Power Electronics with Wide Bandgap Devices
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Lecture-1
Introduction: Wide Bandgap Devices

INTRODUCTION WIDE BANDGAP DEVICES

Welcome to the course on power electronics with wide band gap devices. This is the first lecture. In this lecture, I am going to discuss about different types of wide band gap devices. This is introductory class. We will try to understand that how these devices are different from the silicon devices.

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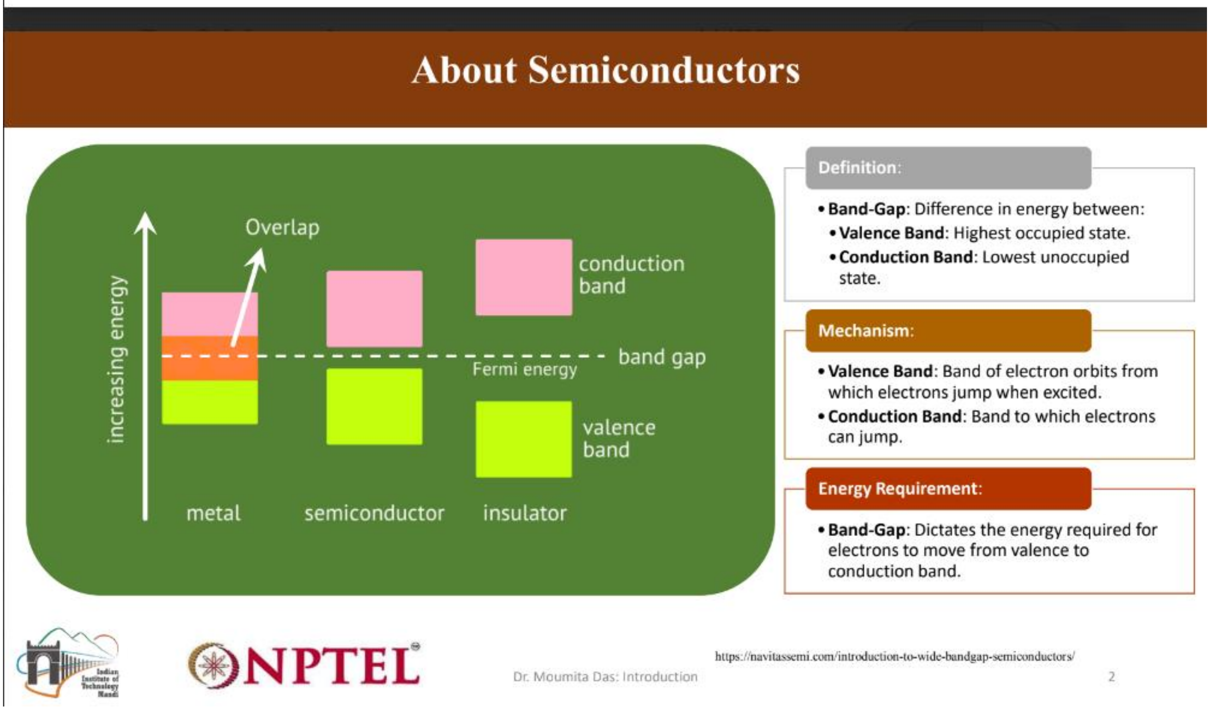

As you can see in the first slide, so here I have given one graph where it is showing the increasing energy with respect to the band gap.

So, the first question in this particular course should come to your mind what is band gap. So, band gap is basically difference or the distance between valence band and conduction band. Now, It can come to your mind or you already know about valence band and conduction band. So, valence band is the band where electrons are occupied at highest level.

Means maximum number of electrons are occupied in valence band. So, if the material is insulator, so then what happens? Then the band gap will be more. that means all the electrons will be occupied in the valence band and there will be none in the conduction band. So, in order to make this particular material to conduct we have to provide highest value of excitation. So, as you can see in the semiconductor, so semiconductor is what? So, it is also one type of material which is having less band gap as compared to the insulator.

So, as you can see here the difference of the insulator band gap and the semiconductor band gap. So, in this particular semiconductor you can see here, so this particular so probably you can see the circle. So, here the band gap is less. So, that means what? So, if we can provide external excitation, so then this semiconductor will be conducting. Now, the third material you can see here metal.

So, here in this case you can see the valence band and the conduction band it is overlapping. That means what? So, it does not need any external excitation to make the material conducting or to bring it to conduction mode we don't have to provide any external excitation. Now we will be dealing with this semiconductor. So semiconductor as you can see here there is some band gap and this band gap is also not constant means with respect to different material this band gap is also variable. Means in insulator it will not conduct as the band gap is very high.

In metal it will be always in conducting state. In case of semiconductor we can make it conduct by providing some external excitation. So you can see here so that this definitions I have written in the right hand side So basically if we can provide some energy which can actually allow the electrons to move from valence band to conduction band, then the material will come to conduction state. So, now in this particular lecture we will be dealing with semiconductors.

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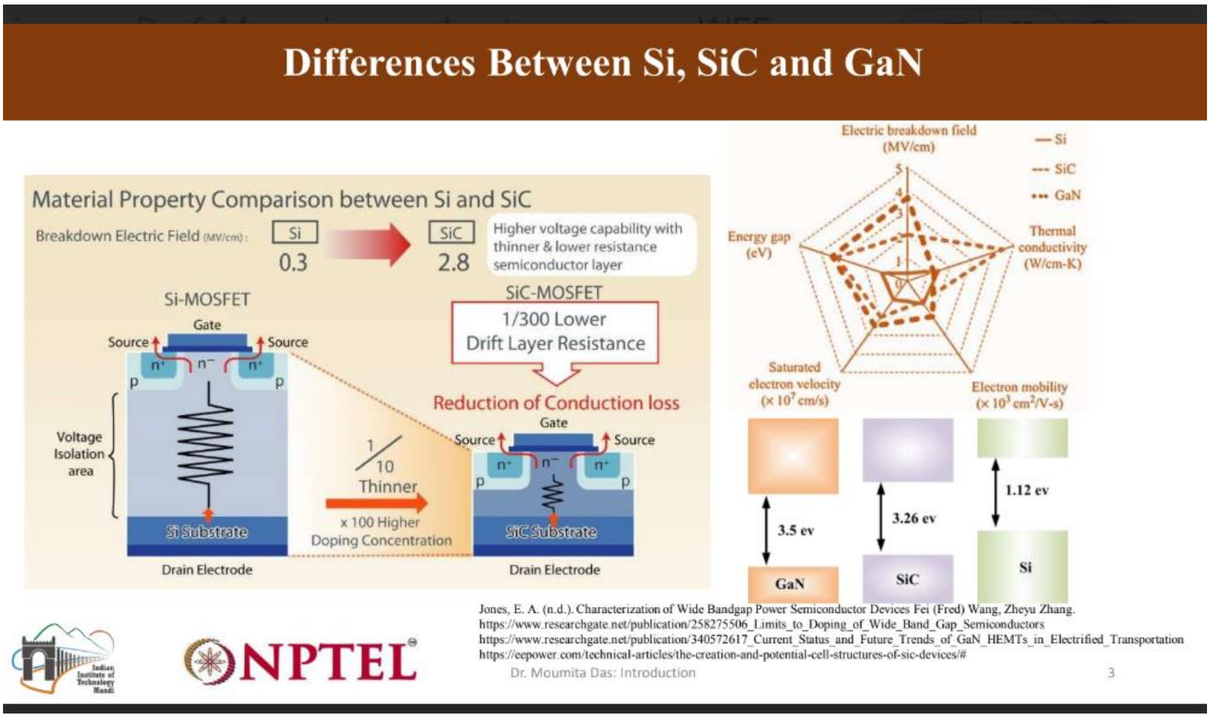

So, mainly I will be discussing about silicon, silicon carbide and gallium nitride.

So some of you probably have heard about this silicon carbide and gallium nitride and they are known as wide band gap devices You can see in this particular graph So I have provided here one graph where the comparison between silicon, silicon carbide and GaN are given So you can see here With respect to the energy gap, so energy gap it is actually shown here the silicon carbide and GAN they are very close to each other. And below this particular graph I have also given this actual value of this band gap. In case of GAN you can see the band gap is 3.5 eV. And in case of silicon carbide 3.

26 eV. They are quite close to each other. Now in case of silicon it is 1.12 eV. So which is much less than silicon carbide and GaN. That is why these devices silicon carbide and GaN are known as wide band gap devices.

Due to higher value of the band gap. Now you can see in this particular graph there are different factors given along with the energy gap. So one factor is electric breakdown field. So you can see as the band gap is higher the breakdown field is also higher in case of silicon carbide and can. And in case of thermal conductivity, you can see, so thermal conductivity, it is also higher than that of the silicon.

And same in case of electron mobility and saturated electron velocity, they are also higher than that of the silicon. So what is the need of these devices? Why we need to consider this wide bandgap devices or what are the advantages we may get? So in the left hand side you can see this material property comparison is given between silicon and silicon carbide. So you can see here the breakdown field for silicon is given. as 0.3 and where the silicon carbide can have 2.

8 so basically silicon carbide is going to have higher voltage capability and it will be much thinner that of the silicon device so you can see here the silicon structure silicon MOSFET structure is compared with silicon carbide MOSFET structure so where The silicon carbide structure it is actually given one tenth of that of the silicon structure. Means for the same rating the size of the device will be much lower and also it will have lower resistance. So, the losses will also be much lower. And the voltage breakdown capability for silicon carbide will have much higher than that of the silicon for the comparable size. So, this is the main motivation to look for this kind of wide band gap devices.

So, basically the focus is to move towards high power density system, high power density means the size will be much smaller as compared to the existing solution. So, in that process we should not lose the efficiency and cost also should not increase. So, for the same system we are trying to achieve much lower size, higher efficiency and low cost. Because silicon materials it has some capability which cannot go beyond that, that is why people started looking for other materials. Then they found this wide band gap devices, they are better in properties as compared to silicon.

So, what ways they are better and how it is going to become advantageous for power electronics application, so that we are going to see in this particular course.

