Design of Power Electronic Converters
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Lecture:18
IGBT

Welcome to the course and design of power electronic converters. So, we were in the module on power semiconductor devices. And prior to this we had discussed diodes and also MOSFETs. Now, another important semiconductor device which is widely used in power electronic converters is IGBTs. So, now, we will be looking into IGBTs.

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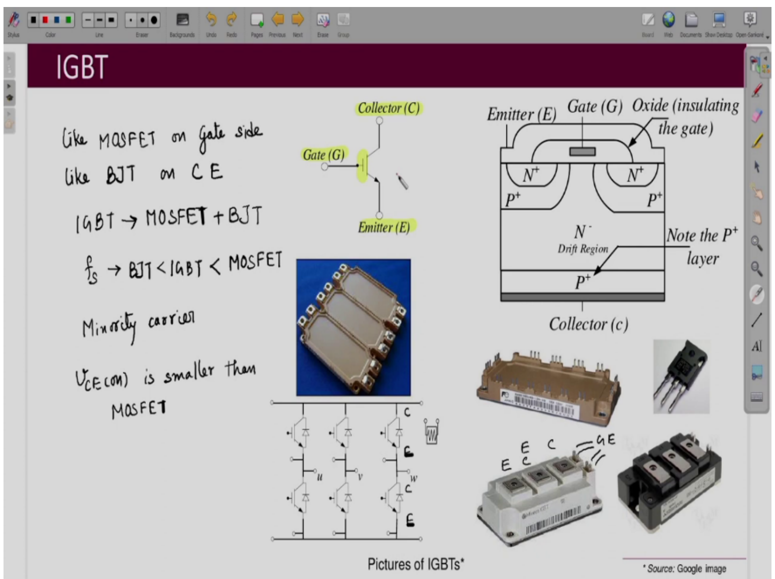

This is the symbol of IGBT you might be already familiar with, this is like the symbol of BJT but, here you observe that there is another line which is drawn, a BJT has only one line in it and like BJT it has got these collectors and emitters but it does not have the base but like MOSFET it also has the gate and this is the physical structure of the IGBT, it consists of this n plus region which is connected to emitter and then in between it has the p plus region and then further it has the n minus drift region and then p plus region.

And that is connected to collector and over here on the gate side it also has that oxide layer and it is similar to the MOSFET. So, now, what we observe from here is that, it is like MOSFET on the gate side. And on this collected emitter side it is like the BJT. So, IGBT is actually a combination of MOSFET and BJT you can say like that so, because of it, what happens is that switching frequency f_s for IGBT this is greater than BJT, it is greater than BJT but is less than MOSFET.

And that is the reason IGBT became very popular, because people earlier either used to use silicone BJTs the problem that used to happen was that the switching frequencies were not very high. Whereas BJTs they can carry a lot of current or their power levels that they can withstand, it used to be much higher for power BJTs.

But for MOSFETs, on the other hand, the power handling capacity was much lesser because they were majority carried devices. And because of being majority carried devices the $R_{DS(on)}$ used to be very high and so, power level for which they can be used became limited. And switching frequencies for all the MOSFETs are very high but power BGTs they could be used for much higher power levels, but their switching frequencies were not so high and moreover they are current controlled devices.

So that I mean the control is little bit more involved in case of BJT whereas MOSFET controlling was much simpler because it was voltage control device. So, this IGBT is turned out to be in between BJT and MOSFET. It could be switched to higher than BJTs lesser than MOSFET and power handling capacities were also somewhere between MOSFET and BJT. Lower than power BJT they can handle but higher than MOSFETs they can handle and that is why IGBTs became very popular and is used a lot in medium power applications especially for DC to AC applications.

So, as I told you another important thing that you should remember is that minority carriers also participate in the conduction through IGBT and that lowers the on-state voltage drop in IGBT. So, collector to emitter on state voltage drop is smaller than MOSFET. Now, these are some of the pictures of IGBT, this is a discrete IGBT you can see the three legs that are there collector emitter and the gate. And then IGBTs are also available in the integrated module form.

So, this is one leg of an IGBT this is by Infineon and this is also two IGBTs together this is another module and these are those three terminals like this over here three terminals that you can see and there you have these two gate emitter terminals as well.

