EE-365 - W2 SEMICONDUCTORS

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SEMICONDUCTOR DEVICES

DIODE, BJT, MOSFET, IGBT, IGCT...

SEMICONDUCTOR DEVICES

There is a large number of semiconductor devices and technologies already in the existence

In terms of involved semiconductor materials

- Silicone (**Si**) based devices - state-of-the-art, well established, proven, cheap
- Silicone Carbide (**SiC**) based devices - available, increased performances: switching speeds, thermal
- Gallium Nitride (**GaN**) based devices - emerging (available) yet somewhat limited to lower voltages

Real semiconductor devices are characterized with:

- limited blocking voltages - not infinite, e.g. 600V, 1.2kV, 1.7kV, 3.3kV, 4.5kV, 6.5kV
- limited conducting current - not infinite, e.g. 1A, 10A, 1kA
- limited switching speed or transition from blocking to conducting state - not zero

We can classify devices, considering their controllability:

- Diodes: on and off states are controlled by the external electrical circuit
- Thyristors: turned on by external signal, but turned off by the external electrical circuits
- Controllable devices that are turned on and off by the external signal: BJT, MOSFET, IGBT, GTO, IGCT

While the ideal devices do not exists, they are often very useful to analyze electrical circuits

Discussion and analysis is mostly restricted to **Si**-based devices

DIODE

Diode is a two terminal device (*Anode, Kathode*) that is controlled by the external electrical circuit conditions

- when a diode is forward biased ($v_{AK} = v_D > 0$) it begins to conduct - **on state**
- during conduction, voltage drop across the diode is rather low - $V_F(I) \approx 1\text{V}$
- when a diode is reverse biased ($v_{AK} = v_D < 0$) it blocks the voltage - **off state**
- during blocking, small leakage current (negative current) flows through a diode
- if external circuit negative voltage exceeds diode reverse blocking diode will be damaged

Considering low forward voltage drop and low leakage current, idealized characteristic can be used for the circuit analysis

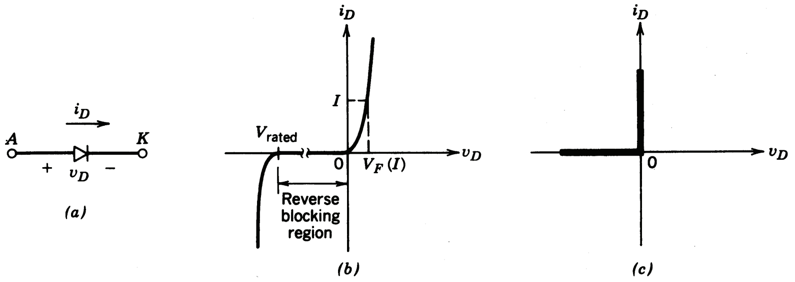


Figure 1 Diodes: a) symbol, b) I-V characteristic (static), c) idealized characteristic.

DIODE CONDUCTION LOSSES

Conduction losses of diodes can be calculated with help of data sheets

The first step is simplification of diode forward characteristics:

- diode forward characteristics can be linearized around operating current value
- temperature affect characteristic and is not the same at $T_j = 25^\circ$ or $T_j = 125^\circ$
- V_{th}: models the treshold voltage
- R_D: models a dynamic resistance
- complete diode is modelled as series connection of source V_{th} and R_D

Conduction losses are the average power dissipated in the diode

$$P_{cond} = \frac{1}{T}\int_0^T V_F(I_F) \cdot I_F(t)dt$$

Considering that average and rms diode currents are:

$$I_{F-AV} = \frac{1}{T}\int_0^T I_F(t)dt, \qquad I_{F-RMS} = \sqrt{\frac{1}{T}\int_0^T I_F^2(t)dt}$$

Taking into account diode model, we have:

$$P_{cond} = V_{th} \cdot I_{F-AV} + R_D \cdot I_{F-RMS}^2$$

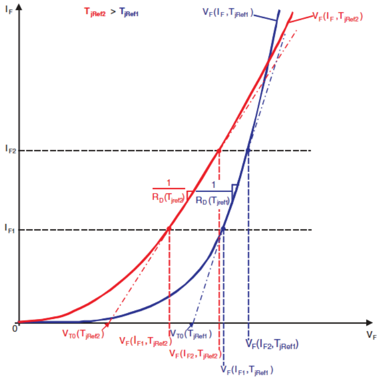


Figure 2 Linearization of diode characteristics.

