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# Power semiconductors

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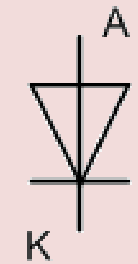
# Introduction

- Here we are going to study semiconductor devices used in power electronics.
- They work under medium and high currents and voltages.
- Some of them only exist as power devices.
- Other are equivalent to their signal counterparts but handling higher currents and voltages.
- Unlike signal devices they usually work in switch mode.
- The following ones will be considered:
  - Diodes
  - Transistors
  - Thyristors
  - Other devices

# Power diodes - Introduction




- They have signal counterparts.
- Like them, they are made from a single p-n junction.
- Chip area and conducted current are higher.
- They have to achieve the following requirements:
  - When forward biased, they have to conduct high currents with low voltage drop.
  - When reverse biased, they have to withstand a high reverse voltage with low leakage current.
  - They must get back to the blocking state after conduction  swiftly and with a low reverse current.

# Power diodes - Blocking

- It happens when the cathode is made more positive than the anode.
- This results in:
  - Migration of  the majority charge carriers to the area near the terminals.
  - The depletion region widens.
  - Appearance of a voltage barrier at the junction approximately as high as the applied voltage.
  - Minority charge carriers current dependent on the temperature, not the voltage.
- Associated parameters:
  - Maximum DC reverse voltage: the maximum amount of voltage the diode can withstand in reverse-bias mode on a continual basis.
  - Maximum reverse repetitive voltage: the maximum amount of voltage the diode can withstand in reverse-bias mode, in repeated pulses of 1ms every 10ms.
  - Peak reverse voltage: *maximum* reverse bias voltage can be applied to diode which does not cause break down. The diode can withstand it  for 10 ms every 10’.
  - Breakdown voltage: can destroy the diode.

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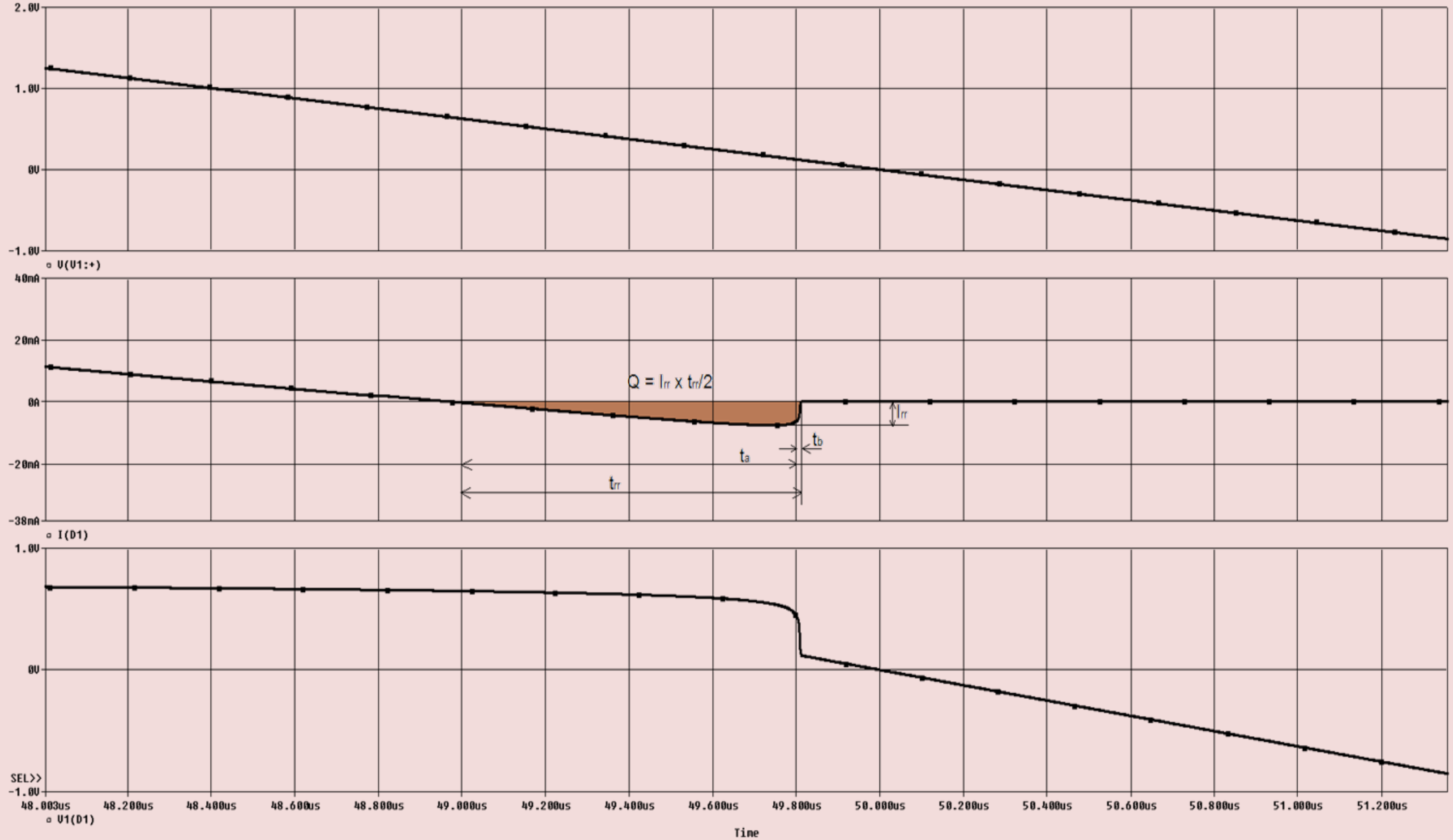
# Power diodes - Conduction