So, these are gate and emitter terminals for two of those IGBTs and this is collector emitter for one of them and the collector emitter for other one. So, those are the ones that you can see here collector emitter, collector and this is another emitter like that. Further what is possible to do is that having one entire inverter a three-phase inverter can be there inside one module and that is what this picture is showing, this is one integrated module having six IGBTs and six anti-parallel diodes inside it.

And this is a picture of an IGBT module of this three-phase inverter only, but of further higher current levels, So, that is why you see that this is bigger than this module. And one more thing that you should remember is that in case of MOSFETs, we said that there is a body diode and so MOSFET without doing any additional connection, they are able to carry the current in the opposite direction. But in case of IGBTs it is not so, so what people do is that they connect an additional anti-parallel diode and that is what is shown here this additional anti-parallel diode is shown here which is connected over here between the collector and emitter.

So, this is something you have to do additionally and most of the manufacturers if they are making IGBT so, with anti-parallel diodes and they will be also providing you the characteristics of the diode and there are IGBTs also made without anti-parallel diodes although they are a little less in use because most of the power electronic circuits that we see they have the anti-parallel diode requirement with the IGBT. So, that is how most of them are manufactured. So, that is why it is important to look into the datasheet whether the anti-parallel diode is provided by the manufacturer or not, or is it just a simple IGBT.

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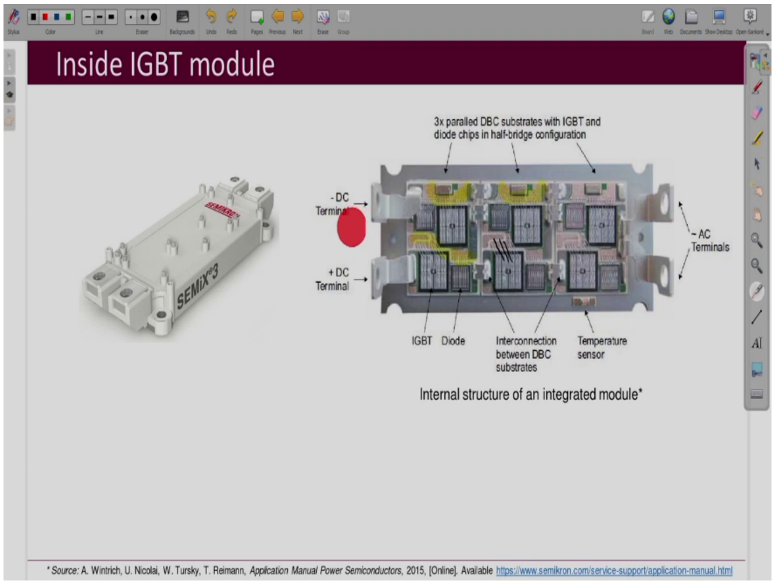

Then I wanted to show you what is inside these modules. How do they look inside if you happen to open those integrated modules. So, this is the module by Semicron. This is Semix-3 that is how they have named it and you can see here these are two big terminals coming out here on this side, they have provided. How does it look inside? So here you can see that these are those six chips of the IGBTs that are provided and also, six of these diode chips that are also given, this is for IGBT and this is for the diode.

And then it is like a small PCB inside the module there all these connections are formed here you can see all these copper traces over here. So, like a PCB inside and then you can also see these bond wires that also you can see interconnecting wires are there inside them. So, they will have their own inductances associated with it and then further this is DC terminals that are given on this side and this AC terminals which are brought on the other side.

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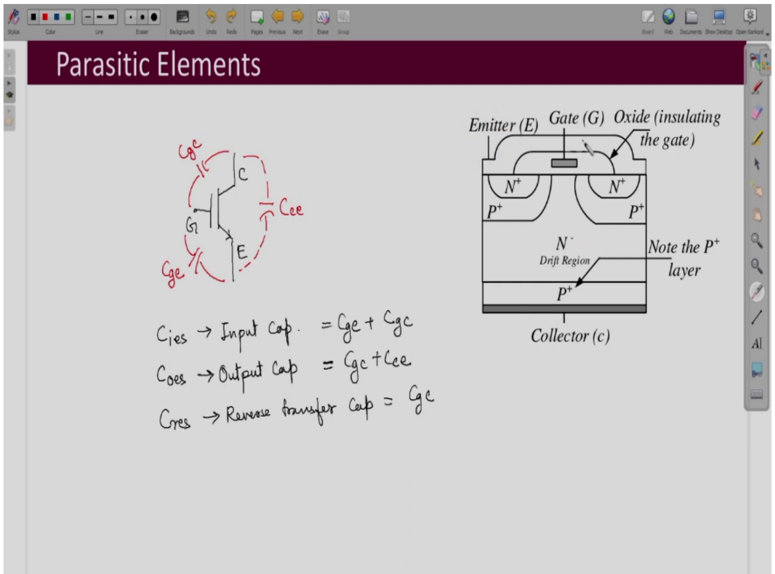

