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Lesson3 (Part A): Power Semiconductors

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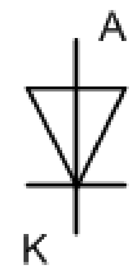
V 1.2

Introduction

- We will study semiconductor devices used in power electronics.
- These devices are designed to handle medium to high voltage and current levels.
- Some of them are specifically designed for power applications and have no small-signal counterpart.
- Others are analogous to their small-signal counterparts, but are designed to handle significantly higher voltages and currents.
- Unlike small-signal devices, power semiconductor devices typically operate in switching mode.
- We will consider the following devices:
  - Diodes
  - Transistors
  - Thyristors
  - Other Devices

Power Diodes - Introduction



- Power diodes are among the devices that have a small-signal counterpart.
- Like small-signal diodes, they are based on a p–n junction.
- However, they have a larger semiconductor die area and a higher current-handling capability.
- The main characteristics required of a power diode are:
  - In forward bias, it must be capable of carrying high currents with a low forward voltage drop.
  - In reverse bias, it must be capable of withstanding high voltages with low leakage current.
  - It must be able to recover its blocking capability rapidly after conduction, with a low reverse recovery current.

Power Diodes – Reverse Blocking

- Reverse blocking occurs when a reverse voltage is applied across the diode terminals, making the anode more negative than the cathode.
- This results in:
  - Majority carriers moving away from the junction toward the outer regions of the semiconductor die.
  - Widening of the depletion region.
  - The formation of a potential barrier across the junction approximately equal to the applied voltage.
  - A minority-carrier current that depends primarily on temperature rather than on the applied voltage.
- Associated Parameters:
  - **Working Reverse Voltage:** Maximum reverse voltage that can be continuously applied without damaging the device..
  - **Repetitive Peak Reverse Voltage:** Maximum reverse voltage that can be repeatedly applied for short periods (10 ms).
  - **Non-Repetitive Peak Reverse Voltage:** Maximum reverse voltage that can be applied occasionally (each 10 minutes) as a non-repetitive transient (10 ms).
  - **Breakdown Voltage:** Reverse voltage at which breakdown of the diode may occur.

Power Diodes – Forward Conduction

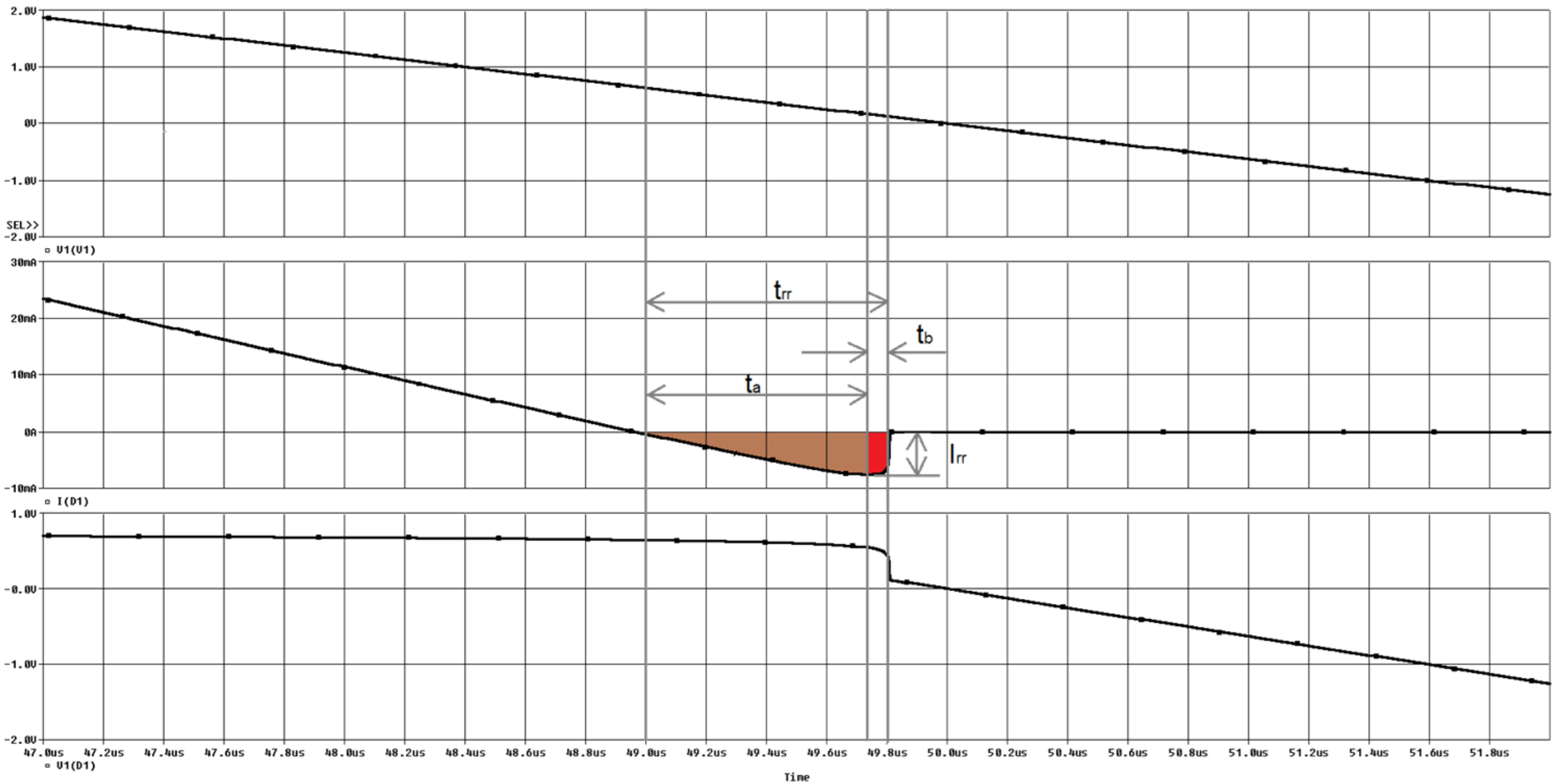
- Forward conduction occurs when a forward voltage is applied across the diode terminals, making the anode more positive than the cathode.
- This results in:
  - Majority carriers moving toward the junction.
  - Narrowing of the depletion region.
  - A majority-carrier current that depends on the applied forward voltage.
- Associated Parameters:
  - **Repetitive Peak Forward Current:** Maximum peak forward current that may occur repeatedly under specified conditions (180º under 110ºC)
  - **Repetitive Peak Forward Current:** Maximum peak forward current that may occur repeatedly under specified conditions(every 10 seconds during 10 ms).
  - **Non-Repetitive Peak Forward Current (Surge Current):** Maximum short-duration current that the diode can withstand under non-repetitive conditions (every 10 minutes during 10 ms).
- Conduction Losses: $P_c = \int_0^T V_{ak} i_a dt$

