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Design of Power Electronic Converters

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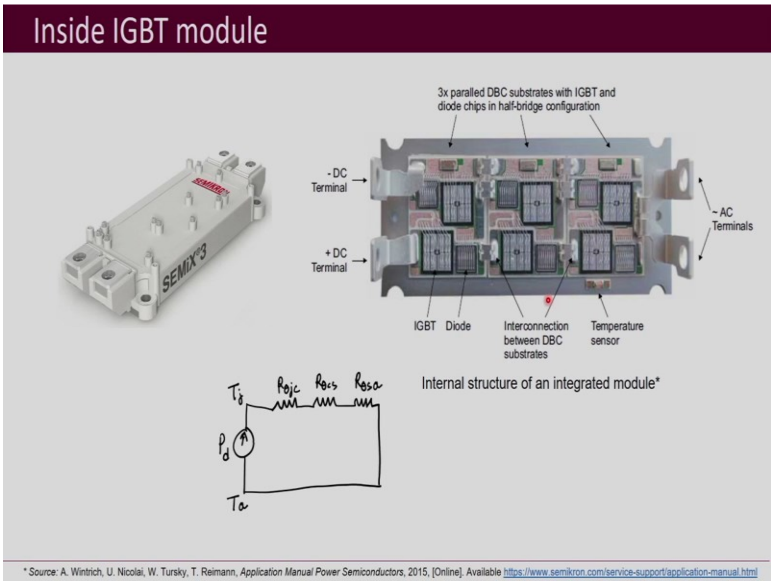
Lecture – 42

Thermal Modelling - 3

Welcome to the course on Design of Power Electronic Converters. We were discussing the module of thermal design. Now, let us look further into thermal modelling.



Inside IGBT module

Internal structure of an integrated module*

* *Source:* A. Wintrich, U. Nicolai, W. Tursky, T. Reimann, *Application Manual Power Semiconductors*, 2015, [Online]. Available https://www.semikron.com/service-support/application-manual.html

Previously we discussed thermal modelling of the steady state response and transient response. We took very simple circuits. So, the circuits were like that the power dissipation was modelled as a current source and then we had thermal resistances and these thermal resistances were taken as electrical resistances.

So, thermal resistance between junction to case, then between case to sink and then thermal resistance from sink to ambient were there. The ambient temperature was taken as the reference and this point was taken as the junction temperature. So, the temperatures were behaving analogous to voltage.

We saw that we can take this kind of a steady state response and then there can be instances, where there may be a sudden change in the power dissipation levels and then there will be also a transient response. So, where transient model is important, there we saw that we can use thermal impedance graphs.

So, up till here whatever we have discussed is a very simplified thing. Now, let us look into an actual device which maybe a power semiconductor device. So, here this shows an internal structure of an integrated module. I have shown this before also to you when we discuss power semiconductor devices. This is a module by Semikron and here you see that these are the DC terminals and these are the two AC terminals which are shown and then there is this IGBT and this anti parallel diode chip.

So, you can see here that there are several IGBTs which are actually connected in parallel and similarly, this is the diode chip and then these are the wires and here this is connected to these traces. So, we see here that on a common plate there are several of these devices, which are placed and you will be seeing that externally this thing will be inside a casing like this.

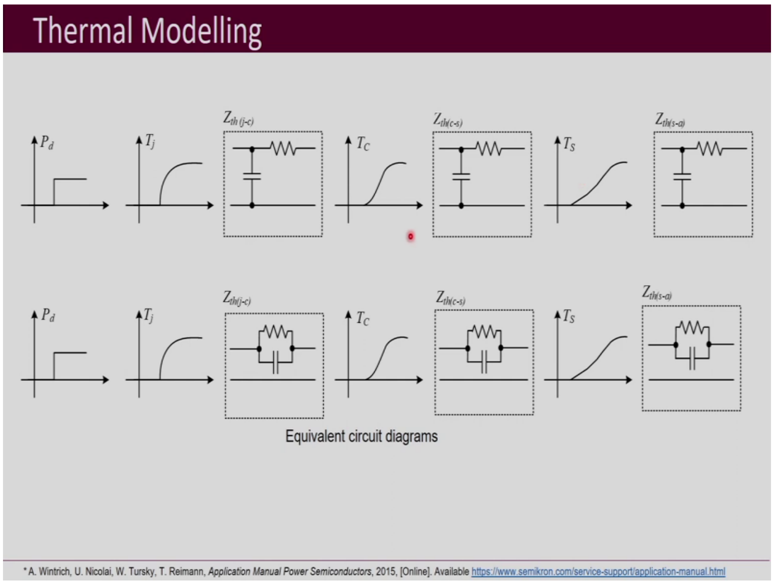
So, when heat dissipation happens inside it, sometimes the diode may be conducting or sometimes the IGBT may be conducting and we saw before that based on modulation strategy or topology and the operating point, the switching loss and conduction loss keep varying. It is a complex phenomenon. We saw that we can just have an estimate of the conduction losses and switching loss.

Further even if we estimated it, you can see the path where the heat will be distributed or the heat is going to flow, and it is not something very fixed. It is not a uniform homogeneous path that we can observe here. There are multiple components kept and there are so many things that are inside it. So, the heat distribution, the flow of heat and its conduction are not going to be very simple. It is going to be a complex phenomenon.

So, if we want to estimate the junction temperature using a model like this or just by using some experimental graphs, then it is still okay. But otherwise if we take just very simple models like this, then it will be giving us erroneous information or erroneous estimation of the junction temperatures. So, the best way to find out the junction temperature is based on thermal losses, by doing a finite element methods, which is called as a FEM analysis.