Now, what are the important parasitic elements associated with IGBTs we will be discussing only the important ones. So, this is IGBT and this is collector, emitter and gate terminal and then you have capacitances associated here between the collector and emitter which you can call it a C_{ce} and there is capacitance between these two which is gate to collector capacitance, C_{gc} and then there is capacitance between gate and emitter which is C_{ge}.

So, this is similar to what we had seen in case of MOSFET also. So, the turn on and turn off characteristics of IGBT is very similar to MOSFET. So, like over there three capacitances played a role in turning on and turning off.

And similarly, it is in case of IGBTs also. So, here this input capacitance C_{ies}, like in case of MOSFET it is the sum of gate to emitter plus your gate to collector capacitance and output capacitance C_{oes} is sum of gate to collector plus collector to emitter capacitance and then there is this reverse transfer capacitance, which is equal to gate to collector capacitance.

And the origin of this is inside this physical structure in between these different layers you have these three capacitances This is not something any physical capacitance I mean a discrete capacitance which you can see outside the MOSFET these are parasitic capacitances because of this internal physical structure of the MOSFET.

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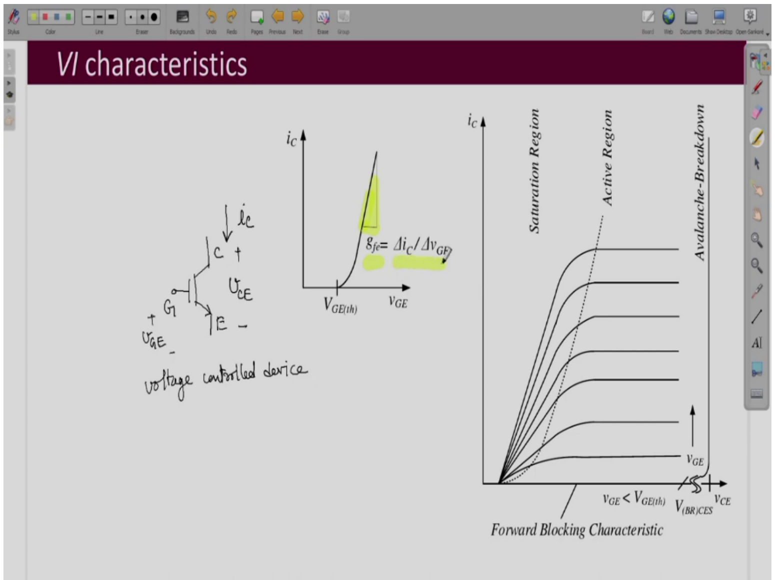

Now, let us look into the VI characteristics. So, this is characteristics between i_C collector current and collector to emitter voltage. So, this is collector to emitter voltage and here this is gate to emitter voltage, which we can apply and this is the current that flows through, the collector current i_C. Now, what we observe here is that as this gate to emitter voltage increases and it becomes above the threshold voltage then the IGBT starts to conduct and after some time this current, this collector current becomes constant.

So, this region in which it is happening like this where you can see both the collector to emitter voltage and collector current, they are both high together simultaneously that is called as the active region, this region is active region and below the threshold voltage when gate emitter voltage over here is below the threshold voltage. So, then the IGBT is not carrying any current, it is not conducting and it can block great amount of voltage. So, that is breakdown voltage collector emitter can block voltage which is positive with respect to the emitter.

So, it is in the cutoff state or the forward blocking characteristics you can say that and then if that voltage becomes greater than the breakdown voltage then of course breakdown is going to happen and if we keep on further increasing gate to emitter voltage then a level comes where you can see that the collector current can increase to very high levels and in that case it is going to be only limited by the external circuit, means whatever circuitry which is additional to it which is connected to the IGBT.

