Advance Power Electronics and Control
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Lecture – 06
Device Physics - IV

Welcome to our lectures on advanced power electronics and control, we shall continue with our device physics, today we shall discuss a new entrant of this family is IGCT, so full form of IGCT is that integrated gate terminated thyristors. I intentionally wish to choose these devices before very popular design; device called IGBT, so that we can compare between both and we can find it out where it can find its applications.

IGCT actually is basically a development on GTO, what are the drawbacks we have found in the GTO; it is actually high dissipation in the gate.

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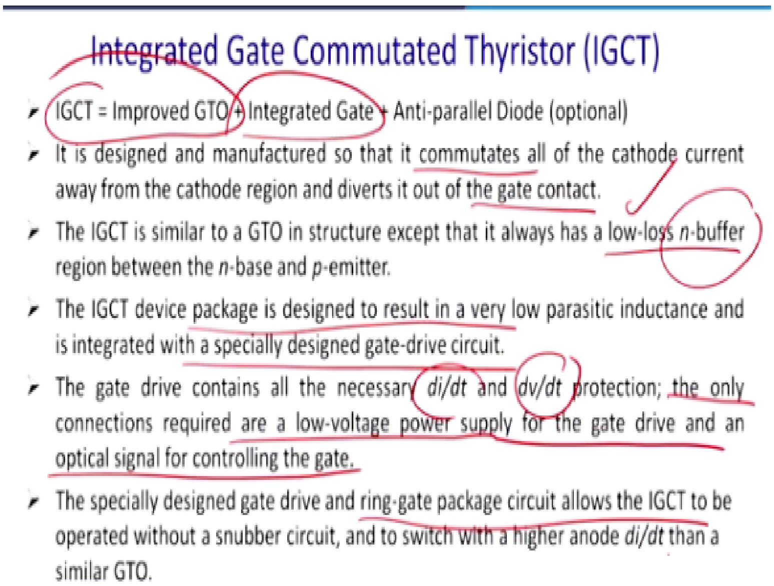

So, it is improved GTO and integrated gate that is the features of IGBT that essentially form BJT when you got an insulated gate that becomes IGBT, it is an actually a combination of the advantage of the MOSFETs and the BJT, here it is essentially a combination of MOSFET and GTO, so integrated gate and also insulated gate and anti-parallel diode, MOSFET I will take at last, so we shall understand it better.

So basically, we are now moving essentially towards basically, the power dimension and power rating available in the market, so that is the; my selected chronology, so first we have discussed about the SCS which has a highest power rating capability followed by GTO there are after IGCT but there can be a debate which one has a more power handling and give a better cost and since it is came little later, so I have taken after GTO only because it is a improve GTO, we require to understand GTO.

So, it is designed and manufactures so that it commutates all the cathode current away from the cathode region and diverts it out of the gate contact, so this is one of the biggest advantage of it, IGCT which has just come little later similar to the GTO in a structure except that it has low loss in buffer that is actually the one advantage of it, we had a buffer region, here also you have a buffer region but it is low loss between the n base and the p - emitter.

So, conduction loss of the IGCT is considerably low than the GTO, IGCT device package is designed as a result of the very low parasitic inductance, there is one of the actual reason requirement of the high di/dt, so if there is a parasitic inductance, it will prevent di dt and integrated with the special design gate drive circuit, it is really complex, the gate drive contains all the necessary di dt and dv dt protections, this package comes with that basically, this is manufactured by the ABB.

So, it has come as a package, so no other company most of my believe and knowledge had now manufacturing it, still it is a sole pertent of ABB, the only connection require is a low voltage power supply for the gate drive and an optical signal for controlling the gate, so it is quite compact, so you as you require optical isolation you can see it somewhere and this will operate over distant location and this is quite requirement for the high voltage application, we require for (()) (04:49).

Specially designed gate drive and the ring gate package circuit allows IGCT to be operated without the snubber, so we will talk about the protections and the gate driver of the design after actually discussing all the devices, so for the dv/dt and the di/dt protection mostly for the dv/dt protections, we require snubber but these has add-on features that it does not require snubber and to switch the higher di dt than this rating of the GTO.

Only thing is that it is an improved version thus it has all the improvement, only one disadvantage is still it is mostly it is single sourced and another issue was it is still lies that you know actually it is quite costly than the rating of the same rating GTOs.

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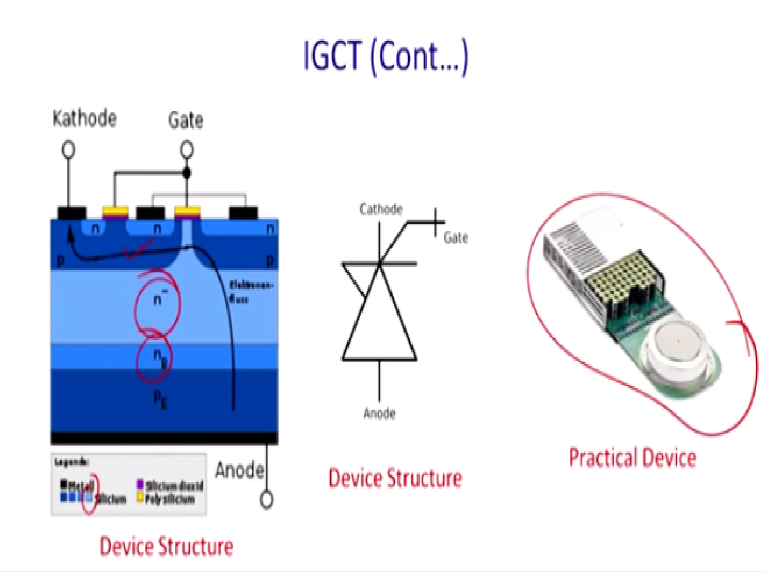

So, this is the device structures cathode and anode and you know this is actually n buffer region, it is doped in such a way it does not offer a very high on state resistance and in between there is actually silicon, silicon doping level is prescribed by the colour, this is the highest doping level and this is the lowest doping level via distance and this is the actually symbol of this device, you have a gate cathode, anode.

Ad this is the practical device, it is comes with the heat sink and everything is a quite compact, it is a something like plug and play device nowadays, this term is used plug and play, so something like that you just connect the gate driver circuit and it would operate nicely but problem lies if there is any fault inside it you have to throw it out.

