Fundamentals of Semiconductor Devices
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Lecture – 54
Transistors for power electronics

Welcome back. So, we have finished the optoelectronic part of this syllabus and the last few lectures now that remain we will start with the uses of different kinds of transistors and what are the different kinds of transistors for application in different areas ok.

So, this will give you a practical feel for the applications of these devices in the different kinds of gadgets and things that you see including as diverse as a mobile phone, a electric vehicle, a solar panel. I mean solar panel will have of transistors, but you will still need power devices to convert solar energy by the way to AC. You will you know as diverse of things as a low noise amplifier power and you know logic memory devices and so on.

We should be aware of what kind of transistor and how to make transistors that are useful for a particular type of application, we should not generically do research or develop. We should definitely know what kind of things are used in which kind of application. So, what are the main areas in which transistors are used widely? That is the question that we have to answer now.

You have now familiarity with basic MOSFET working and also the working of HEMT - high electron mobility transistor and you know FET's, so and also BJT's by the way bipolar junction transistor. Bipolar junction transistor is a little different kind of transistor because you inject current there in the base.

This discussion will primarily be confined to field effect transistor. Field effect transistors like MOSFETs or you know HEMTs for example, or MOSFETs; Field effect transistor are where you apply field to deplete the channel charge and modulate the current. So, in the context of field effect transistor we shall discuss this applications of transistors and you will see that there are many things that are never covered in text books and syllabus, but which you should be definitely aware of you will realise that in this lecture now.

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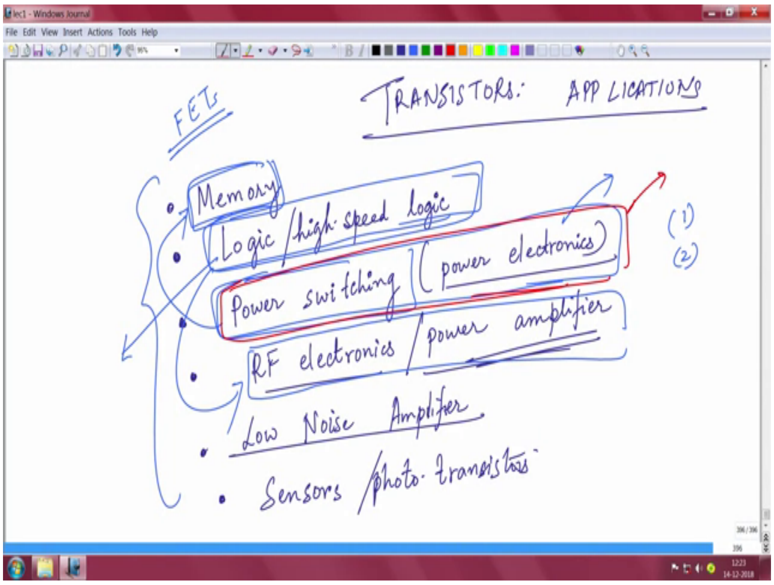

So, let us come to white board. So, what are the applications of transistors? What are the primary applications of transistors; what are the primary applications of transistors? So, if I take transistors what are the primary applications? In which areas are transistors used, can you tell me? There are many areas let us talk about that number 1: you use transistors in memory; memory devices, your flash memory right, your solid state drive memories in not the not the magnetic hard drives, but the flash memory you use transistor structures there.

Then, you have logic; high speed digital logic and that I do not have to tell you. High speed digital logic is what has enabled the this Moore's law, this processors all this processors like Pentium, Intel processors and you know iOS android all these processors that you use in your cell phones, laptops you know which is basically drives the Moore's law that is actually logic, digital logic NAND, NOR gates ok. Those use transistors that is why our modern electronics revolution has taken place by the way.

Then you use in power switching, hard power switching. These are used in power conversion ok. These are used in power electronics ok. Power electronics you will be surprised to know that actually the upcoming electric vehicle market is heavily dependent on power electronics. Everything is now power electronics by the way; the way you convert power. Your laptop receives power from 220 volt socket, but your laptop is not charging at 220 volt, it is charging at 15 volt probably. So, you have to convert that power that power electronics ok. It is a very large area by the way.