Power Diodes – Dynamic Behavior

- Reverse Recovery: is the process by which a diode regains its reverse-blocking capability after conducting in the forward direction and subsequently being subjected to reverse bias.
  - **Forced Reverse Recovery**: If the forward current decreases very rapidly, stored charge carriers remain in the device after the current crosses zero. These carriers temporarily allow reverse current to flow before the diode fully recovers its reverse-blocking capability.
    - **Storage Time:** Time interval from the forward-current zero crossing to the peak reverse recovery current.
    - **Fall Time:** Time interval from the peak reverse recovery current until the reverse current decreases to 25% of its peak value.
    - **Reverse Recovery Time (trr):** Sum of the storage time and fall time.
    - **Peak Reverse Recovery Current (Irr):** Maximum reverse current reached during the reverse recovery process.
  - **Natural Recovery**: If the current decreases sufficiently slowly, reverse recovery effects may be negligible.

More detailed information is available here.

Forced Reverse Recovery



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

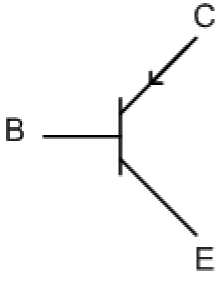
[Multimedia content available]

Power Diodes – Dynamic Behavior

- Forward recovery: During turn-on, a finite amount of time is required for charge carriers to establish the conduction state across the junction region. This causes a transiently high anode-to-cathode voltage.
  - Peak Forward Recovery Voltage: Maximum transient anode-to-cathode voltage reached during turn-on.
  - Forward Recovery Time: Time required for the forward anode-to-cathode voltage to settle to its steady-state conduction value.
- Forward recovery is a shorter transient than reverse recovery and generally results in lower switching losses.

Power Bipolar Transistor – Introduction

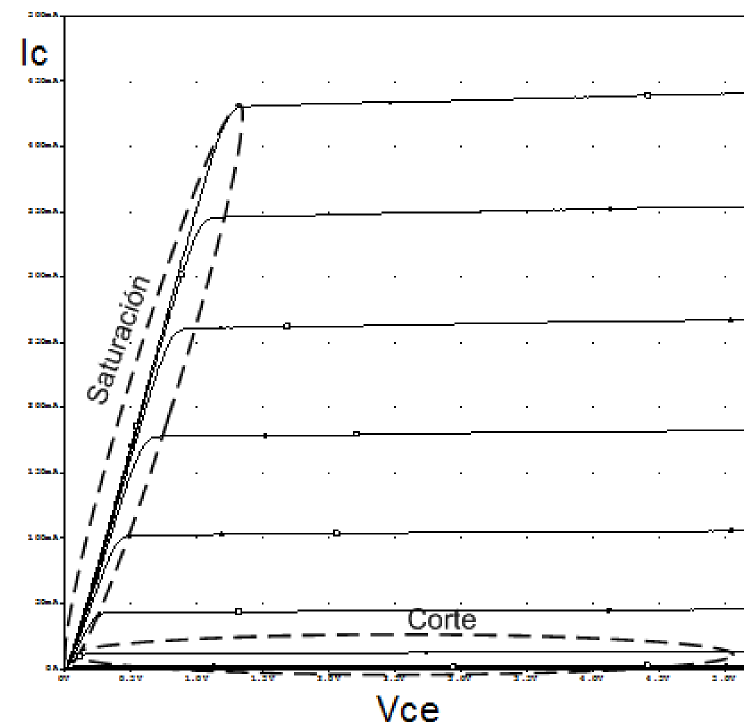
- Power BJTs are bipolar junction transistors capable of carrying high currents and withstanding high voltages.
- **Darlington** configurations are commonly used to provide high current gain and avoid excessively high base-drive current requirements
- The development of newer power semiconductor devices has largely relegated BJTs to low- and medium-power applications.
- In power applications, transistors typically operate in the cutoff and saturation regions as switching devices, while operation in the active region is generally avoided.