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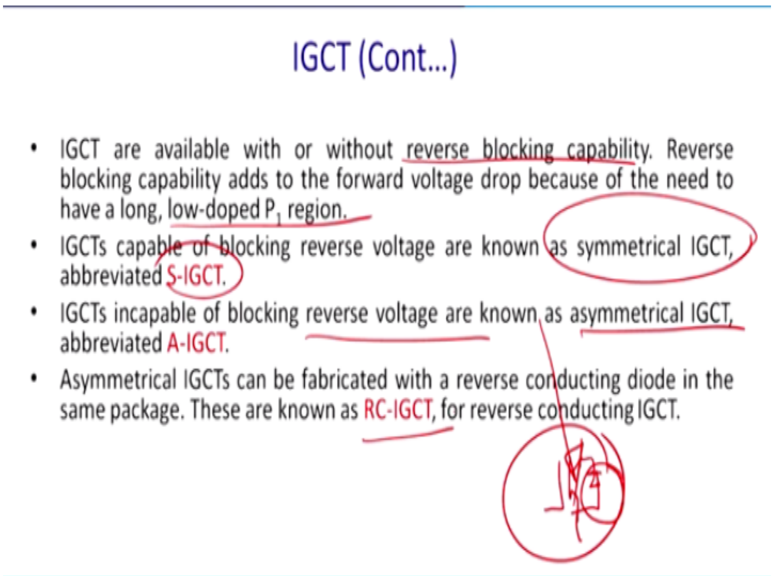

So, IGCT's are available with or without reverse blocking capability, so that is the manufacturer, you can choose a different kind of IGCT as you require, if you require for the actually, application like VSI and you are fitting an inductive load like your drives and all those things where you require to have a forward blocking mode but bi-directional current mode, then generally it comes with anti-parallel diode.

Reverse blocking capability adds to the forward voltage drop because it need to have a long and the low doped P region, IGCT capable of blocking reverse voltage as known as the symmetrical IGCT as I abbreviated same as your GTO, so it is yes, IGCT, IGCT in capable of the blocking reverse voltage by putting the anti-parallel diode, then it becomes a asymmetrical IGCT or abbreviated at A-IGCT that is quite frequently used in VSI kind of applications.

While it is understand it, you know actually, in case of the voltage source inverter, so you generally require current to be bi-directional and for this since you know, in case of the if it is IGBT you have to provide the anti-parallel diode because if you have a lagging power factor then what happens then 1 voltage is positive then current also be negative, then also this actually the anti-parallel diode comes into the picture.

Ultimately, so in this kind of application you have to provide this kind of anti-parallel diode and that makes it the configuration asymmetric; asymmetrical IGCT can be fabricated with the reverse conducting that that is what I was saying in the same package and it is known as RC-IGCT and you can have a very fast recovery diode that is an advantage because it does not have a body diode unlike MOSFETs.

And so you can choose a very high conducting and high featured anti-parallel diode depending on the kind of switching frequency you are using.

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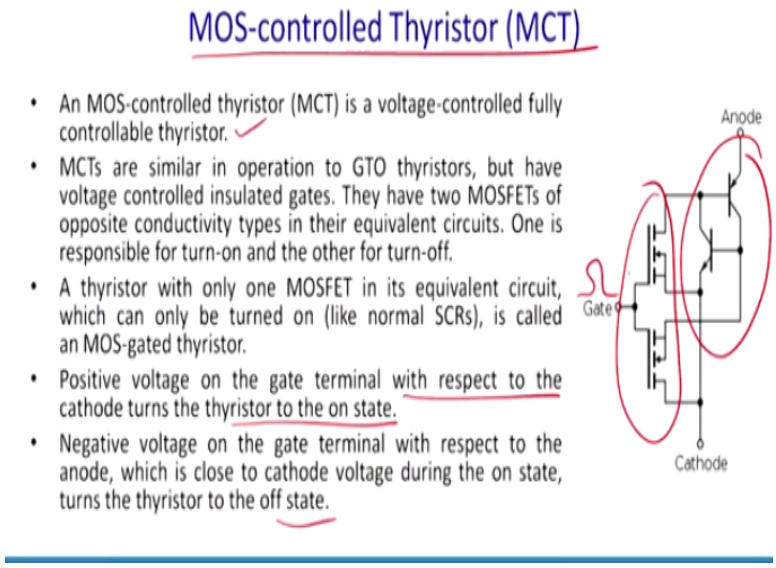

Now, this is the structures of the MOS controlled thyristors, this is another member of the thyristors that is called MOS controlled, the only difference you know is that you have this gate driver part has been modified by using that 2 MOSFETs and MOS control thyristors is a voltage controlled, fully controlled thyristors, it can turn it on and turn it off by this MOS devices.

But power rating and power handling capability of is very low compared to the IGCT because it is basically, it comes from the gate driver power is really MOSFET, so power handling capability is quite low. MCTs are similar in operation as GTO but have a voltage controlled insulated gate, they have 2 MOSFETs opposite conducting types in their equivalent circuit, one is responsible for turn-on mostly the upper one and other is responsible for the turning off.

So, positive voltage on the gate terminal with respect to the cathode turns the thyristors on the on state and a negative voltage on the gate terminal with respect to the anode which is close to the cathode voltage during the off state transits thyristors on, so we will operate at a gate voltage since this is an insulated gate, very low amount of current will flow thus power dissipation in GTO is a big concern and that aspect has been considerably reduced.

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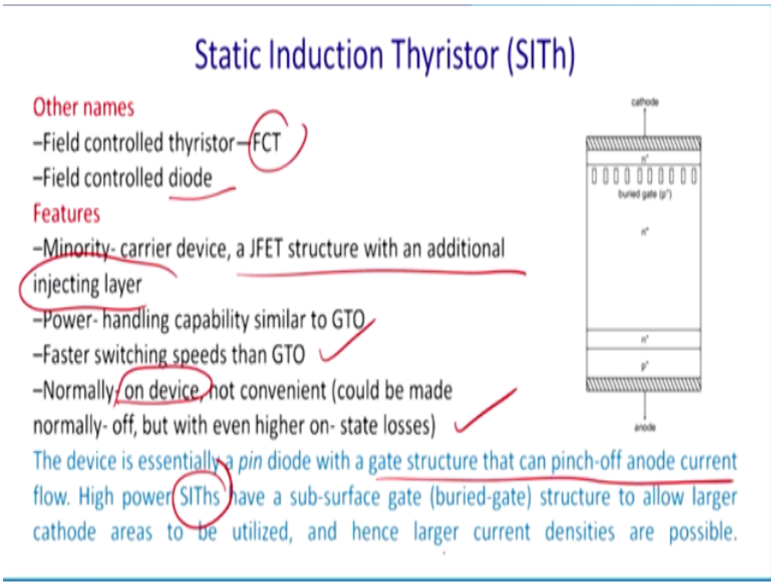

But problem lies you know actually its power handling capability is quite low, so another members of the thyristor is called static induction thyristors, so there actually it is field controlled thyristors or FCT or field controlled diode and it has a features like the minority carrier device, a JFET structures with an additional injecting layer is been provided by the method of induction.