And, then you have RF electronics. RF electronics is basically like a power amplifier ok. Your RF power amplifier where you amplify the signal you amplify the RF signal to get power output it you know your cell phones, your radars, satellites you know they have you know 5G communication that will be used now. They are all RF electronics by the way ok, they are RF electronics.

Then of course, there is low noise amplifier. Low noise amplifier is basically it is a transistor also are there to essentially eliminate noise so that they can operate at very low noise situation. Then of course, you can use transistors also as sensors by the way, you can use them as photo transistors right and there are many other applications, but these are a primary applications.

Now, which kind of transistors are used in which of these? Is the transistor used for memory the same as the transistor used for logic? Is the transistor used for logic the same as this used in power switching? Probably not; so, one thing is that we should know what kind of transistors are used in which of this application and second thing that is one thing. And the second thing we should know is what does it take for a transistor to be qualified as for example, a power amplifier or a power switching transistor or a logic transistor or a memory transistor, what is that quality or what are those qualities that define or that validate a transistor to be suitable for a particular application?

For example, I will take a MOSFET that has been that is used in a logic or a high speed digital logic kind of thing. Now, high speed digital logic that is there in your laptop or cell phone that is in the processor that works at very high speed and switches on and off which is a digital logic you are using in you are using in digital logic, can I use that transistor? For example, as an RF power amplifier? Can I can it amplify an RF signal?

Or suppose I take a power electronics transistor that is switching power from AC to DC or DC to AC can I use that transistor as a memory device. Because eventually I am talking about field effect transistor and field effect transistors are more or less the structure is the same. So, why cannot I use one in terms of other or why cannot we you know substitute the one with the other. So, these are some of the things that we will now study.

So, we will go sequentially, but I will not follow the exact sequence that I told you. First thing we will study is transistors for power electronics, we will study transistors for power electronics that I will study first what kind of transistors are used in power electronics what are the power electronic applications. I have been telling you hybrid vehicles power conversion. But what are technically what are the power electronic applications and why do we need them ok?

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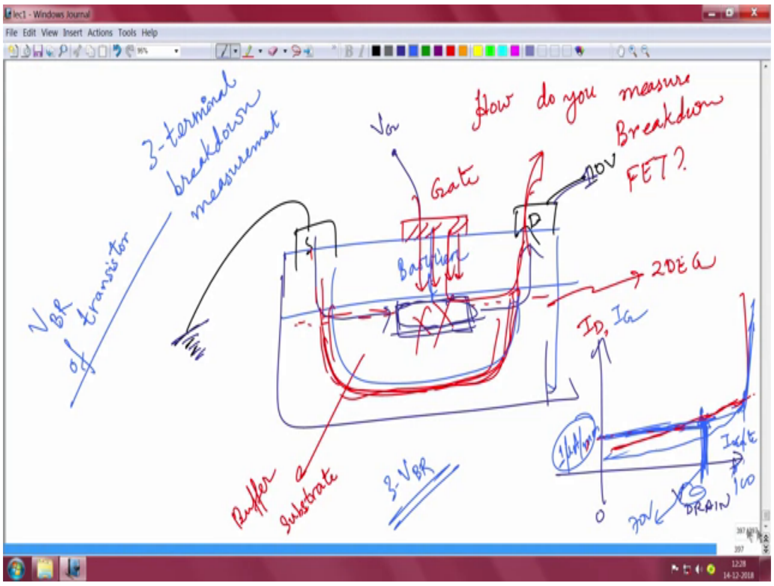

Before I go into that, I will just tell you one simple thing and that is called how do you measure the breakdown of a transistor a field effect transistor? How do you measure the breakdown; how do you measure the breakdown of a transistor? How do you measure do you know? The breakdown of a transistor is measured in something called 3-terminal breakdown measurement. 3-terminal breakdown measurement ok; this measurement is used to basically measure that.