DIODE SWITCHING CHARACTERISTICS

Power diode switching waveforms will depend on:

- the external circuit conditions where diode is used
- diode characteristics and technologies involved

Diodes are often used in circuits involving inductances where di/dt is limited

Example switching waveforms:

- before t_1: diode is off, blocking negative voltage and with zero current
- during $t_1 - t_2$: turn on with limited di/dt, followed with minor voltage overshoot
- between t_2 and t_3: diode is on and conducts current determined by external circuit
- during t_3: start of turn-off process, current reaches zero
- during t_4: current goes negative in order to remove stored charges
- during t_5: once diode voltage goes negative, diode currents falls to zero
- after t_5: diode is off, blocking negative voltage and with zero current

Diode reverse recovery data are part of data sheets

- Q_{rr} - recovered charge
- $t_{rr} = t_4 + t_5$ - reverse recovery time

Fast-recovery diodes have smaller reverse-recovery time compared to line diodes

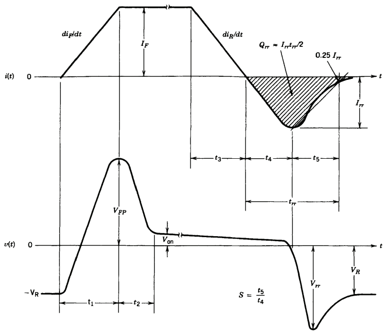


Figure 3 Diode characteristics voltage and current waveforms.

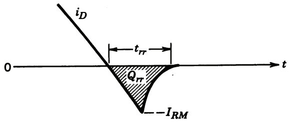


Figure 4 Reverse recovery during turn-off.

Depending on the application requirements, various types of diodes are available:

Schottky diodes

- characterized by very low voltage drop, typically around 0.3V
- their blocking voltages are limited to 50V - 100V
- higher blocking voltages are possible with **SiC**-devices

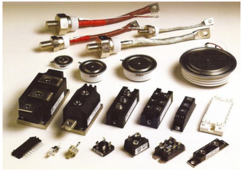
Fast-recovery diodes

- used together with other controllable switches at high frequencies
- characterized with low t_{rr} in the range of few μs

Line-frequency diodes

- designed for low on-state voltage and low-frequency applications, e.g. 50Hz
- as a trade-off they have rather large t_{rr}
- available in high voltage (kV) and current (kA) ratings

Diodes can be packaged differently, either as single devices or electric circuits



CONTROLLABLE SWITCHES

There are two types of semiconductor devices with no or limited controllability

- Diodes: on and off states are controlled by the external electrical circuit
- Thyristors: turned on by external signal, but turned off by the external electrical circuits (will be covered later)

For most of converters we actually need controllable semiconductor devices

Controllable devices that are turned on and off by the external control signal:

- BJT - Bipolar Junction Transistor
- **MOSFET** - Metal Oxide Semiconductor Field Effect Transistor
- IGBT - Insulated Gate Bipolar Transistor
- GTO - Gate Turn-Off Thyristor
- IGCT - Integrated Gate Commutated Thyristor

Converter design and operating characteristics must take into account semiconductor properties:

- device blocking voltages
- device rated currents
- device switching speed
- gate drive requirements
- device packaging and thermal capabilities

BJT is a three terminal device (*Collector, Emitter, Base*) that is fully controlled