Now, in this course, we will not be looking into all that. You may be familiar with FEM. FEM is basically like a mesh analysis method where you divide the structure into very thousands of small structures and then the analysis is performed. But, that is an analysis which requires software and then you have to learn those software.

Then you have to understand how FEM can be used for finding out the rising junction temperatures based on thermal losses. So, people use much simpler models, which gives good estimations of the junction temperature, that means how the junction temperature may be varying with the power dissipations.



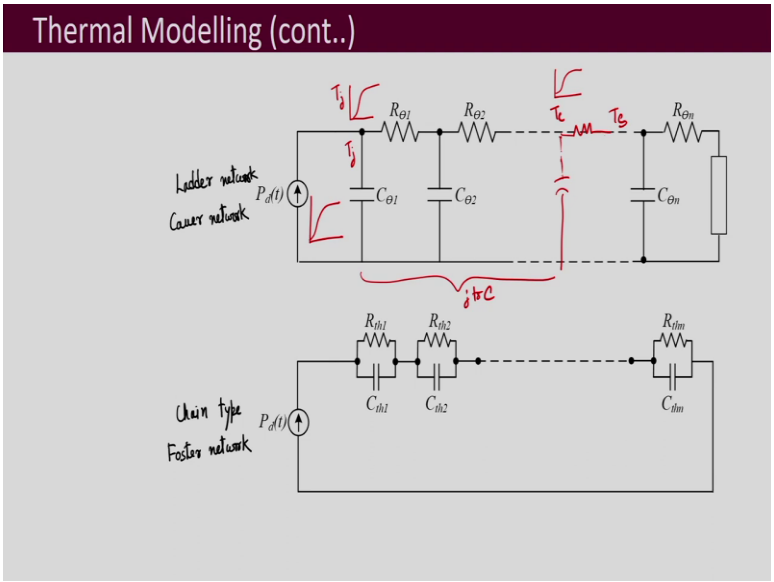
Thermal Modelling

Equivalent circuit diagrams

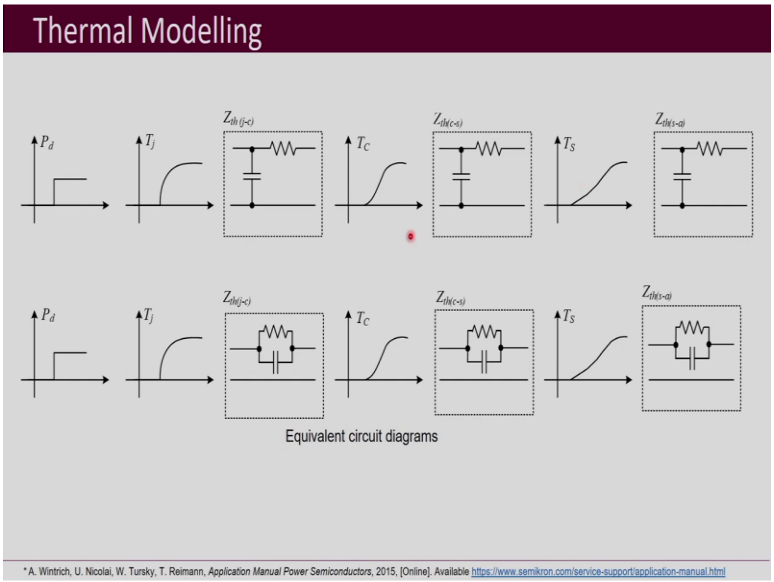
* A. Wintrich, U. Nicolai, W. Tursky, T. Reimann, *Application Manual Power Semiconductors*, 2015, [Online]. Available https://www.semikron.com/service-support/application-manual.html

So, those simplified models are based on these kind of equivalent circuits. So, this is an equivalent circuit. You can see here that this consists of a capacitor and a resistor. For junction to case this kind of an equivalent circuit can be drawn, then from case to sink another R and C circuit can be drawn and then similarly for the heat sink, sink to ambient can be drawn.

Here you observe that if this is the change in power dissipation, accordingly the response of the change in the junction temperature could be something like this and this could be for the case temperature T_c and this could be the response of the sink temperature.



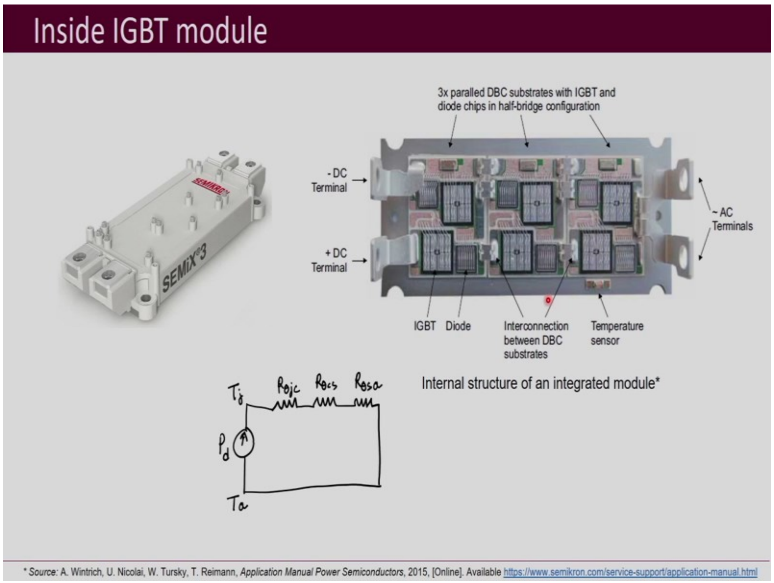
Thermal Modelling (cont..)