So, what happens is that I am drawing a schematic of a normal transistor some barrier is here like a HEMT for example and then there is a 2D electron gas here or some charge. It can be a silicon inversion MOSFET also it is a charge that is there 2D electron gas is there. You have a source here, you have a drain here, this is grounded. This is applied to some volt 10 volt, 20 volt whatever the current is supposed to flow here like this.

Of course, there is a gate here. Using the gate what you do is that using the gate you can if you go to negative voltage of the gateway where you can apply appropriate voltage, you can pinch off this charge. You can deplete that charge below the gate ok. Below the gate you can deplete the charge or pinch off the channel by applying an appropriate negative voltage on the gate that much you are aware of. Once the channel is pinched off what will happen? Current cannot flow; if the channel is depleted by an appropriate negative voltage, then current will not be able to flow between source and drain.

So, what you do is that the way you measure 3-terminal breakdown is that you apply a gate voltage such that you deplete the channel very strongly. Suppose at minus 4 volt you can deplete the channel you got to minus 5 volt ok. You make sure that channel is completely depleted by applying an appropriate gate voltage. Now, you ground the source and you sweep the drain voltage gradually. So, you ground the source and you sweep the drain voltage V drain; you sweep the drain voltage from 0 to whatever and you monitor the source current the source drain current here, what is the current that is flowing. It should not flow ideally.

There should not be any current should flow because, the channel is pinched off there should not be any current that flows here ok, but you that is why the current the leakage current will be very low the drain current. You monitor the current coming out of the drain. Where will the current come out from? There are two sources; one source is that it can come out through this substrate, but this substrate or it is this is called buffer or you can call it substrate by the way.

This substrate should not be able to leak ok; whether it is a MOSFET or it is a HEMT this substrate should not be able to leak. If is it a good substrate, it should not leak, but of it is a leaky substrate it will leak. So, that is the drain current you monitor. It should be ideally very low like nanoamps or picoamps of current. It should not be like high like milliamps or amps, it should be very very low current.

And, another source is gate. The gate also might leak by the way. If the gate leaks through the barrier then also gate will contribute. So, you might also want to monitor the gate current; the gate current also might leak I gate. So, this you measure and you keep increasing the voltage. So, at some voltage this will suddenly increase it will break down because this buffer that you are carrying the current this buffer will breakdown or the gate will something will breakdown that voltage may be say 100 volt, [FL] 200 volt whatever, is called 3-terminal breakdown voltage.

And, typically you measure this 3-terminal break down voltage of transistors sometimes you do not want that this destructive breakdown suddenly should occur. So, what you do is that you define some limit. Suppose, I defined a limit leakage limit of 1 micro amp per millimetre if whenever that current is reached that point I will define as a breakdown maybe say 70 volt or maybe 500 volt, whatever.

I will define some limit like 1 micro amp per millimetre and this is a 2-dimensional device by the way that is why amp per millimetre and then at that particular voltage when it reaches that particular current I will define as a 3-terminal breakdown measurement. So, when I talk about breakdown of a transistor V breakdown of a transistor I am talking generally of this 3-terminal breakdown measurement in an FET, please remember that.

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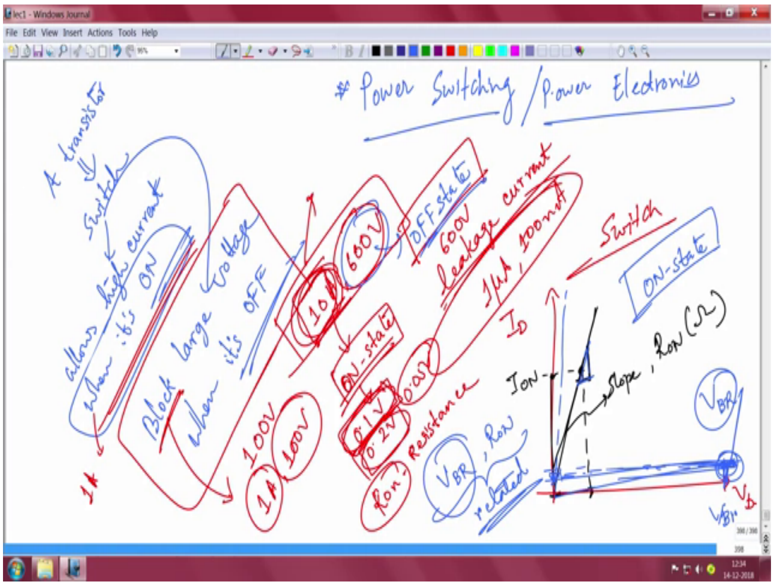