- BJT were much more used in the past, and rather rarely today
- internally it is a three (four) layer structure of differently doped material, but with two pn junctions
- npn BJTs are more used then pnp BJTs
- load current flows from collector to emitter, with low drop across device (saturation)
- it is a current controlled device and base current must be continuously supplied to keep device on
- base current must be sufficiently high $I_B > I_C/h_{FE}$, where h_{FE} is DC gain of the device
- negative temperature coefficient causes certain issues with paralleling and current sharing
- MOSFET and IGBTs are rather used today instead of BJTs

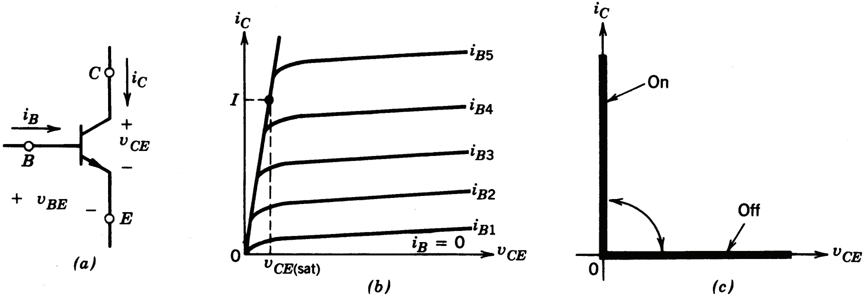


Figure 5 A BJT: a) symbol for npn BJT, b) I-V characteristic (static), c) idealized characteristic.

MOSFET is a three terminal device (*Drain, Source, Gate*) that is fully controllable

- MOSFET is a voltage controlled device and widely used today
- V_{GS} must be above threshold value $V_{GS(th)}$ for device to be turned on
- V_{GS} must be continuously applied for device to be in on-state
- however, no gate current flows, except during switching transition when gate capacitance is charged or discharged
- MOSFET switching times are very low (tens or hundreds of ns) allowing for high switching frequencies
- MOSFET on-state resistance $r_{DS(on)}$ is low, but increases with device blocking ratings, $r_{DS(on)} = kBV_{DSS}^{2.5-2.7}$
- positive temperature coefficient allow easy paralleling of devices and good current sharing

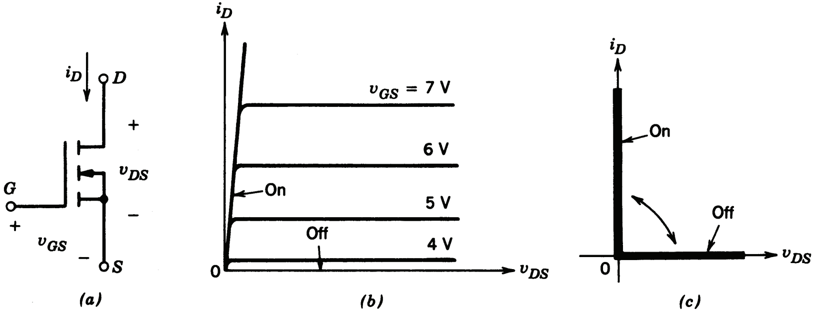


Figure 6 A MOSFET: a) symbol for n-channel MOSFET, b) I-V characteristic (static), c) idealized characteristic.

GTO is a three terminal device (*Anode, Cathode, Gate*) that is fully controllable

- like the Thyristor, GTO can be turned on by a short gate pulse (once forward biased)
- once on and conducting, GTO does not require gate current to be present
- unlike the Thyristor, GTO can be turned off by applying negative gate-cathode voltage
- this causes negative gate-cathode current for short period, that is typically very large (e.g. one third of anode current)
- GTO can block negative voltages
- practical circuits with GTO require snubbers (RCD) to reduce dv/dt at turn-off

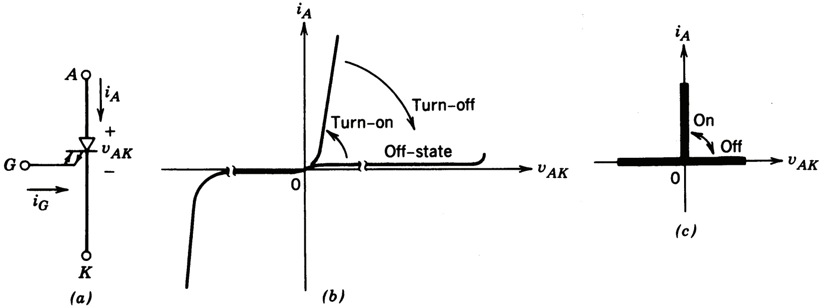


Figure 7 A GTO: a) symbol, b) I-V characteristic (static), c) idealized characteristic.