Power handling capability is similar to the GTO, faster switching speeds than GTO, this can be actually these are the few add on now comes into the pictures in GTOs normally, on device and problem is it is normally on, so you have to have a normally off by applying the gate voltages by method of induction. Non convenient and could be normally off but even for the higher on state losses.

So, this is one problem you can; do you want the switches to be normally off, when a switch became normally on, this is a disadvantage, so for this system if you can you can make it the switch actually normally off but problem lies then the conduction losses will be considerably higher and the advantage of it will be missed out, this device essentially a pin diode with a gate structure that can pinch off the anode current.

Higher power SITHs have subsurface gate or buried gate structures and allow larger cathode areas to be utilize hence, largest current densities are possible but still you know actually it is not pretty commercially viable and this is not quite available also in normal ratings and that design require, so hopefully these are the development but among this development of course, this IGCT is the forerunner and hopefully this device will catch up in different kind of power electronics applications, okay.

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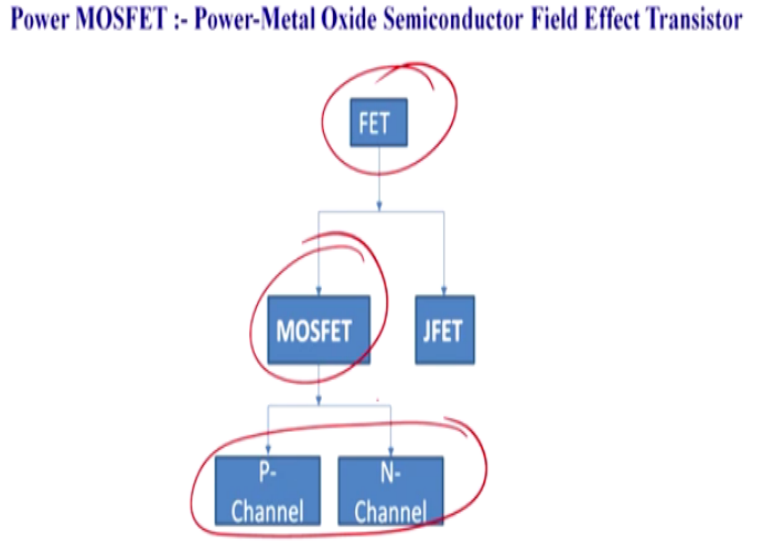

Now, let us come across power metal-oxide semiconductor field effect transistors, so that is FET, you have studied FET in the linear electronics or the low power electronics, it is same thing but you will find that actually power rating is at least 100 or 1000 times higher. FET can be operated at a very high switching frequency and has very low losses, gate losses, so these are the 2 actually the features.

And for this reason actually, we have a MOSFET and from there, we have a this P channel and the N channel MOSFET, these are the very frequently used in low power electronics devices mostly in DC to DC converter for its compact size and high frequency applications.

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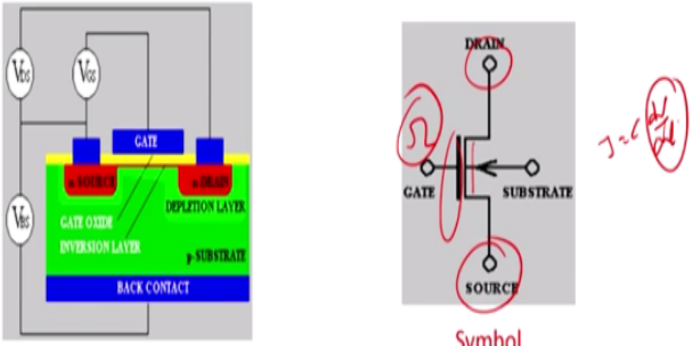
MOSFET Device Physics



Structure

Symbol

So, this is the structures of the MOSFET, we have actually VDS that is tend to source voltage and we call drain and the source generally high voltage site is said to be the drain and other site is said to be the source and we have GS that is a connected between this actually source and the gate and what happened you know actually this is called drain and this is called source, then it can be actually different kind of MOSFET that is enhancement MOSFET, depletion MOSFETs.

Whenever you have giving a pulses, so there will be an induction and generally it has a silicon dioxide or any kind of insulating medium, there will be a capacity effect and due to the induction, there will be a charge carrier, then the channel will be form and with this channel current will flow, so essentially so it is insulated, current flowing through areas would be quite low but since there is a capacitor so, I = c dv/dt.

So, ultimately whatever will be the gate pulses frequency in to c that will be the amount of the I but since value of the c is quite low; this current also will be quite low, so you allow to go to the higher frequencies.

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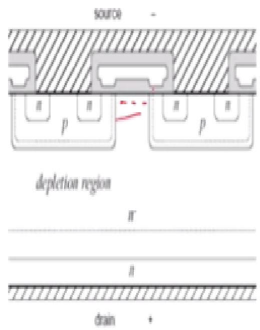
MOSFET Device Physics (Cont...)

Off-State:

- p-n⁻ junction is reverse biased
- Off-state voltage appears across n⁻ region.



So, this is the one of the layer, so this is actually the p-n junction reverse biased and off state voltage appears across the n region, so channel required to be formed because this is the channel is broken, once we apply a voltage there will be a channel form, so that will actually they carry the current and this is called normally off kind of MOSFET and this is we generally prefer.

An n channel MOSFET since the conduction devices or electron, so channels is made of electrons, this is quite faster than the p-channel devices, so most of the application we prefer n-channel MOSFET were the pre channels MOSFETs but in few application, we avoiding short circuit conditions, the combination of N and P MOSFETs are used, so that once upper thyristors is on, lower thyristors is automatically on and have negative gate voltage and vice-versa.