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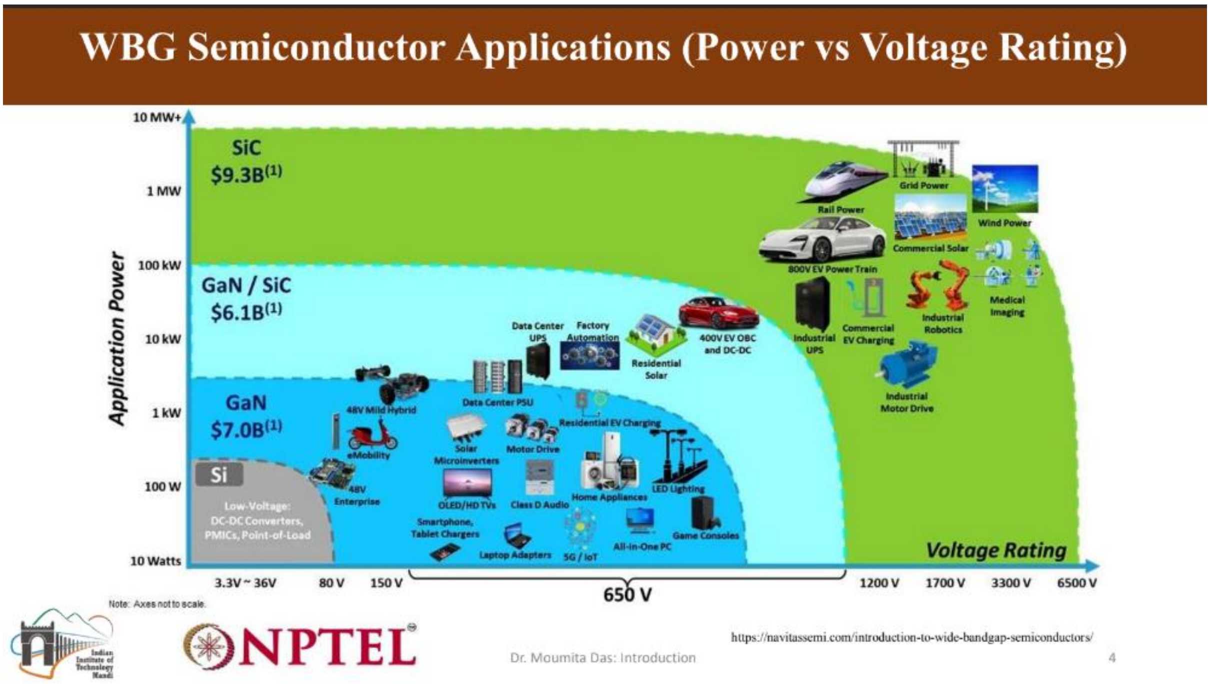

So, these are some applications where basically wide band gap devices are kind of can be used and it is actually kind of projected that in future most of the power electronics applications will be replaced by wide band gap semiconductors rather than silicon devices. So you can see here so silicon it is now kept at the beginning level So basically in terms of power level and the voltage level it is shown here the application where the silicon will be limited that will be for comparatively low power and low voltage level Although you are probably familiar with that silicon devices are available for high voltage So, the problem is that once we try to go for high power level the size of the system and efficiency those reduces. So, we have to select a optimum point where the size, efficiency, cost everything will be optimized. By considering those factors in this particular graph it is shown that silicon will be limited for low power low voltage level.

and for higher voltage than that of the 80 volts till 650 volts the applications mainly will be focusing using GaN devices so the applications you can see here some of the applications are given where basically GaN will be suitable or can be applicable mainly this laptop, adapter, PCs ,then home appliances then solar micro-inverter, motor drives, residential EV charging, e-mobility and then hybrid vehicles. So, those are the some of the applications which are shown here where GaN will be more applicable than that of the silicon or silicon carbide and there is a overlapping period here it is shown here overlapping region where both GaN and silicon carbide will be suitable so what are those applications so the voltage level will be from 650 to 1200 volts so where the applications will be focusing mainly data center UPS, then residential solar, then electric vehicles. So, where any of the devices either GaN or silicon carbide can be used, but it is advisable to not use silicon as it may have higher size and lower efficiency. So that is why this silicon in those applications can be replaced with GaN or silicon carbide. Now beyond 1200 volts you can see here beyond 1200 volts.

So the application will be focusing mainly with silicon carbide devices. So the silicon carbide devices are basically capable of having higher voltage capability. The breakdown voltage will be here shown it is shown maximum it can be till now what is available is 6.5 kV. So, where exactly those devices will be applicable? So, you can see here one of the applications is rail power.

So traction application, EVs , high voltage EVs ,so EVs can be different types 2 wheeler, 3 wheeler ,then 4 wheeler, then heavy electric vehicles , so there are also different voltage levels in EVs so some EVs they are considering 48, some are considering 400 volts now in near future people are focusing on high voltage EVs means the voltage level will be 800 volts voltage level of the battery so there this silicon carbide devices will be suitable. Then the commercial EV charging, industrial robotics, industrial drives, medical imaging, then wind power. So all these places silicon carbide will be more suitable than that of the GaN or silicon devices. So these are the some of the applications. So, it is expected to use this wide band gap devices or these devices will have much more advantage as compared to silicon for these applications.

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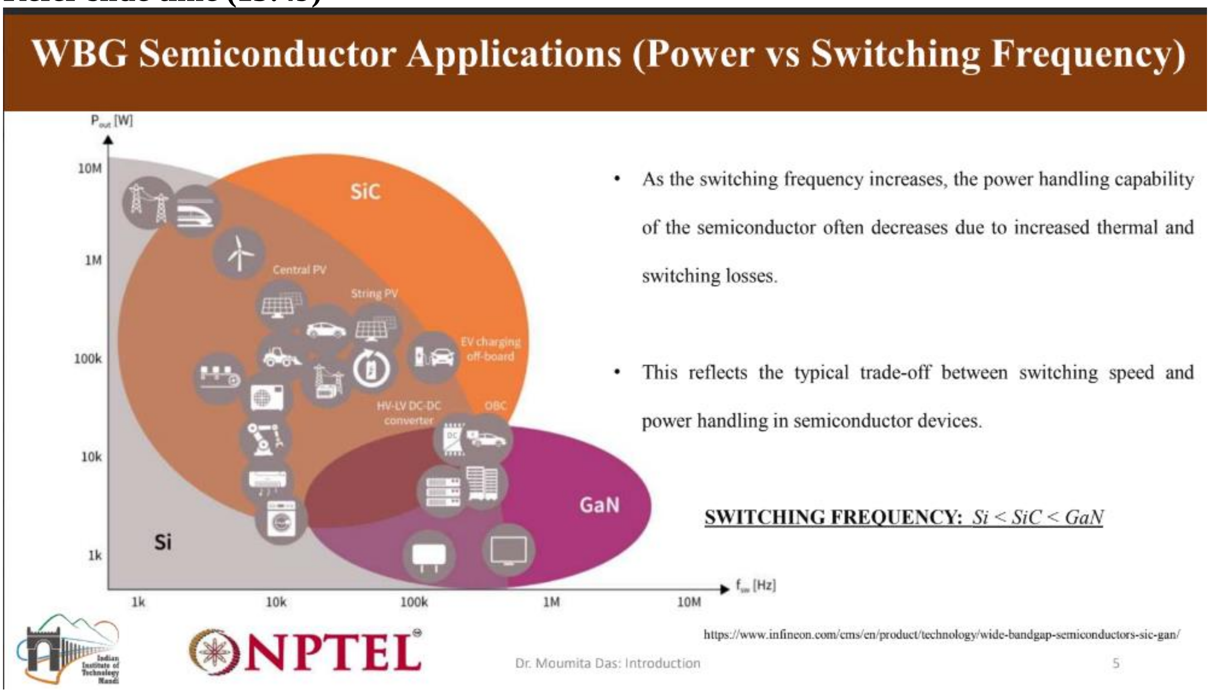

Now, with respect to this frequency and the power level if we try to see then you can see here. So the grey one is shown here is for silicon. So silicon as most of you already know as we try to go for higher frequency level then the power level will be limited. Means it cannot happen that we can have both high power and high frequency. So in case of silicon, so if we try to go for higher frequency, let's say 100 kHz in that level, then the power level will be limited.

It will be less than 1 kW. Now if we try to achieve high power, let's say 100 kW or more than that, then the frequency will be limited. It can be maximum of 1 kHz or 10 kHz. So you can see from this particular graph. So output power versus frequency. Now where exactly GaN and silicon carbide stands? So GAN you can see the pink color graph here shown.

So here GaN will be suitable for very high frequency application. Very high frequency means it can go to Gigahertz level so here it is shown 1 megahertz and it is like to near to 10 megahertz So, there the obviously the power level will be limited. Now, if we try to operate the power electronics converter at high power level. So, the GaN is capable of operating here you can see in this graph. It can go till let's say 10 kilowatt.

So, there the frequency here the 10 kilowatt there the frequency will be limited. Frequency then it will be maximum of 1 megahertz or less than that. So that is where the limitation comes for GaN. So GaN will be more suitable for very high frequency applications or the medium power and high frequency applications. So here we are considering 1 megahertz as high frequency.

Now where exactly silicon carbide stands? So you can see this orange graph. So where the silicon carbide it is shown it will be more suitable for very high power level very high power level means the power level you can see here it can go maximum to 10 mega watts now if it is operating at that power level then obviously the frequency will be limited so in that time the frequency will be some few tens of kilohertz but this device is suitable to operate at around let's say 500 or 600 kilohertz So there the power level will be limited to let's say 100 kilowatts Silicon carbide devices are more suitable for very high power applications So medium frequency and high power. So GaN is suitable for medium power and high frequency and silicon carbide devices are suitable for high power and medium frequency where the silicon operation is limited to comparatively low power and low frequency applications. So, the part where the silicon carbide is limited, so it is shown here, so below 100 kilohertz and 100 kilowatts power level. So, there we can get optimum operation by using silicon devices.

So, this is what is given here in this particular slide.

