Refer Slide Time: 47:41). We have to pay for everything. We do not have breakdown voltage, you can pay by putting this, but there are better devices.

(Refer Slide Time: 47:48)



Now, let us take a look at one more thing in the gallium arsenide based (Refer Slide Time: 47:53). I am just leaving the indium phosphide based system right now. Go back to the gallium arsenide based system (Refer Slide Time: 47:57) they have. After seeing all these things, the gallium arsenide guys started getting worried because that is a better technology. What better performance, what you do? If you recall what we said yesterday, the problem was… This is the gallium arsenide based HEMT. We discussed now the indium phosphide based system. There are three types out of which aluminum indium arsenide, gallium indium arsenide (Refer Slide Time: 48:25) or indium phosphide is best; we get high performance. Going back to gallium arsenide based, (Refer Slide Time: 48:33) gallium arsenide, buffer layer 0.8 micron – it can again be super lattice or undoped gallium arsenide, 0.8 micron undoped gallium arsenide. This thickness can be reduced to (Refer Slide Time: 48:47) of 0.8. Then 30 angstroms of undoped aluminum arsenide, gallium arsenide, (Refer Slide Time: 48:54).

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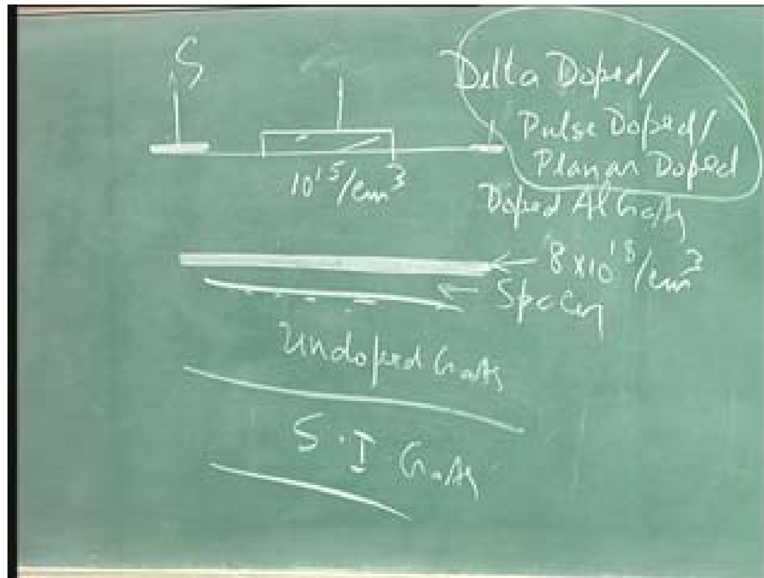

This is the same as what we have been discussing. Just to avoid confusion, I am putting it here. You have the undoped gallium arsenide on semi-insulating gallium arsenide with the buffer layer of course in between. I am just skipping that to avoid confusion. This is the channel layer and on the top of that, we have a spacer. What is that? Undoped AlGaAs. On the top of that, we have got usually doped AlGaAs and then of course, you have the Schottky barrier and you have the contact here – source, drain.

We saw the problem with this device was…. Forget about the aluminum content, but we are putting up with that so that you get about 0.3 delta E_C and a good device. To get better transconductance, what we have seen is you have to reduce this thickness of this layer (Refer Slide Time: 50:10). We must reduce it but when you reduce the thickness, what happens? You get better transconductance, but then, you must increase the doping. When you increase the doping, the upper limit comes up because of this Schottky. What you do is if you look at the diagram, you will choose this as 10 to the power of 15 – top layer, but you introduce a layer that is very thin of the order of about 3 angstroms, that is, planar doping. This layer is 8 into 10 to the power of 18 per centimeter cube.

What is required in the total integrated doping here? Put very heavy doping here (Refer Slide Time: 51:08) spacer layer, which will supply all the electrons that are required here

at the channel and this layer which is making contact with this Schottky, make it slightly doped. Total integrated doping is here (Refer Slide Time: 51:20). This type of device is called delta doped or pulse doped or planar doped. Any of the names is okay. If you hear delta doped HEMT, do not get worried. The only difference is that we have put heavy doping here (Refer Slide Time: 52:21), close to that, just 3 angstroms.

Now, you can understand the extent of pressure the technologist bears. He has to grow 10 to the power of 18 into 8; 8 instead of 18 doping layer which is about 3 angstroms (Refer Slide Time: 52:39) control for the entire layer. The pressure is taken by the technologist ultimately. Here also, you can see that there is a contact layer that is actually a smaller bandgap material.