- It happens when the anode is made more positive than the cathode.
- This results in:
  - Migration of the majority charge carriers to the junction.
  - The depletion region shrinks.
  - Majority charge carriers current depends on the voltage.
- Associated parameters:
  - Maximum average forward current: the maximum average amount of current of 180° sine wave pulses, the diode is able to conduct in forward bias mode keeping the case at a certain temperature (110 ° C).
  - Maximum peak repetitive current: can be withstood for 1ms every 20ms.
  - Maximum peak current: can be withstood for 10ms every 10’.
- Conduction losses: $P_c = \int_0^T V_{ak} i_a dt$

# Power diodes – Dynamic characteristics

- Reverse recovery: passing over from the conduction to the blocking state after a reverse voltage is applied.
  - Forced: if the current reduction is too steep, after zero passaging, a certain amount of carriers change their direction thus making reverse conduction possible for a while:
    - Storage time ($t_a$): time between zero crossing and the maximum reverse current.
    - Fall time ($t_b$): time between maximum reverse current and its 25%.
    - Reverse recovery time ($t_{rr}$): sum of the two previous ones.
    - Recovery current ($I_{rr}$): peak current reached in this process.
  - Natural: when the current reduction pace is low the previous parameters can be overlooked.

# Forced reverse recovery




$Q_{rr} \approx I_{rr} \times t_{rr}/2$

Multimedia content available

# Power diodes – Dynamic characteristics

- Forward recovery: Turn-on process requires a certain time so the charge carriers can flood the depletion region. This creates a peak anode to cathode voltage.
  - Forward recovery voltage.
  - Forward recovery time: time necessary to stabilize anode to cathode conduction voltage.
- Forward recovery is a shorter phenomenon and provokes less power losses.

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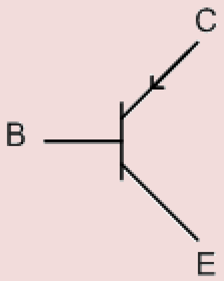


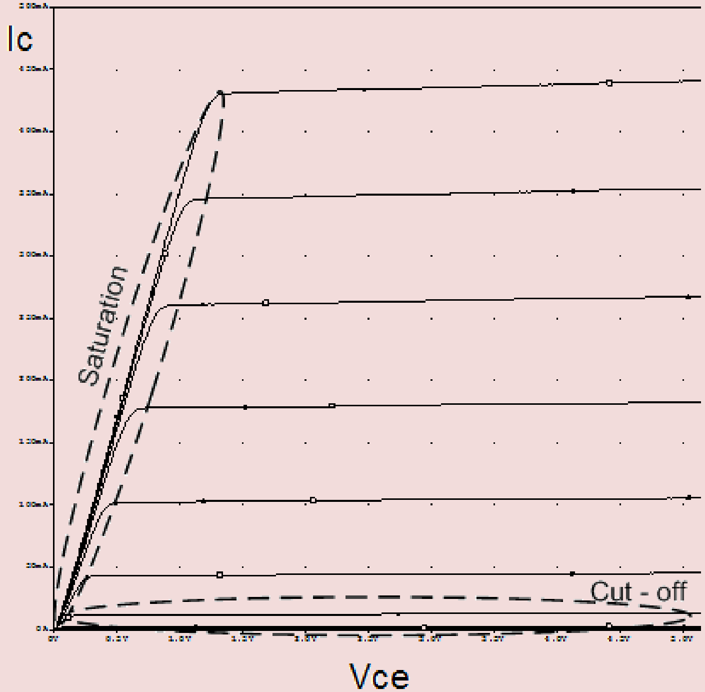

# Bipolar power transistor - Introduction

- These BJT can conduct high currents and withstand high voltages.
- They frequently adopt a Darlington configuration to avoid the need for a high base current.
- The irruption of new devices has relegated BJTs to low and medium power ranges.
- In power applications transistors often work in cut-off and saturation regions thus avoiding the active one.

# Power BJT – Static characteristics

- In the cut-off region, base current has to be very low. To make collector current as low as possible and to impose the lowest possible collector to emitter voltage, the base terminal may be short circuited or even made slightly negative.
  - In cut-off region, collector current is very small although it grows slightly with the collector to emitter voltage. The transistor behaves approximately as an open circuit.

- In the saturation region, the base current has to be high enough. Collector to emitter voltage is low but increases proportionally to collector current.
  - The transistor behaves as a low value resistor, although ideally it should behave as a short circuit.



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# Power BJT – Dynamic characteristics

- Parasitic capacities at the junctions and the charge carriers diffusion time at the base region cause the switch process (from cut-off to saturation and vice versa) not to be immediate.
  - Delay time: since the base terminal is forwardly biased until the collector current reaches 10% of its final magnitude.
  - Raise time: time the collector current lasts from 10% to 90% of its final value.
  - Turn-on time: the two previous ones added together.
  - Storage time: since the base terminal is unbiased until the collector current drops to 90% of its previous saturation value.
  - Fall time: time taken by the collector current to fall from 90% to 10% of its previous saturation value.
  - Turn-off time: the two previous ones added together.
- At both turn-on and turn-off significant current and voltage values coincide and provoke the appearance of power peaks. Average power loss will depend on the proximity of those peaks, that is, the operation frequency.