So, that region is called as saturation region. So, here this is saturation region, but for that the amount of gate emitter voltage that we have to apply should be sufficient enough. So, from here what we observe is that if we change this V_{GE} then we can make it go from cutoff to active to saturation. So, that is why this is also a voltage control device

And now, let us look into this transfer characteristics. So, this is a graph between gate to emitter voltage and the collector current i_C and as I have explained what you see is that before this threshold voltage is reached for this gate to emitter region there is no current it is in the blocking state it does not carry any current after that this collector current increases, and it increases very sharply. So, there is a slope associated with it. There is this slope and this slope is given by this new transconductance, forward transconductance. So, this is similar to again MOSFET, we also had the same term and this Δi_C by ΔV_{GE}.

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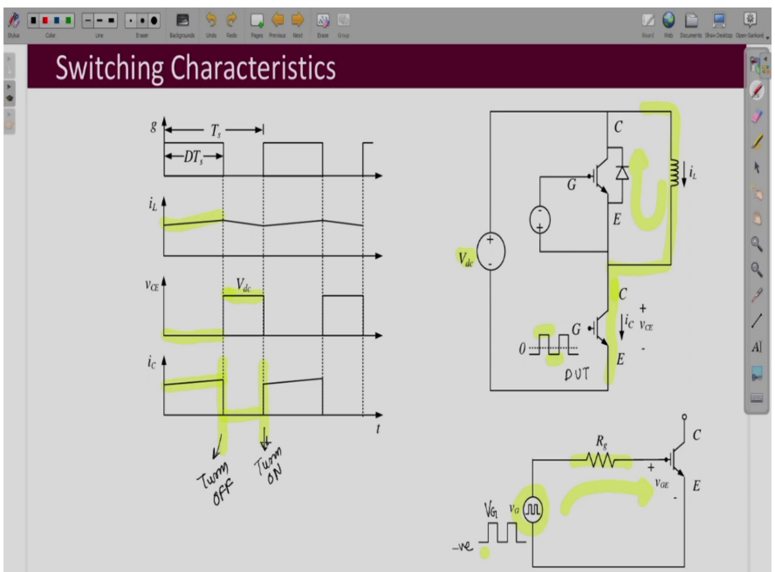

Now, let us look into the switching characteristics of IGBT as I have already told you the switching characteristics of IGBT is very similar to MOSFET and so, the way it is studied is also very similar to MOSFET. So, the circuit that we can use to study the switching characteristics will be like this, you can have this kind of an IGBT with anti-parallel diode and this IGBT can be turned off by applying opposite voltage in the gate to emitter area. So, emitter is made positive with respect to gate. So, this is turned off. So, that means, this is blocking and is not going to conduct.

So, it is only the anti-parallel diode which is what we will be using for studying the switching characteristics of this IGBT, this lower IGBT. So, this is the device under test many times it is also written as your D U T. So, then what happens is that as you provide a gate pulse to it, that means this is the highest state over here as we provide gate pulse to it positive gate pulse then it turns on, it starts to conduct and then current flows through this from here through this inductor and when it is turned off, that means we apply negative voltage between gate and emitter. At that time this current flywheel and flows through this anti-parallel diode.

And what we do here, there is a driver circuit which we can represent like this pulsed voltage source which is giving v_G pulses and the maximum it provides V_G and here let us say some negative voltages also provided. Then in between there is a gate resistor R_g and through that this gate emitter region gates charged and discharged. And this part is gate emitter voltage V_{GE} which we will be seeing. And how it changes as turn on and turn off happens.

And if we see the ideal current and voltage waveforms. So, this is i_L, while the switch is on, it slightly increases, so if it is heavily inductive and at that time ideally collector emitter voltage is 0 and at that time this collector current is equal to i_L and after that as the device is turned off it blocks this voltage V_{DC} and at that time the current is 0.

So, over here is this turn off happening and over here is this turn on happening. So, this is turn on and this is turn off. So, these are the regions that we have to look into to study the switching characteristics.