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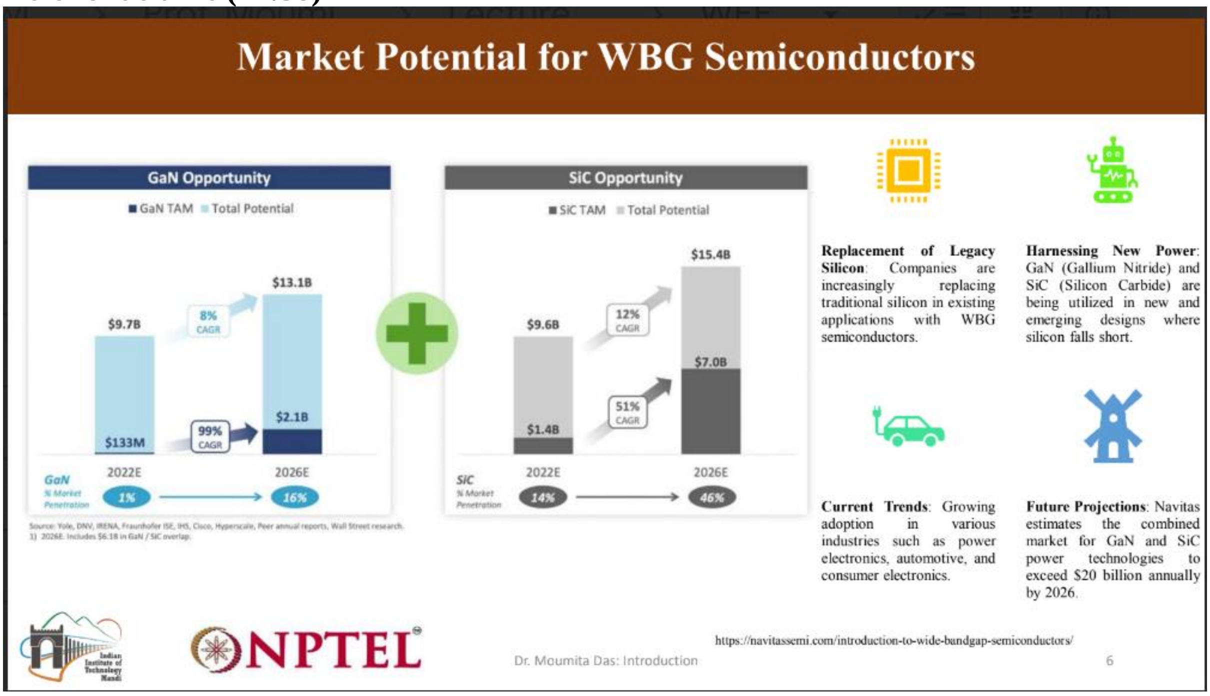

So, you can see here, so the trend, so market of this wide band gap devices, so where exactly we are focusing. So, basically right now we are focusing to replace the silicon devices with wide band gap devices. now this wide band gap devices are basically gallium nitride and silicon carbide they are available commercially. There are other wide band gap devices also like diamond which is still in research level it is not yet available commercially that is why for power electronics application it is very difficult to find out what can be advantages using those devices or what can be challenges we can see by using those devices.

So, that is why this course is limited for gallium nitride and silicon carbide type of wide bandgap devices. So now this current trend, so you can see here in industries and then different applications like whatever you can see around you like electric vehicles, renewable energy, consumer electronics. So there the current trend is to replace the silicon with wide band gap devices. Now in future it is estimated that silicon carbide and GaN power technologies It will exceed 20 billion dollar annually by 2026.

This is what is given here in this graph. So it is shown here that with respect to GaN opportunity. So right now it is shown that in 2022 what is the condition and in 2026 what will be the situation. So GaN market will increase from 1% to 16%. and the right one for silicon carbide you can see here so right now the usage of these devices for different applications it is around 14% and it is expected to increase 46% by 2026 .

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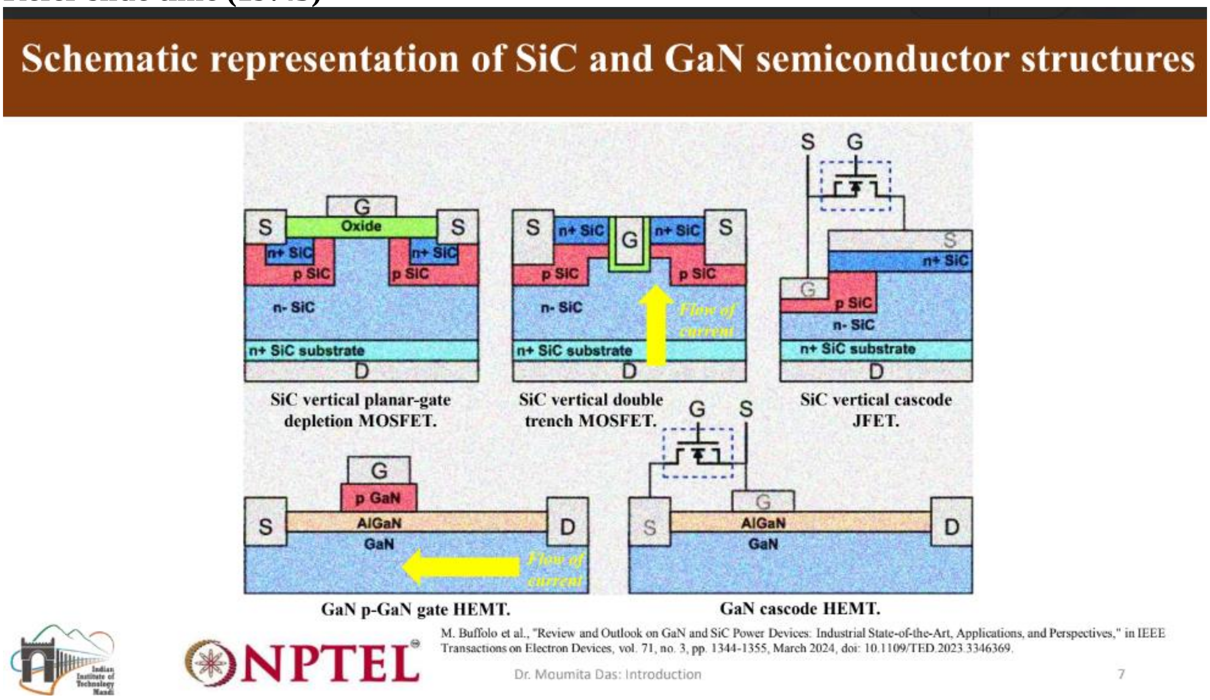

Now schematic representation of this silicon carbide and GaN it is shown in this particular slide So, right now I will just show you this structure.

Details I will be discussing in next class. so you can see here so there are different types of structure given one is silicon carbide vertical planar gate depletion MOSFET another is silicon carbide vertical double trench MOSFET another is silicon carbide vertical cascode JFET so you can see here so the current flow direction for silicon carbide so the drain is at the bottom layer and from bottom layer it is going towards upside now This structure is quite similar to the silicon structure which you already know. Now in case of GaN the structure is completely different. You can see here this GaN p-GaN gate HEMT and then GaN cascode HEMT. So this p-GaN structure it is you can see there are actually drain source and then horizontally it is having current flow from drain to source. And this structure you can see here, this P-GaN, L-GaN and the GaN layers are formed here in this particular way.

And if it is cascade kind of structure, so there will be one low voltage silicon device connected on top of this particular device. So, where basically the gate is placed in case of P-GaN structure, there the low voltage silicon structure is present. Why is so? I will show you in the next slide.

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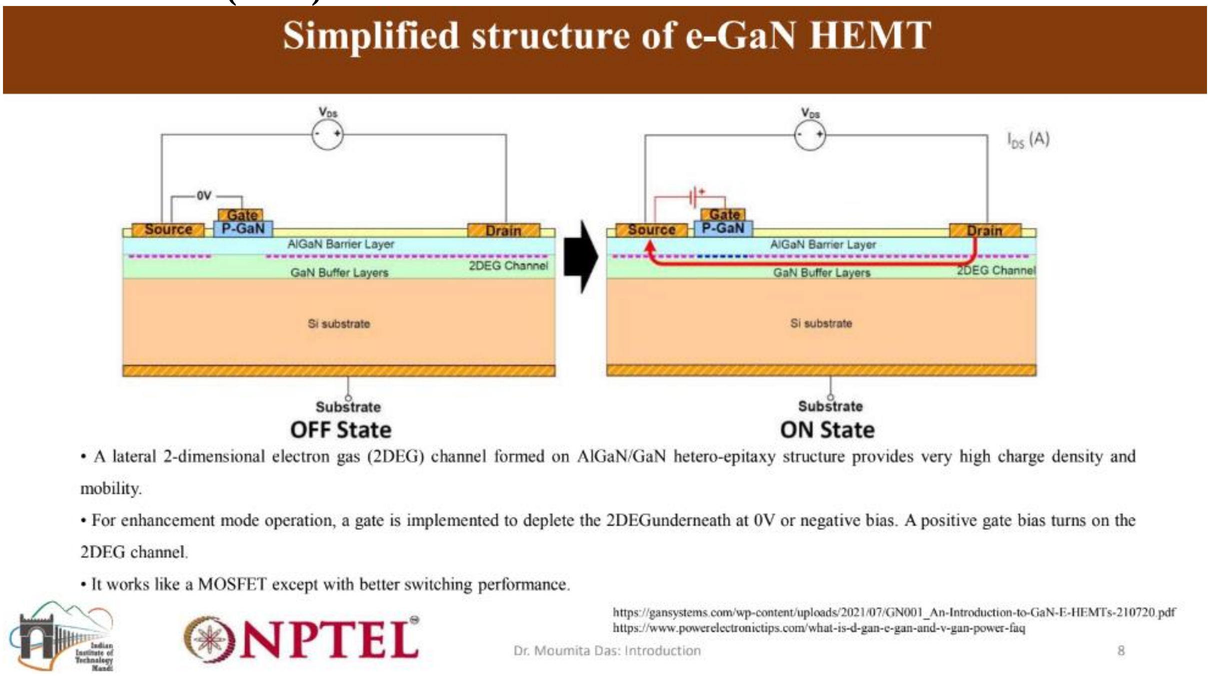

So basically this is the simplified structure of GAN. So I am not discussing in details about silicon carbide structure because the operation is similar to that of the silicon.