IGBT

IGBT is a three terminal device (*Collector, Emitter, Gate*) that is fully controllable

- IGBT is voltage controlled, like MOSFET, and requires little energy for turn-on
- IGBT has low on-state voltage drop, like BJT, even for large voltage blocking devices
- IGBT can be designed to block negative voltages, like GTO
- IGBT switching times are low (few μs) allowing for high switching frequencies (not as high as MOSFET)
- commercially available voltage ratings go up to $6.5kV$

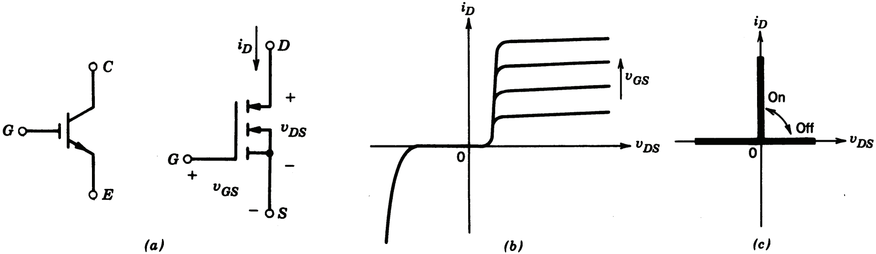


Figure 8 A IGBT: a) symbol, b) I-V characteristic (static), c) idealized characteristic.

Ideal switch is characterized:

- when OFF - blocks arbitrary large forward and reverse voltages
- when OFF - no (leakage) current flow through the switch
- when ON - conducts arbitrary large current
- when ON - has zero voltage drop across the switch
- when SWITCHING - reaction and transition is instantaneous
- when SWITCHING - requires no power on the control terminal
- when in USE - produces no losses

Real switches are somewhat different:

- when OFF - blocks according to designed voltage class
- when OFF - leakage current flow through the switch
- when OFF - produces (negligible) Blocking losses
- when ON - conducts up to defined current values
- when ON - has low voltage drop across the switch
- when ON - produces Conduction losses
- when SWITCHING - reaction and transition are with delays
- when SWITCHING - requires (small) control power
- when SWITCHING - produces Switching losses
- when in USE - still efficient, despite all of the above

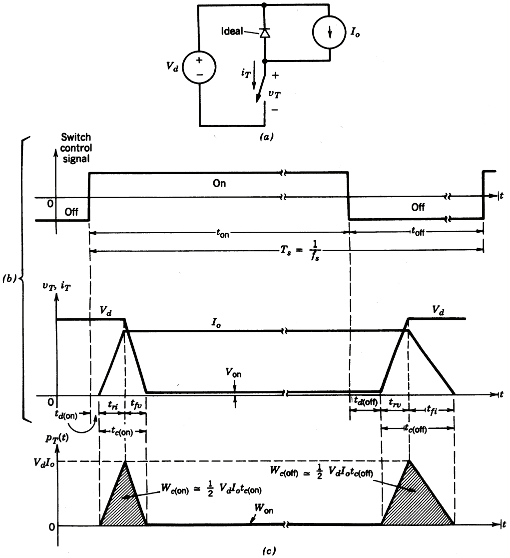


Figure 9 Generic switching voltage and current waveforms (including losses).

