Fundamentals of Semiconductor Devices
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Lecture - 55
Transistors for power electronics (contd.) & for RF electronics

Welcome back. So, if you recall in the last lecture, we had introduced the different types of an applications in which transistors are used and we started with power switch a transistor used as a power switch in the area of power electronics. It is very expanding you know application and a market. Most of the things that we see around you know where power conversion is needed actually use a transistor, a transistor as a switch to make the circuits ok.

And we discussed about some of the parameters that are important what are the considerations we should keep in mind in terms of discussing power transistors, like the most importance are breakdown voltage and on resistance. Things like a gain or saturation of current are not important for power switch, what is important is the on resistance and the breakdown voltage right, a transistor has to act as a switch right.

So, I told you that dominant technology silicon, but their upcoming technologies like silicon carbide, gallium nitride which are also offering much better solutions and you might wonder why are these applications that are actually using these technologies. You might think of a laptop which you plug into the wall plug socket that has 220 volt a voltage, but the laptop is charged at 20 volt.

So, you have to convert that 220 volt to 20 volt from AC to DC because the laptop charges in DC same with mobile phones which use the 5 volt line so DC line. So, you have to convert the 220-volt AC on your wall plug socket to a 5 volt DC. So, you have to step down the voltage.

So, all these conversions from AC to DC, DC to DC and so on stepping on stepping down are done using power electronic switches and circuits and these are made of transistors and diodes ok. So, that is why the on resistance and breakdown voltage of transistor switches are very important. We will continue from there; we will come through the white board and as we recap the last lecture if you recall.

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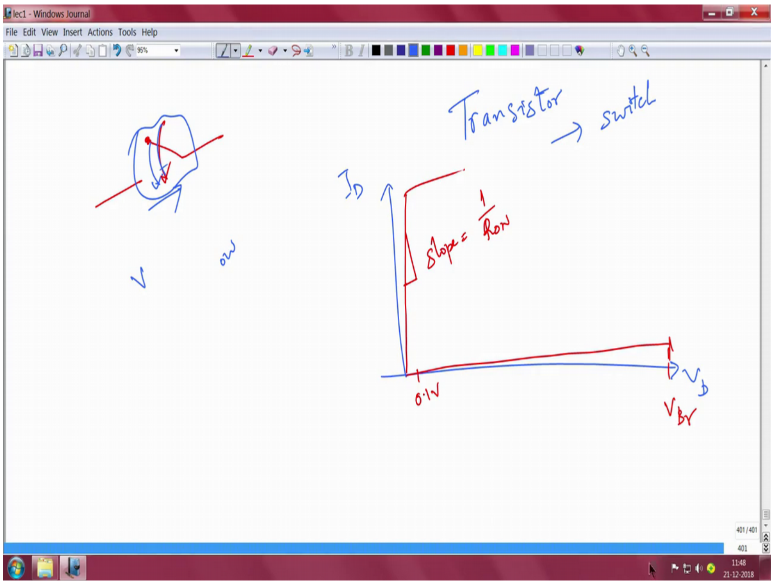

A transistor as a switch right so we will a transistor as a switch has to essentially allow when it is on I am quitting the output current and here I am plotting the output voltage; when it is on it has to conduct very high current at very low voltage like that and when it is off it should block very large voltages at very low current. So, breakdown voltage is here and the slope here is basically 1 by the resistance.

You on the on resistance to be very slow which means at very small voltage like point one volt drop you are able to carry very high current almost like metal ok. And it very large voltage also you are basically blocking agent off state so that will behave like an insulator in a way a transistor switch should go ideally from like a metal to insulator, you know it should be able to carry very high current in the on state and very low current in the off state ok. So, it is like a switch right which.

So, you have a switch here, the switch will on off on and off when it is off it should block a large amount of current when it is on it should conduct a large amount of current when it is off it should block a large amount of voltage; when it is on it should be able to carry large amount of current without much voltage drop here ok, when it is on when the switch is closed.

So, that is why the breakdown voltage should be high and the on resistance should be low in order for a transistor to behave like a good switch and it should be able to move that fast. So, when for example, you know the current when the current is for example, if you have a voltage and a current you know if I plot the voltage and the current waveforms.

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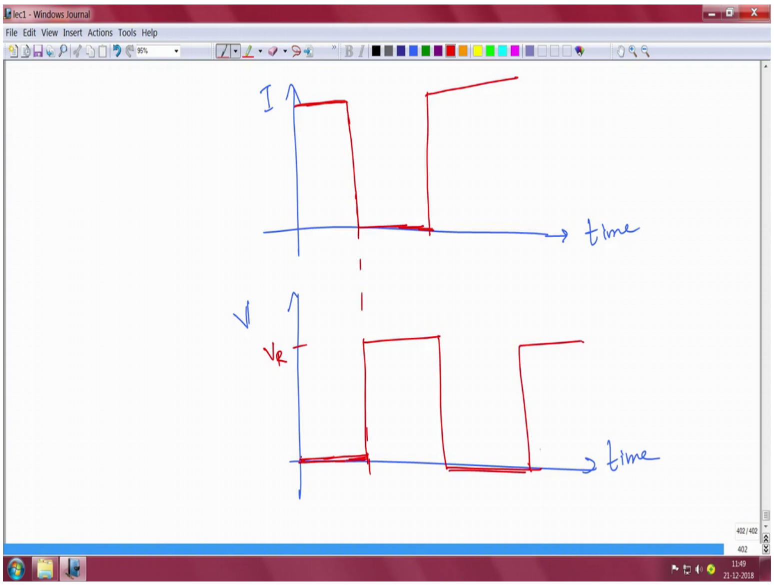

If you want to plot the current and the voltage waveforms, so, here I am plotting for example, the current waveform across a switch and here for example, I am plotting a voltage waveform across the switch and this is with respect to time by the way ok, time you have to switch it very fast either.