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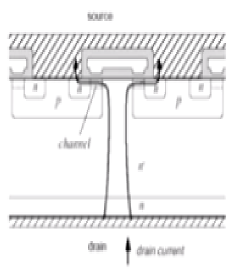
MOSFET Device Physics (Cont...)

On-State:

- Here p-n⁻ junction is slightly reverse biased
- Conducting channel is induced by positive gate voltage.
- Drain current flows through n⁻ region and conducting channel.
- Total on resistance includes resistance of n⁻ region, conducting channel, source and drain contacts.



So, in that case we use p channel but you have to sacrifice on the switching frequencies, so these are the few takeaways from here, the p-n junctions is slightly reverse biased, conducting channel is used to be conducting channel is induced by the positive gate voltage in case of the n channel MOSFET, drain current flows through the n region of the conducting channel, total resistance includes the resistance of the n region and the conducting channel and the source channel.

But amount but doping is so high that you know the resistance of this devices is quite low in the ranges of the merely (()) (17:04) region.

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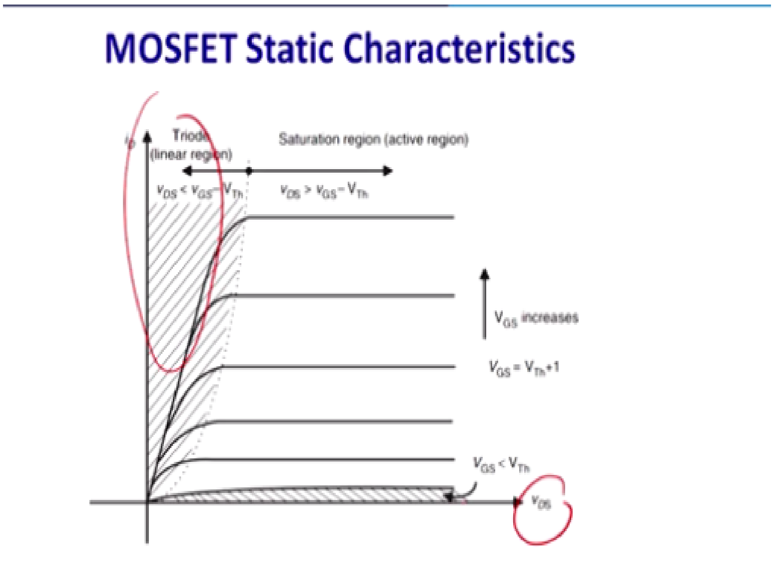

So, this is a typical characteristics of the MOSFET which you have studied into the analog electronics, so this is actually drain to source voltage and these are the different actually gate voltage, so ultimately this region is basically the saturation region so and this region is an active region, we want and this region is a cut off region where actually gate voltage is quite low and we want basically to operate our devices in the active region.

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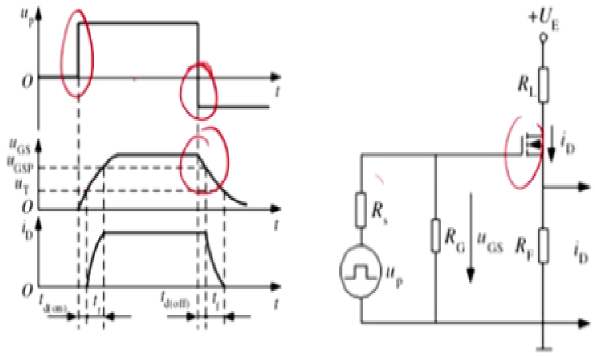
MOSFET Switching Characteristics



So, this is a switching characteristics of this MOSFET, so you turn it on thereafter since there is a capacitor effect, there will be a RG, there will be actually RS and so it will actually charge these things, so voltage will build up across this gate and gradually what will happen, then current also will try to flow from this, so there will be a TD as a delay time where actually this UP is a pulse and this is basically the voltage across this driver.

So, it will take some time to grow once it reaches 10% of it, then you will see that actually currents start picking up, once actually gate current reaches the 90% of it, then you will find that it almost reaches the total current and gate current will saturate here, there after at this point you decided to turn it off, so for this reason, what will happen you know it will gradually fall and you have to give little bit of negative voltage to turn it off and to take out the charges in the TAF region to make it off.

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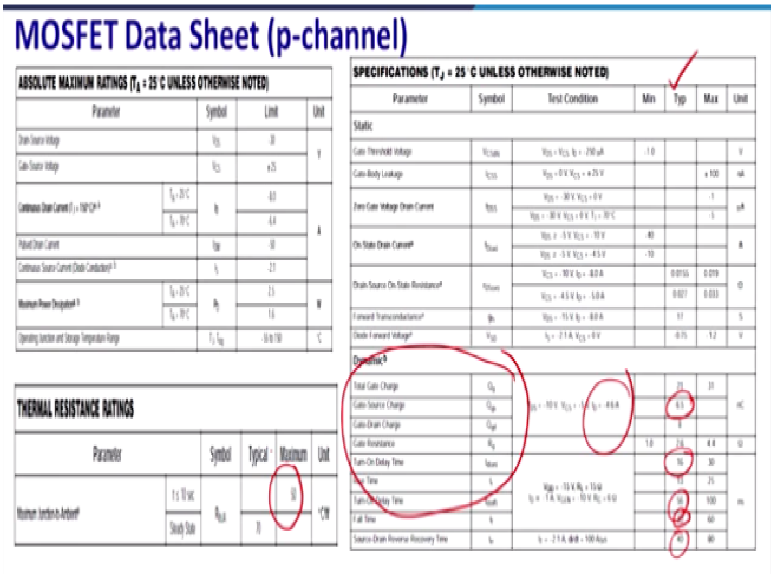

So, you required to have a little bipolar of the supply, so this is one of the MOSFETs datasheets which is frequently been used, this is the data sheet of the p-channel MOSFETs, so what is important here you know mostly few aspects, this is basically the gate characteristics, it is a gate to source charge, so depending on this actually your driver if you are pulse sinking capability of this driver, let us say some ampere, 0.5 ampere or 1 ampere then this has to be filled.

So that kind of switching frequency you can go similarly, you will have a drain to source and if you divide it by voltage you get the capacitance, your data sheet also specifies the capacitance, you see that a turn on delay which you have find it here turn on delay, so this delay is essentially will be actually in the range of 15 to 30 nanoseconds, so it can easily can be operated in the range of the megahertz level.