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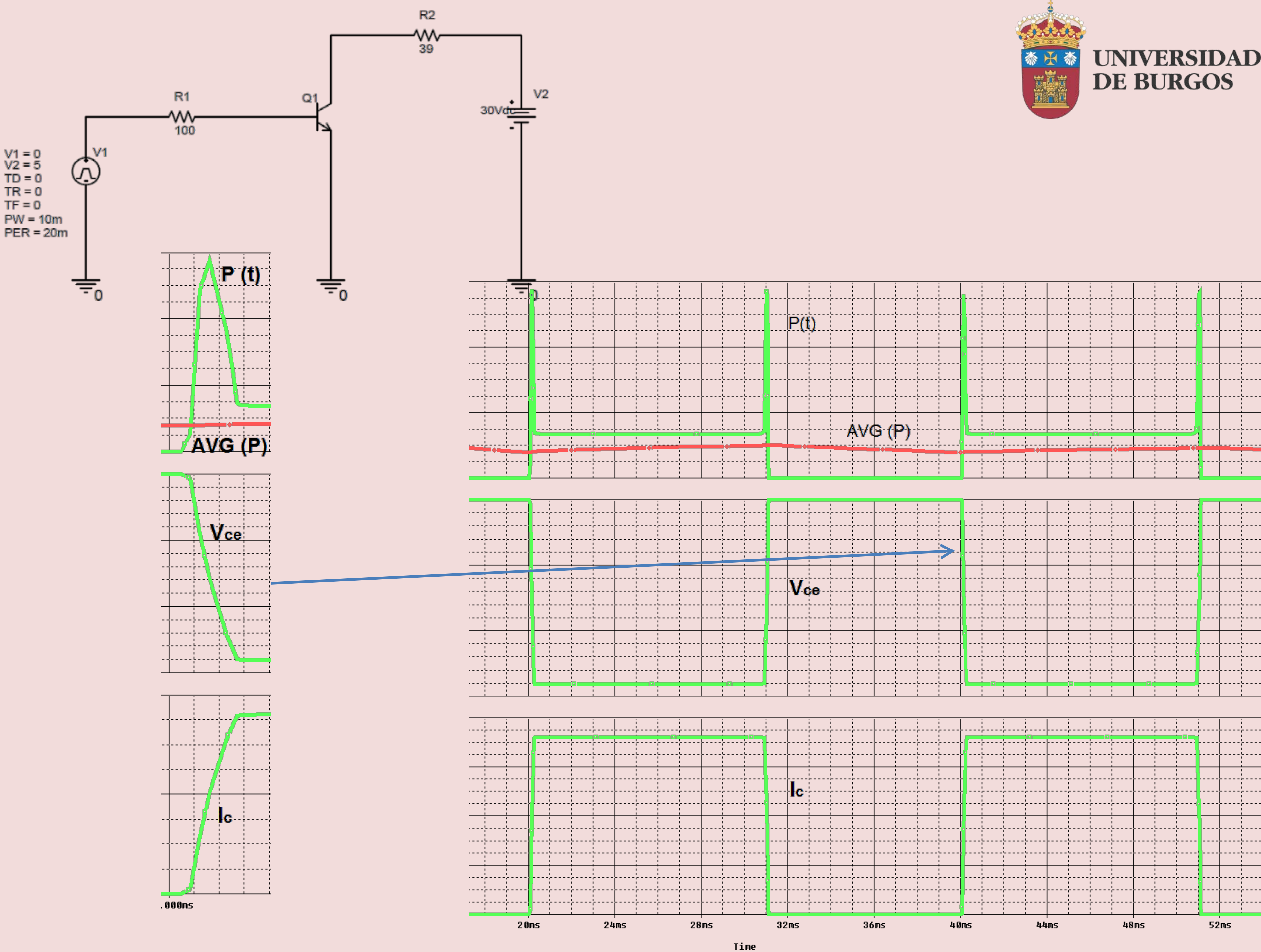

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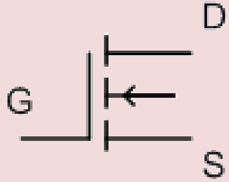
# Power FET - Introduction




- They are FET capable of conducting high currents and withstanding high voltages.
- For this purpose they are given some constructive characteristics aimed to increase the base's influence and to reduce source to drain resistance.
- In power electronics transistors usually work in cut-off and saturation regions (switching), thus avoiding the active one.
- In power electronics enhancement devices are used.

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# Power FET – Static characteristics

- Saturation is achieved applying a sufficient voltage to gate terminal so the channel is created. Source to drain voltage is low but increases proportionally to drain current.
  - The transistor behaves as a low resistance although it should be ideally a short-circuit.
  - Gate current is negligible.
- Cut-off is achieved by removing base voltage, which results in channel disappearance. Drain current is very low, lower than leakage current in bipolar transistors.
  - Cut-off operation is very close to a perfect open circuit.