So, and the voltage is in the off state I will use a another colour, when the voltage you know you are you are going to use you are you are going to have very high current you are going to have very high current. In that in that window the voltage drop should be very low very low and when the ideally you know voltage drop should be 0 across the switch when the current is very high. And when the current comes down to 0 and the current comes down to 0 [FL] its completely open circuit the voltage blocking should come up high this is the reverse biased voltage, whatever breakdowns voltage you give it should be like that right.

And again when the current rises up the voltage should come down and so on and so forth right there is an ideal switch, but in reality an ideal a switch does not exist ideally and. So, the transistors have their own finite behaviour.

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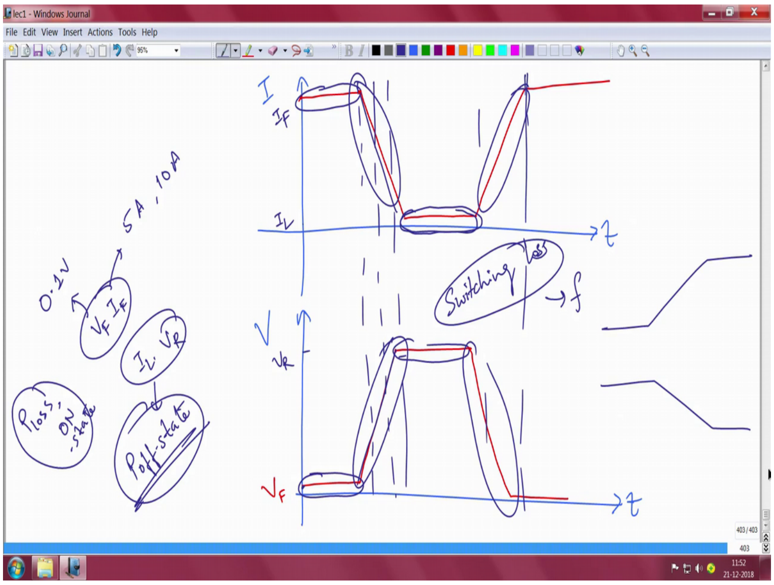

That is what we were talking about in the last class. So, in what happens in reality is the this is your time this is your current this is your time and this is your voltage across the switch this is your time. In reality what happens is that when your current is high and you are carrying say may be 5 amperes or 10 amperes of current ideally a voltage should be 0 across the switch it should not drop any voltage, but there is a small finite voltage drop that is a V forward drop that will happen and then the current will fall on instantaneously.

The moment you switch you change the voltage you know your change the voltage will take some time to rise, in that time the current will take some time to fall. And the current will not come 0 exactly there will be a small leakage in the background the voltages come up here again when you switch off the voltage you will take some time to come and the current will take some time to turn on right. So, you see this current is there which is very high we you know forward current I F maybe 10 amps 5 amps 1 amps whatever.

Ideally this voltage drop here should be 0, but you know in reality there is a small finite voltage drop. So, the product of this forward voltage drop with the forward current that we are carrying this is suppose to be this is very high say 5 amp or ten amp or whatever. This is suppose to be 0, but it actually not 0 is probably like 0.1 volt or whatever a small voltage will drop. The product of this will give you the power loss during the on state, this is the on-state power loss because you are looking some power because of the product right.

Similarly, in this state the current should be ideally 0 when switch is off the voltage should be high as the breakdown voltage here, but actually the current is not 0 there is a small amount of leakage current that goes I can call it I L leakage current. So, I l times this V R whatever reverse voltages are blocking the products gives you the off state current loss, off state voltage loss sorry.

So, there is a this also off state power loss sorry there is a power loss in the off state there is the power loss in the on state these actually our finite losses that you want to minimize and if you see the transient there is always this transient where the current decreasing gradually the voltage is increasing gradually. So, the product of this and this; the product of this and this also is not 0 it also has a peak small you know there and that is call switching loss or the transient loss you know the switching transient loss.

Similarly here the product of this and product of this because they are in the same time zone, you know one function is going like this one function is coming like this the product of that will also be you know very important and that is called switching loss and the switching loss depends on frequency if you switching it very fast then stitching loss also will increase ok. So, these are the three types of losses nevertheless we should be generally aware of.

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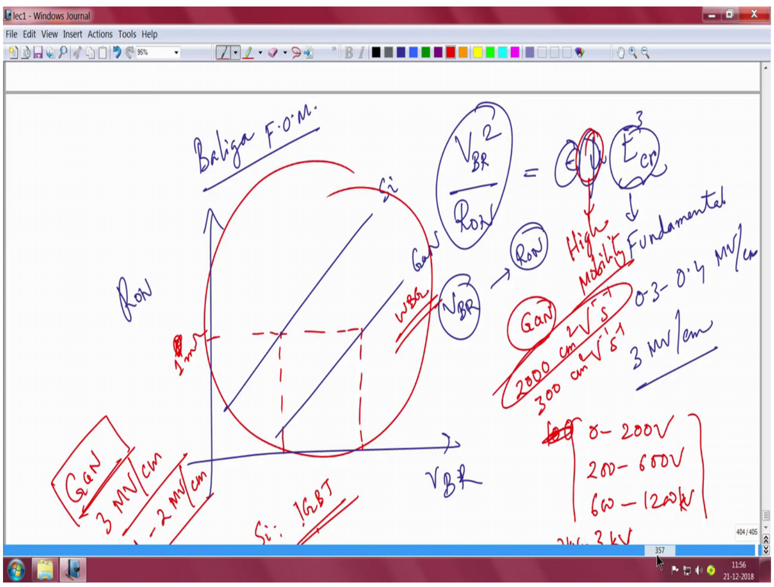

And I told you that one of the important things is that there is called Baliga figure of merit Baliga figure of merit which essentially relates the on resistance and the breakdown voltage. So, it says that the breakdown voltage divided by the on resistance is actually constant, which depends on the dielectric constant the mobility of the material and the critical electric field times the square.