Power Bipolar Transistor – Static Behavior

In **cutoff**, the base current must be reduced to a very low value. To minimize collector leakage current and maximize the collector-to-emitter blocking capability, the base may be shorted to the emitter or even driven slightly negative with respect to the emitter.

- In **cutoff**, the collector current is very small and increases slightly with collector-to-emitter voltage. The transistor therefore behaves approximately as an open circuit.



In **saturation**, sufficient base current must be supplied to drive the transistor fully on. The collector-to-emitter voltage is low, although it increases with collector current.

- The transistor behaves approximately as a low-value resistance, ideally approaching a short circuit.

Power Bipolar Transistor – Dynamic Behavior

- The parasitic junction capacitances and the finite carrier diffusion time through the base prevent instantaneous switching between cutoff and saturation.
  - **Delay Time (td):** Time interval from the application of base drive until the collector current reaches 10% of its final value.
  - **Rise Time (tr)**: Time required for the collector current to rise from 10% to 90% of its final value.
  - **Turn-On Time (ton):** Sum of the delay time and rise time.
  - **Storage Time (ts):** Time interval from the removal of base drive until the collector current falls to 90% of its saturation value.
  - **Fall Time (tf):** Time required for the collector current to fall from 90% to 10% of its saturation value.
  - **Turn-Off Time (toff):** Sum of the storage time and fall time.
- During both turn-on and turn-off, significant voltage and current coexist across the transistor for a finite period of time, producing peaks in instantaneous power dissipation. The average switching power loss depends on how frequently these switching transitions occur and therefore increases with switching frequency.

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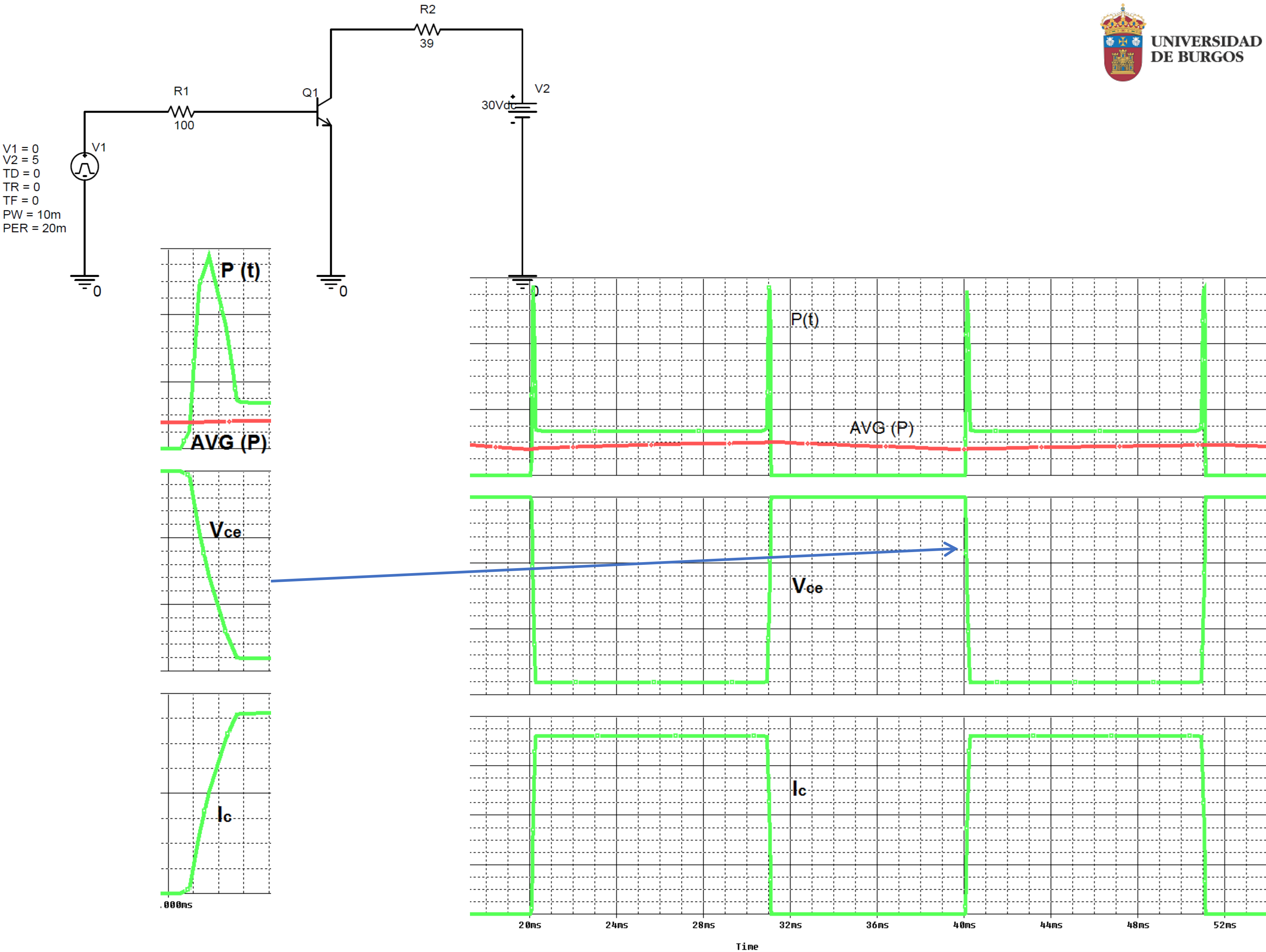
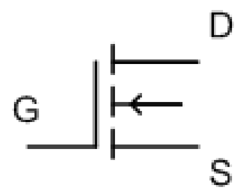