But in case of GaN what happened? So basically GaN How the current conducts in the reverse direction? So that is quite interesting. So you can see here when drain to source voltage is applied. So basically the two dimensional electron gas layer is formed between Al GaN and GaN layer. So, that is because piezoelectric polarization and through this layer current will flow.

So, you can see in the right one. So, when positive voltage is applied to the gate. So, then drain to source current is flowing through this two-dimensional electron gas layer. And this two-dimensional electron gas layer is actually very new kind of concept in any semiconductor material or as compared to silicon material, silicon device. So, you can see here, so when the zero voltage is applied, so that time the device will be still in conduction state. so this is depletion type of device so that is why we have to provide negative voltage in order to completely turn off the device because this two dimensional electron gas layer is already formed so the current path already exist so if we don't provide negative voltage so then it will be normally on type of device and in order to use this particular device for power electronics converter that will be a challenging task because the device is already in on condition and if we don't turn off so then there will be GaN operation so that is the reason this GaN device needs negative gate voltage in order to completely turn off so this is for p-GaN HMT structure

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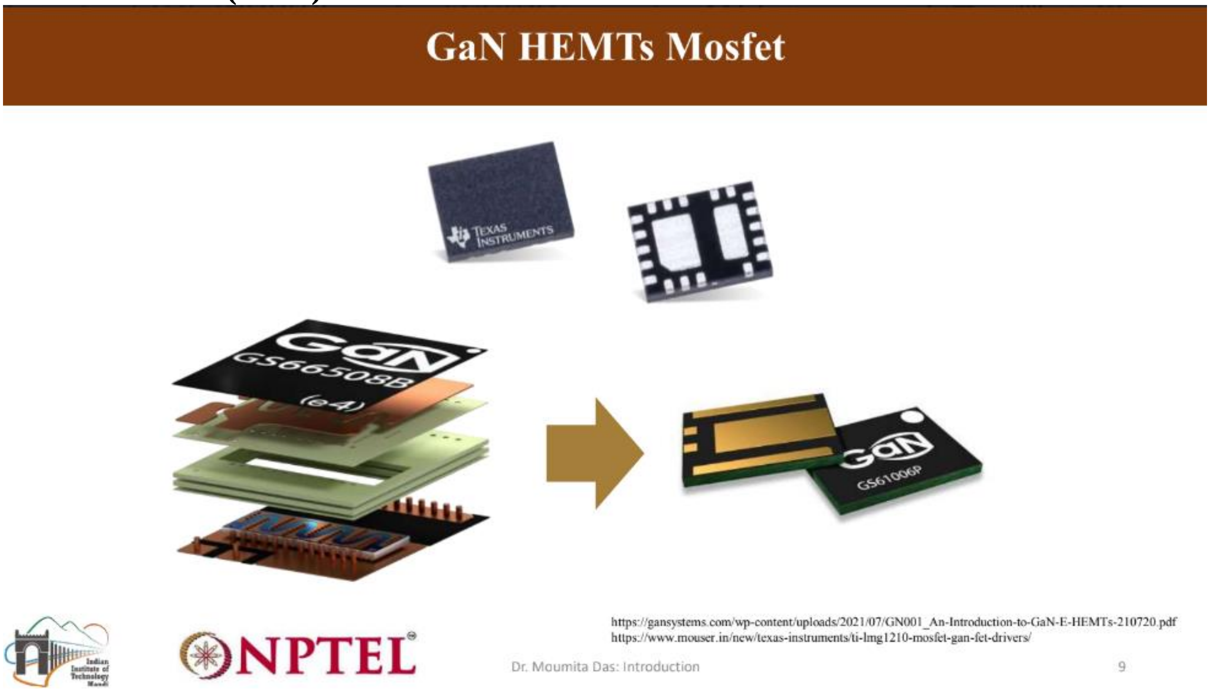

now you can see here this is how the GaN MOSFET looks like so there are different layers which are actually placed and this is SMD kind of device and in this particular device which is shown here so GS66508B so it is bottom cooled kind of device means So the PCB where the device will be placing so there only you have to provide heatsink if it is required otherwise you cannot connect the heatsink on top of the device So this is that's why bit challenging to connect heatsink and special kind of requirement of heatsink or the knowledge of heatsink connection is required.

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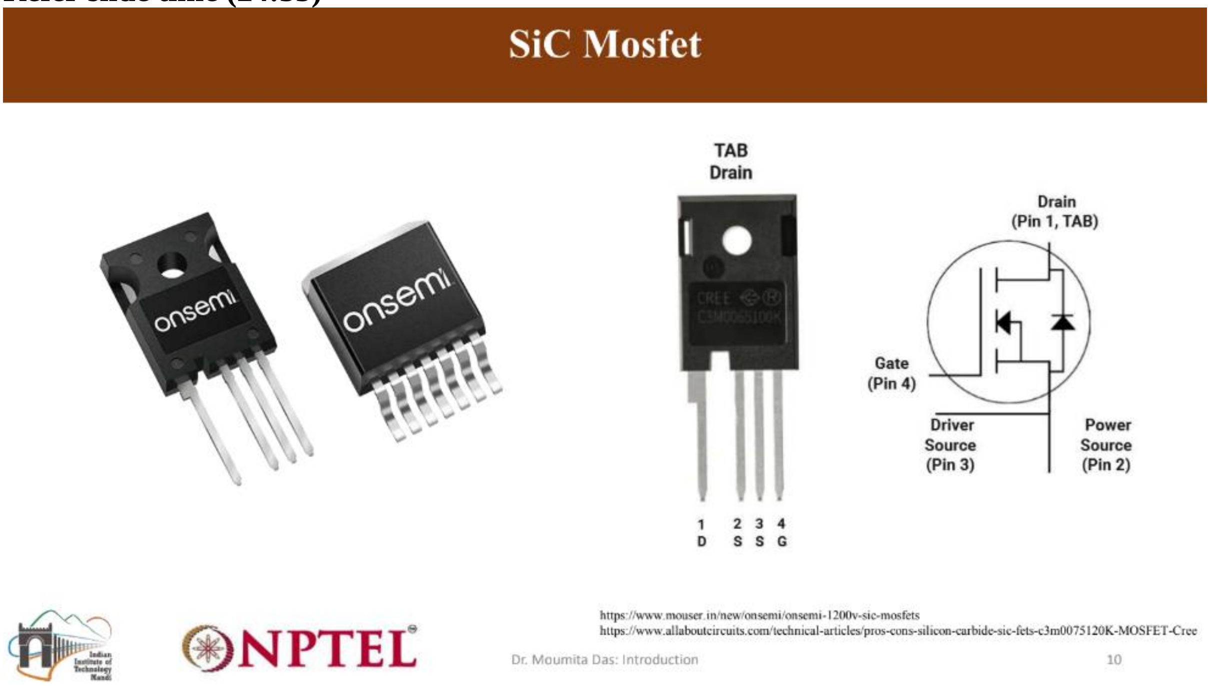

and this is the structure of silicon carbide MOSFET this is how it looks like it is similar to that of the silicon device it is having different drain source gate and you can see here this is the symbol of the silicon carbide MOSFET.

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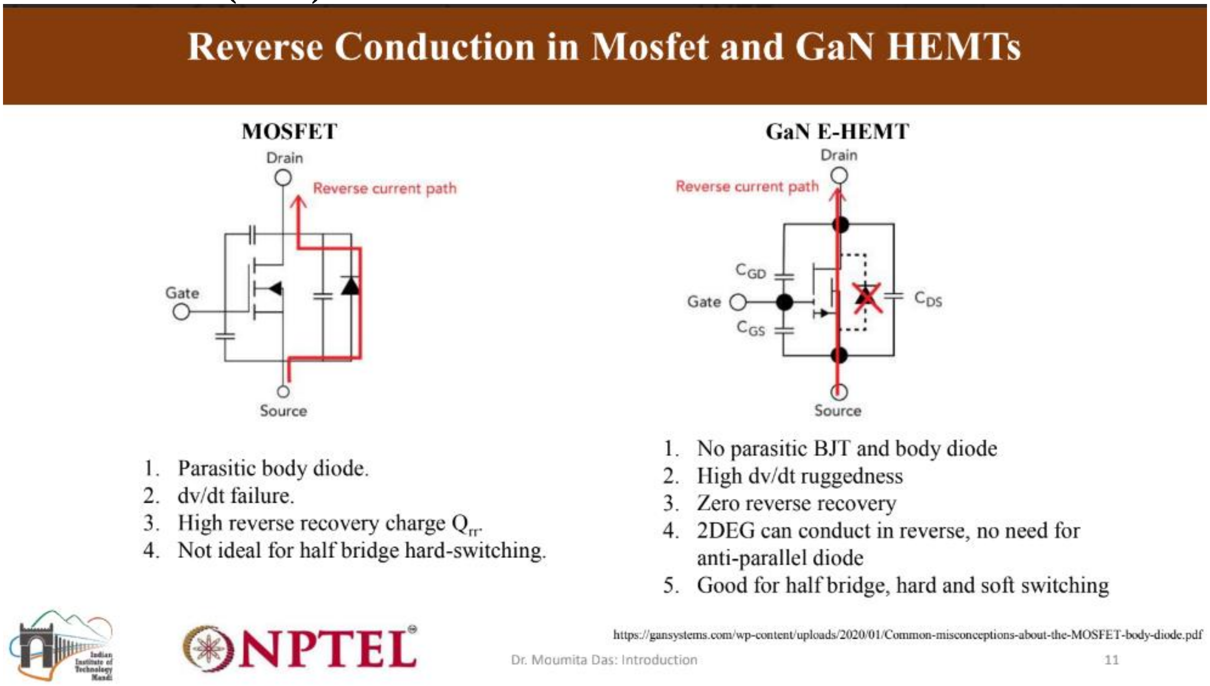

This is the comparison of the GaN device with respect to MOSFET so you can see here the GaN device is shown in the right hand side in the left hand side it is MOSFET So the reverse current flow path for GaN is very interesting because it doesn't have reverse diode connected to it.