Similarly, rise time it is this thereafter you got this is a typical values, so we will take this column only and they are to turn off delay is around 56 nanosecond and this will be 36 nanoseconds and recovery time is around 40 nanosecond, so these time what we have talking in the case of the microseconds, now it is nano seconds, so thus it can be used for the high switching frequency kind of application.

However, what is the difference between that; the current handling capability of these devices are quite low, it is just -4.6 ampere and you know also there are few aspects then you know gate threshold voltage required to be you know of this region and apart from that you require basically to be operated in the range of the 70 volt quite less than the other voltage.

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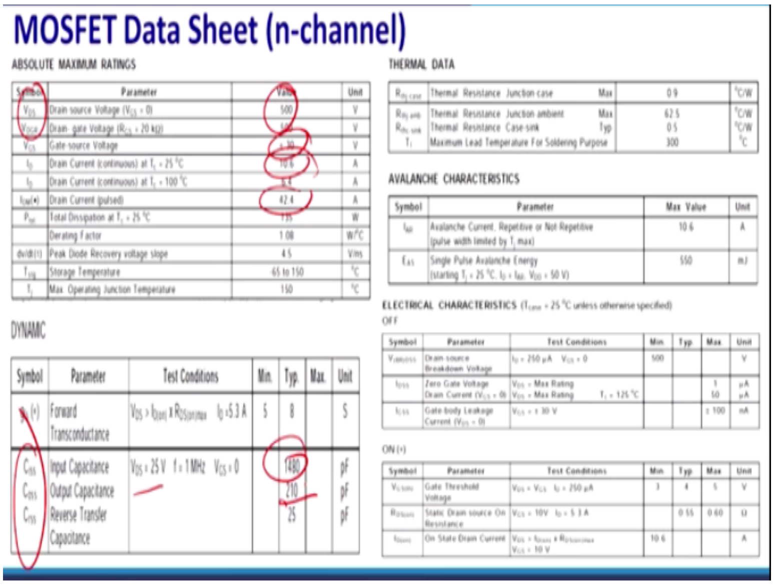

So, VDS can be 500 volt but where we are talking about 1000 volts and more than that so, drain to source voltage will be this and VGS voltage source will be +-30 and ID for 25 degree centigrade, it can be around 10.6 ampere, so for the 100 degree centigrade, it has to be derated, so it has to be this much and 10 current, if it is pulse kind of waveform, so it can be as high as a 42 amperes and these are the data sheets you have to design, we will show it how to design.

And this is the values of the different capacitance, so this is for 1 kilo hertz and VGS = 0 and VDS = 25, these are the value will come out input capacitance will come into the picture, this is basically the CGS will generally is presents input capacitance, so that will be around 1480, output capacitance is this much generally, it is close to the same values of the DS but we have to draw the actual circuits.

And the reverse transfer capacitance is around this much, so these are the actually the data sheets of a MOSFETs and from there you require to design one circuit where it finds this application mostly, since for this high voltage frequency application and low power rating, low voltage setting also, it finds its application mostly in DC to DC converter.

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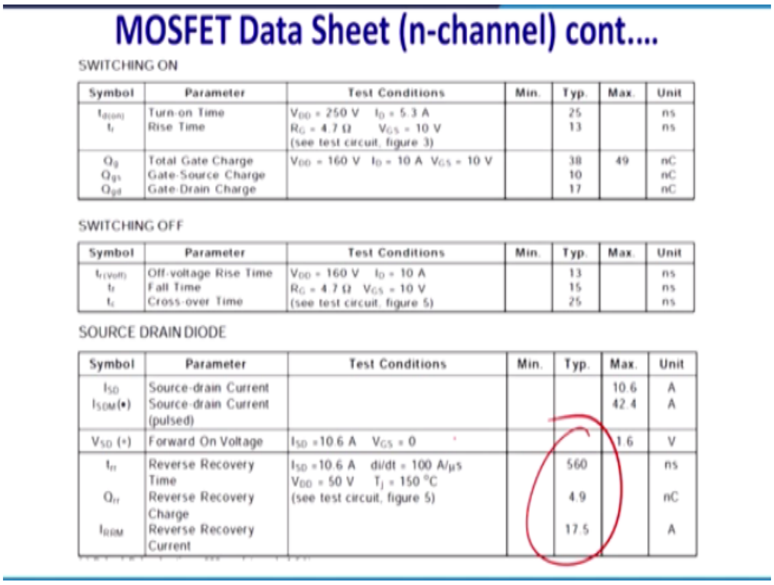

MOSFET Data Sheet (n-channel) cont....

SWITCHING ON

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
$t_{d(on)}$ t_r	Turn-on Time Rise Time	V_{DD} = 250 V I_D = 5.3 A R_G = 4.7 Ω V_{GS} = 10 V (see test circuit, figure 3)		25 13		ns ns
Q_g Q_{gs} Q_{gd}	Total Gate Charge Gate-Source Charge Gate-Drain Charge	V_{DD} = 160 V I_D = 10 A V_{GS} = 10 V		38 10 17	49	nC nC nC

SWITCHING OFF

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
$t_{r(Voff)}$ t_f t_c	Off-voltage Rise Time Fall Time Cross-over Time	V_{DD} = 160 V I_D = 10 A R_G = 4.7 Ω V_{GS} = 10 V (see test circuit, figure 5)		13 15 25		ns ns ns

SOURCE DRAIN DIODE

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
I_{SD} I_{SDM}(•)	Source-drain Current Source-drain Current (pulsed)				10.6 42.4	A A
V_{SD} (•)	Forward On Voltage	I_{SD} = 10.6 A V_{GS} = 0			1.6	V
t_{rr} Q_{rr} I_{RRM}	Reverse Recovery Time Reverse Recovery Charge Reverse Recovery Current	I_{SD} = 10.6 A di/dt = 100 A/μs V_{DD} = 50 V T_j = 150 °C (see test circuit, figure 5)		560 4.9 17.5		ns nC A

Now, you can see these are the turn on time are in the micro; and in nanoseconds, so QR so this is the values you know these values also in microsecond and for this reason, this devices can be operated in a very fast mode.