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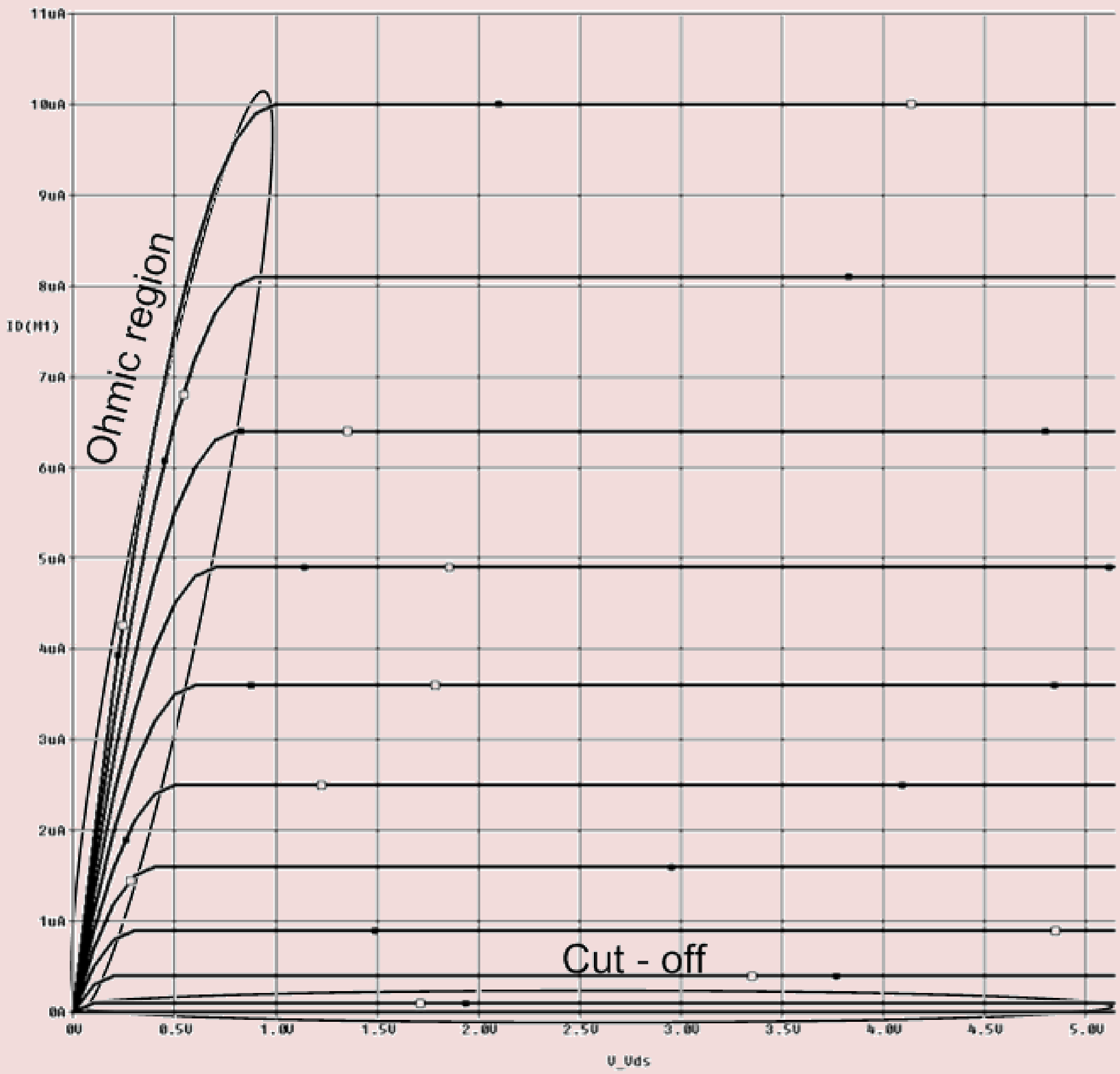
# Power FET – Static characteristics



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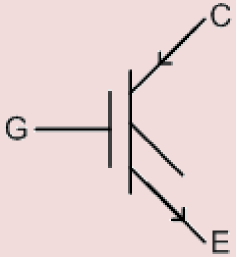
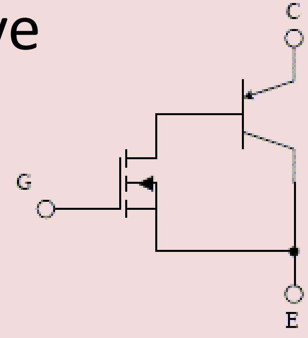
# Power FET – Dynamic characteristics

- FETs switch faster than bipolar transistors due to the lack of minority charge carriers' diffusion.
- The gate to source parasitic capacity poses a limit on the gate's voltage response to excitation, towards both cut-off and saturation:
  - Delay time: since the base terminal is forwardly biased until the drain current reaches 10% of its final magnitude.
  - Raise time: time the drain current lasts from 10% to 90% of its final value.
  - Turn-on time: the two previous ones added together.
  - Discharge (turn-off delay) time: since excitation is removed from the gate terminal until the drain current drops to 90% of its previous saturation value.
  - Fall time: time taken by the drain current to fall from 90% to 10% of its previous saturation value.
  - Turn-off time: the two previous ones added together.
- At both turn-on and turn-off significant current and voltage values coincide and provoke the appearance of power peaks. Average power loss will depend on the proximity of those peaks, that is, the operation frequency.

# IGBT - Introduction




- Insulated Gate Bipolar Transistor (IGBT): this device aims to combine the advantages of the bipolar (low conduction losses) and FET (low excitation current and high switching speed).
- From the constructive point of view it combines a FET, at its input (gate) with a bipolar at its output (collector to emitter). These are the names of its terminals.
- Unlike the previous ones, it has no signal equivalent.
- Its behavior is similar to the FET's with the collector to emitter voltage axis displaced approximately one volt to the right (more collector to emitter voltage for the same collector current), with a more steep saturation curve (lower equivalent resistance).



# IGBT – Static characteristics

- In saturation region, the IGBT is affected by a higher collector to emitter voltage than the FET which however is offset by a lower equivalent resistance.
- In cut-off region it behaves very closely to a FET.
- Saturation losses are lower than a FET's, but higher than a bipolar's.
- A voltage gradient Vce provokes, through parasitic capacity $C_{CG}$ the appearance of a current that charges parasitic capacity $C_{GE}$ . If the voltage in this capacity, $V_{GE}$, exceeds the MOS threshold voltage, the IGBT will undesirably turn on, which result in a loss of control and significant power losses.