In case of MOSFET you can see there is a reverse diode which generally forms in any device in silicon, silicon carbide any device it will have reverse diode which will be formed in the device and which will allow current to flow in the reverse direction. Now this is also known as parasitic body diode of the MOSFET and then due to this there can be possibility of dv/dt failure and also due to this reverse recovery problem may arise and this is not actually ideal kind of device for half-bridge hard switching operation. Now come to that GaN switch. So GaN switch is having structure which doesn't have any anti-parallel body diode. So does that mean that there will be no reverse current flow? There will be reverse current flow.

So how it flows? So the flow will be from source to drain. How this current flow will be? That will be through the two dimensional electron gas layer. You can see here due to the absence of this body diode. So basically this device is having high dv/dt ruggedness. And as the diode is not present, so there will be no time required for reverse recovery.

So there will be zero reverse recovery time or loss. And this device is suitable or ideal for half-bridge hard switch or soft switch operation. So basically as compared to silicon and silicon carbide, GaN has different structure and also symbol is different. It doesn't have body diode. That is actually advantageous because you know there will not be any reverse recovery problem. So is that the only thing? also there will be a disadvantage due to the absence of this reverse diode.

So, this reverse current flow can cause high voltage drop means the losses during the reverse operation will be much higher than that of the silicon or silicon carbide device in case of GaN device.

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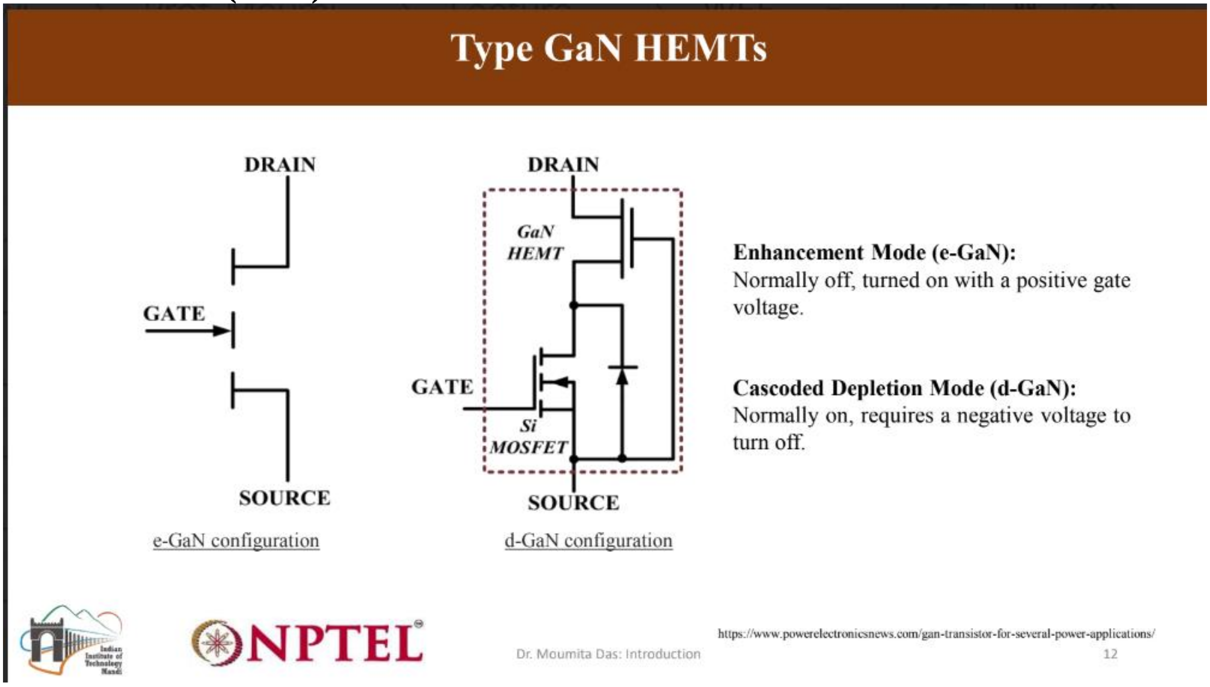

so you can see here this symbol of GAN so the left one is the e-GaN configuration and then right one is the d-GaN configuration so which is also known as cascode depletion mode device so the left one is enhancement mode device or e-GaN device. it is normally off turn on with a positive gate voltage and the cascoded depletion mode device it is normally on and requires a negative voltage to turn off and this device you can see here the structure is basically it is having one GaN device which is actually connected to one silicon MOSFET so the gate where it is connected so gate will be the silicon MOSFET gate and which will help the GaN device to turn on. So this is the difference between e-GaN and d-GaN configuration.

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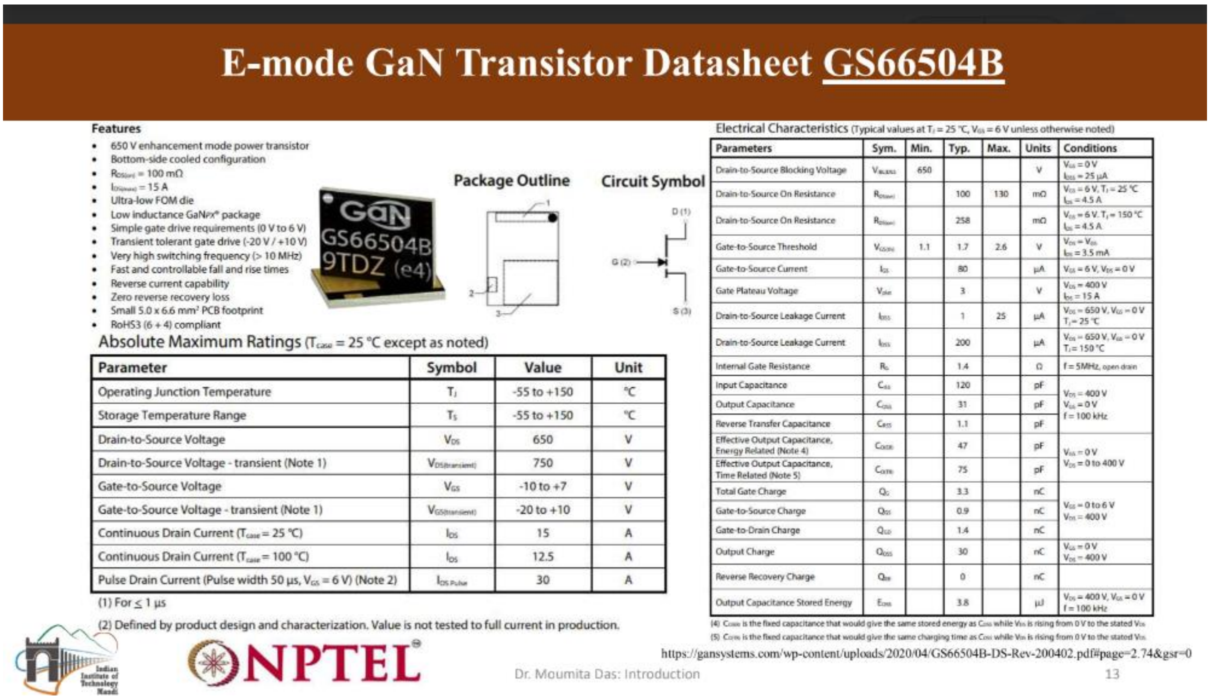

Features

- 650 V enhancement mode power transistor
- Bottom-side cooled configuration
- $R_{DS(on)}$ = 100 mΩ
- $I_{DS(max)}$ = 15 A
- Ultra-low FOM die
- Low inductance GaNPX® package
- Simple gate drive requirements (0 V to 6 V)
- Transient tolerant gate drive (-20 V / +10 V)
- Very high switching frequency (> 10 MHz)
- Fast and controllable fall and rise times
- Reverse current capability
- Zero reverse recovery loss
- Small 5.0 x 6.6 mm² PCB footprint
- RoHS3 (6 + 4) compliant

Absolute Maximum Ratings (T_{case} = 25 °C except as noted)

Parameter	Symbol	Value	Unit
Operating Junction Temperature	T_J	-55 to +150	°C
Storage Temperature Range	T_S	-55 to +150	°C
Drain-to-Source Voltage	V_{DS}	650	V
Drain-to-Source Voltage - transient (Note 1)	$V_{DS(transient)}$	750	V
Gate-to-Source Voltage	V_{GS}	-10 to +7	V
Gate-to-Source Voltage - transient (Note 1)	$V_{GS(transient)}$	-20 to +10	V
Continuous Drain Current (T_{case} = 25 °C)	I_{DS}	15	A
Continuous Drain Current (T_{case} = 100 °C)	I_{DS}	12.5	A
Pulse Drain Current (Pulse width 50 µs, V_{GS} = 6 V) (Note 2)	$I_{DS\ Pulse}$	30	A

(1) For ≤ 1 µs

(2) Defined by product design and characterization. Value is not tested to full current in production.