I think may be this cube I forgot this exact number it has probably cube or square. Anyways it depends on the critical electric filed which is a fundamental material property the critical electric field of silicon for example, is fixed and that is like 0.3 to 0.4 megavolt per centimeter. For gallium nitride that is 3 megavolt per centimeter and so on ok. So, this critical electric field is fixed. So, what this means is and a mobility and the dielectric constants also fixed.

What it means is that you know the on resistance and the breakdown voltage trade off with each other and if you want a higher breakdown voltage you also will get a higher are on which is going to affect your on-state behavior. So, either you get a better on state behaviour or with a off state behaviour you have to optimize between the two you cannot get best of two and you can actually plot this same thing the on resistance versus the breakdown voltage.

And this gives you another lines like this for silicon for example, and then there is this technology gallium nitride which is over. So, you know for a given for a given on resistance say you know 1 milliohm or so you can get a breakdown of silicon of some 100 volt may be in gallium nitride you can get a 1000 volt.

Which means for the same current you are actually getting much higher blocking voltage in the in the in the white band gap technology like gallium nitride that is why they promise of gallium nitride and other technology is come up here. Does not mean that they are going to replace silicon just like that because silicon has a very large market and this power switches have their own markets you know are we talking about low voltage like you know 0 to 200 volt sort of applications you know lieder applications or some other low power sort of things. Or you are talking about 200 to 600 applications it that might include solar inverters and many of the charge you know the DC DC converters motor drives.

You might also talk about 600 to 200 volt applications hybrid vehicles and lot of host of other applications you might also talk about locomotives and all where you have 3 kilo volt 2 kilo volt the applications and so on.

.So, there is a market size there is also a cost component to it, anyway silicon has many devices as I told you in the last class IGBT which is which is a vertical device thyristors, alimos, you know coolmos all these are different kind of the topologies of silicon that are being exceptionally well at that limit of the theoretical performance limit. Whereas, gallium nitride for example, the theoretical limit has not been reach because of the material problems the material they may exists the huge research area why this is not be able to you know reach the theoretical limit. For example, the theoretical limit of gallium nitrite is 3 mega centimeter is the breakdown voltage, but practically you only get between 1 to 2 mega volt per centimeter because of material problems and material challenges.

So, it has not been able to reach the full potential, there is a lot of researches re there. Reason I keep talking about gallium nitrite is because it is widely acknowledged that is gallium nitride is the most talked about and the most widely prevalence semi conductor after silicon, all the white light it is that you see are actually gallium nitrite. So that is why you know is the most dominant semiconductor technology after silicon today. So, this is whatever power devices and you know these power switches we have talked about you know a basic things like DC DC converter or inventors all these users these switches.

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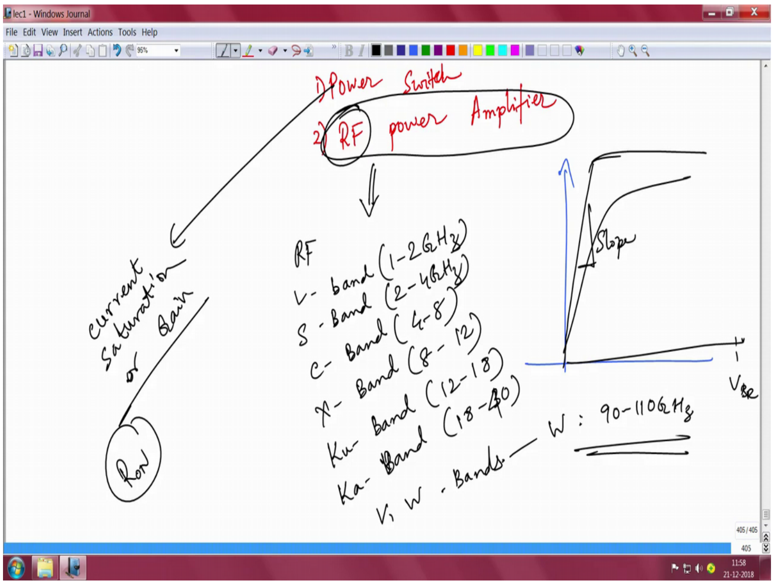

And now you know what kind of things I needed of course, if you look into Baliga figure of merit. A material also needs to have a material also needs to have a high mobility; the mobility term comes there it needs to have a high mobility; high mobility to actually get the better Baliga figure of merit.

So, we know if you have if you have a if a transistor has a mobility of 2000 centimeter square per volt second versus another transistor that has only 300-centimeter square per volt second. Then you ideally would like to go the transistor that has higher mobility because that will give you a higher Baliga figure of merit provided it has also a good breakdown voltage. So, that is about power transistor that we have talked about now ok.