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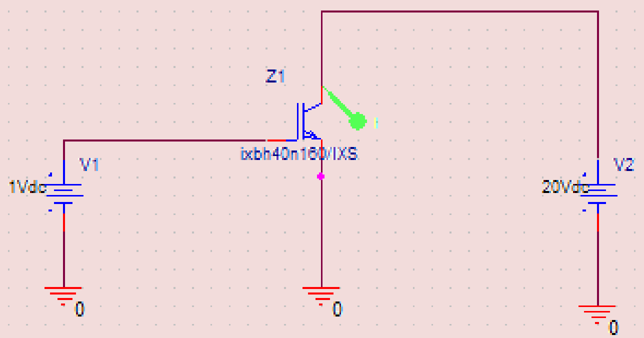
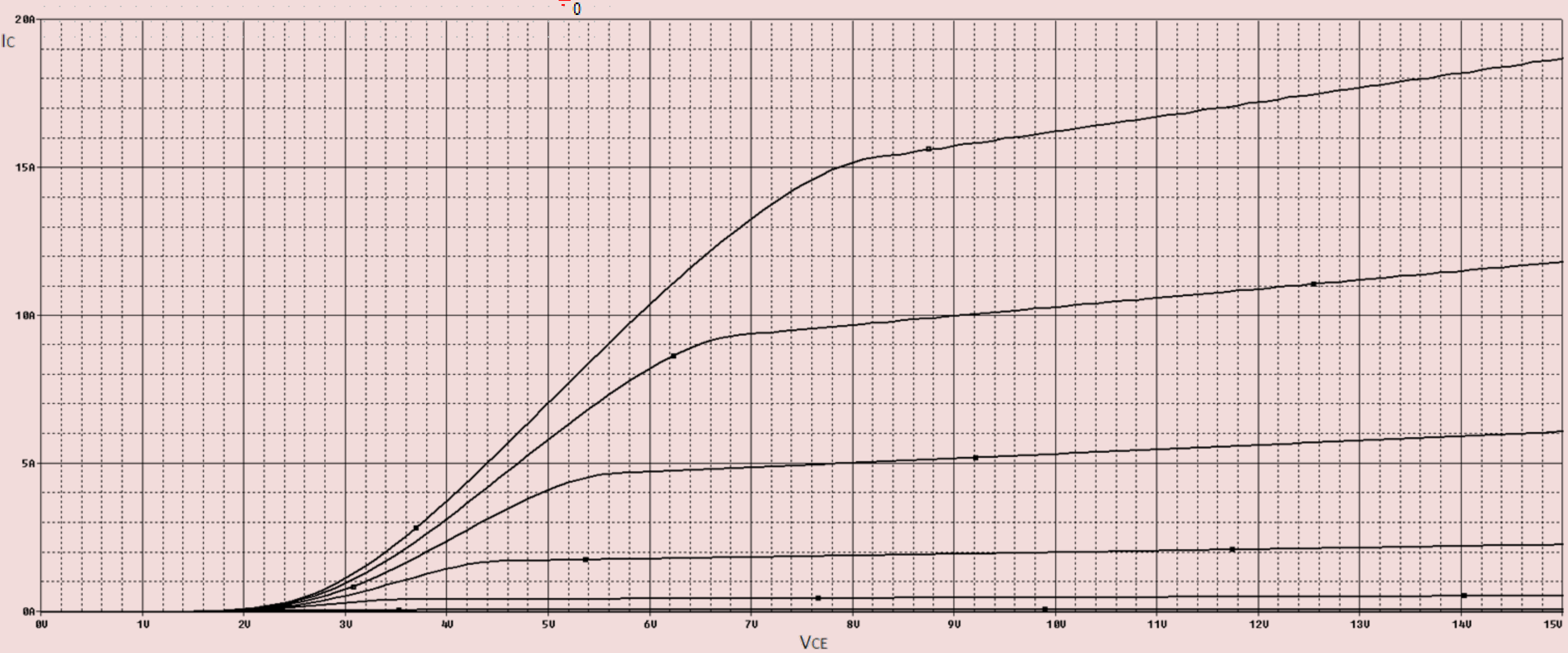
# IGBT – Static characteristics



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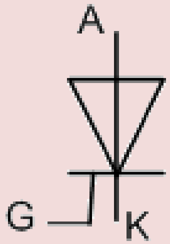
# IGBT – Dynamic characteristics

- IGBT’s turn-on time is similar the FET’s.
- Turn-off time is between the FET and the bipolar.
- Switch speed therefore is also between that of both devices but closer to the FET’s.
- Power losses are also somewhere in between.
- All in all, the IGBT combines power and speed characteristics of both types of transistors, closer to the best case and therefore close to the goal of achieving the best of each one.
- An excessive voltage gradient would encounter trapped charges not totally evacuated. For this reason the maximum gradient allowed will be lower than if the device was in static condition.