Now, I will come to the first category of transistors, what are the kind of transistors needed and what are the applications for the first category of transistors which has transistors for power switching or power electronics. This transistors do not need to have any gain ok. They do not need to have any gain necessarily. Unlike in RF amplifier where you need a again power amplifier, in case of power switching devices you do not exactly need a gain.

So, as a power switch a transistor I am talking about an FET, but in general a transistor a transistor can act as a switch. What does a switch do? A switch allows current to go very high current to go; very high current to go or flow 1 second very high current to flow or pass through when it is on and a switch should block large voltage or whatever voltage you want, it should block large voltage when it is off.

So, a switch has two states; one is ON state and one is OFF state. A transistor can be used as a switch. In the ON-state you should the transistor should be able to carry large amount of current at a very low voltage that voltage that you are applying is called the forward voltage drop. It should be able to carry very large current at very low applied voltage so that you are your ON resistance is very low, you are saving energy because you are able to carry high current by spending minimum energy ok. And that is typically in the linear region by the way.

And then in the OFF state when you switch OFF the switch or the transistor it should be able to block large voltage maybe 100 volt, 50 volt, 200 volt, 1000 volt whatever, it should be able to block that voltage when it is OFF. So, if it is able to block a voltage of say 100 volt and if it is able to carry a current of say 1 ampere you call it rated at 1 ampere, 100 volt transistor. This 1 ampere and 100 volt do not come together you do not apply 100 volt and get 1 ampere of current by the way, that is wrong.

When you say that I have a transistor that is rated at 10 amps and 600 volt, it does not mean that you apply 600 volt and you are getting 10 amps of current that is not true, then the power will be 6 kilowatt. Your device will melt, that is not what is happening. This current rating corresponds to ON-state of the switch. In the ON-state of the switch you are able to carry 10 amperes of current; of course, it is not a continuous current, you pulse it. A very narrow duty cycle you pulse it so that this 10 amperes of current will go only for very few in nanoseconds or microseconds for example.

And, the voltage dropping across the transistor will be very low. It will be something like say 0.1 volt or 0.2 volt or something very small voltage and that voltage and this current will define the ON resistance; ON resistance of the device and you want the ON resistance to be as low as possible which means at very low voltage like 0.1 volt or 0.2 volt you want to get very high current like whatever 1 amp, 5 amp, 10 amp whatever.

And, this 600 volt corresponds to the OFF-state of the device. This 600 volts corresponds to OFF state of the device and this ampere is the current is corresponding to ON-state of the device. In the ON-state, the voltage that is dropping will be very low something like

0.1 volt even maybe 0.05 volt or so on. This number is not in the rating, but you should know that, you should ask that because this will define the ON resistance R ON.

Similarly, this voltage rating of 600 volt is in the OFF-state and in the OFF-state it will block 600 volt for example. When it blocks, there has to be a leakage current also and that leakage current typically should be much smaller than the current carry that will carry in the ON-state which is 10 amp. If you are carrying a current of 10 amp, then your OFF-state leakage current should be very low maybe 1 micro amp or 100 nanoamp or so on. This is not mentioned in the rating.

So, this 600 volt or 1000 volt or 100 volt blocking that you say is in the OFF-state whether the reverse leakage is very low ok. So, now, how does it behave like this is the condition, now how does it behave like a switch? So, I can plot the drain current I D versus the drain voltage V D and ideally you have current that goes like this, but I will not draw the saturation part, I am only interested in the linear region here.

So, if you operate at this point for example you know that is at very low voltage. This V D should be very very low 0.1 volt or less than that and you are getting some current called I ON. The slope here that slope will correspond to the resistance actually, the ON resistance that this voltage divided by this current is called ON resistance which is R ON and this R ON should be as low as possible which means this slope should be high; that means, you should be able to get very high current at very low voltage and where this is the ON-state of the device.