So, enough of power transistor now, I told you there is also other applications if you recall one application was the power switching that we have talked about now, the transistor and the power switching application the second very important application is actually RF power amplifier this is the different kind of applications and the requirements of the transistor would be very different.

For example, in the power switch I only talked about two things that you know the current should be very high at very low voltage right and when it is off it should be blocking a large voltage here V BR. So, only talked about the slope here I did not talk about the current saturating there right. For example, in the power switch you know current saturation was not talked about, current saturation or gain was not talked about.

What was talked about was the one resistance, like the slope of the id right in the linear regime.

So, that was the power switch power amplifier will be a different ball gain and power amplifier has different applications and different ways what do you mean by power amplifier it basically RF power amplifier. So, you know RF signals radio frequency signals, radio frequency signals have different bands people in different areas categorize them in different ways, but in the RF circuits or RF devices terminologies RF bands are divided as you know things like S-band L-band C-band then you have X-band these are different actually bands Ku-band these are bands of RF frequencies Ka-band.

And then you have more other bands like V, W bands these are different bands of RF devices ok, I think first should be L and then should be S, I will check and let you know in the next class first sure, but I think it should be L and S.

So, one of this is 1 to 2 gigahertz of frequency in the electromagnetic waves this is 2 to 4 gigahertz of electromagnetic waves, this is 4 to 8 gigahertz, this is 8 to 12 gigahertz, this is 12 to 18 gigahertz. This is 18 to I guess 30 gigahertz and then more, into 40 probably and then this is more and in W Hertz W band was probably like 90 to 110 gigahertz and so on.

So, these are different frequency ranges of RF or electromagnetic signals that will come through space to your cell phone or radar or anything you know the antenna will detect them you have to actually amplify the signal you know and you have low noise amplifier power amplifier that does different kind of jobs for you have to amplify the signal.

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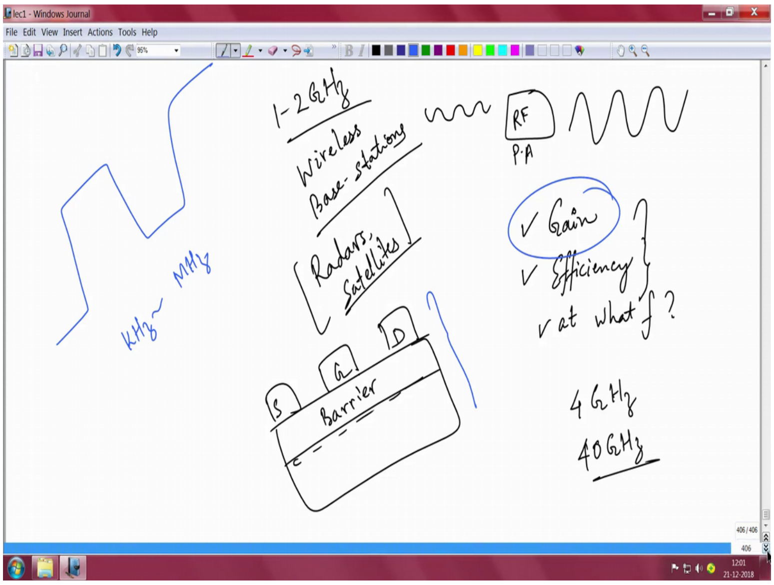

And so you know you if you have an RF signal that is coming at this magnitude if it goes through an RF power amplifier RF PR amplifier as PA, then the magnitude will increase the same frequency. It is a very complicated device; it is a transistor in many other passives elements will be there. So, the heart of this will be a RF transistor; in the RF transistor the important thing is that it should have a very high gain or you know gain is a very important figure and it also a good efficiency right good efficiency at actually this thing.

So, if you have a higher gain higher efficiency you are also able to at what and also at what frequency can you do that up to what frequency can you do that. If you can amplify a single at 4 gigahertz does not mean that you will be able to amplify a signal as 40 gigahertz also right.

So, there is many aspects to it and these are RF signals that are ubiquitously used or you know use all the time in your cell phones you know, most of your cell phones will work it in 1 to 2 gigahertz for example, most of your cell phones will work at 1 to 2 gigahertz. So, you have this wave this electromagnetic waves that carry all the information into your cell phone you know that gives you the internet connection for example.

You also have to transmit the signals back to the nearest base station you need you need power amplifier right, you need power amplifier to boost the signal and send. So, you know the this kind of applications is used in commercial wireless mobiles, you know in handsets you use in handsets in base stations mobile base stations that use this large power RFs, amplifiers to basically pump and send a signals everywhere. You also use them in military radars in satellites for communication satellites we will use that you know use have this transmission receiving module and then they will transmit RF signal for different kind of applications.

Now again these transistors will be exactly again the transistor, you will essentially have a source drain and gate. So, I am talking about a field effect transistor for example, this could be your barrier layer or dielectric or oxide or whatever you will have a source drain, you will also have a gate and then there will be a channel here and I am talking about field effect transistor mostly. But we can also talked about bjt and stuff like that. So, this transistor will be same, but now you have to talk about gain for example, and whether it can handle RF at such high speed.

Remember the power switch you know I was talking about on off, on off that typically goes in few kilohertz range to maybe a megahertz range, but here we are talking about gigahertz. So, RF signal is very different right is very different ball game and we should be you know generally aware of what are the things that are used in RF what are the important, just like we had a Baliga figure of merit.