# Thyristor (SCR) - Introduction



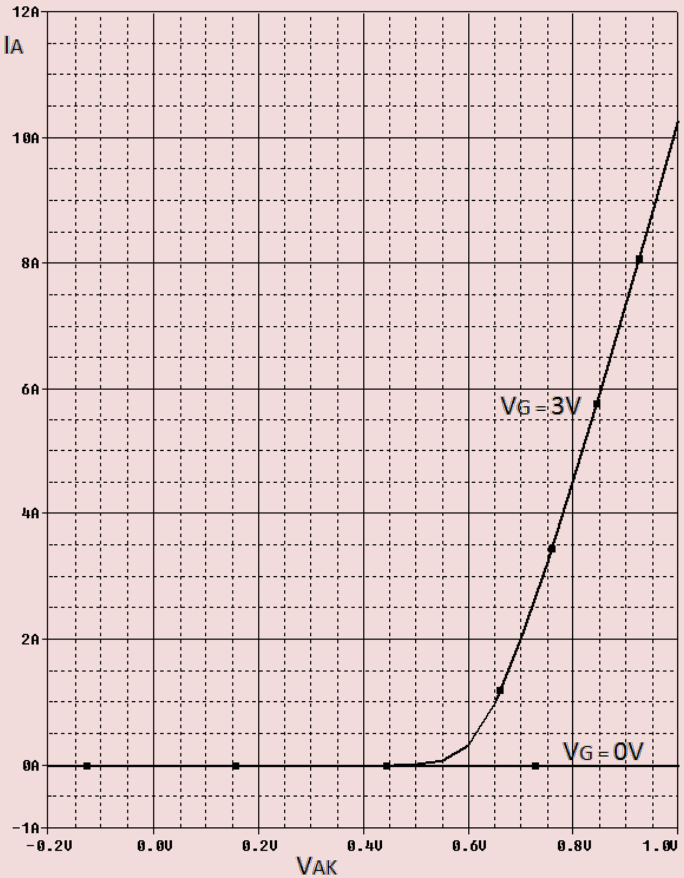

- It is devoted only to power electronics applications.
- SCR (Silicon Controlled Rectifier): it works very much like a rectifier (diode), but a controlled one.
- Control terminal (gate) makes possible for an external circuit to put it on conduction state, provided a positive and sufficient anode – cathode voltage is applied.

# Thyristor (SCR) – Static characteristics – cut off

- The thyristor is in cut-off condition when:
  - Anode – cathode voltage is positive but gate voltage referred to ground is not positive (direct cut-off).
  - Anode – cathode voltage is negative (reverse blocking) regardless of gate's condition.
- In blocking state only the leakage current is present. It grows slightly as anode – cathode voltage does and more significantly as temperature rises.
  - In direct blocking state it may reach the direct breakout current and turn the device to condition without any damage.
- Voltage parameters are analogous to the diode's but affecting both direct and reverse situations:
  - Maximum DC reverse/direct voltage:.
  - Maximum reverse/direct repetitive voltage.
  - Peak reverse/direct voltage.
  - Breakdown reverse/direct voltage.

# Thyristor (SCR) – Static characteristics – conduction

- Anode's current is imposed by external circuit (it is not related to the gate) and must be kept over the to prevent spontaneous blocking.
- Anode to cathode voltage is kept around 1'5 – 2V.
- Working parameters are analogous to the diode's:
  - Maximum average forward current (it can also be expressed in terms of rms current).
  - Maximum peak repetitive current.
  - Maximum peak current.
- Conduction losses: $P_c = 1{,}3 * I_{Am} + rI_A{}^2$
  - 1,3V: voltage drop.
  - $I_{Am}$: anode's average current.
  - r: dynamic thyristor's resistance.
  - $I_A$: anode's rms current.



# Thyristor (SCR) – Switching

- When switched on the thyristor shifts from direct blocking to conduction and remains in that condition.
- Accidental trigger:
  - Due to overvoltage: an excessive anode – cathode direct voltage may cause the current to reach its breakout value.
  - Due to voltage gradient: anode – cathode voltage may put the device in conduction state even if it is not high provided it is applied rapidly. The required positive slope $dV_{AK}/dt$ depends on the final voltage and external temperature (less gradient is needed as these two magnitudes increase). It is usually given in terms of $(dV_{AK}/dt)_{máx}$ for a given final voltage value (2/3 maximum direct repetitive voltage).
- Switching by gate pulse: it is the usual switching procedure. An electrical pulse is provided on the gate terminal (when anode – cathode voltage is positive).
  - Delay time ($t_d$): since the pulse is applied to the gate terminal until anode's current reaches 10% of its final value.
  - Rise time ($t_r$): from 10% to 90% of on state current.
  - Turn on delay time ($t_{on}$): the sum of both.
- At the moment of switch on, anode's current slope must not exceed a certain value $(di_A/dt)_{máx}$ . This is so because right after switch on the current is restricted to a small fraction of the pn junction, close to the gate terminal. As a consequence, a temporarily high current density may damage the device.