Power FET – Introduction

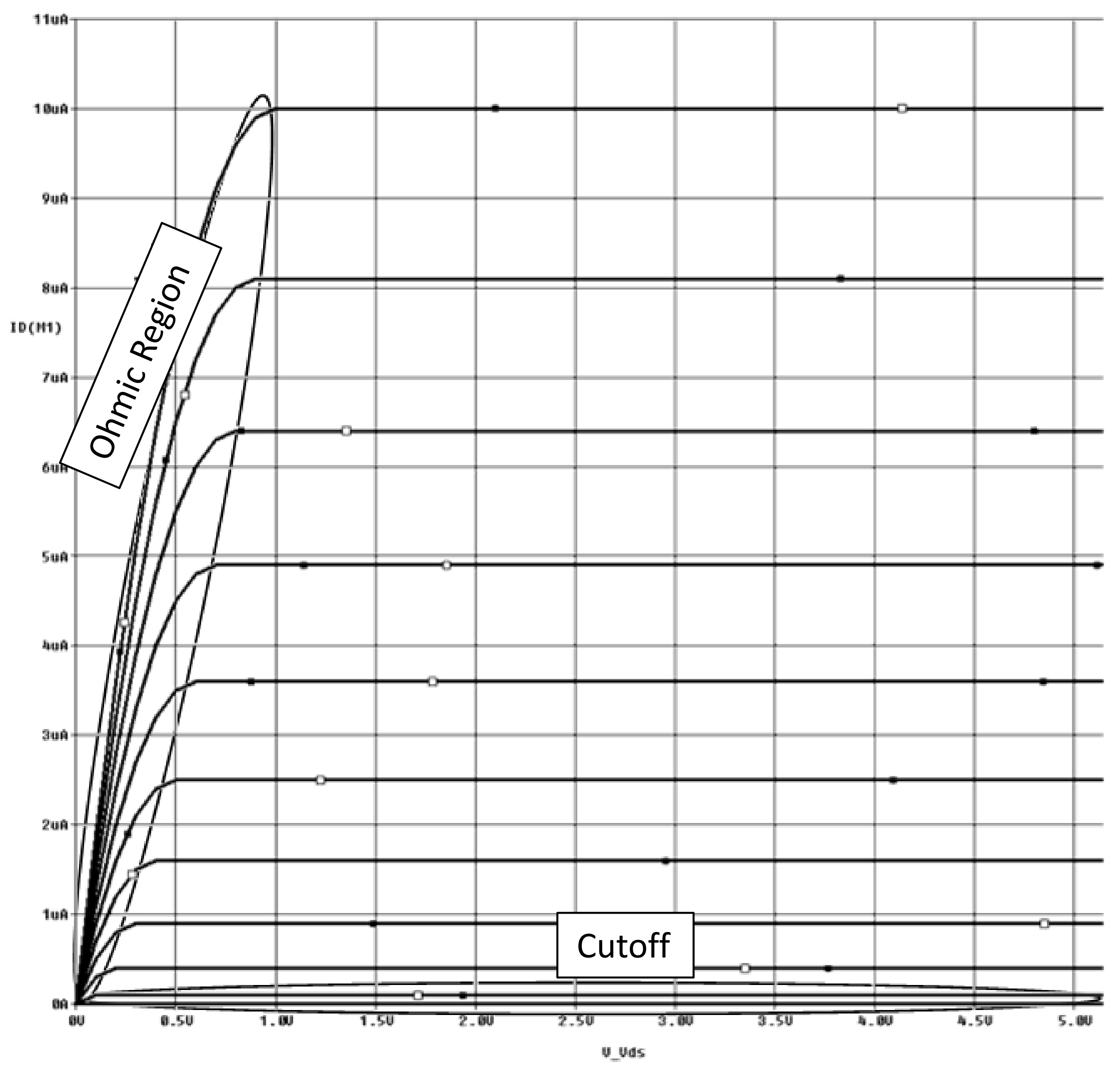
- Power FETs are field-effect transistors designed to carry high currents and withstand high voltages.
- Their device structure is specifically optimized to improve gate control and reduce drain-to-source on-resistance.
- In power applications, these transistors typically operate in the cutoff and on-state regions as switching devices, while linear operation is generally avoided.
- Enhancement-mode devices are normally used in power electronics.