Thermal Modelling

Equivalent circuit diagrams

* A. Wintrich, U. Nicolai, W. Tursky, T. Reimann, *Application Manual Power Semiconductors*, 2015, [Online]. Available https://www.semikron.com/service-support/application-manual.html



Inside IGBT module

Internal structure of an integrated module*

* *Source:* A. Wintrich, U. Nicolai, W. Tursky, T. Reimann, *Application Manual Power Semiconductors*, 2015, [Online]. Available https://www.semikron.com/service-support/application-manual.html

Now, using this if we connect all of them, we will get a network kind of like this where you have this power dissipation which is in the form of a current source and then these RC equivalent circuits are just connected one after another. So, now, when we look into it, this can be modelled as several small RC circuits and then they can be connected together. Also note that there is something, what was called as thermal coupling.

It means that many times these IGBTs, diodes and many of the components are placed on the same base plate. So, if in one of the devices loss is taking place, then it is getting heated. Because of it if it is all mounted on the same base plate kept on the same base plate, then through that the heat will transfer and it will transfer to the other components as well. So, they will also get heated.

So, that means there will be thermal coupling between them. So, now, these are kind of simple *RC*. If we are connecting them, or there is connection between all these things, then they are just not individual elements and we can treat their temperatures individually as discrete and separate. So, there can be several RCs that can be there for a particular device and can be modelled now. Total no. of them may be depends on the physical structure, the experiments which the manufacturers are performing and no. of RCs, which the manufacturers are taking. So, many of them may be there or sometimes only three, four RC maybe connected. So, then this kind of connection is performing and that is called as the ladder network or also called as the cauer network. So, then this can be used to find out the junction temperature or in between different places like the case or the sink, how much is the temperature and how is the temperature varying.

So, let us say here, the power dissipation was varying in this way, then you can simulate it and then based on it, you can find out this junction temperature (T_j) over here. The junction temperature (T_j) is varying at this point. Let us say this is the case for now. These many of them can be from junction to case and then there may be few for case to sink also.

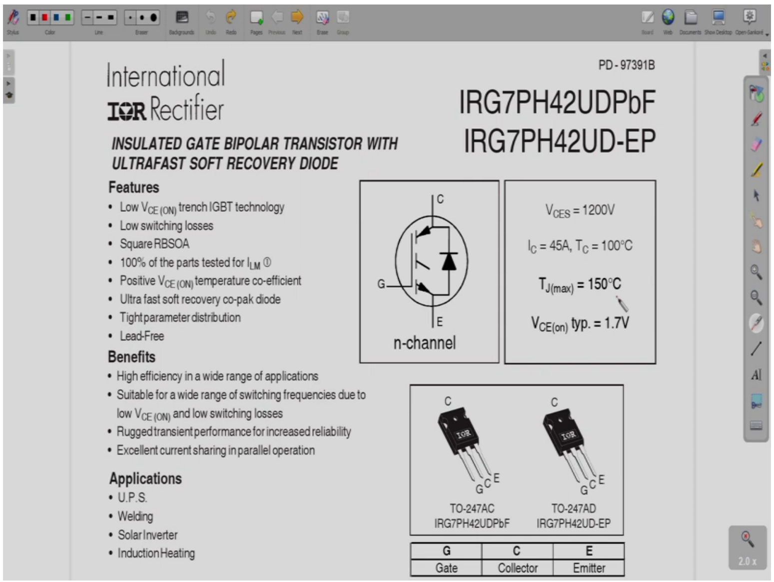
Let us say there is only one from case to sink. So, this will be for the sink temperature. So, here again you can observe how the case temperature is varying based on the power dissipation curve or whatever is the signal that is varying here. So, how is the case temperature varying and similarly, you can observe how is the sink temperature varying and then you can keep the ambient temperature fixed or that also may be varying. So, you can observe all these things.

So, these are like simplified SPICE simulations that can be performed like a very simple thermal model and then it can be used to observe how the temperatures that means the case temperature, the junction temperature or in between also the temperatures at the various places inside the module may be varying. You can get an estimate of it. Now, this is more or less based on the physical structure of the power device.

But sometimes or actually many times we are interested in this junction temperature and the case temperature. Also, we are just interested in the final nodes. We are not interested in inside what is happening. The whole of this power module can be treated like a black box. So, they are another model and that can be used when *R* and *C* are in parallel.

So, this is like another equivalent instead of this one and here *RC* is in parallel. So, you can have from junction to case, then case to sink and sink to ambient. These kind of *RC* equivalence may be there. Again you can obtain this junction temperature, case temperature, sink temperature, and how they vary the response that can be observed.

So, if we connect all of them together and then represent it in the form of a network, you will be obtaining this kind of the network. In this network it matches with this kind of response of only the input and the output temperature. So, only if we are interested in the final junction temperature, then this model can also be used. So, this is also called as the chain type network and it is also known as the foster network. Now, manufacturers of data sheets may or may not provide these information or R and C values of the foster or cauer network. It depends on some of the manufacturers. Some of them provide or some do not.