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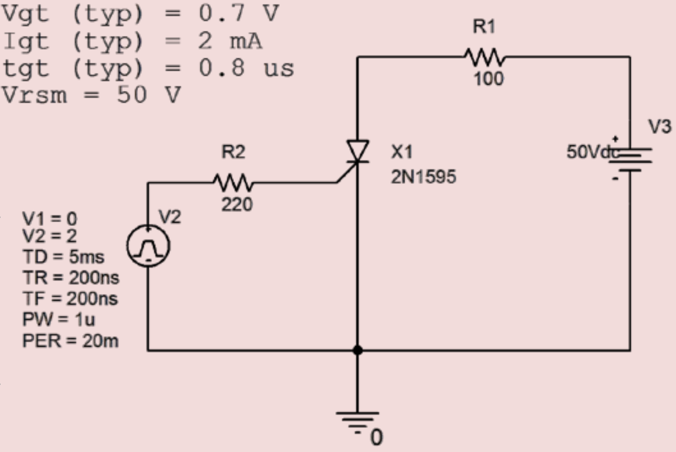
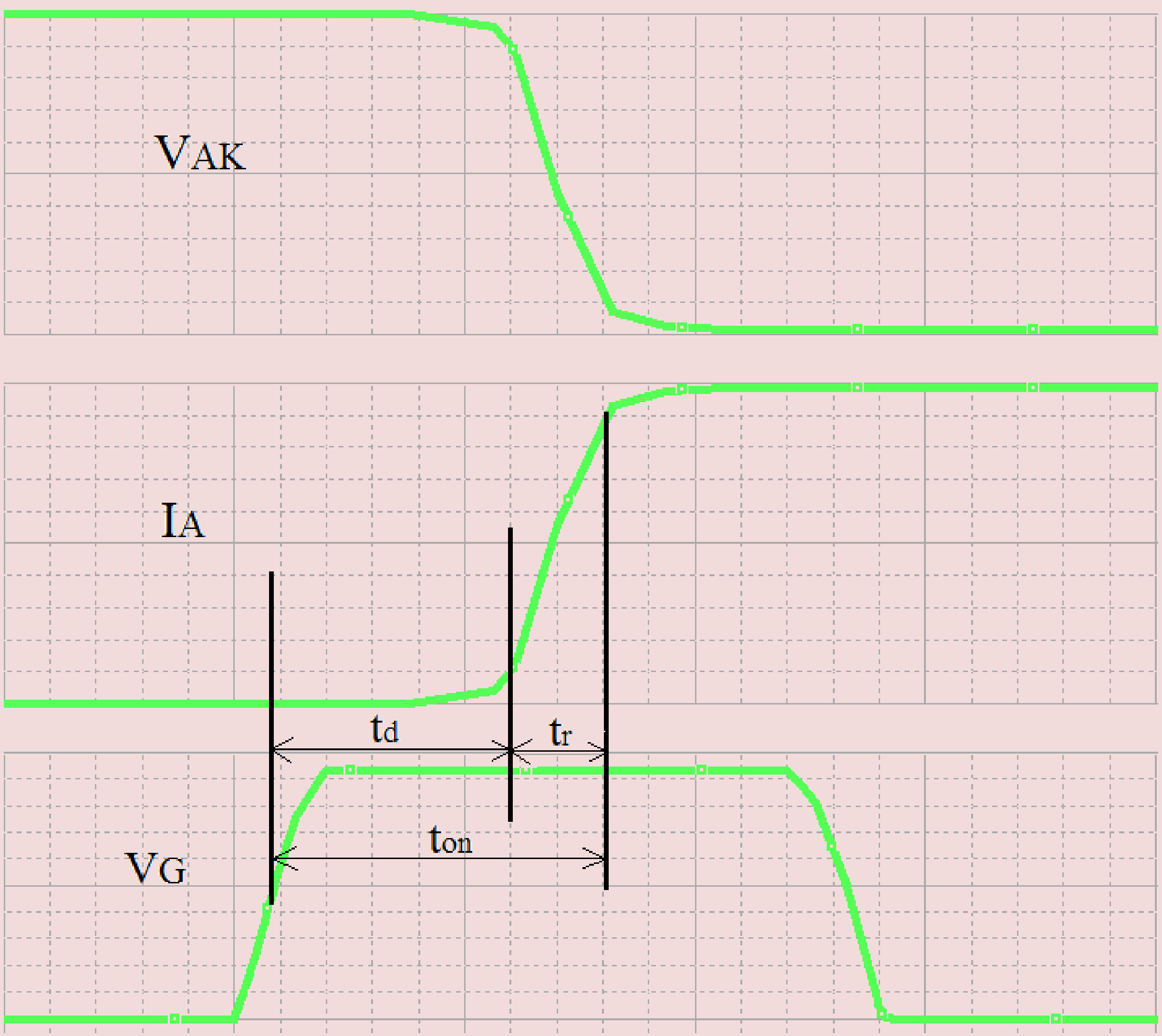
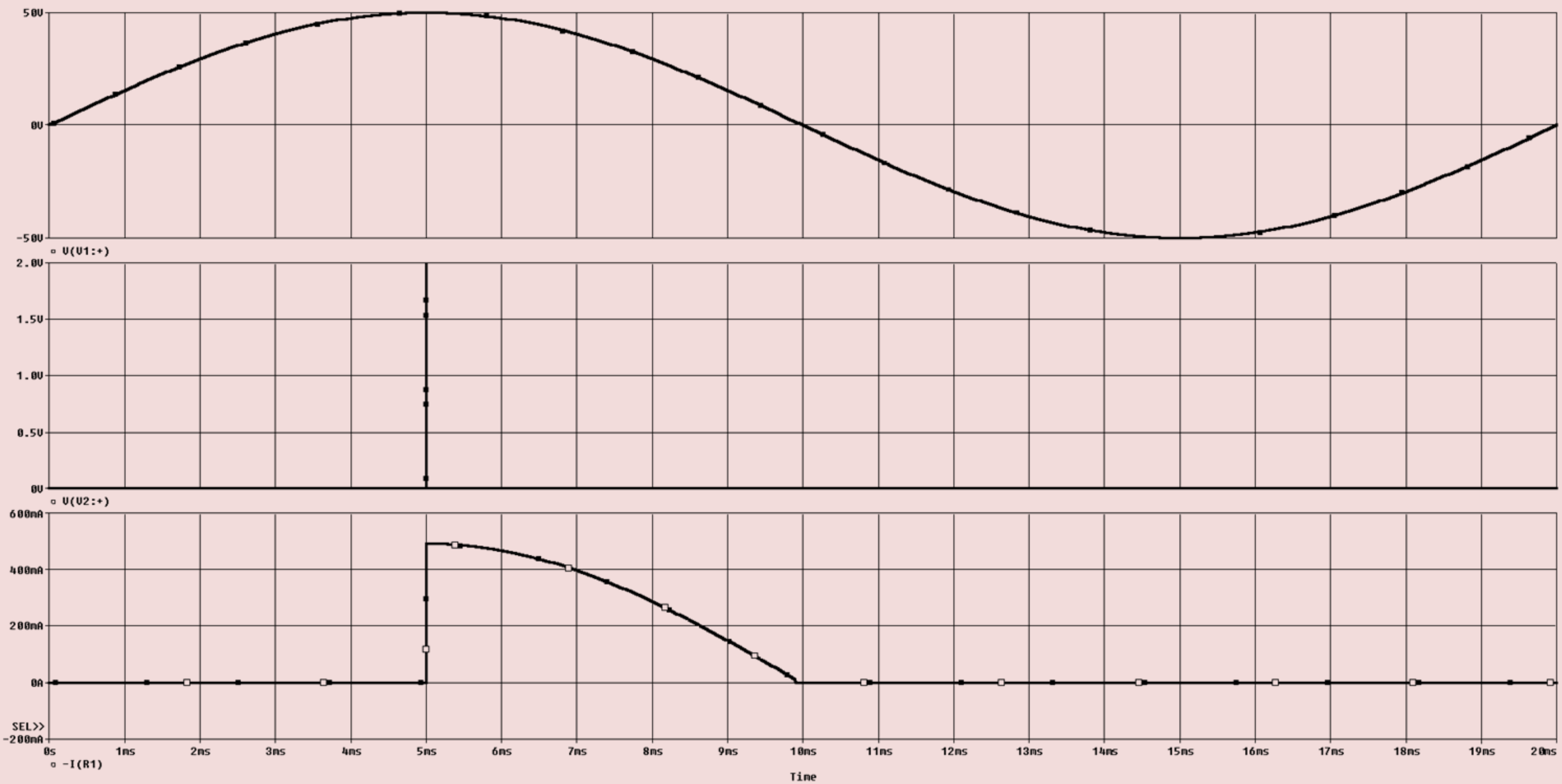
2N1595
Vgt (typ) = 0.7 V
Igt (typ) = 2 mA
tgt (typ) = 0.8 us
Vrsm = 50 V