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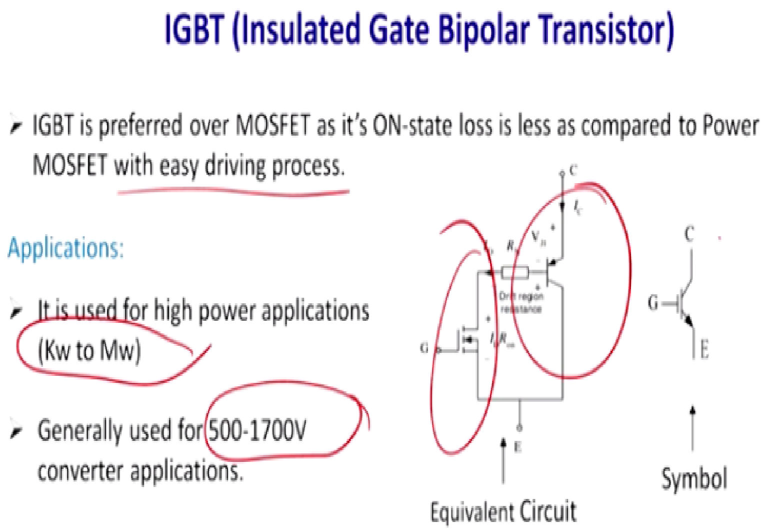

Now, let us come to the another important member of this power electronics that is insulated gate bipolar transistors, this invention itself is a mark of the change of the face of the power electronics, so Dr. Baliga, actually in G, General Electric discovered it and we are Indian, so we should be proud of his discovery, IGBT is preferred over the MOSFET because of its on state loss as compared to the MOSFET with a very easy driving process.

But you know actually, we have seen a very short lived another device which shall; for this we have not discussed, it has been actually discarded that is BJT, power BJT because of the high current it has been put off, so Professor. Baliga actually integrated the power BJT and the MOSFET and came out a new device called insulated gate bipolar transistors, so it can handle the power of kilowatt to the even it is possible to have a megawatt level.

Generally, we ranges, varies and we are very frequently used for our day to day application in a kilowatt level and it is arranged in this kind of application that is mostly for the medium voltage drains applications and all the invention and the development of the topology were based on these devices, so multi-level inverter and all those things for high voltage applications was considering this IGBT.

So, it is very important member of it, what happen here actually it come; it is this part is essentially the MOSFET, the gate part is MOSFET and this part is I, it is basically the transistors and for this is the symbol is this.

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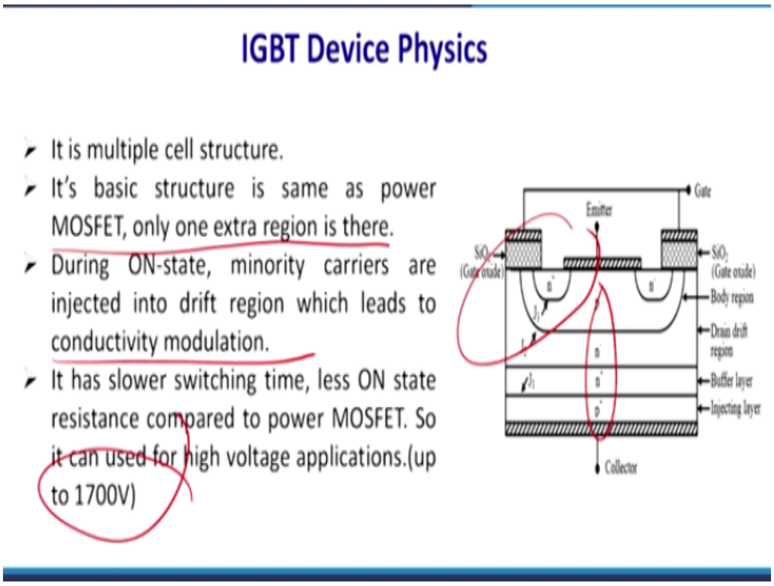

So, in between you definitely get a transistors that is PNP and in between you also will get a MOSFET, so this part is a transistor and this part essentially is the MOSFET, it has a multi cell structures, so it is combinations of the MOSFETs and the BJT, the basic structure is same as power MOSFET only one extra region is there during on state, minority carrier are injected into the drift region which leads to the conductivity modulation that mean conductivity increases.

It has slower switching time less on state resistance compared to the power MOSFET and so it can have a higher power handling capability, so it can be used for the high voltage applications up to 700 or 2000 volt.

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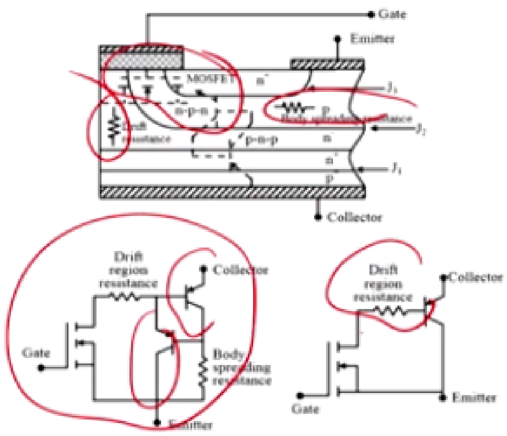
IGBT Device Physics (Cont…)



Parasitic Thyristor in an IGBT cell

And this is basically, the MOSFET part of it and this is basically the transistor part of it and this is the drift region, so this is the MOSFET part of it and PNP constitute this basically the transistors and so this is the model and body spreading resistance is there, so this is the body spreading resistance, what happened you know that will handle gives you a forward blocking capability.

So, for this it can be used for the high voltage applications and this is the drift region resistance, this is basically the diffusion resistance, so by changing the value of the resistance you can operate faster or slower but what happened then if you have a lower drift region resistance, you will find that power handling capability of the device is considerably reduced.

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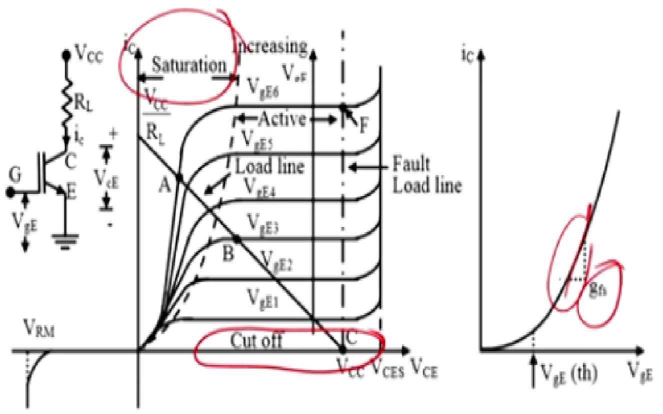
IGBT Static Characteristics



Output Characteristics

Transfer Characteristics

This characteristics same as the characteristics of the BJT which you have studied in the normal BJT applications in your analog electronics, so this is your load line and this is the IC and VC and this is for the different kind of instead of IB, you will have the gate voltage, this is the only change, so you will have this trans conductance, so for this is, this is the actually power line and accordingly, you will have a VG which is for the current IC for the different values of VG.