Power FET – Static Behavior

- The transistor is turned on by applying a sufficiently high gate-to-source voltage to create a conductive channel. The drain-to-source voltage is low, but increases with drain current.
  - In the on-state, the transistor behaves approximately as a low-value resistance, ideally approaching a short circuit.
  - The steady-state gate current is negligible.
- The transistor is turned off by removing the gate drive, causing the conductive channel to disappear. The drain current is very low and is typically lower than the leakage current of bipolar transistors.
  - In the off-state, the transistor behaves very nearly as an ideal open circuit.

Power FET – Static Behavior



Power FET – Dynamic Behavior

- MOSFET switching is faster than bipolar transistor switching because it does not involve minority-carrier storage and diffusion effects.
- The gate-to-source capacitance and other parasitic capacitances limit how quickly the gate voltage can respond to the drive signal during both turn-on and turn-off:
  - **Delay Time (td(on)):**Time interval from the application of the gate-drive signal until the drain current reaches 10% of its final value.
  - **Rise Time (tr):** Time required for the drain current to rise from 10% to 90% of its final value.
  - **Turn-On Time:** Sum of the turn-on delay time and rise time.
  - **Turn-Off Delay Time (td(off)):** Time interval from the removal of the gate-drive signal until the drain current falls to 90% of its on-state value.
  - **Fall Time (tf):** Time required for the drain current to fall from 90% to 10% of its on-state value.
  - **Turn-Off Time:** Sum of the turn-off delay time and fall time.
- During both turn-on and turn-off, significant voltage and current coexist across the transistor for a finite period of time, resulting in peaks in instantaneous power dissipation. During both turn-on and turn-off, significant voltage and current coexist across the transistor for a finite period of time, resulting in peaks in instantaneous power dissipation.

MOSFET for Reverse-Polarity Protection

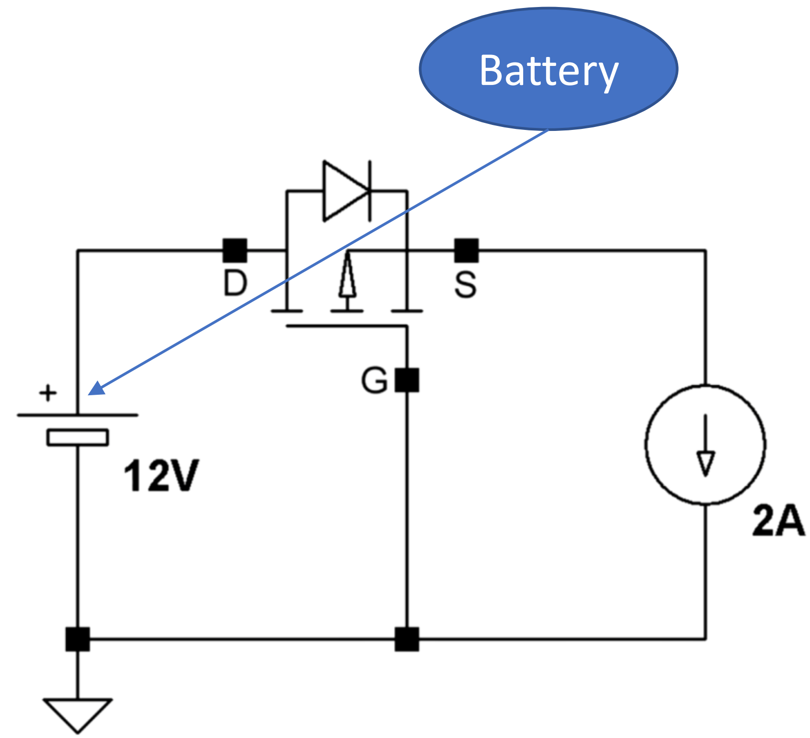
- P-Channel MOSFET for Reverse-Polarity Protection

- V_{DSS} rating must be higher than the maximum battery voltage

- Conduction losses are significantly lower than when using a conventional series diode

$$P = I^2R = I^2 \times Rds_{ON}$$

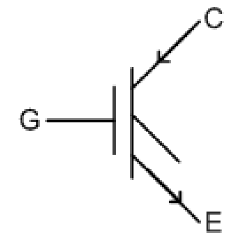
- A MOSFET with the lowest practical Rds_{ON} should be selected. Use the maximum Rds_{ON} value specified in the datasheet for worst-case design



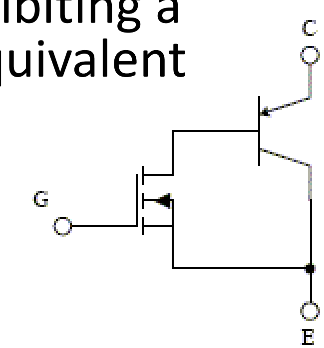
Electrical Characteristics T_C = 25°C unless otherwise noted