Electrical Characteristics (Typical values at T_J = 25 °C, V_{GS} = 6 V unless otherwise noted)

Parameters	Sym.	Min.	Typ.	Max.	Units	Conditions
Drain-to-Source Blocking Voltage	$V_{BL(DSS)}$	650			V	V_{GS} = 0 V, I_{DSS} = 25 µA
Drain-to-Source On Resistance	$R_{DS(on)}$		100	130	mΩ	V_{GS} = 6 V, T_J = 25 °C, I_{DS} = 4.5 A
Drain-to-Source On Resistance	$R_{DS(on)}$		258		mΩ	V_{GS} = 6 V, T_J = 150 °C, I_{DS} = 4.5 A
Gate-to-Source Threshold	$V_{GS(th)}$	1.1	1.7	2.6	V	V_{DS} = V_{GS}, I_{DS} = 3.5 mA
Gate-to-Source Current	I_{GS}		80		µA	V_{GS} = 6 V, V_{DS} = 0 V
Gate Plateau Voltage	V_{plat}		3		V	V_{DS} = 400 V, I_{DS} = 15 A
Drain-to-Source Leakage Current	I_{DSS}		1	25	µA	V_{DS} = 650 V, V_{GS} = 0 V, T_J = 25 °C
Drain-to-Source Leakage Current	I_{DSS}		200		µA	V_{DS} = 650 V, V_{GS} = 0 V, T_J = 150 °C
Internal Gate Resistance	R_G		1.4		Ω	f = 5MHz, open drain
Input Capacitance	C_{ISS}		120		pF	V_{DS} = 400 V, V_{GS} = 0 V, f = 100 kHz
Output Capacitance	C_{OSS}		31		pF	
Reverse Transfer Capacitance	C_{RSS}		1.1		pF	
Effective Output Capacitance, Energy Related (Note 4)	$C_{O(ER)}$		47		pF	V_{GS} = 0 V, V_{DS} = 0 to 400 V
Effective Output Capacitance, Time Related (Note 5)	$C_{O(TR)}$		75		pF	
Total Gate Charge	Q_G		3.3		nC	V_{GS} = 0 to 6 V, V_{DS} = 400 V
Gate-to-Source Charge	Q_{GS}		0.9		nC	
Gate-to-Drain Charge	Q_{GD}		1.4		nC	
Output Charge	Q_{OSS}		30		nC	V_{GS} = 0 V, V_{DS} = 400 V
Reverse Recovery Charge	Q_{RR}		0		nC	
Output Capacitance Stored Energy	E_{OSS}		3.8		µJ	V_{DS} = 400 V, V_{GS} = 0 V, f = 100 kHz

(4) $C_{O(ER)}$ is the fixed capacitance that would give the same stored energy as C_{OSS} while V_{DS} is rising from 0 V to the stated V_{DS}

(5) $C_{O(TR)}$ is the fixed capacitance that would give the same charging time as C_{OSS} while V_{DS} is rising from 0 V to the stated V_{DS}

So let's see the data sheet of these devices. So how these devices are different from each other that we can see from the data sheet. So this data sheet is for the GaN transistor which is having rating of 650 volts. and this is bottom side cool device as you can see here from this device structure so the top side it is written GaN and then GS66504B the part number of the device and the bottom side it is having different points so basically access point of the drain ,gate, source all will be placed in the bottom side and this is SMD type of device And then this kind of the requirement of SMD type of device for GaN is due to the arise of low inductance in the package. So, package, so whatever you have seen for silicon carbide or silicon that can cause arise of high inductance and that can cause problem for high frequency operation that is why these kind of devices are having package which is SMD in nature and much thinner than that of the silicon or silicon carbide device so you can see here so this gate drive requirement is 0 to 6 volts And then transistor can tolerate minus 20 to plus 10 volts. Means if we by accidentally if we provide minus 20 volts or plus 10 volts still the transistor will be able to survive.

And it is suitable to operate very high switching frequency. Very high means it is even suitable for operation more than 10 megahertz. Then this is fast and controllable fall and dice types and reverse current capability. It is suitable for reverse current flow operation and it is having zero reverse recovery loss. And the size of the PCB footprint it is very small.

You can see here this is 5 multiplied by 6.6 mm square. So it is this small. So now you can see the operation of this device is suitable for a junction temperature minus 55 to plus 150 degree Celsius. So this device can be used in places where the temperature can go in negative side minus 55 degree Celsius and positive side plus 150 degree Celsius. and storage temperature is also same and drain to source voltage as I have already told you 650 volts now this drain to source voltage during transient condition can also be 750 volts if there is any spike or anything which is of 750 volts still the device can survive. The gate to source voltage it is given that minus 10 to plus 7 volts so you can provide any voltage in between so it can be let's say minus

5 to plus 6 so in that level so during transient condition the device will be able to take minus 20 to plus 10 volts the continuous drain current rating in this device is 15 ampere at 25 degree celsius if the temperature rises to 100 degree celsius then the continuous drain current will be lower which will be around 12.

5 amperes. And if there is any pulse current or the transient current, which is of 30 ampere, then the device will be able to operate. Now, you can see in the right hand side, electrical characteristics for this device is given. So, here important thing to notice is that drain to source on resistance. So, drain to source on resistance for this particular device is 0.258 ohm or 258 milliohm so you can understand from this that conduction loss will be lower now the threshold voltage which is very important for this particular device you can see here minimum is 1.

1 volts and typically it is 1.7 and maximum is 2.6 volts means what if in case if we provide any gate voltage which is from let's say 0 to 6 volts so if there is any transient of 1 volt comes during the off time in the gate then that will cause the device to false turn on that is the reason it is always advisable to provide negative voltage then at least there will be some gap between the threshold voltage and the gate voltage But if there is no gap so there can be problem of false turn on. So that is one of the main problem of this kind of devices. The threshold voltage is very low. Now Gate to source current it is given Igs it is 80 micro ampere. and drain to source leakage current it is given typically it is around 1 micro ampere so the losses will be less.

Drain to source leakage current it is 200 micro ampere now internal gate resistance you can see here 1.4 ohm. it is given 1.4 ohm so now The main thing for this device operation at high frequency, the capacitances, different parasitic capacitances, input, output and reverse transfer capacitance. You can see here this reverse transfer capacitance is around 1 pF, output capacitance 31 pF and input capacitance 120 pF.

The very low value of this parasitic capacitances allow the device to operate at high frequency. Because the gate charge requirement is very low in this particular device. So this is the reason the device is suitable to operate at very high frequency.

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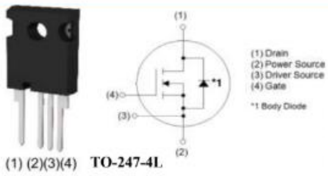
SiC Power Mosfet Datasheet SCT3030ARHR

V_{DSS}	650V
$R_{DS(on)}$ (Typ.)	30mΩ
I_D *1	70A
P_D	262W



●**Absolute maximum ratings** (T_{vj} = 25°C unless otherwise specified)

Parameter		Symbol	Value	Unit
Drain - Source Voltage		V_{DSS}	650	V
Continuous Drain current	T_c = 25°C	I_D *1	70	A
	T_c = 100°C	I_D *1	49	A
Pulsed Drain current (T_c = 25°C)		$I_{D,pulse}$ *2	175	A
Gate - Source voltage (DC)		V_{GSS}	-4 to +22	V
Gate - Source surge voltage (t_{surge} < 300ns)		V_{GSS_surge} *3	-4 to +26	V
Recommended drive voltage		V_{GS_op} *4	0 / +18	V
Virtual Junction temperature		T_{vj}	175	°C
Range of storage temperature		T_{stg}	-55 to +175	°C

●**Electrical characteristics** (T_{vj} = 25°C unless otherwise specified)

Parameter	Symbol	Conditions	Values			Unit
			Min.	Typ.	Max.	
Transconductance	g_{fs} *5	V_{DS} = 10V, I_D = 27A	-	9.4	-	S
Input capacitance	C_{iss}	V_{GS} = 0V	-	1526	-	pF
Output capacitance	C_{oss}	V_{DS} = 500V	-	89	-	
Reverse transfer capacitance	C_{rss}	f = 1MHz	-	42	-	
Effective output capacitance, energy related	$C_{o(er)}$	V_{GS} = 0V V_{DS} = 0V to 300V	-	230	-	pF
Total Gate charge	Q_g *5	V_{DS} = 300V	-	104	-	nC
Gate - Source charge	Q_{gs} *5	I_D = 27A V_{GS} = 18V	-	19	-	
Gate - Drain charge	Q_{gd} *5	See Fig. 1-1.	-	55	-	
Turn - on delay time	$t_{d(on)}$ *5	V_{DS} = 400V	-	6	-	ns
Rise time	t_r *5	I_D = 40A V_{GS} = 0V/+18V	-	26	-	
Turn - off delay time	$t_{d(off)}$ *5	R_G = 0Ω, L = 750μH	-	25	-	
Fall time	t_f *5	L_σ = 50nH, C_σ = 10pF See Fig. 2-1, 2-2, 2-3.	-	25	-	
Turn - on switching loss	E_{on} *5	E_{on} includes diode reverse recovery.	-	203	-	μJ
Turn - off switching loss	E_{off} *5		-	175	-	

https://fscdn.rohm.com/en/products/databook/datasheet/discrete/sic/mosfet/sct3030arhr-c.pdf#page=1.00&gsr=0

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Now let's see the data sheet of silicon carbide and where exactly it is different from the GaN. So you can see here this device is also shown for same voltage level this is 650 volts and Rds on here it is 30 milli ohm So you can see here this conduction loss is much lower and the drain current capability is 70 ampere So, in this case you can see here different other factors.

So, basically drain to source voltage 650 volts continuous drain current is 70 ampere for 25 degree Celsius and it can reduce to 49 ampere if the temperature increased to 100 degree Celsius. Now pulse drain current capability for this particular device is 175 amperes. That is very high. And gate to source voltage it is advisable to give minus 4 to plus 22 volts.

Anything in between that. So Basically, the voltage level generally suggested for this particular device is 0 to plus 18 volts. It can also be given 0 to plus 15 volts which is of similar level of silicon device. you can see here different capacitances for this device so this input capacitance output capacitance and reverse capacitance so you can see here the input capacitance for this device is 1526 picofarad output capacitance is 89 picofarad and reverse capacitance is 42 picofarad This is much higher than that of the GaN device. That is the reason silicon carbide device operation will be less than that of the GaN device operation in terms of frequency level. So, GaN is GaN can operate at much higher frequency than that of the silicon device due to presence of lower value of these different parasitic capacitances.

And accordingly the gate charge level of the silicon device is also will be different. So these are the different rise time and fall time for the silicon carbide device. And this is the symbol of the silicon carbide device you can see here. So basically 1 and 4 these two points are given for gate and drain and then 2 and 3 are for source.