International
IOR Rectifier

PD - 97391B

IRG7PH42UDPbF
IRG7PH42UD-EP

INSULATED GATE BIPOLAR TRANSISTOR WITH ULTRAFAST SOFT RECOVERY DIODE

Features
- Low $V_{CE\,(ON)}$ trench IGBT technology
- Low switching losses
- Square RBSOA
- 100% of the parts tested for I_{LM} ①
- Positive $V_{CE\,(ON)}$ temperature co-efficient
- Ultra fast soft recovery co-pak diode
- Tight parameter distribution
- Lead-Free

Benefits
- High efficiency in a wide range of applications
- Suitable for a wide range of switching frequencies due to low $V_{CE\,(ON)}$ and low switching losses
- Rugged transient performance for increased reliability
- Excellent current sharing in parallel operation

Applications
- U.P.S.
- Welding
- Solar Inverter
- Induction Heating

$V_{CES} = 1200V$

$I_C = 45A$, $T_C = 100°C$

$T_{J(max)} = 150°C$

$V_{CE(on)}$ typ. = 1.7V

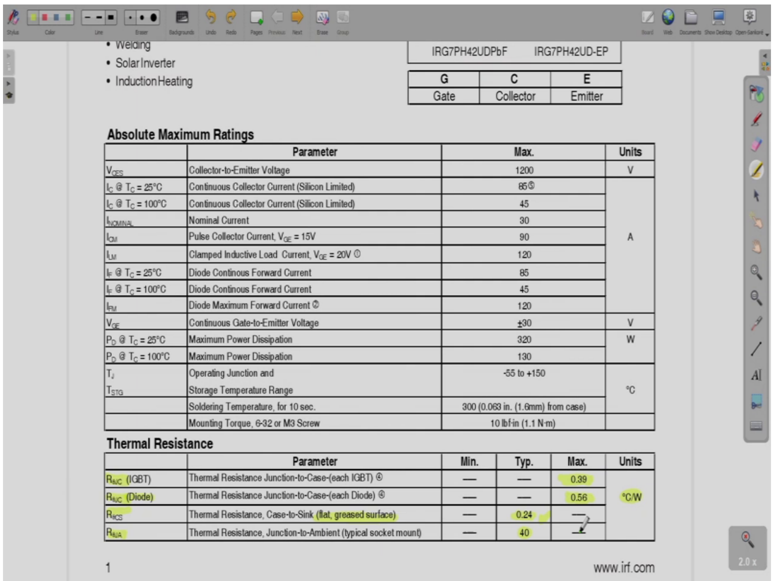
TO-247AC
IRG7PH42UDPbF

TO-247AD
IRG7PH42UD-EP

G	C	E
Gate	Collector	Emitter

Now, let us look into the data sheets of some of the devices. This is the datasheet of an IGBT and the ratings are *1200 V* and current rating in case temperature of *100*°C, is *45* A. This collector to emitter on state voltage drop ($V_{CE(on)}$) is typical voltage drop and it is *1.7 V*. Maximum junction temperature is given as *150*°C.

Now, we have looked at into this datasheet before and at that time I discussed several of the parameters that are mentioned in this datasheet. But I had skipped the terms which are associated with a thermal design. So, let us look into those now. So, here you see that the maximum junction temperature is mentioned here, which is *150*°C. Now, let us see further.



- Welding
- Solar Inverter
- Induction Heating

IRG7PH42UDPbF	IRG7PH42UD-EP	
G	C	E
Gate	Collector	Emitter

Absolute Maximum Ratings

	Parameter	Max.	Units
V_{CES}	Collector-to-Emitter Voltage	1200	V
I_C @ T_C = 25°C	Continuous Collector Current (Silicon Limited)	85⑤	A
I_C @ T_C = 100°C	Continuous Collector Current (Silicon Limited)	45	
$I_{NOMINAL}$	Nominal Current	30	
I_{CM}	Pulse Collector Current, V_{GE} = 15V	90	
I_{LM}	Clamped Inductive Load Current, V_{GE} = 20V ①	120	
I_F @ T_C = 25°C	Diode Continous Forward Current	85	
I_F @ T_C = 100°C	Diode Continous Forward Current	45	
I_{FM}	Diode Maximum Forward Current ②	120	
V_{GE}	Continuous Gate-to-Emitter Voltage	±30	V
P_D @ T_C = 25°C	Maximum Power Dissipation	320	W
P_D @ T_C = 100°C	Maximum Power Dissipation	130	
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to +150	°C
	Soldering Temperature, for 10 sec.	300 (0.063 in. (1.6mm) from case)	
	Mounting Torque, 6-32 or M3 Screw	10 lbf·in (1.1 N·m)	

Thermal Resistance

	Parameter	Min.	Typ.	Max.	Units
$R_{\theta JC}$ (IGBT)	Thermal Resistance Junction-to-Case-(each IGBT) ④	—	—	0.39	°C/W
$R_{\theta JC}$ (Diode)	Thermal Resistance Junction-to-Case-(each Diode) ④	—	—	0.56	
$R_{\theta CS}$	Thermal Resistance, Case-to-Sink (flat, greased surface)	—	0.24	—	
$R_{\theta JA}$	Thermal Resistance, Junction-to-Ambient (typical socket mount)	—	40	—	

1 www.irf.com

So, further what we see here that this is the thermal resistance junction to case. Now, this is the steady state resistance and you can see here this is given as *0.39*. So, $R_{\theta JC}$ is *0.39* which is mentioned. It has got an anti-parallel diode. So, that is also given for the diode which is *0.56*. So, thermal resistance of the diode is more and from case to sink this is given is *0.24*.

Now, they have mentioned *0.24*. But, you should note that for what they have mentioned. They have written that for flat and greased surface. The case to sink typical thermal resistance that you may get is about *0.24*. The total thermal resistance is from junction to ambient that means it is the sum of the junction to case, case to sink and then sink to ambient. So, if we add up all of them, it could be about *40* as the typical value. So, *°C/W* is the unit in which this thermal resistance is provided.