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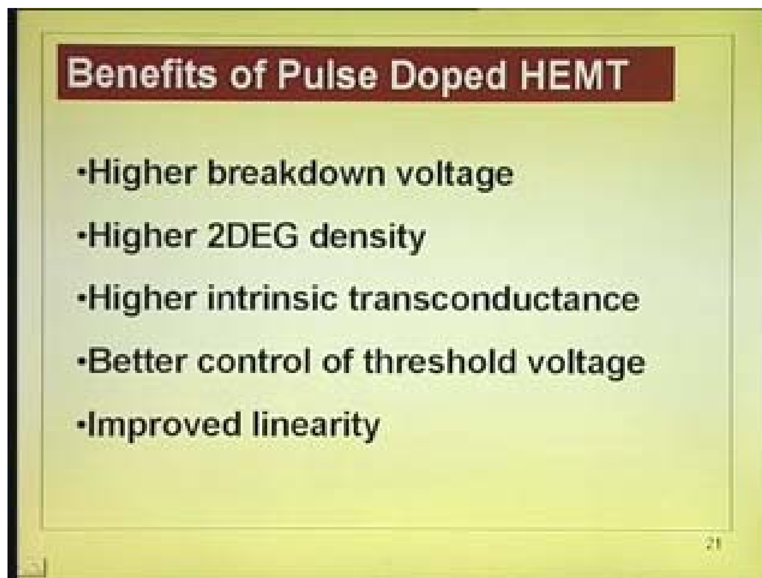

The benefit of this pulse doped HEMT is higher breakdown voltage. The higher breakdown voltage is because gallium arsenide substrate is there and we you not change aluminum content too high; this is 0.26. Higher two-dimensional electron gas, more doping is there at the edge, more electrons will be collected here and because of that, you get higher two-dimensional electron gas density. The band bending will depend on how much is the relative doping between the two layers. V_{bi} plus delta E_C; V_{bi} goes up if the doping is higher.

Higher intrinsic transconductance. Why? You can now afford to reduce the thickness, because all the doping is present here. Once we reduce the thickness, the C_S is actually larger and you get higher transconductance. We get better control of threshold voltage. Without worrying about doping, we can change this thickness (Refer Slide Time: 53:59). So, you get better control, that is, total doping concentration is at V_{p0}. So, you can get better control without worrying about thickness. Of course, the linearity of the transconductance is also an added merit, but I think these are the main advantages here.

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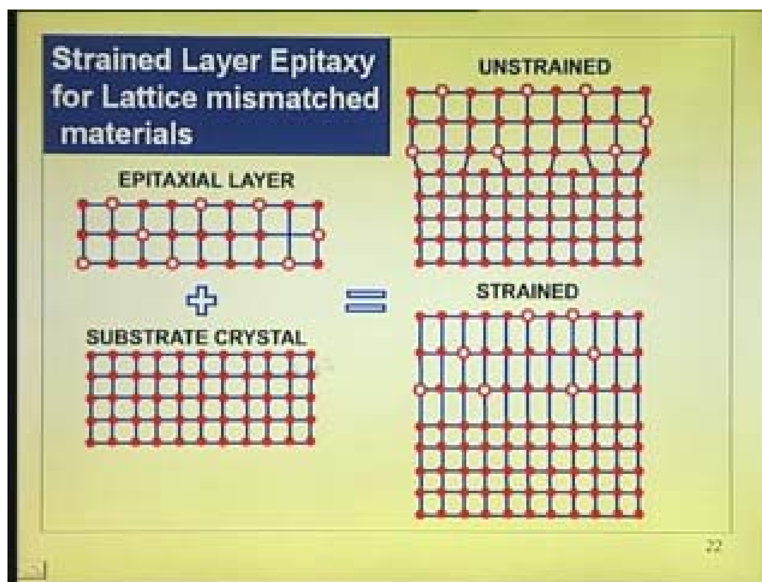

I will not touch upon much of this now, but I will just show you, because I have just a few minutes left out here. There is another type of device that has emerged over the past few years; I am talking right up to the current. Another type of device is emerging, where you can use gallium indium arsenide as the channel layer with gallium arsenide structure. Nothing like that, because today, you can get semi-insulating gallium arsenide, which is very pure. We do not have to worry about the buffer layer, you do not have to worry about defects, but still, you can put a buffer layer and you can put gallium indium arsenide on gallium arsenide. Now, what are we worried about? I will take up a detailed discussion next time, but I will tell you what is going to be there.

We are worried about realizing an epitaxial layer of gallium indium arsenide on gallium arsenide because of lattice mismatch. What happens if there is lattice mismatch? If you can tolerate that lattice mismatch, if there are no defects generated during that growth, then you can put gallium indium arsenide on gallium arsenide, gallium indium arsenide channel layer will have high mobility, and on top of that, put gallium arsenide, which is the n plus layer, which you can also make delta doped. Then, you do not have the problem of aluminum content. You have got 1.43 as the bandgap of gallium arsenide and you have got bandgap of gallium indium arsenide as 0.75. So you have got 0.5 electron Volts as the delta E_C.; you get that sort of benefit. There, if you see, I will go through this particular layer in detail next time, but this is the substrate of one lattice, this is the substrate of another lattice constant, this is more. If you arrange, you can get this type of structure, where the intermediate layer is defective (Refer Slide Time: 56:22). You can see the bonds are broken. That is what you get if you grow lattice-mismatched devices. Tremendous amount of stress is there, pulling each other and defect will be generated. What we would like to show is or see is that you can generate without defects a layer like this, provided you grow a very thin layer – that is called as strained layer concept. We will discuss that in the next lecture, few things before we go to HBT.