When you have the OFF-state of the device when you switch OFF the channel or you pinch off the device then you should be able to block a very large amount of voltage. So, it will go like this at very large voltage V Br or V breakdown you should be able to get very low current like microamps or nanoamps or you know 100 of nanoamps or picoamps would be better, you should be able to get very low very low current or almost no current that is your leakage current that is your reverse bias voltage. So, the break down what happens essentially breakdown will happen there is a breakdown voltage.

So, apparently it is breakdown voltage that you can get and this ON resistance that you can get are related they are related. So, please remember that ON-state resistance on resistance corresponds to only ON-state current and the breakdown voltage corresponds to the OFF-state condition when the leakage should be low and the breakdown voltage and the ON-state resistance are actually related to each other by something called Baliga figure of merit; something called Baliga figure of merit.

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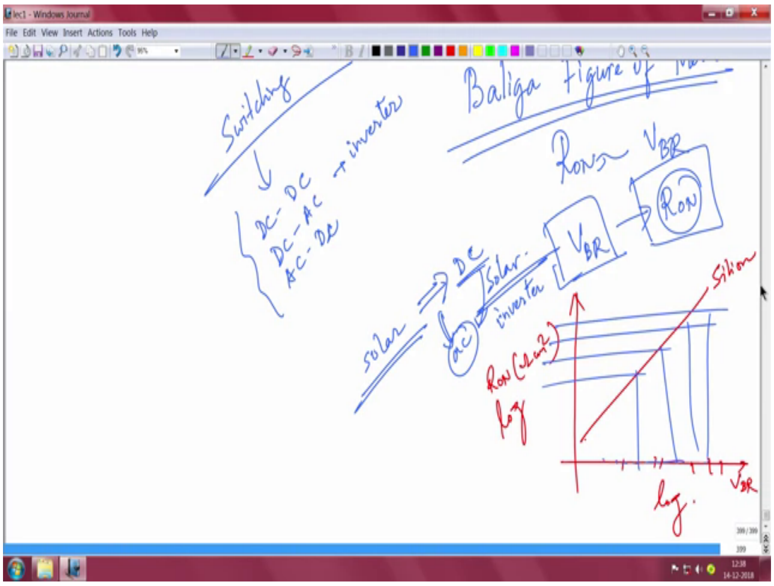

Baliga figure of merit is a figure of merit for power switching transistor to indicate how good a transistor is and Baliga figure of merit essentially puts a limit to ON resistance and breakdown they are related to each other they are related to each other. So, Baliga figure of merit says that if you increase the; if you increase the breakdown if you increase the breakdown voltage for a better offset characteristic then your ON resistance also will increase. If your ON resistance increases then your ON-state current drive will suffer. So, Baliga Figure Merit gives a limit fundamental limit between the breakdown voltage that your device can handle and the ON resistance that your device can allow the current to flow.

So, you cannot get best of ON resistance and breakdown at the same time you have to sacrifice one for the sake of other and there is a limit to it which is defined by the strictly by the material parameters like mobility and the you know the critical electric field which is a metal dependent property and so on. So, these devices are used for switching.

And, because you can block the voltage you can let current go and his switching have huge applications in DC-DC conversion, power conversion DC to AC conversion AC to DC conversion; DC to AC by the way is called in the application is called an inverter.

The inverter that you have at home converts the energy in a battery to AC because your table fans and everything runs on AC energy.

Similarly, sunlight solar energy is DC; solar energy is DC right, sunlight is DC. But, you cannot transmit DC I mean you should people translate AC know in the household and your tables and the your table fans, your lamps, TV they will run on AC which means the sunlight has to be converted from DC to AC using an inverter. So, these are called solar inverters.

There are different categories of invertors with different specification; one of them is solar inverter. This conversion of power from DC to DC and AC to AC, DC, AC this is done by power switching ok. This is done by power switching and power switching is possible by using this transistors which can act as a power switch; this can act as a power switch.