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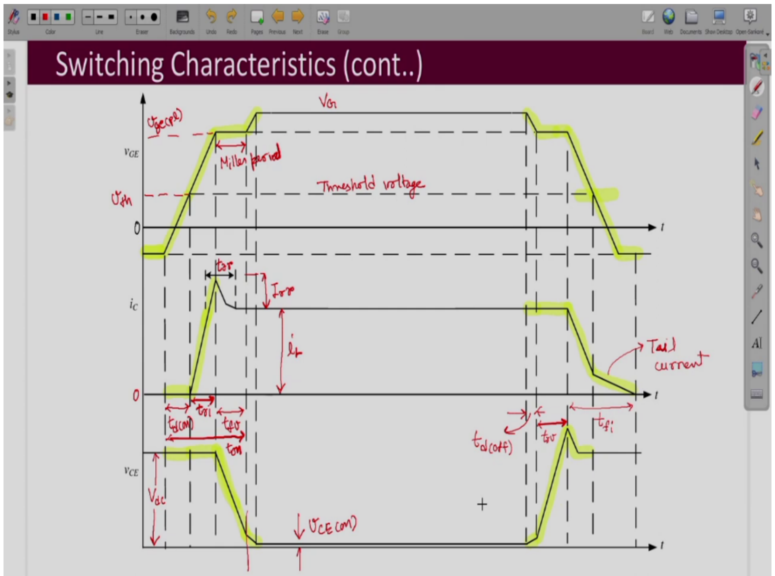

So, let us look into the switching characteristics. So, before turn on a negative voltage is applied in the gate emitter. So, this is 0 over here. So, a negative voltage is applied. Negative voltage is there before the IGBT is given any gate pulse then as it is given gate pulse this negative voltage starts to deduce and then it increases and then it reaches to a certain point while that period what we observe is that this collector current is 0 and this collector emitter voltage is not changing. So, before turn on what is the voltage over here.

So, this is equal to V_{DC}. This is the voltage it is blocking and this current is 0 over here and so, then there is no change. So, this part we can call it as the delay time, so, $t_{d(on)}$ and till here what it reaches is the threshold voltage we call it as V_{th}, so, this is threshold voltage line.

After that what happens is that this current increases and it may actually shoot up it may have an overshoot and during this time this gate to emitter voltage also increases and there is no change in the collector emitter voltage. So, this is associated with the rise in current. So, this we can call it as t_{ri}, rising current and this part IGBT turn on is associated with diode turn off. So, this is reverse recovery time of the diode and this is actually reverse recovery current of the diode.

And this is like how we have seen in case of MOSFET as well. And by this time, it actually reaches this gate to emitter voltage it reaches to the Miller voltage we can call it is so V_{ge_Miller}, it is denoted by several times as $V_{GE(pl)}$ and then after this t_{ri} interval what happens is that this Miller period is there and during this Miller period the gate to emitter voltage does not change. But this $V_{DS(on)}$ this collector to emitter voltage that decreases during this Miller period.

So, this we can name it as the fall time of the voltage t_{fv}, after the Miller period is over what happens whatever is the rest of the voltage the difference between Miller voltage and this voltage V_G which is applied by the driver that this gate to emitter region that makes it over and so over here this reaches to the final on state voltage drop of the IGBT which is $V_{CE(on)}$ you can write it. And here by this time this current has already reached to its steady state or the conduction current which is i_L.

So, now, what we see here is that by this time the device is on. So, this is turn on time, t_{on}. This is then can be written as

$$t_{on} = t_{d(on)} + t_{ri} + t_{fv}$$

So, we saw that, that this is similar to MOSFET how the MOSFET turn on happens now, if we look into the IGBT turn off, then what we see is that that is also similar to MOSFET. First the voltage reaches to the Miller voltage and at that time almost there is no change in the voltage and current.

So, this is $t_{d(off)}$ the delay during the off time and then during the Miller period what happens is that first the voltage builds up and then maybe overshoot because of stray inductances and the current does not change at that time. And then after that from the miller voltage it goes to the threshold voltage and during that time the voltage is almost settled back to V_{DC} the blocking voltage but there is a significant decrease in the current.

Now, in case of MOSFET we had seen that it almost becomes close to leakage current, but here in case of IGBT this does not happen there is some significant current which is left over here and that further goes to the leakage current while this gate to emitter voltage goes from threshold voltage over here to the actual blocking negative voltage, means in the blocking state whatever is the negative voltage we applied to the gate to emitter and this current is tail current.

And this is what makes the turn off process of IGBT slower than that of MOSFET. So, that is why IGBTs switch at lesser frequencies than that of MOSFET because of this tail current and why do we have this tail current because you know that an IGBT is not a majority carrier device, both the types of carriers holes and electrons they both participate in the conduction. So, while it has to be turned off the both have to be removed.

So, this interval is rising interval for the voltage so we can name it as t_{rv} and this the interval for fall in current t_{fi} we can name it like that. So,

$$t_{off} = t_{d(off)} + t_{rv} + t_{fi}$$

So, we saw that switching characteristics of MOSFET and IGBT are similar except for the tail current the IGBT has got a tail current and that is what makes it a slower device than MOSFET.