Symbol	Parameter	Test Conditions	Min	Typ	Max	Units
On Characteristics						
$V_{GS(th)}$	Gate Threshold Voltage	$V_{DS} = V_{GS}$, $I_D = -250\ \mu A$	-2.0	--	-4.0	V
$R_{DS(on)}$	Static Drain-Source On-Resistance	$V_{GS} = -10\ V$, $I_D = -23.5\ A$	--	0.021	0.026	Ω

IGBT – Introduction



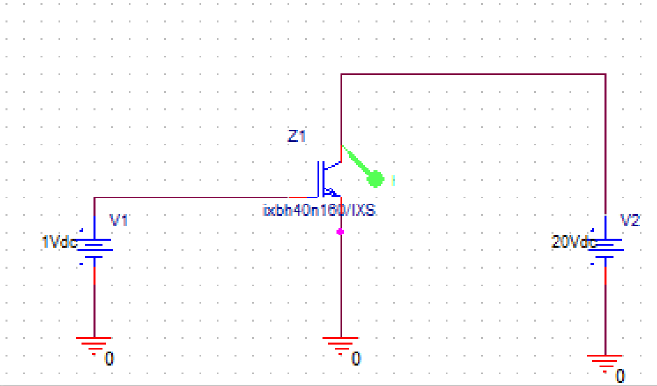
- Insulated-Gate Bipolar Transistor (IGBT): a power semiconductor device designed to combine the advantages of bipolar transistors—low conduction losses—with those of MOSFETs—low gate-drive power and high switching speed.
- Because of its internal structure, an IGBT combines a MOS-gated input with bipolar conduction at the output. Its terminals are therefore referred to as Gate, Collector and Emitter.
- Unlike the devices discussed previously, the IGBT has no direct small-signal counterpart.
- Its output characteristics resemble those of a power MOSFET, but are shifted toward a higher collector-to-emitter voltage—approximately one additional volt for a given collector current—while exhibiting a steeper on-state characteristic corresponding to a lower equivalent differential resistance.

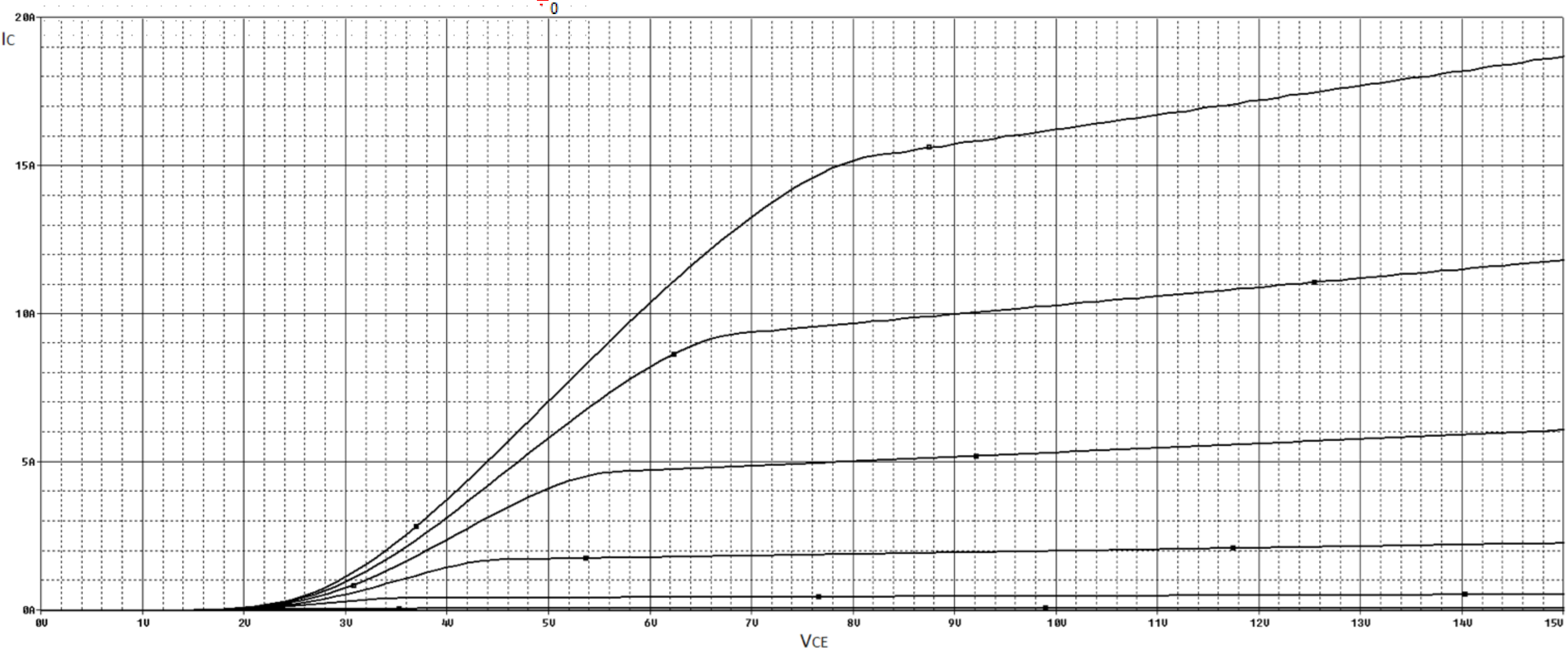


IGBT – Static Behavior (I)