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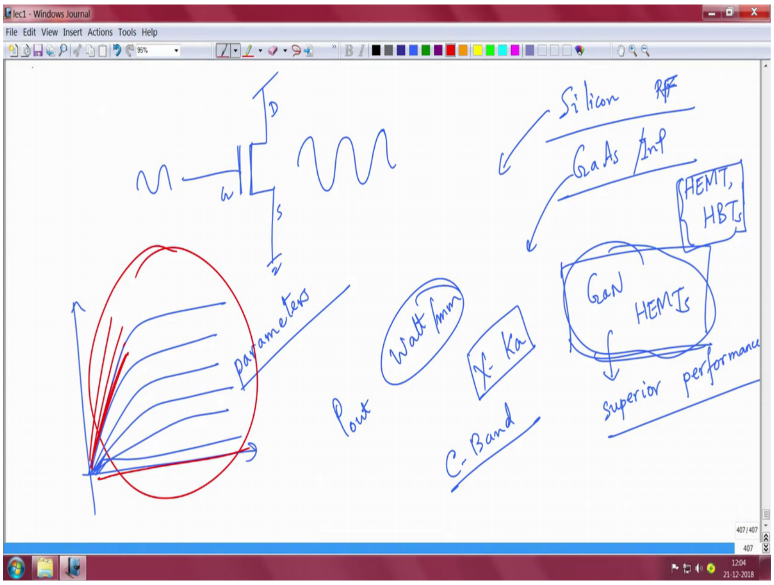

We also have an equivalent figure of merit in RF that is very important. So, before I come to the different technologies I will let you know quickly that silicon RF of course, is used. Silicon RF because it is cheap, it is you know it may not be the best when performance, but it is cheap and silicon transistors for RF are definitely used. Gallium arsenide indium phosphide in their HEMTs High Electron Mobility Transistor as well as HBTs are very widely used one of them is definitely in your cell phone right now to actually act as a transverse your module.

You know in the in the module you need a gallium arsenide indium phosphide HBT or HEMT in your handset mobile base stations are now using increasingly gallium nitride HEMTs to actually do that. Because you know this can give you better performance, superior performance can be given although the cost is will more superior performance whether the cost is the different thing its a economy. But from the performance point of view GaN HEMTs for example, can give you superior performance, gallium arsenide indium phosphate can work at really high frequency applications.

And silicon of course, has a cause advantage these are dominant technologies that are used in RF, silicon gallium arsenide indium phosphide in gallium nitride devices they have their own you know things like for example, if you talk about higher bands like X-band or Ku-band Ka-band and of course, you can get silicon transistors, but their output power is very low, you talk about output power, it talk about watt or watt per millimeter you know how much watt you are delivering in RF output power.

So, the silicon devices at very high frequencies have low output power lower efficiency and all. So, gallium nitride devices for example, can very high output power at least 5 to 10 times and very high efficiencies. So, they are being increasingly used in RF now you know different things will need different kind of applications set comb (Refer Time: 18:16). But C-band is very widely used and silicon are course is there, but now you know the dominant market player is gallium nitride that is entering.

So, what is all about this power amplifier? So, you have to essentially amplify a signal right you can talk about a transistor like this in is a transistor signal that you know you know this is this is the transistor this is the source, this is the drain, this is the gate. The idea is there at the gate you will have a small signal and output you should get a large signal here I mean you should amplify the signal here. So, this is how a transistor should look like in general in a power.

So, what are the what are the parameters or what are the what are the criteria for a power amplifier to work properly you know if it is a device, it is a power the it is a power transistor of course, and power amplifier will have some more elements at say that we did. But you know if you talk about an IV characteristics if you talk about an iv characteristics of a transistor, then what is it that you are looking for in this iv transistor that will qualify your device as a good power amplifier.

Now, for example, in power switch I know that the I only concern about the slope here if the slope is good and if the breakdown is good here. And then I am happy, but in a power amplifier the frequency comes into picture and gain comes into picture. So, an output power also comes into picture. So, the qualities and the parameters that you are looking at in an RF power transistor would be different from that in a just a power switch for DC DC converter for example,. So, let us look at into that is right now.

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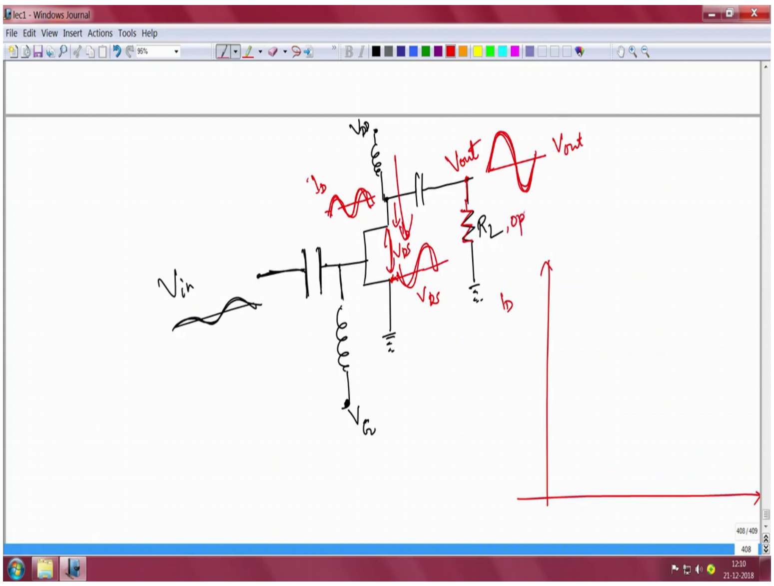

So, let me draw a schematic of very simple maybe a transistor, you know I have I have a transistor like this. So, I will just draw a schematic here it can be any field effect transistor this gate here in the gate you might have a capacitance the gate; the gate capacitance that you have here right and of course, you have lot of elements here capacitance will come out everywhere because its RF signal.