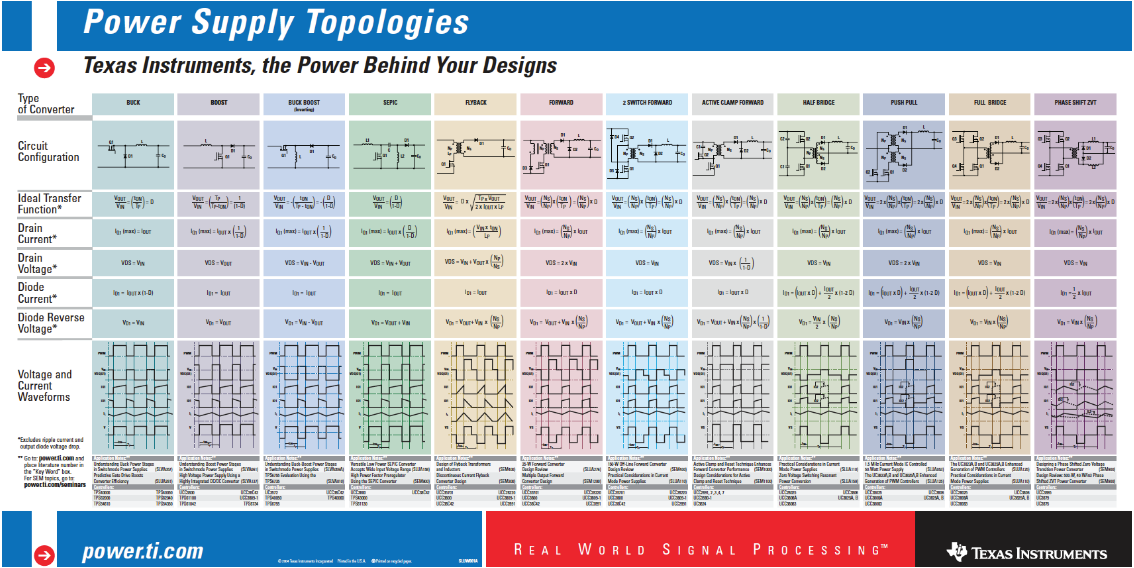


Figure 10 Texas Instruments SMPS poster - observe stresses provided for the main devices.

MOSFET AND DIODE SELECTION, RMS AND AVG CALCULATIONS

Adequate MOSFET and DIODE should be selected considering:

- Maximum voltage stress of the MOSFET in the circuit
- Maximum current of the MOSFET in the circuit
- Maximum voltage stress of the DIODE in the circuit
- Maximum current stress of the DIODE in the circuit

- Use theory/PLECS to determine stresses
- Determined values are minimum requirements
- List of devices is provided to you
- Choose final devices accordingly
- Verify

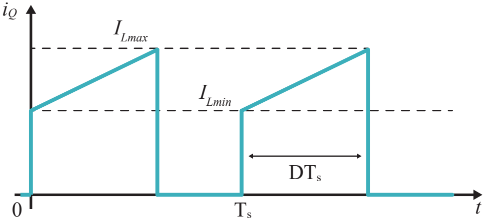


Figure 11 Current waveform of the MOSFET in the steady-state (Buck)

Expressions for RMS and AVERAGE current can be easily derived

- recall basic definition for RMS calculation

$$I_{rms} = \sqrt{\frac{1}{T_s}\int_0^{T_s} i^2(t)dt}$$

- recall basic definition for AVG calculation

$$I_{avg} = \frac{1}{T_s}\int_0^{T_s} i(t)dt$$

- from the typical current waveforms define $i(t)$ for MOSFET
- from the typical current waveforms define $i(t)$ for DIODE
- these calculations are available in many textbooks

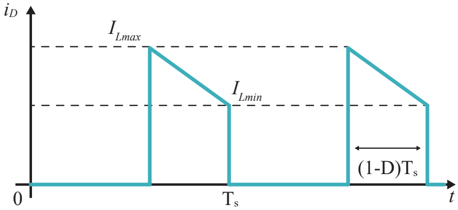


Figure 12 Current waveforms of the diode in the steady-state (Buck)

SEMICONDUCTOR SELECTION

Table 1 The list of offered MOSFET devices. The parameter U_{ds} is the rated drain-source voltage, whereas the I_{cont} stands for continuous drain-source current. All devices are in the TO-220 package.