And this region is a saturation region, then generally we do not operate this devices into the saturation region, then gate resistance is control, we try to actually maintain into the active region and this is the cut off region as same as from the BJT, so we required to find it out actually linear region of it, so that is the this part is almost linear, so for this reason this is the transconductance, we try to incorporate and this will be the values of the IC versus GE.

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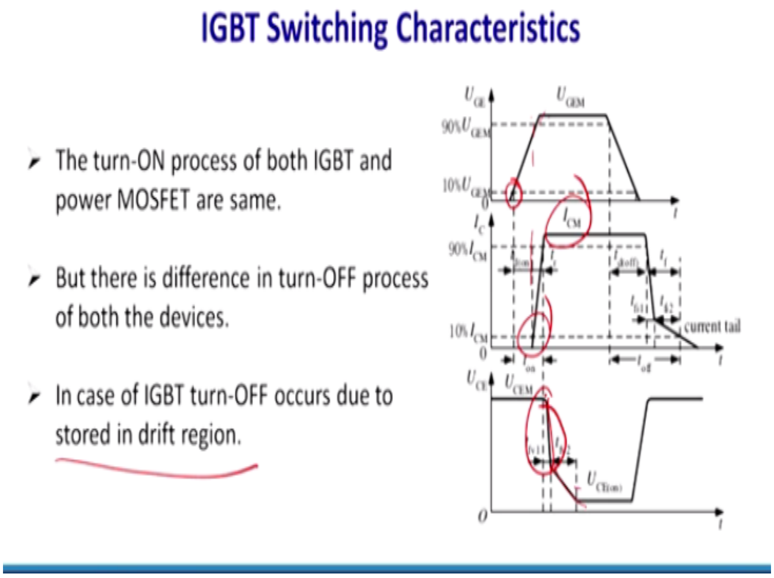

Now, this characteristics is same, you give a pulse, once you give a pulse, when it is actually this is the till you will find that when actually this applied pulses has come to the 10% of the value gate pulses, then everything will start, once it almost reaches 90% of the value then you will find that actually current through these devices will go to the only 10% of this device and same way also you will find that voltage will start topping from this point.

Once it reaches the 90% of the value, you will have a double slope characteristics, this is called bunch of devices, so it will fall this much, thereafter in remaining time it reaches the maximum value of the current so and it will have a different slope, so it is a doubles of characteristics, so this IGBT has a unique features, all the device had a single sub turn on process but IGBT has a double slope turn on process.

So but there is a difference between the both the devices in case of the IGBT, turn off occurs due to the stored in drift region, so for this is reason, what happened; in this region you know it will (()) (30:14) there after once it reaches only 10% of it then voltage will drop and will settle down to the on state voltage and from there we try to measure that you know whether it is go into the active region, we do not allow this actually, this IGBT to go to the saturation region.

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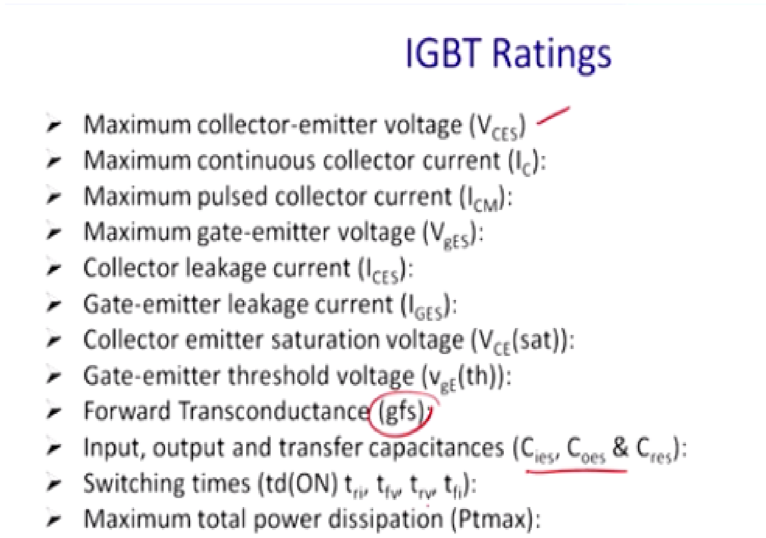

Then short circuit condition will prevail, so these are the few important aspect of the IGBT; maximum collector to the emitter voltage is said to be the VCS, maximum continuous collector current is IC that we will see in the datasheet, maximum pulsed collector current is ICM, maximum gate emitter voltage is VGS, collector leakage current in on state is actually ICS, gate emitter leakage current IGES.

Collector emitter saturation voltage is VC sat, gate emitter threshold voltage, these are the important parameters of Vg th, there is a terminal equivalent of it, forward transconductance GS which we have shown in the graph, input output transfer capacitance as we have seen in a MOSFET datasheet in ICS, OS and IRS, switching time that is rise time, fall time, reverse time and for the different mode. Maximum total power dissipation Pt max, so what are the difference of the MOSFETs and the IGBT.