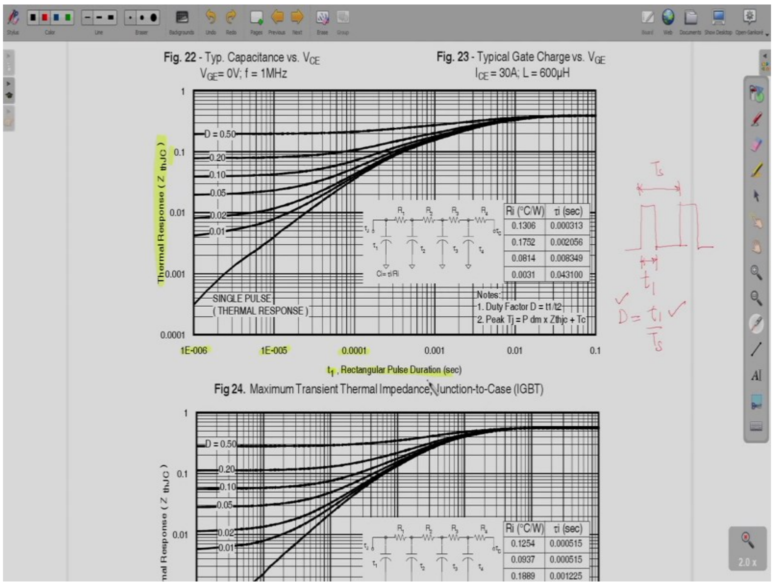


Fig. 22 - Typ. Capacitance vs. V_{CE}
V_{GE} = 0V; f = 1MHz

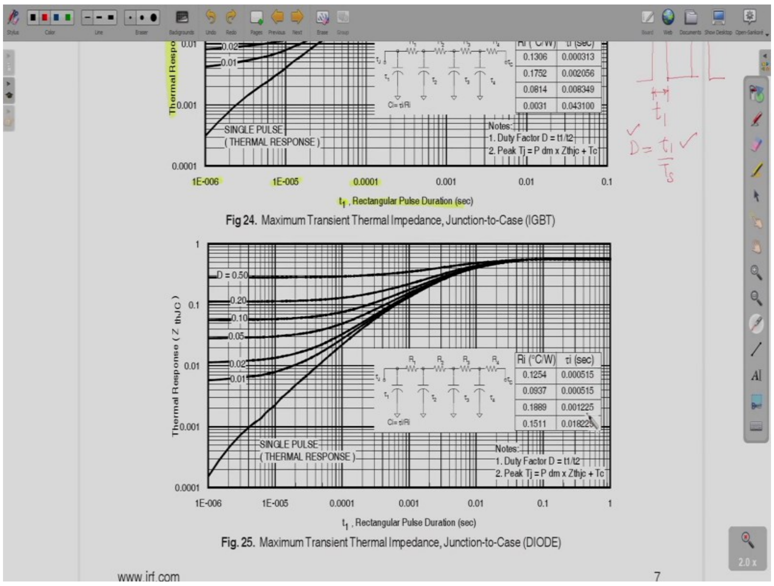
Fig. 23 - Typical Gate Charge vs. V_{GE}
I_{CE} = 30A; L = 600µH

Ri (°C/W)	τi (sec)
0.1306	0.000313
0.1752	0.002056
0.0814	0.008349
0.0031	0.043100

Notes:
1. Duty Factor D = t1/t2
2. Peak Tj = P dm x Zthjc + Tc

Fig 24. Maximum Transient Thermal Impedance, Junction-to-Case (IGBT)

Ri (°C/W)	τi (sec)
0.1254	0.000515
0.0937	0.000515
0.1889	0.001225



Ri (°C/W)	τi (sec)
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0.0814	0.008349
0.0031	0.043100

Notes:
1. Duty Factor D = t1/t2
2. Peak Tj = P dm x Zthjc + Tc

Fig 24. Maximum Transient Thermal Impedance, Junction-to-Case (IGBT)

Ri (°C/W)	τi (sec)
0.1254	0.000515
0.0937	0.000515
0.1889	0.001225
0.1511	0.018225

Notes:
1. Duty Factor D = t1/t2
2. Peak Tj = P dm x Zthjc + Tc

Fig. 25. Maximum Transient Thermal Impedance, Junction-to-Case (DIODE)

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So, further if we look for thermal characteristics in the datasheet, you will observe that these two graphs are provided and these are the thermal impedance graphs. So, here what we observed that this is the thermal response that means it is the thermal impedance from junction to case and on this x axis these are t_p value or t_1 which is written over here. It is denoted as t_1, which is the rectangular pulse duration.

So, that means if you have a rectangular pulse like this and the duration of this pulse is t_1, with respect to that the thermal impedance is measured over here. So, this is the thermal impedance which is provided and then you see that finally it reaches to this value which will be usually close to steady state values. Now, this is for single pulse. It means that you just give a pulse like this and after that you stop that. It means that it is not a repetitive pulse.

Then it also gives other graphs. You can see here that this is written is *0.01*, *0.02*, *0.05*, *0.1*, *0.2*, *0.5*. So, these are the duty ratios. So, if we have a repetitive pulse like this, and the time period over here is T_s. So, duty ratio will be t_1/T_s. So, t_1 value is given and duty ratio value is also given. So, you can definitely find out the T_s value there.

So, for those kind of repetitive pulses, these thermal response that means the thermal impedances are also provided here. Now, this kind of a network is provided and you can see here that this node is written as T_J that means it is the junction temperature node and T_c is the case temperature node. So, in between that four *RC* have been connected.

So, they have divided the junction to case into four *RCs*. I told you that there can be several *RC* which can be connected. It depends on how many times they want to divide the structure into. So, here the manufacturer has shown four *RC*s and you can see that that those R_1 values are also given here for these four R's. Then instead of giving the value of capacitance directly, they have given the time constants for each one of them. So, you can find out the capacitance values also.