So, the Baliga figure of merit. There is a Baliga figure of merit can be plotted actually. The Baliga figure of merit can be plotted I will say it is; the way you can Baliga figure of merit is that you plot on resistance which will be ohm centimetre square for example, is normalised area and versus breakdown the breakdown voltage. The curve will look like this say for silicon.

So, in other words no matter what you make silicon FET silicon Schottky diode or whatever you make as you increase the breakdown voltage; this is log by the way, this is also log by the way, this is a log-log plot. So, it will look like this like that. What it means is that as you increase the breakdown voltage in the OFF-state which is good you also sacrifice the ON-state resistance, you drop more and more resistance in the device which basically will makes the device lose its efficiency. So, this is your silicon, but depending on the material parameter things could be different.

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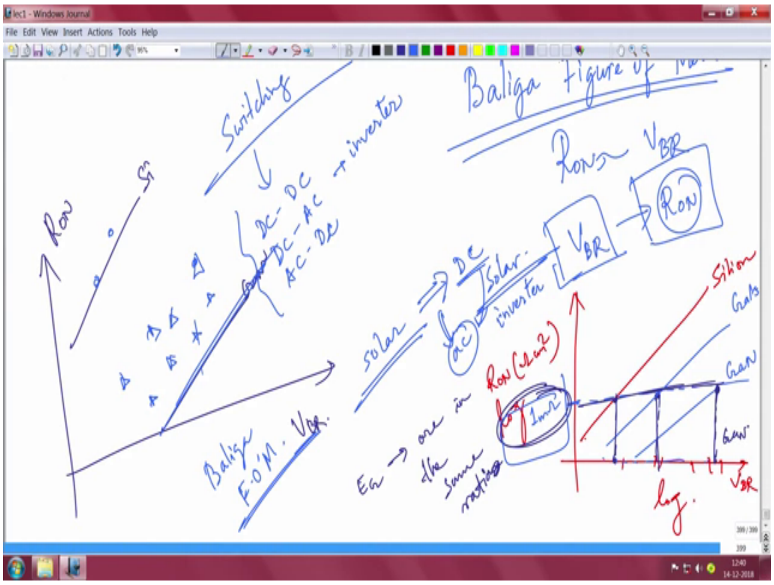

For example, gallium arsenide could be like this; it is better than silicon and gallium nitride could be like this. What does it mean? It means that for a given on resistance say 1 milliohm centimetre square for a given ON resistance you will have some breakdown voltage of silicon. But, a higher breakdown voltage in gallium arsenide and an even higher voltage drop in gallium nitride which means for the same ON resistance for the same ON resistance your gallium nitride device will give you better a superior breakdown voltage than gallium arsenide and gallium arsenide will give you superior voltage or breakdown voltage then silicon.

That is primarily because your band gaps are in the same ratio; are in the same ratio. That is why, with higher band gap material you are able to get higher breakdown you know you are able to get higher breakdown and you will see here that your ON-state current is actually you know I mean the ON-state resistance is the same. So, you are comparing the different device technologies across the same ON resistance, but that that gives you different types of breakdown voltages ok.

So, this is an important aspect to highlight the superiority of wide band gap material in terms of getting higher breakdown voltage for the same sort of ON resistance ok, same sort of ON resistance. And, of course, people have done many plots and research along this line. So, this is your R ON for example, this is your V breakdown for example, what they will do is that if this is your silicon limit and this is your gain limit then they will do this scatter plot where with other things you know here, here. The gallium nitride things might be here ok. The gallium nitrite is not quite rich the theoretical limit because the gallium nitride you know the actual breakdown voltage is lower than the theoretical breakdown voltage. So, that is why it is here.

This is this is actually the representation of the Baliga figure of merit; Baliga figure of merit to indicate which materials are better for power switching application. If your ON resistance is the same it means your power loss is same in ON-state, but you are going to get higher breakdown voltage; higher breakdown voltage. And when I talk about power devices this can act as a switch for DC-DC converter or you know solar inverter and so on there are many kinds of devices actually there are also in the market.