So, capacitance is actually play a very important role this is your V in the input voltage the you are giving and a input voltage is very small voltage that is a radio RF signals. So, voltage here you might have some inductance and other things here that I am not talking about right now ok.

But you will bias this, you will bias this at gate voltage you will apply DC bias on the gate of course, you have to apply DC bias in the gate, but there is also an input you know an RF signal that is riding on the DC bias that si this riding on the DC bias please remember that. Of course, the source is grounded here now this is drain, but on the output side also there might be a capacitance right and then there might be a load resistance there might be a load resistance right; there might be a load resistance here. And of course, there is a V DD that is the drain; that is the drain bias the supply voltage that might also have an inductance or other elements see here, but that is we do not worry about that.

So, what is happens here is that smalls small riding voltage V in will lead to a large change in the what will what is it called the I D the drain current the drain current that is flowing in this direction right the drain current that this flowing in this reaction that is I D you will get a large swing, it is called a swing. You will get a large swing in the drain current here and at large swing in the drain current will lead to large swing in the drain voltage V DS, you know a large swing in the drain voltage can be there this is the drain.

This is source of course,, but I am just talking about the V DS V DS, there will be large swing in the drain voltage here and if there is a large swing in the drain voltage then there might be a large swing in the output voltage this is your output voltage this is your output voltage. So, in the output voltage also we get a large swing although you are feeding inside a small swing in the input. You get a large swing in the output ok that is how you know the basic schematic of a RF power transistor looks like.

So, what happens is that you know you have; you have for example, the I D V D characteristics here, the I D and then the V D characteristics right I D V D characteristics the let me actually draw it in a different page maybe.

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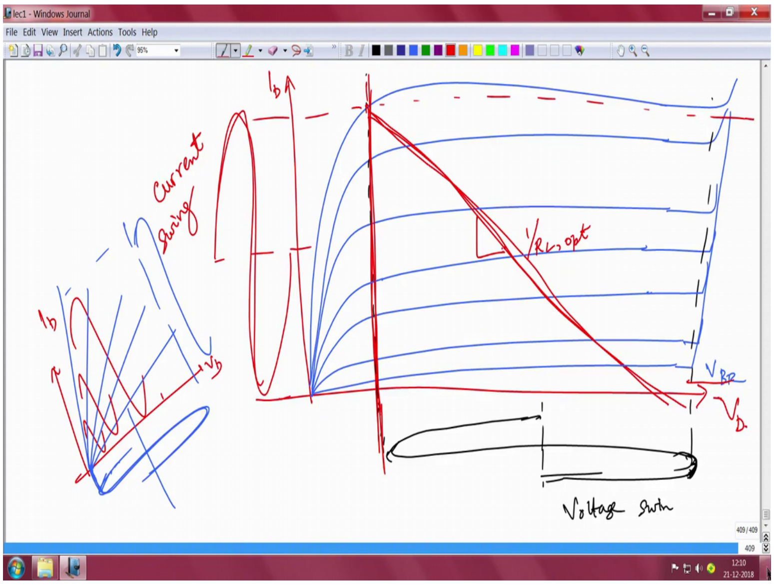

So, you have the id the drain current right and then you have a drain voltage here right and you have this, you know you have this I D V D family of curves here right, sorry you have this family of curves here like that.

So, what happens is that your if you look and this called the knee voltage right where it is banding essentially and this is suppose your breakdown voltage your device will break down here ok; your device will break down here. Maybe its heating or whatever is breaking dawn here over here, then you have your window in which your voltage can swing, this is the swing in which your voltage can be.

This is the maximum voltage swing you can have, on the output side the voltage swing can be maximum this it cannot extend beyond that ok. This swing has to be there this is call your voltage swing ok, this is your voltage swing, if it goes above then it will break down if it goes below here you cannot get gain right.

So, this is your voltage swing and similarly you will have your current swing also and the current swing will be between and a maximum current you have here which is this and you know this 0. So, your current if I draw it here the current swing will be right, this is your current swing ok. Your current swing will be there it will be between the highest point the lowest point here ok.

So, that is your current swing and that is your voltage swing and ideally you will have a load line that is the operating bias of the device will decide this load line along which you are dividing and the slope of this load line actually is the optimum output resistance the low resistance where will have the device loaded.

And the situation is very important in this device, because you see your power is your swing is limited up to here that is where the device you know the device saturation starts from here. If the current does not saturate for example, if I take I D and V D and the current does not saturate, it is all like this. If there is no saturation of current then how will you define the voltage swing? The voltage swing will have to be define from this 0 only know 0 to here whatever.

Then your output power will be 0 because your voltages is coming to 0 ok, your voltage is coming to 0 and your current also will come to 0 because you cannot defined a swing in the current which is the swing. So, it will be everywhere right, like it does not have a low value and a high value. If you put the swing here it will be something like that if you if you decide the voltage to be here then your swing will be like that and like that and like that and like that eventually you can get no power at all.

You it is very important that your device saturates in power in I D V D. So, that you can get a swing in the voltage as well as a swing in the current and there is a slope here the load line, this load line essentially is manifestation of the current here. So, there is the current flowing here and you know there is a low the resistance you putting the optimum resistance will decide; the optimal resistance will decide where you are biasing the device so that you can get the maximum swing.