No.	**Manufacturer**	**Product**	U_{ds} (V)	I_{cont} (A)	$R_{ds,on}$ @ 25 °C (mΩ)
1	Infineon	IRFB5620PbF	200	18	60
2	Rohm	RCX300N20	200	16.3	60
3	Onsemi	FDPF18N20FT-G	200	10.8	120
4	Rohm	RCX200N20	200	10.8	100
5	Onsemi	FQPF630	200	6.3	340
6	Nexperia	PHP18NQ11T	110	13	80
7	Vishay	SiHF530	100	10	160
8	ST	STP16NF06	60	11	80

Table 2 The list of offered Schottky diode devices. The parameter U_{dc} refers to the maximum dc blocking voltage, whereas I_{cont} is the continuous forward current. All devices are in the TO-220 package

No.	**Manufacturer**	**Product**	U_{dc} (V)	I_{cont} (A)	U_f @ 25 °C (V)
1	Taiwan	MBR16150	150	16	0.95
2	Taiwan	SRAF10150	150	10	0.95
3	Onsemi	MBR10100G	100	10	0.70
4	ST	STPS20SM60	60	20	0.57
5	Onsemi	MBR1660	60	16	0.75
6	Vishay	VT3045BP	45	30	0.58
7	Vishay	VFT2045BP	45	20	0.57
8	Vishay	VS-12TQ045-M3	45	15	0.56

MOSFET AND DIODE POWER LOSSES

MOSFET power losses

- Use INFINEON Application Note
- Use Data Sheet of your MOSFET
- Define your operating point
- Use your RMS value for that operating point

- MOSFET has no threshold voltage
- Dynamic resistance R_{DSon} is *available* in data sheet
- Switching losses require slightly more involved calculation
- Turn-on and Turn-off currents are seen from waveforms
- Rise and fall times can be calculated from data sheets

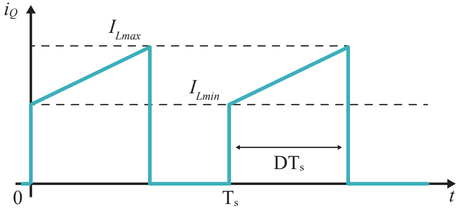


Figure 13 Current waveform of the MOSFET in the steady-state

DIODE power losses

- Use INFINEON Application Note
- Use Data Sheet of your DIODE
- Keep the same operating point as for MOSFET
- Use your RMS and AVG values for that operating point

- DIODE has threshold voltage u_{D0}
- Dynamic resistance R_D is *available* in data sheet
- Linearize on-state characteristics of your device
- Reverse recovery losses will be neglected for calculations
- Verify that your numbers make sense

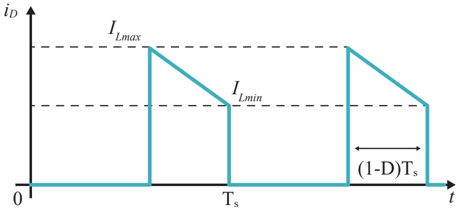


Figure 14 Current waveforms of the diode in the steady-state

MOSFET conduction losses

- INFINEON Application Note has all details

$$P_{T,cond} = R_{T,on} \cdot I_{T,rms}{}^2$$

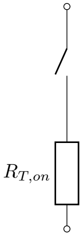


Figure 15 Equivalent circuit of a MOSFET, consisting of an ideal switch and an on-state resistance $R_{T,on}$.

DIODE conduction losses

- INFINEON Application Note has all details

$$P_{D,cond} = U_{D,f} \cdot I_{D,avg} + R_{D,on} \cdot I_{D,rms}{}^2$$

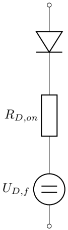


Figure 16 Equivalent circuit of a real diode, consisting of an ideal diode, an on-state resistance $R_{D,on}$ and a forward voltage $U_{D,f}$.