- In the on-state, an IGBT generally exhibits a higher collector-to-emitter voltage drop than a MOSFET at low current. At high current levels, however, this can be offset by its lower effective on-state resistance.
- In the off-state, its behavior is broadly similar to that of a power MOSFET.
- Its conduction losses are generally lower than those of a comparable high-voltage MOSFET under suitable operating conditions, although its on-state voltage drop is higher than that of a saturated bipolar transistor.
- A high rate of change of collector-to-emitter voltage (dVCE/dt) can produce a current through the parasitic gate-to-collector capacitance CCG. This current can charge the gate-to-emitter capacitance CGE and raise VGE above the device threshold voltage. If this occurs, the IGBT may turn on unintentionally, causing loss of control and additional power dissipation.

IGBT – Static Behavior (II)





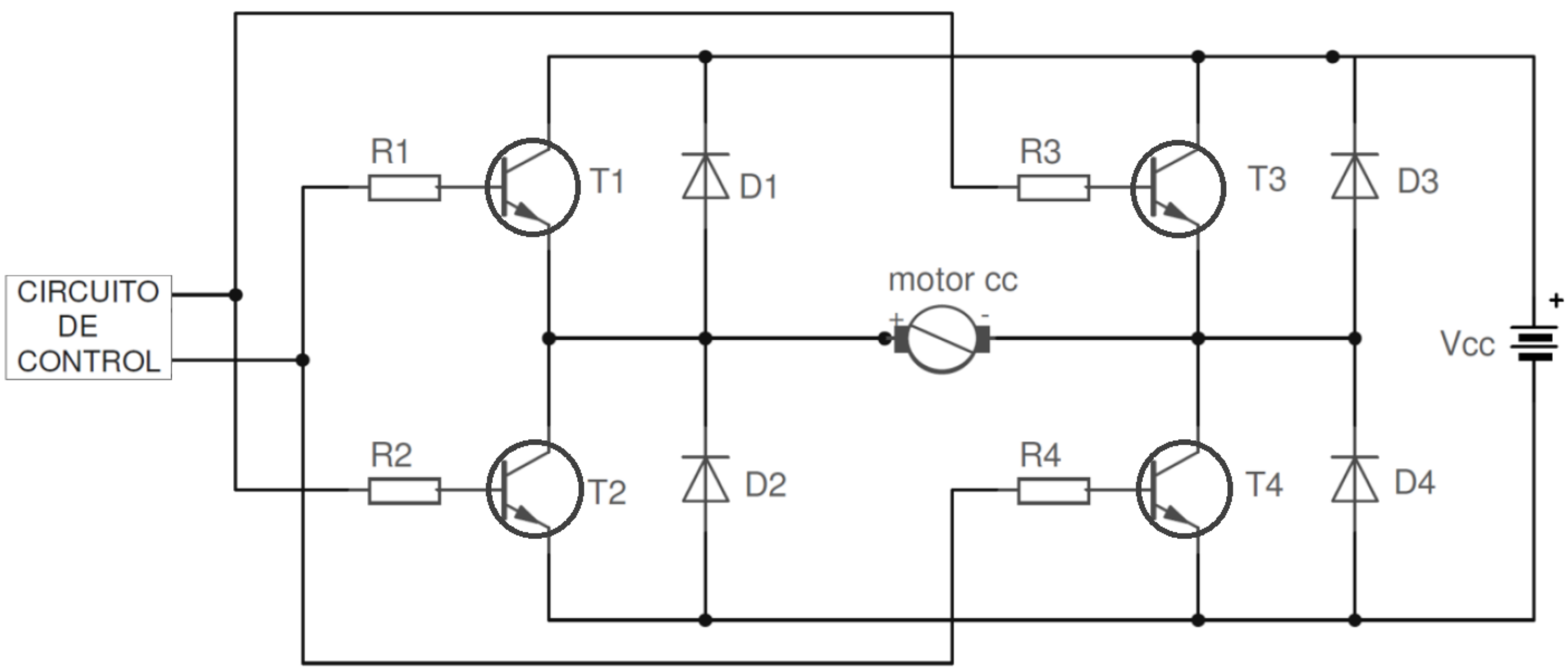
IGBT – Dynamic Behavior

- The IGBT turn-on time is similar to that of a power MOSFET.
- Its turn-off time is generally longer than that of a MOSFET but shorter than that of a bipolar transistor.
- Its switching speed therefore lies between those of the two devices, although it is generally closer to that of a MOSFET.
- Power dissipation also tends to fall between that of MOSFETs and bipolar transistors, depending on the operating conditions.
- Overall, the IGBT combines many of the power-handling and switching characteristics of bipolar transistors and MOSFETs, providing a useful compromise between conduction performance, switching speed and ease of gate drive.
- An excessive rate of change of voltage (dVCE/dt) can interact with residual stored charge and parasitic capacitances, potentially causing unwanted transient effects. Therefore, the allowable dynamic dVCE/dt may be more restrictive than the corresponding static voltage rating.