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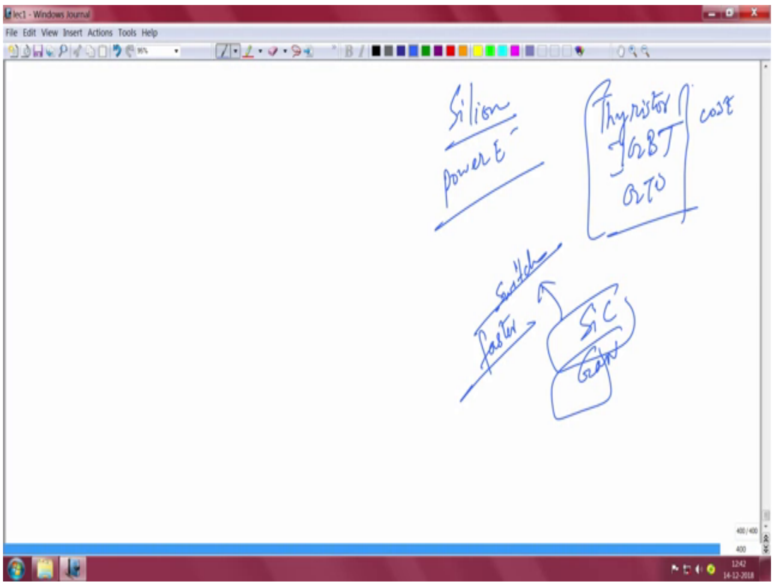

And you know in silicon is also a dominant player in this power electronics power electronics switching market; silicon is also a pretty dominant. It has many devices called thyristor for example or IGBT in Insulating Gate Bipolar Transistor, IGCT, GTO these devices are power devices that can switch at very large voltages at you know good frequency of kilo Hertz for example and can convert power.

Of course, there are new technologies like silicon carbide technology, gallium nitride technology which are also challenging silicon dominance and they can normally give same or higher breakdown voltage at the same on resistance, but they can even switch faster; especially gallium nitride can switch faster. So, when you want to get some fast switch that can also block kilovolt and carry amps of current, gallium nitride or silicon carbide might be better than you know then using a silicone device, but silicon device veins on cost. So, there is no comparison to that there; there is no comparison to that there.

So, you know this actually is a market game. This is also eventually given by cost. But, the primary thing here is that that you should look out is that whether it is a silicon or a wide band gap material like gallium nitride. The question is can you block voltage while allowing high current to flow in small voltage drop? Yes and the figure of merit is Baliga figure of merit. So, you know that Baliga figure of merit of Silicon is much lower or much worse than that of gallium nitride which means for a given condition silicon will not be able to perform as well as gallium nitride as far as power switching applications are concerned.

But, still Silicon is still a dominant player because of cost because many private companies or many vendors would like to minimise the cost and silicon performs lower maybe, but the cost is also lower. So, people are still there is a competition between silicon carbide gallium nitride technologies and they compete in different spaces, that I will tell you in the next class.

So, here we will end the class today. Just we introduced what are the different things, then I told you about different kinds of transistors or different applications of transistors where different types of transistors can be used. We started with power switching devices, I gave you some examples of how power switching things are done and the Baliga figure of merit the relation between ON resistance and breakdown voltage I illustrated; told you that silicon is much worst in Baliga figure of merit, still silicon is doing well because silicon is cheap and it is scalable very well.

But, new technologies are coming up for gallium nitride and silicon carbide that are useful going to be promising for things like hybrid vehicles, electric two-wheelers your you know laptop adopters, solar energy panels, you have to convert energy from DC to AC for example, all this applications need this switches. This switch basically carries very high current at low voltage drop and blocks very large voltage with wery low leakage that is the characteristics and naturally white band gap materials will perform better of course, the (Refer Time: 26:54) to be a good. So, there is a lot of research going on here in this area.

In the next class, we will continue little bit what is remaining on the power switching front and go to RF amplifier; what kind of transistors are needed for RF amplifier and what are the properties of the material and the device you need to make a better RF transistor ok, is the not the same thing as getting a better power switching device. And this both will be very different from memorial logic devices that we will cover in sometime later ok.

So, thank you for your time.