MOSFET Driving

$$P_{T,cond} = R_{T,on} \cdot I_{T,rms}{}^2$$

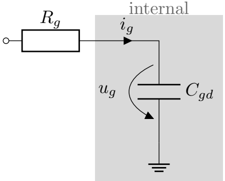


Figure 17 Simple circuit representing the charging process of the gate.

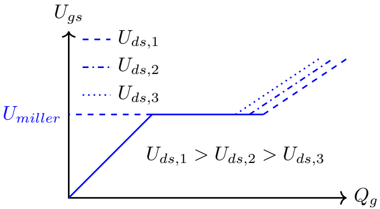


Figure 18 Reading the voltage of the Miller plateau U_{miller}.

MOSFET Switching losses

- Step-by-step details for calculations are provided in the INFINEON Application Note
- Relevant data of your MOSFET are in its data sheet
- Info about losses is needed for thermal design

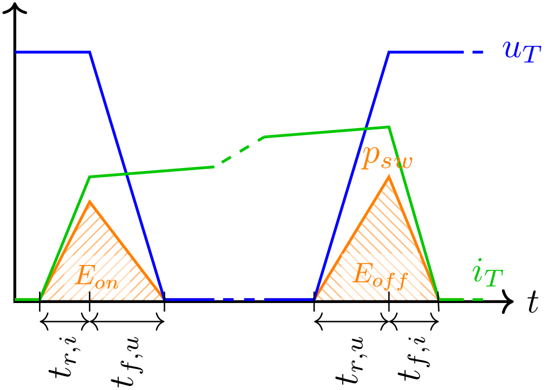


Figure 19 Illustration of the switching energies E_{on} und E_{off}.

Heat transfer modes

- Conduction
- Convection
- Radiation

Power loss (heat)

- Has to be removed from the device
- Conduction - to the heatsink/pad
- Junction temperature is critical/limited
- Ambient temperature (variable)
- Device thermal resistances are given
- Design problem: Select suitable heatsink

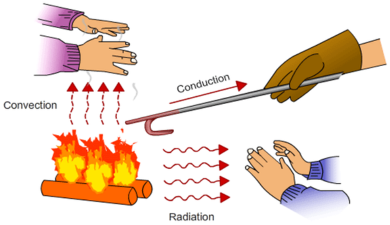


Figure 20 Modes of heat transfer (*Source: Google Search*)

Thermal impedance: quotient of the time function of a temperature difference divided by the impressed power dissipation (power losses).

$$Z_{th}(t) = \frac{T_1(t) - T_2(t)}{P}$$

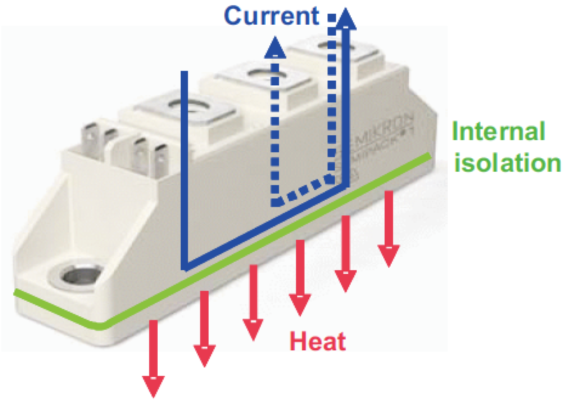


Figure 21 Basic principle behind power semiconductor module thermal management (*Source: SEMIKRON Application Manual Power Semiconductors*)

Thermal resistance: static upper value of the thermal impedance.

$$R_{th} = \frac{d}{\lambda \cdot A} \quad [\frac{K}{W}]$$

- λ - heat conductivity $[\frac{W}{mK}]$
- d - material thickness $[m]$
- A - heat flow area $[m^2]$

Different values of interest (datasheet)