So, this over here is denoted as τ_1, τ_2, τ_3, τ_4. These are the time constants. So, from here you can get an idea of the simple model of the cauer network and then also from there you can see how the junction temperature may be varying, based on the power distribution. Now, further we see that there is another graph which is shown below and this is the junction to case for the diode.

So, this graph is for the diode and the upper one is for the IGBT. So, the same thing is provided for the diode also. You can see here that these are the duration of the rectangular pulses and then based on a single pulse first this thermal response is given, the value of thermal impedances are provided. Then further for different values of duty ratios also they are provided and then this cauer network that they have used for this diode, which is with parallel to IGBT, for that also they have given the value.

So, you can see these resistances here and for the Diode Model they have provided those and also the corresponding time constants are given here.

PD - 95664

International
IOR Rectifier

SMPS MOSFET

IRFP90N20DPbF

HEXFET® Power MOSFET

Applications

- High frequency DC-DC converters
- Lead-Free

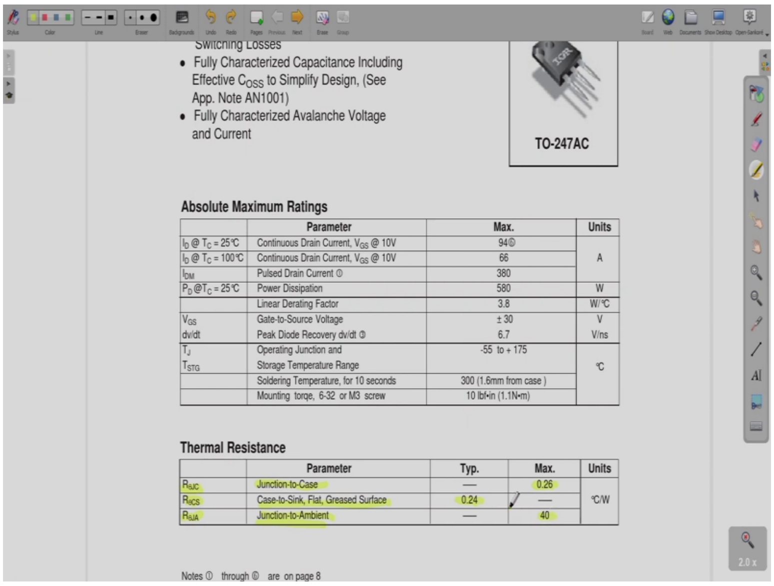
V_{DSS}	$R_{DS(on)}$ max	I_D
200V	0.023Ω	94A⑥

Benefits

- Low Gate-to-Drain Charge to Reduce Switching Losses
- Fully Characterized Capacitance Including Effective C_{OSS} to Simplify Design, (See App. Note AN1001)
- Fully Characterized Avalanche Voltage and Current

Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	94⑥	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	66	
I_{DM}	Pulsed Drain Current ①	380	
P_D @T_C = 25°C	Power Dissipation	580	W
	Linear Derating Factor	3.8	W/°C
V_{GS}	Gate-to-Source Voltage	± 30	V
dv/dt	Peak Diode Recovery dv/dt ③	6.7	V/ns



Switching Losses

- Fully Characterized Capacitance Including Effective C_{OSS} to Simplify Design, (See App. Note AN1001)
- Fully Characterized Avalanche Voltage and Current

Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	94⑥	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	66	
I_{DM}	Pulsed Drain Current ①	380	
P_D @T_C = 25°C	Power Dissipation	580	W
	Linear Derating Factor	3.8	W/°C
V_{GS}	Gate-to-Source Voltage	± 30	V
dv/dt	Peak Diode Recovery dv/dt ③	6.7	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to + 175	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torqe, 6-32 or M3 screw	10 lbf•in (1.1N•m)	

Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	0.26	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	0.24	—	
$R_{\theta JA}$	Junction-to-Ambient	—	40	

Notes ① through ⑥ are on page 8

Now, let us look into the datasheet of a MOSFET. We have also discussed this datasheet before. Now, here we will be just looking into again those things which are important from thermal design perspective. So, this is *200 V*, *94 A* MOSFET and this is the $R_{DS(on)}$ value which is provided here. You can use this for the conduction loss calculation.

In conduction loss and switching loss calculation using the different parameters the turn on times, turn off times are provided in the datasheet. Those also in great length we have discussed when we discussed the power semiconductor devices. So, I am not revisiting those things again here. So, now, here you can see that this is the junction to case thermal resistance which is provided as *0.26* for the MOSFET.

Now, in this case, we see that for the diode separately it is not provided. Because it is part of the MOSFET itself. It has the body diode. Then the case to sink is of grease to surface flat greased surface and typical value of this is *0.24*. The junction to ambient for this device is giving us *40 ºC/W*.