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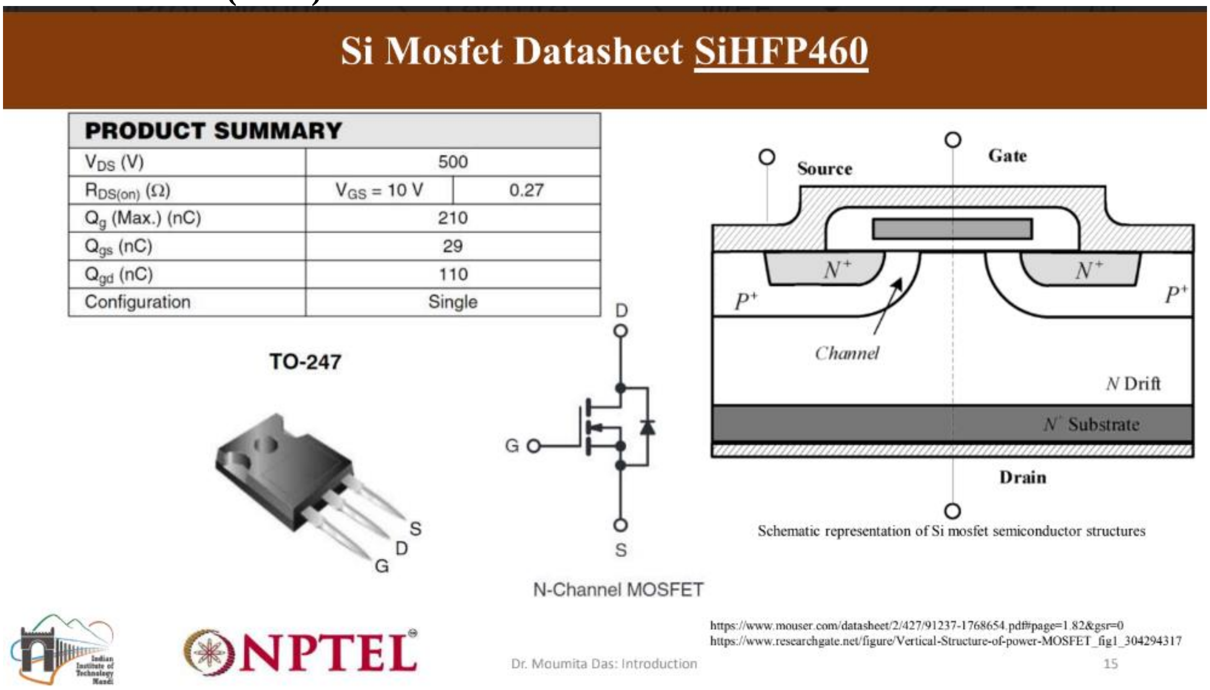

PRODUCT SUMMARY		
V_{DS} (V)	500	
$R_{DS(on)}$ (Ω)	V_{GS} = 10 V	0.27
Q_g (Max.) (nC)	210	
Q_{gs} (nC)	29	
Q_{gd} (nC)	110	
Configuration	Single	

Now let's see the silicon MOSFET. So the silicon MOSFET the voltage level is slightly lower than that of the GaN and silicon carbide which is 500 volts. Here the RDS on is 0.27. So you can see here this is much higher than that of the silicon carbide device. and the structure of this silicon device.

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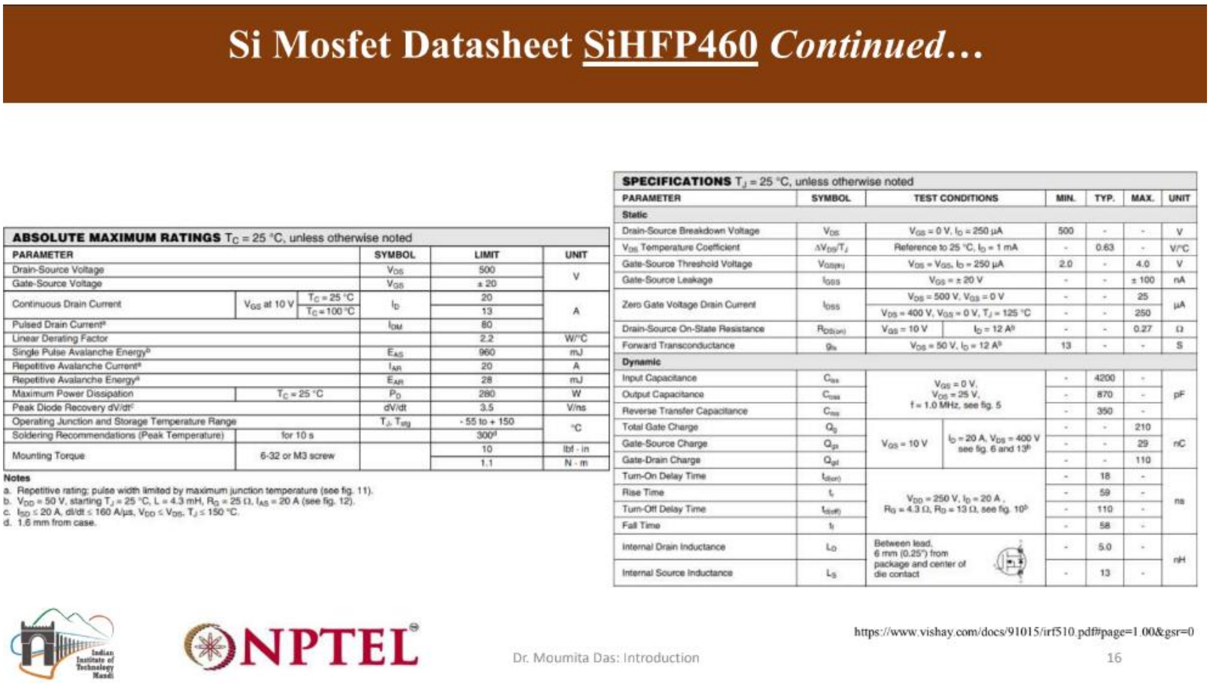

ABSOLUTE MAXIMUM RATINGS T_C = 25 °C, unless otherwise noted

PARAMETER			SYMBOL	LIMIT	UNIT
Drain-Source Voltage			V_{DS}	500	V
Gate-Source Voltage			V_{GS}	± 20	
Continuous Drain Current	V_{GS} at 10 V	T_C = 25 °C	I_D	20	A
		T_C = 100 °C		13	
Pulsed Drain Current[a]			I_{DM}	80	
Linear Derating Factor				2.2	W/°C
Single Pulse Avalanche Energy[b]			E_{AS}	960	mJ
Repetitive Avalanche Current[a]			I_{AR}	20	A
Repetitive Avalanche Energy[a]			E_{AR}	28	mJ
Maximum Power Dissipation	T_C = 25 °C		P_D	280	W
Peak Diode Recovery dV/dt[c]			dV/dt	3.5	V/ns
Operating Junction and Storage Temperature Range			T_J, T_{stg}	- 55 to + 150	°C
Soldering Recommendations (Peak Temperature)	for 10 s			300[d]	
Mounting Torque	6-32 or M3 screw			10	lbf · in
				1.1	N · m

Notes

a. Repetitive rating; pulse width limited by maximum junction temperature (see fig. 11).
b. V_{DD} = 50 V, starting T_J = 25 °C, L = 4.3 mH, R_G = 25 Ω, I_{AS} = 20 A (see fig. 12).
c. I_{SD} ≤ 20 A, dI/dt ≤ 160 A/μs, V_{DD} ≤ V_{DS}, T_J ≤ 150 °C.
d. 1.6 mm from case.

SPECIFICATIONS T_J = 25 °C, unless otherwise noted

PARAMETER	SYMBOL	TEST CONDITIONS		MIN.	TYP.	MAX.	UNIT
Static							
Drain-Source Breakdown Voltage	V_{DS}	V_{GS} = 0 V, I_D = 250 μA		500	-	-	V
V_{DS} Temperature Coefficient	$\Delta V_{DS}/T_J$	Reference to 25 °C, I_D = 1 mA		-	0.63	-	V/°C
Gate-Source Threshold Voltage	$V_{GS(th)}$	V_{DS} = V_{GS}, I_D = 250 μA		2.0	-	4.0	V
Gate-Source Leakage	I_{GSS}	V_{GS} = ± 20 V		-	-	± 100	nA
Zero Gate Voltage Drain Current	I_{DSS}	V_{DS} = 500 V, V_{GS} = 0 V		-	-	25	μA
		V_{DS} = 400 V, V_{GS} = 0 V, T_J = 125 °C		-	-	250	
Drain-Source On-State Resistance	$R_{DS(on)}$	V_{GS} = 10 V	I_D = 12 A[b]	-	-	0.27	Ω
Forward Transconductance	g_{fs}	V_{DS} = 50 V, I_D = 12 A[b]		13	-	-	S
Dynamic							
Input Capacitance	C_{iss}	V_{GS} = 0 V, V_{DS} = 25 V, f = 1.0 MHz, see fig. 5		-	4200	-	pF
Output Capacitance	C_{oss}			-	870	-	
Reverse Transfer Capacitance	C_{rss}			-	350	-	
Total Gate Charge	Q_g	V_{GS} = 10 V	I_D = 20 A, V_{DS} = 400 V see fig. 6 and 13[b]	-	-	210	nC
Gate-Source Charge	Q_{gs}			-	-	29	
Gate-Drain Charge	Q_{gd}			-	-	110	
Turn-On Delay Time	$t_{d(on)}$	V_{DD} = 250 V, I_D = 20 A, R_G = 4.3 Ω, R_D = 13 Ω, see fig. 10[b]		-	18	-	ns
Rise Time	t_r			-	59	-	
Turn-Off Delay Time	$t_{d(off)}$			-	110	-	
Fall Time	t_f			-	58	-	
Internal Drain Inductance	L_D	Between lead, 6 mm (0.25") from package and center of die contact		-	5.0	-	nH
Internal Source Inductance	L_S			-	13	-	

you can see here gate drain and source and this is basically schematic representation of the silicon MOSFET which is similar to that of the silicon carbide you can see here so the drain to source voltage is 500 volts and gate source voltage it can be plus minus 20 volts and it has continuous drain current capability 20 ampere at 25 degree Celsius and 13 ampere for 100 degree Celsius now other points you can just go through so the important thing here I'll just show to you is the parasitic capacitances so the parasitic capacitances here you can see Input capacitance of the silicon device is 4200 pF.