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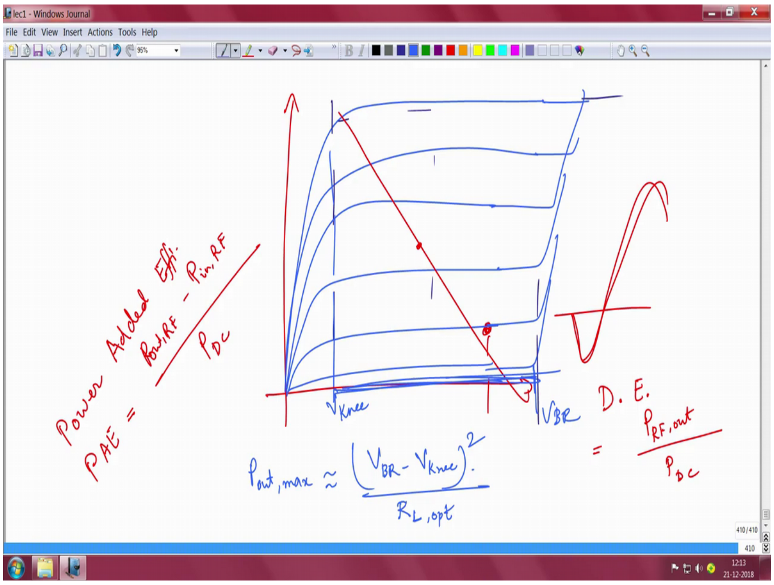

So, what I mean is that what I mean by that is there I will just draw a small schematic here ok; I will just draw a small schematic here. Suppose this is your I V this is I D V D characteristics, this is breaking down here ok. So, to get maximum power you want to bias at the middle of this so that you get the maximum swing here, you get the maximum power. And so you are biasing at some midpoint here right, suppose because that is why you are able to get both the swings and middle up middle right.

But if you are biasing, if you are not biasing the device here you are a biasing the device for example, here your device operating point is here then you will be able to get only this much swing. The other swing can be more, but you know you will not get the optimum power here it swing and similarly your current swing will also be less right. So, want the maximize the product of the voltage and the current swing. So, you have to get the optimum load line for you operate, only then you will be able to get the gain and so current saturation is very important here.

And one of the important terms that you call in this side of device is called Drain Efficiency DE, the drain efficiency is basically what is the RF output power you are getting, what is the RF output power you are getting divided by what is the DC power you are putting in ok; that is one important parameter. And then one another important parameter is called power added deficiency ok; Power Added Efficiency which is called PAE. That is defined as what is the output RF power minus what is the input RF power because input also you are giving a small swing right, divided by what is the DC power you are supplying that is called your that is called your power is efficiency that is a very important number.

And the output power, the output power maximum output power you will get from such device is given by the breakdown voltage here, this is the breakdown voltage and this is the knee voltage right, this is the knee voltage. So, the swing is limited between these know. So, it will be breakdown voltage minus knee voltage because that is the swing you are getting square divided by R L, the load resistance optimum this swing that takes into account or current also by the way. So, this is your the maximum output power that you are going to get from the power transistor ok.

To work as a power transistor of course, you know it many of the important things are there one of the things that is there which we shall not discuss here in details or anything is called small signal model.

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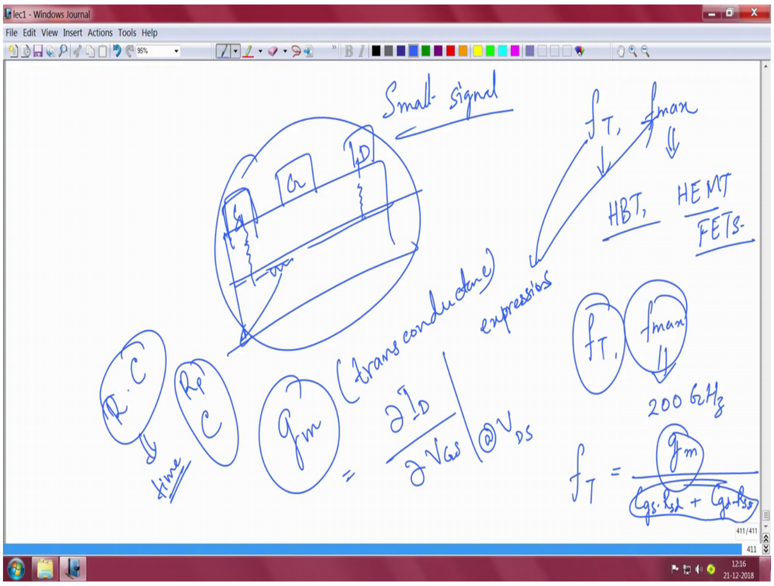

So, small signal model will tell you how fast the device can work, the two parameters I called you f T and f max, f T is defined as the current gain cut off frequency that is the frequency at which the input and the output current will be have the same magnitude so that your gain becomes 1.

And the f max is defined as that frequency at which your input and output power will be the same. So, it is called power gain cutoff frequency. So, now, HBTs and HEMTs will have their own distinct you know, but and sort of a or FETs will have their own small signal model that will tell you the expression for exactly this cutoff frequency for f T or cutoff frequency of f max. You can get that cutoff frequency expressions, I will not write that down here in this course is model 11.

But a higher f T means that in generally tells about the speed of the device higher f max tells you at up to how much frequency you are going to get some power. So, for example, if your f max is 200 gigahertz it means at 200 gigahertz you are going to get a get off get off one gain of 1, 1 which means there is no gain after 200 gigahertz. So, all your gain will happen a frequencies lower than, you know lower than 200 gigahertz ok. So, that is important thing.