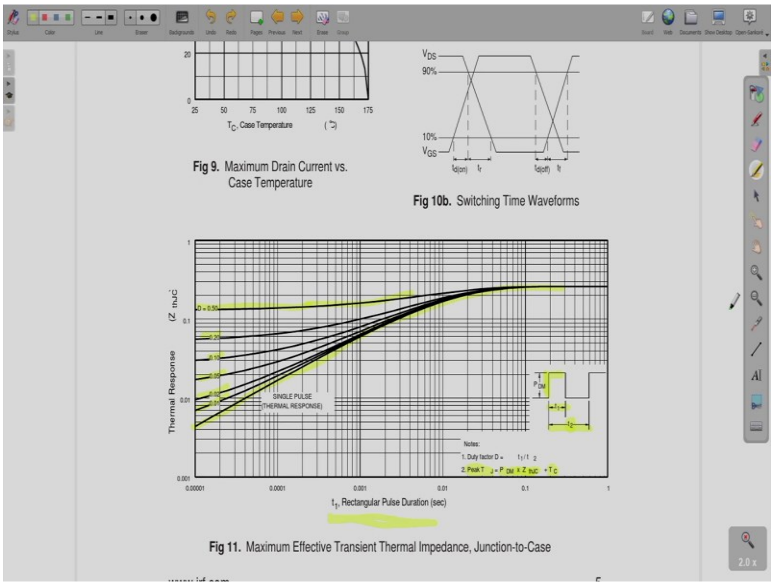


Fig 9. Maximum Drain Current vs. Case Temperature

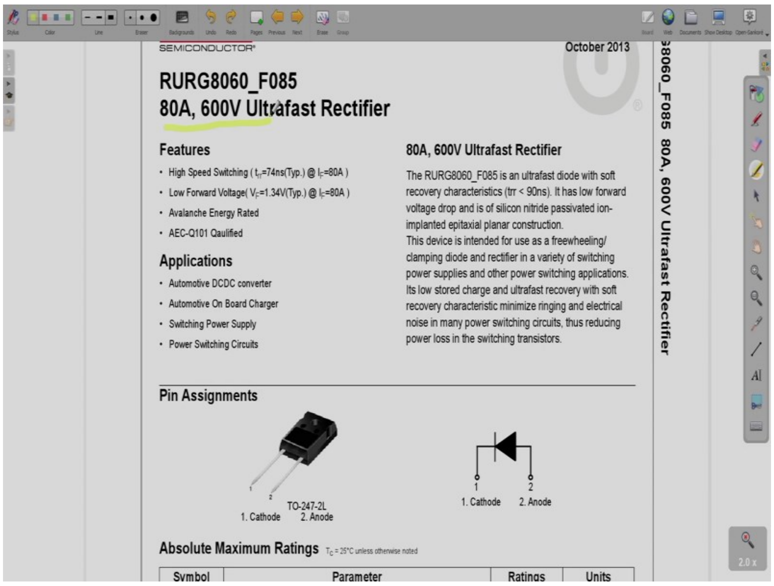
Fig 10b. Switching Time Waveforms

Fig 11. Maximum Effective Transient Thermal Impedance, Junction-to-Case

Now, here you can see that this is the rectangular pulse duration. So, this is the rectangular pulse and the time period of the repetitive pulse denoted here is t_2 and P_{DM} is the magnitude of the power dissipation. So, if we have to calculate the peak temperature junction temperature (T_J), you will be using the formula of P_{DM}. The peak temperature junction temperature (T_J) will be this P_{DM} into thermal impedance plus the case temperature T_C.

So, here you can see that this is for the single pulse that means it is non repetitive and then for that if you give repetitive pulses, the duty ratios are provided over here and the thermal response, the thermal impedance are given over here. So, this is something similar to the previous datasheet of IGBT.

But no doubt is here that they have not given any equivalent circuit and those *RC* values are not provided. So, I was telling you that it depends on the manufacturer. Some manufacturers provide and some of them do not provide. Those networks could be used for seeing how the temperatures may be varying.



SEMICONDUCTOR®

October 2013

RURG8060_F085

80A, 600V Ultrafast Rectifier

Features

- High Speed Switching (t_{rr}=74ns(Typ.) @ I_F=80A)
- Low Forward Voltage(V_F=1.34V(Typ.) @ I_F=80A)
- Avalanche Energy Rated
- AEC-Q101 Qaulified

Applications

- Automotive DCDC converter
- Automotive On Board Charger
- Switching Power Supply
- Power Switching Circuits

80A, 600V Ultrafast Rectifier

The RURG8060_F085 is an ultrafast diode with soft recovery characteristics (trr < 90ns). It has low forward voltage drop and is of silicon nitride passivated ion-implanted epitaxial planar construction.

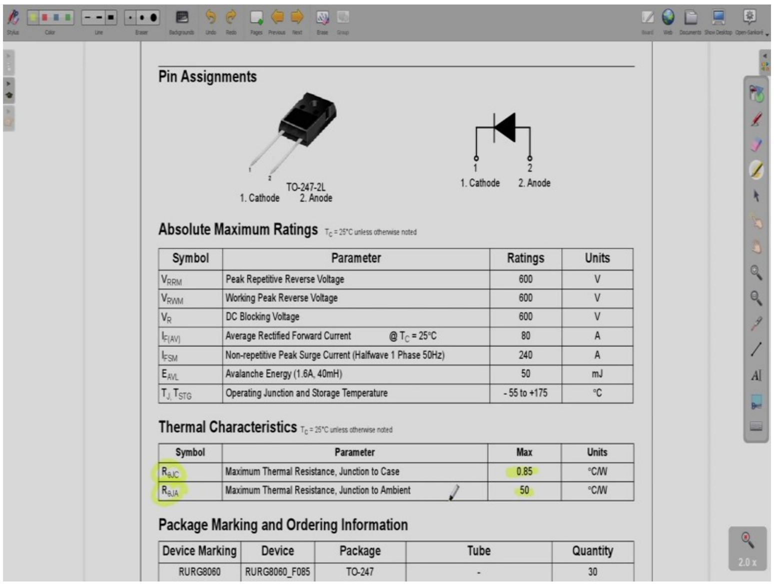
This device is intended for use as a freewheeling/ clamping diode and rectifier in a variety of switching power supplies and other power switching applications. Its low stored charge and ultrafast recovery with soft recovery characteristic minimize ringing and electrical noise in many power switching circuits, thus reducing power loss in the switching transistors.