Output capacitance is 870 pF and reverse transfer capacitance is 350 pF which is higher than silicon carbide and much much higher than that of the GaN device. This is the reason the operation of the silicon is limited to comparatively lower frequency level. And also there are like delay time and rise time for this silicon device is given here. So this is just to show you the difference of different capacitances and what is the reason so that the devices can operate at high frequency. And there are other points which are also available in the data sheet that you can just go through and eventually we will look into it different parts for different types of discussion.

So for driver designing part I will be showing different part from the data sheet. So that we will see later.

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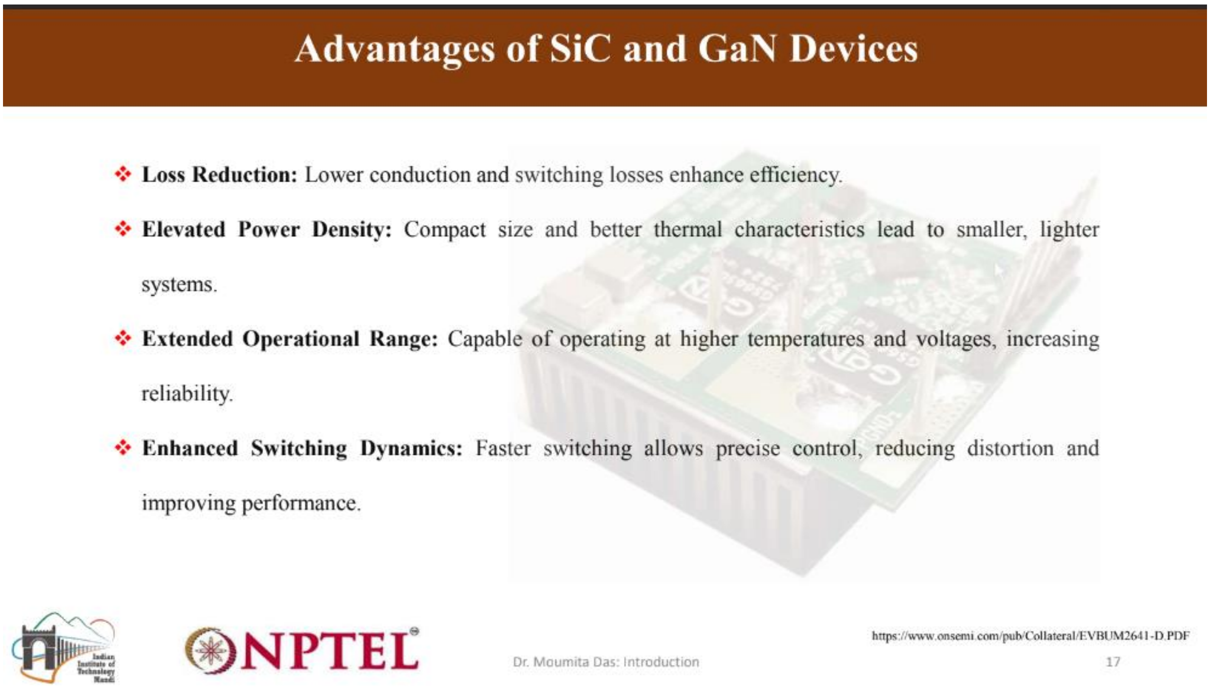

So now the advantages. What are the advantages of silicon carbide and the GaN devices? So first thing is the loss reduction. So you can see here As the capacitances are much lesser than that of the silicon device. So, GaN is having much lesser capacitance than that of the silicon carbide and which is having lesser capacitance than that of the silicon.

So, then the gate charge drain charge it is requirement of those charges are much less. So, then rise time and fall time will be much lesser. So, it is much less in case of GaN as compared to silicon carbide as compared to silicon. So, then what will happen the switching losses will be much lower. So, switching losses in case of GaN will be lower than that of the silicon carbide which is having which is also having lower switching losses than that of the silicon.

So, the efficiency will increase in these devices. So, the we can operate at much higher frequency which will reduce the size and the efficiency also will be higher. The second point is the elevated power density. as you know like as these devices allow us to operate at higher frequency so then what happens then the size of the overall system will reduce down size of the passive component will reduce down and if the losses are less so the heat sink requirement will also be less the details of this heat sink and the thermal modeling will be seen later in this course so Basically the size will be much more compact and it will have better thermal characteristics which will lead to smaller lighter systems. Now third point is the extended operational range. So now these devices are suitable to operate at high voltages and also which will be suitable to operate at high temperature as compared to silicon devices Means if the temperature increases the failure of the devices will be much lower as compared to silicon device So the reliability of the overall system will increase So as you have seen one property as the temperature increases current level reduces.

Similarly different other parameter in the device it will increase. So that will cause more losses to occur and that will again cause more heat generation and temperature again will increase. And this will cause failure of the system. If the device's properties doesn't change much with the increase of the temperature then what will happen? The system will be able to operate at high temperature level and then reliability of the system will also increase. And the fourth point is that enhanced switching dynamics. Then this faster switching will allow precise control, reduce distortion and improve the performance.

So basically the dynamic performance will be better than that of the silicon. Steady state performance will remain same but due to the less switching time it will have less time when this oscillation will be there or the distortion will be there. So then the dynamic of the overall system will improve. Now you know about the advantages.

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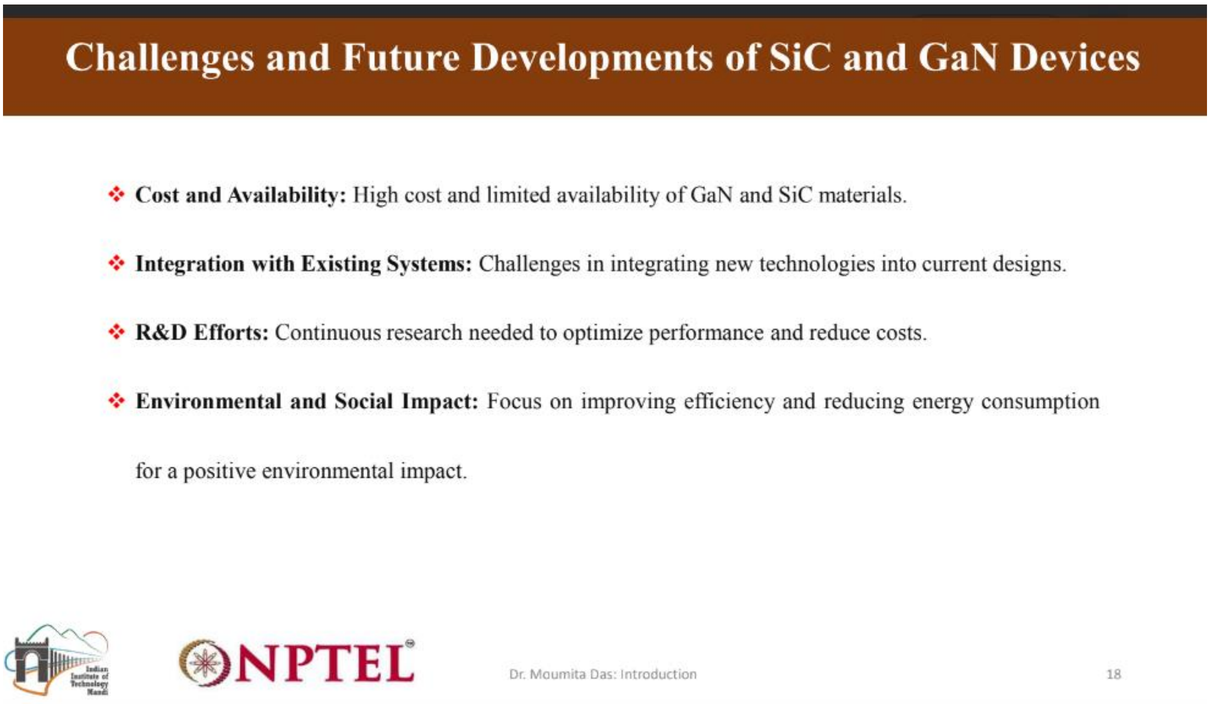

Obviously these devices are having better properties than that of the silicon.

And it is expected to achieve better system by using these devices. But this doesn't come without a cost. There are challenges. and this will give us the window for research. in this particular area. So, what are the challenges? First is the cost and availability because these devices are new and not many manufacturers are available for these devices.

So, accessibility of these devices are also not as easy as silicon devices and also they are much costlier than that of the silicon device. so that is the first challenge so basically first is the very high cost and also it is not easily available you have to spend a lot of money to get these devices for your work or for any application now second thing is that integration with existing system so basically these devices are new so it is having new design So these devices cannot be integrated directly with the existing system. Let's say for GAN. GAN has different gate drive requirement. So then currently the driver whatever available for silicon devices we cannot directly use for GAN application.

So it cannot be directly integrated to the existing system. So this is another challenge. Third is that These devices require continuous research and development to not only to reduce the cost and also to find out other properties. In data sheet you may or may not find all the properties as the silicon device. So silicon device data sheet if you open you will find much more information than that of the silicon carbide or GaN. So some information still unknown. So in order to know this information continuous research in this particular area is required so that we can have all the information.

That is one opportunity. Also like that comes in the way for application. So, still unknown factors are there for which in any application those devices cannot be directly used. And the fourth one is the environmental and social impact. So now we know that these devices can give us better efficiency and reduce energy consumption. So these are for environmental reason it is very good and it has like positive social impact also. But still we are not sure until and unless we completely use it in any application and also there are another important thing is that in industry the unavailability of the manpower who are kind of trained using these devices so the people who are working in industry they are using silicon for long time so they know about the device the system with those device how it will behave but in case of GaN and silicon carbide the knowledge is not there much for the industry people so that is why in order to use it completely this knowledge is required So, this is one of the main challenges for the development of the silicon carbide and GaN based systems.

Let's hope in future probably more number people will have knowledge of these devices. So, it will help industry to accept these devices or technology based on these devices which will eventually help to reduce the cost and it will increase the availability and also other factors will also become kind of positive with respect to these devices. Thank you. This is all for today's lecture. More on these devices I will be discussing in the next class.