- $R_{th(j-c)}$ - junction to case thermal resistance
- $R_{th(c-s)}$ - case to heatsink thermal resistance
- $R_{th(s-a)}$ - heatsink to ambient thermal resistance
- $R_{th(j-a)}$ - junction to ambient thermal resistance

$$R_{th(j-a)} = R_{th(j-c)} + R_{th(c-s)} + R_{th(s-a)}$$

Temperature difference

$$\Delta T_{j-s} = T_j - T_s$$

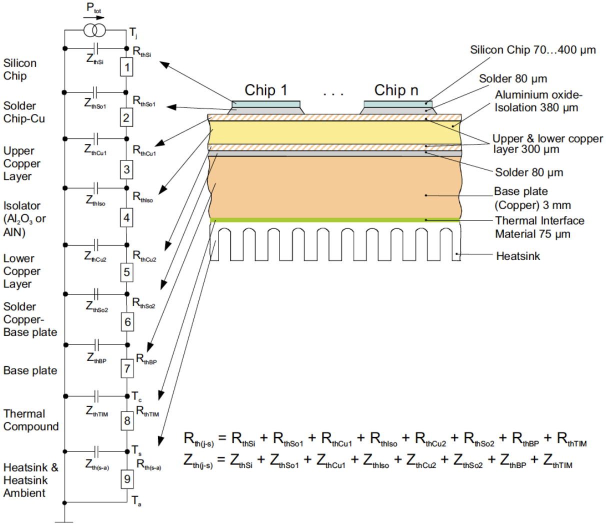


Figure 22 Basic structure of a power semiconductor module and physical modeling of the thermally relevant layers (*Source: SEMIKRON Application Manual Power Semiconductors*)

Few things to consider

- check package power dissipation capability
- your degree of freedom is $R_{th(s-a)}$
- option 1: use Heatsink
- option 2: use large PCB copper area

Check for junction temperatures:

- your calculated losses (MOSFET, DIODE)
- your device datasheet thermal data
- your ambient temperature?
- keep junction temperature below 125° C
- check MOSFET max temperature
- check DIODE max temperature

$$T_j = T_a + P_{loss} \sum R_{th}$$

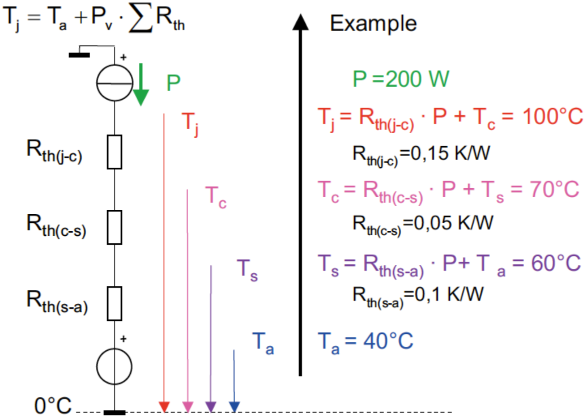


Figure 23 Example temperature calculation under steady state conditions (*Source: SEMIKRON Application Manual Power Semiconductors*)

Table 3 List of the offered heatsinks.

No.	Manufacturer	Product	R_{th} (K W^{-1})	Figure
1	Ohmite	FA-T220-64E	3.00	24
2	Ohmite	FA-T220-25E	4.70	24
3	Ohmite	EA-T220-51E	7.50	25
4	Ohmite	EA-T220-38E	10.40	25
5	Wakefield-Vette	265-118ABHE-22	14.00	26
6	Ohmite	E2A-T220-25E	16.40	27
7	Wakefield-Vette	OMNI-220-18-25-1C	24	28
8	Wakefield-Vette	OMNI-220-18-50-2C	12	29
9	Wakefield-Vette	OMNI-220-18-75-3C	8	30


Figure 24


Figure 25


Figure 26


Figure 27

Figure 28

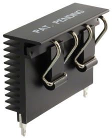


Figure 29 C

Figure 30