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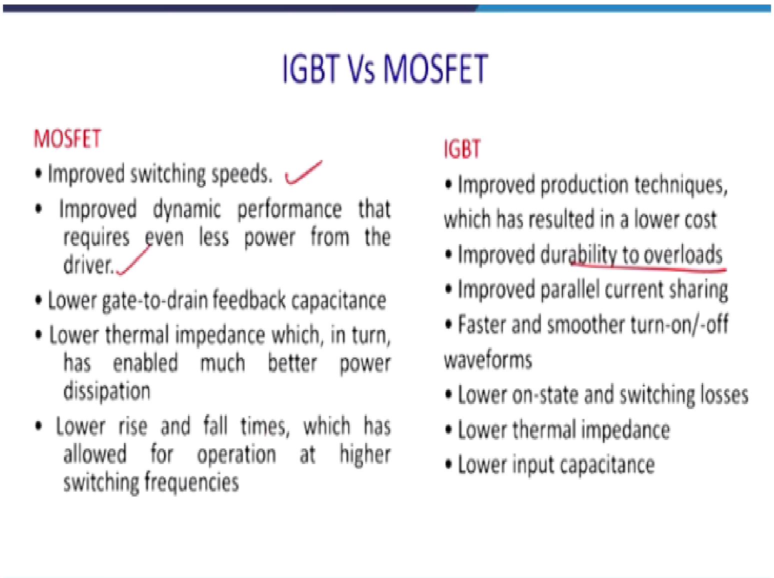

MOSFET is applicable for the high frequency applications, so improve switching speed but in case of the IGBT, we have an improved production technique that leads to optimal switching frequency not as high as that MOSFETs but it has got a higher current and a voltage handling capability. Improve dynamic performance that requires even less power from the driver, so we have optimized basically the efficiency energy point of view this MOSFETs.

Improved due to the overload for higher loading and all, lower gate to drain feedback capacitance improve parallel current sharing capability, so if you use the current handling capability of this driver to be increased, so you can put into the operation these parallel devices, lower thermal impedance in turn has an enable much better power dissipation, faster and smooth turn on and turn away form we have seen there is a punch through.

So, the 2; two while turn on there is a voltage drops in a two curves that leads to you know better mode of control of the short circuit protection, lower rise and fall time which has allowed for the operation of the high switching frequency, so lower on state switching losses, thermal impedance is quite low and lower input capacitance, so that you can put this faster operation, if it is a higher capacitance, so ultimately you require more current or the less frequency.

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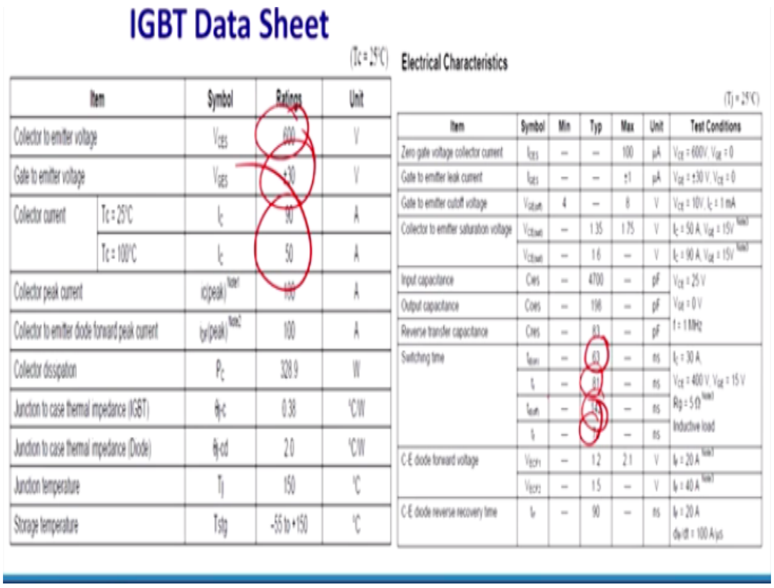

IGBT Data Sheet

(Tc = 25°C)

Item		Symbol	Ratings	Unit
Collector to emitter voltage		V_{CES}	600	V
Gate to emitter voltage		V_{GES}	±30	V
Collector current	Tc = 25°C	I_C	90	A
	Tc = 100°C	I_C	50	A
Collector peak current		$i_C(peak)$ Note1	100	A
Collector to emitter diode forward peak current		$i_{DF}(peak)$ Note2	100	A
Collector dissipation		P_C	328.9	W
Junction to case thermal impedance (IGBT)		θ_{j-c}	0.38	°C/W
Junction to case thermal impedance (Diode)		θ_{j-cd}	2.0	°C/W
Junction temperature		T_j	150	°C
Storage temperature		Tstg	-55 to +150	°C

Electrical Characteristics

(Tj = 25°C)

Item	Symbol	Min	Typ	Max	Unit	Test Conditions
Zero gate voltage collector current	I_{CES}	–	–	100	μA	V_{CE} = 600V, V_{GE} = 0
Gate to emitter leak current	I_{GES}	–	–	±1	μA	V_{GE} = ±30 V, V_{CE} = 0
Gate to emitter cutoff voltage	$V_{GE(off)}$	4	–	8	V	V_{CE} = 10V, I_C = 1 mA
Collector to emitter saturation voltage	$V_{CE(sat)}$	–	1.35	1.75	V	I_C = 50 A, V_{GE} = 15V Note3
	$V_{CE(sat)}$	–	1.6	–	V	I_C = 90 A, V_{GE} = 15V Note3
Input capacitance	Cies	–	4700	–	pF	V_{CE} = 25 V, V_{GE} = 0 V, f = 1 MHz
Output capacitance	Coes	–	198	–	pF	
Reverse transfer capacitance	Cres	–	83	–	pF	
Switching time	$t_{d(on)}$	–	63	–	ns	I_C = 30 A, V_{CC} = 400 V, V_{GE} = 15 V, Rg = 5 Ω Note3, Inductive load
	t_r	–	81	–	ns	
	$t_{d(off)}$	–	[illegible]	–	ns	
	t_f	–	[illegible]	–	ns	
C-E diode forward voltage	V_{ECF1}	–	1.2	2.1	V	I_F = 20 A Note3
	V_{ECF2}	–	1.5	–	V	I_F = 40 A Note3
C-E diode reverse recovery time	t_{rr}	–	90	–	ns	I_F = 20 A, di/dt = 100 A/μs

So, this is the one of the data sheets of the IGBT, so this is the rating, this is a quite low rating IGBT because we have try to choose the same rating of the MOSFETs, so close to that rating we have chosen an IGBT, so for this is it is 600 volt but you can see that current rating there was only around 10 ampere, it can go actually as high as 90 ampere, so the huge actually improvement on the current rating part of it.

And these are the few parameters that is T on, it was quite high it was around 10 or 15 in case of this, this is a double but anyway so but current is also double, so you have to this is TR is around 81, TD is 142, TAV is a actually around 74, so these are the all the datas, thank you for your attention we have complete our discussions on the device physics part and in next class, we shall analyse the devices.

And we shall discuss about the gate drive and little protections part of it and thereafter we shall start with the normal topology, thank you for your attention.