8060_F085 80A, 600V Ultrafast Rectifier

Pin Assignments

Absolute Maximum Ratings T_C = 25°C unless otherwise noted

Symbol	Parameter	Ratings	Units



Pin Assignments

Absolute Maximum Ratings T_C = 25°C unless otherwise noted

Symbol	Parameter	Ratings	Units
V_{RRM}	Peak Repetitive Reverse Voltage	600	V
V_{RWM}	Working Peak Reverse Voltage	600	V
V_R	DC Blocking Voltage	600	V
$I_{F(AV)}$	Average Rectified Forward Current @ T_C = 25°C	80	A
I_{FSM}	Non-repetitive Peak Surge Current (Halfwave 1 Phase 50Hz)	240	A
E_{AVL}	Avalanche Energy (1.6A, 40mH)	50	mJ
T_J, T_{STG}	Operating Junction and Storage Temperature	- 55 to +175	°C

Thermal Characteristics T_C = 25°C unless otherwise noted

Symbol	Parameter	Max	Units
$R_{\theta JC}$	Maximum Thermal Resistance, Junction to Case	0.85	°C/W
$R_{\theta JA}$	Maximum Thermal Resistance, Junction to Ambient	50	°C/W

Package Marking and Ordering Information

Device Marking	Device	Package	Tube	Quantity
RURG8060	RURG8060_F085	TO-247	-	30

Now, let us look for those same things in the datasheet of a diode. So, this is fast recovery diode of *80 A, 600* V. We see from here that in this thermal characteristics, junction to case resistance and junction to ambient resistance are provided. So, junction to case thermal resistance is *0.85* and *50* could be the maximum thermal resistance from junction to ambient.

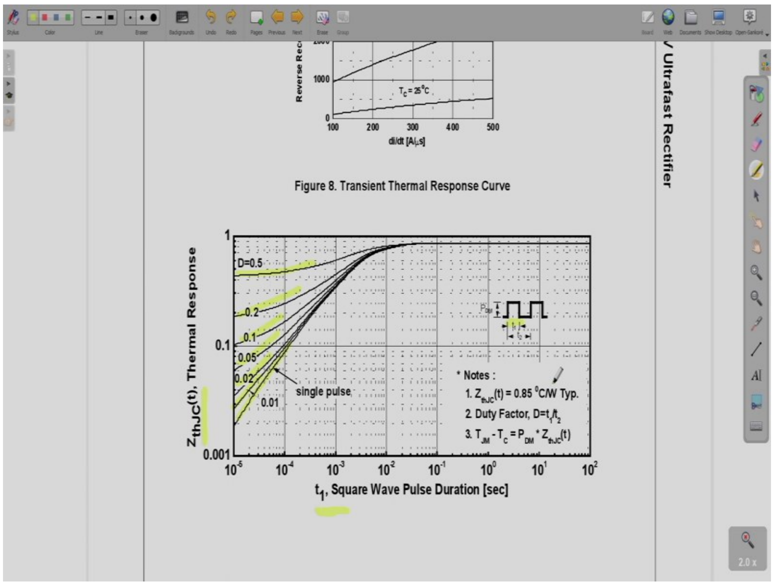
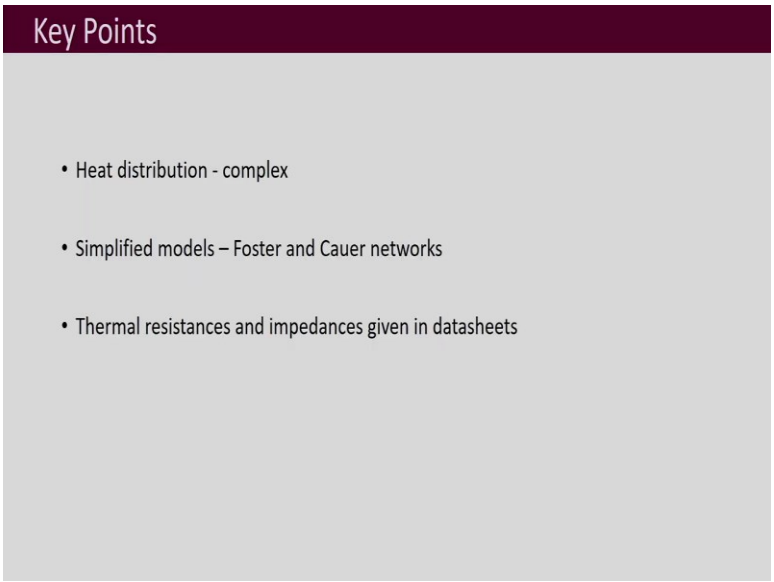


Figure 8. Transient Thermal Response Curve

Here, you can see that in the thermal response the thermal impedance graph is provided. The same thing is that thermal impedance is Z_{thJC} and t_1 is the square wave duration. So, for the single pulse and for repetitive pulses of different duty ratios also these graphs are provided and I mean you can use it in a similar way that we saw for MOSFET and IGBT.


Key Points

- Heat distribution - complex
- Simplified models – Foster and Cauer networks
- Thermal resistances and impedances given in datasheets

So, the key points of this lecture are that the heat distribution in device is a complex phenomenon. There are many complex methods by which the junction temperature could be analyzed. But usually for power electronic engineers, they are more complicated and people like to use simple models and simplified models like foster and cauer networks, which can be used for finding out the input temperatures and the output temperature, the junction temperature (T_J) without going into a lot of details.

In the data sheets by manufacturers, sometimes they give the information for Cauer networks or sometimes they do not. But, in all the data sheets they provide the information of thermal resistances of the device and the thermal impedance graphs of the device. Thank you.