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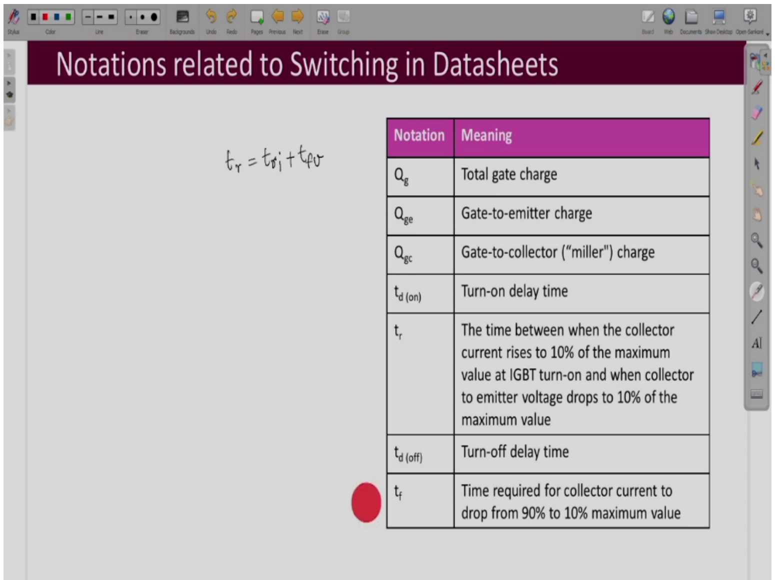

Notation	Meaning
Q_g	Total gate charge
Q_{ge}	Gate-to-emitter charge
Q_{gc}	Gate-to-collector ("miller") charge
$t_{d\,(on)}$	Turn-on delay time
t_r	The time between when the collector current rises to 10% of the maximum value at IGBT turn-on and when collector to emitter voltage drops to 10% of the maximum value
$t_{d\,(off)}$	Turn-off delay time
t_f	Time required for collector current to drop from 90% to 10% maximum value

Next, what are the terms in the data sheets, which are associated with switching gate charge Q_g, then gate to emitter charge, then the Miller charge gate to collector, the turn on delay time, this we just discussed now the rise time t_r. So, this t_r, I have told this before also this is

$$t_r = t_{ri} + t_{fv}$$

Then this is turn off delay and then t_f is associated with the fall of the current during turn off.

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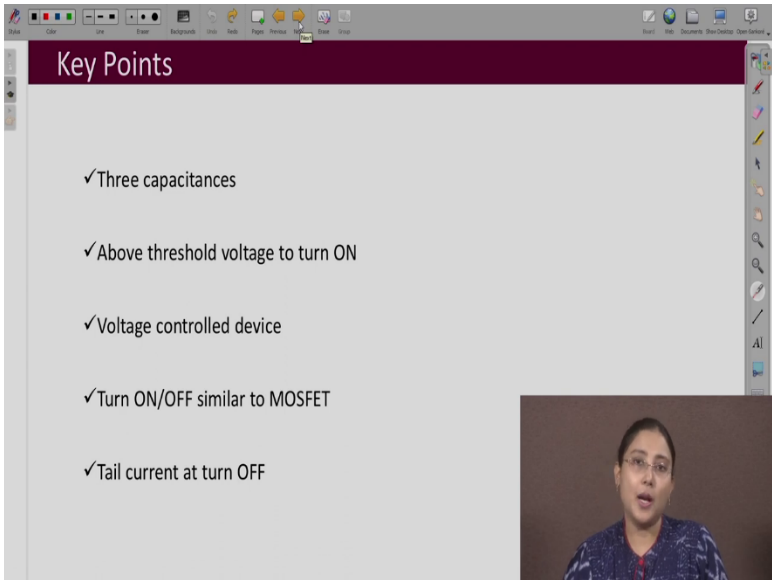

So, what are the key points of this lecture, three parasitic capacitances are important. They play an important role in the turn on and turn off of the IGBT and the voltage, gate to emitter voltage has to be above threshold voltage for it to turn on. And it is a voltage controlled device like MOSFET and turn on and turn off is similar to MOSFET. But there is tail current in IGBT which is not present in MOSFET and which makes IGBT relatively slower device then MOSFET. Thank you.