And the most important transistor parameter, now you might ask you know I have a transistor I have a source I have a drain and I have a gate ok, it is good that you told me about the drain efficiency the RF you know the load line the swing, the power added efficiency, all things are good.

But from the transistor point of view that parameter there is that needs to be high or that needs to be low which actually decides how high the f will be or how high the f max will be or how better you know do you get the power devices and all this thing is called trans conductance or g m.

You have heard this and you have learned about this long back, transconductance is defined as the output current, the derivative of output current with respect to the gate voltage at a particular drain voltage ok. So, the transconductance needs to be very high, at high trans conductance means that you will get a better frequency response or a higher speed device and along with trans conductance you will have many parasitic elements.

The resistances and the capacitances that are there in the circuit for example, the source and drain system contact resistance, some contact resistance some channel resistance all this will contribute to parasitic resistance. And similarly the big patches of source and drain and all they will also work as capacitors and so you will have some large area capacitances also.

So, you know that are the all the parasitic resistances and all the parasitic capacitances, the multiplication gives you this which is the time constant, those are time constants that increase the delay of the device from its intrinsic performance that lead the device from an intrinsic performance.

So, your f T and f max you know you have you will big expression, but in generally if you talk about you know just like n f Tof a HEMT or a just like you know you have a HEMT or FET, then f T will depend on g m and then you have many capacitance resistance products like C gs times some R sd then some gate drain capacitance time some are source drain resistance and so on.

There are many expressions here in a way all these are parasitic resistances and capacitances that will actually tend to reduce the frequency response, that will tend to reduce the speed of the device ok, that will tend to speed of the device. You need to make sure that your mobility is electron velocity is high the parasitic resistances capacitances are low and your gm needs to be very high in order to get a better speed transistor.

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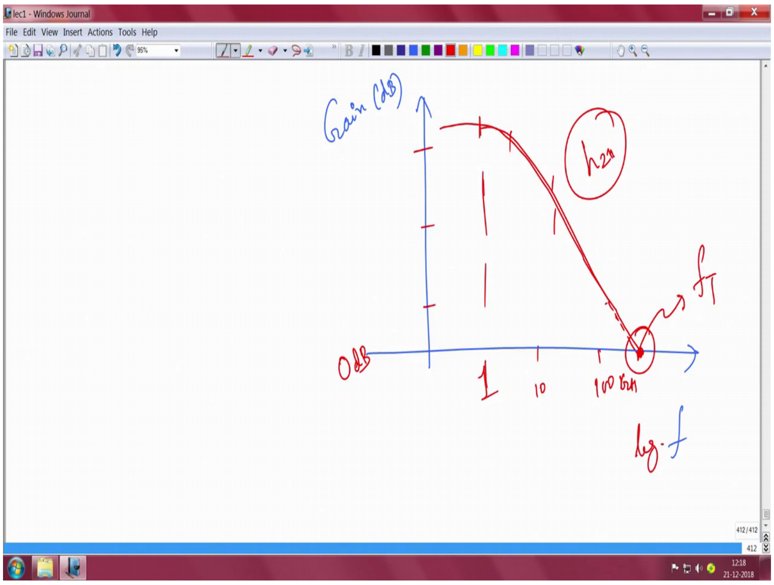

So, for example, if you plot the gain of a I F transistor and the gain is plotted in dB. If you plot the gain as a function of frequency here than you know it is a dB of course, the gain will stay flat and then drop at a rate of 20 dB per decade. So, the gain is dropping like 20 20 dB in 1 1 decade of frequency. So, this is the log scale of the fr3equency by the way.

So, you will have say 1 gigahertz, 10 gigahertz the 100 gigahertz these are 1 1 decade know. So, 20 dB 20 dB till fall for decade, the slope it which it will fall and you know if the gain become 0 dB which means the gain is 1 log of 1 is 0 right.

If the gain become 0 dB that point and if this is the current gain frequency right then you will define is this particular point as the f T where again become 0, where a gain becomes 0. Typically there is the parameter call h two one it is an h parameter did you plot lets than going to that and this plotting of the h 21 parameter this is actually like the gain the current gain and wherever it becomes 0 dB that point is call your current gain cutoff frequency. And typically that is how you decide you know you can do this measurements in vector network analyzer to find out how the device works and so on and so forth.

So, let us end of the class here. So, we have now studied also RF transistors, now you have studied you know power and RF both transistors. There is a little bit of RF transistors still remaining in the; that we will cover in the next class. There is an important figure of merit from the transistor point of view not the circuit point of view ok, from the transistor point of view there is a figure of merit just like you had figure of merit of Baliga figure of merit in power switching. Similarly in RF devices there is also a figure of Michael Johnson figure of merit and the Johnson figure of merit will tell you how better a material where device can be for power amplification ok, power high power high speed are transistors ok.

So, we will discussed about power Johnson figure of merit and the different computing technologies and you know what are the things we should keep in mind if we want to design a better RF transistor for example. Apart from the obvious which is reducing the parasitic capacitance and resistances, but from the device point of view ok and then we will decide and then we will go forward in next lectures to things like transistors from memory applications transistors for logic which is basically nothing, but CMOS that you know.

And then maybe in the last 1 or 2 lectures we will you know quickly discuss what are the steps in practical life, in fabrication world to make these devices that we have studied till now very briefly and if time permits we will solve some question papers of some popular entrance exams. So, that will get some feel of how to do numericals associated with this whole course ok. So, we will end the class here today.

Thank you for your time.