# Thyristor (SCR) – Triggering characteristics.

- The pulses delivered to the gate terminal must comply with several requirements to ensure turn on. :
  - Pulse width must be long enough to allow the anode's current to reach its **holding current value ($I_H$)**.
  - **Latching current / gate trigger current ($I_{GT}$)** is the minimum gate current that guarantees turn on at working temperature.
  - Gate – cathode voltage must be above the **gate trigger voltage ($V_{GT}$)** at working temperature. Actually this voltage produces the former current value thus ensuring trigger.
- In order to avoid accidental turn-on, vendors provide:
  - Gate non-trigger voltage **($V_{GD}$)**.
  - Gate non-trigger current **($I_{GD}$)**.
- To recap:
  - A voltage/current value above the trigger one ensures turn-on.
  - When both voltage and current are below the non-trigger values an unwanted trigger will not occur.
  - In any other scenario the result is uncertain.


50V
0V
-50V
V(V1:+)
2.0V
1.5V
1.0V
0.5V
0V
V(V2:+)
600mA
400mA
200mA
0A
SEL>>
-200mA
0s
1ms
2ms
3ms
4ms
5ms
6ms
7ms
8ms
9ms
10ms
11ms
12ms
13ms
14ms
15ms
16ms
17ms
18ms
19ms
20ms
-I(R1)
Time

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# Thyristor (SCR) – Blocking

- Blocking the thyristor through the gate terminal is not possible.
- When anode current drops below its holding value **($I_H$)** natural blocking occurs.
- When the reduction pace ($di_A/dt$) is too high, the thyristor may end up conducting negative current exactly like diodes do.
  – Turn-off time ($t_q$): elapsed time since current has gone to cero (or negative) until a positive anode to cathode voltage can not turn on the device without trigger impulse.
- Blocking can be **forced** on the thyristor:
  – By means of a sufficient reverse anode to cathode voltage.
  – By means of a current source opposed to the direct anode current.

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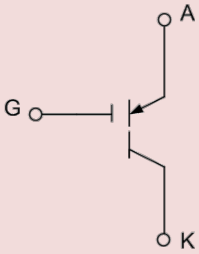
# MCT (MOS Controlled Thyristor)




- It is a hybrid device similarly to the IGBT.
- It is composed of two MOS transistors. One of them is meant to turn on the device whilst the other one turns it off.
- In this case the reference terminal is the anode.
- When in direct blocking a negative anode to gate voltage turns the MCT on.
- When conducting a positive gate to anode voltage turns it off.
- Turn off is only possible when current is below the so called **peak controllable current**. Above this an attempt  to turn the MCT off may destroy it. In that case the MCT behaves as any other thyristor.
- The width of the triggering pulses on the gate terminal depends on the current. It is recommended to maintain the pulses throughout the whole conduction/blocking period.
- It is made up from multiple  parallel cells in parallel so it can withstand higher current gradients.

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# Other devices

- GTO: Gate turn-off thyristor. A thyristor that can be turned off from the gate terminal.
- DIAC: a self protecting device that conducts both positive and negative current when breakdown voltage is reached.
- TRIAC: a DIAC with a control terminal to turn it on in any current sense before it reaches the breakdown voltage.
- Hybrid devices: apart from IGBT and MCT there are many other hybrid devices with similar characteristics.

# References


- Electrónica de Potencia. Salvador M. García, Juan A. Gualda Gil. Thomson Editores Spain, Paraninfo S.A., 2006
- Thyristor Theory and Design Considerations. Handbook. HBD855/D Rev. 1, Nov−2006. ON Semiconductor