The H-Bridge

An H-bridge is a power electronic circuit consisting of four electronic switches that can apply either positive or negative voltage across a load. By controlling the direction of current flow, it can reverse the direction of rotation of a motor or generate an alternating output voltage.

<u>Typical applications</u>: DC and AC motor drives

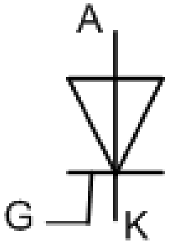


MOSFET vs IGBT

Characteristic	MOSFET	IGBT
Voltage Range	Low to medium voltage, typically up to approximately 400–600 V	Medium to high voltage, typically from several hundred volts to the kV range
Current Capability	Suitable for moderate to high currents, depending on voltage rating and device technology	Well suited to high-current applications, particularly at medium and high voltages
Conduction Losses	Very low at low and medium voltages due to low $\mathbf{RDS_{on}}$	$\mathbf{VCE_{SAT}}$ is relatively weakly dependent on current compared with MOSFET resistive conduction, making IGBTs advantageous in many high-voltage, high-current applications.
Switching Speed	Very high; suitable for switching frequencies from tens or hundreds of kHz into the MHz range in appropriate applications	Lower than MOSFETs; commonly used at switching frequencies up to several tens of kHz, depending on device and power level
Switching Losses	Generally low, particularly during turn-off, due to the absence of minority-carrier tail current	Higher turn-off losses due to **tail current** caused by stored minority carriers.
Typical Applications	DC–DC converters, switched-mode power supplies, low- and medium-power motor drives and consumer electronics	Variable-frequency drives, industrial inverters, electric traction, renewable-energy converters and medium- to high-power drives.

Thyristor (SCR) – Introduction

- The thyristor is a semiconductor device specifically intended for power applications.
- SCR stands for Silicon Controlled Rectifier. As its name suggests, it operates as a controlled rectifier: like a diode, it conducts primarily in one direction, but its transition to the conducting state can be controlled.
- For this purpose, the SCR includes a control terminal called the gate. An external gate signal can trigger the device into conduction, provided that the anode is sufficiently positive with respect to the cathode.

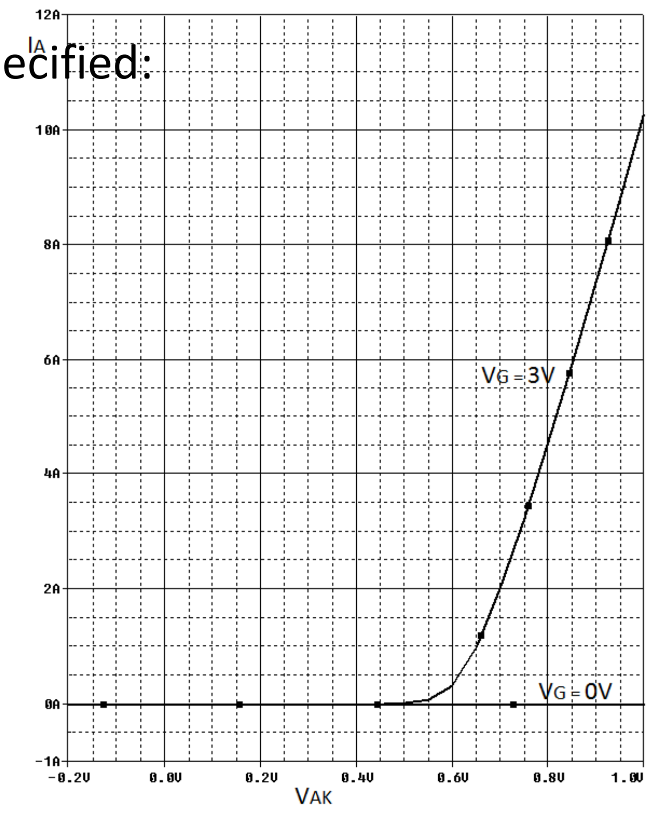


Thyristor (SCR) – Static Behavior: Blocking State

- The thyristor is in the blocking state under either of the following conditions:
  - The anode-to-cathode voltage is positive, but no sufficient positive gate signal is applied with respect to the cathode: forward blocking
  - The anode-to-cathode voltage is negative, regardless of the gate condition: reverse blocking.
- In the blocking state, only the device leakage current flows. This current increases slightly with anode-to-cathode voltage and more significantly with temperature.
  - Under forward-blocking conditions, if the anode-to-cathode voltage exceeds the forward breakover voltage, the thyristor may switch into conduction without a gate trigger. This does not necessarily destroy the device, provided its ratings are not exceeded.
- Voltage ratings analogous to those of a power diode are specified for both forward and reverse blocking:
  - Forward / Reverse Working Voltage.
  - Forward / Reverse Repetitive Peak Voltage.
  - Forward / Reverse Non-Repetitive Peak Voltage.
  - Forward Breakover Voltage / Reverse Breakdown Voltage.

Thyristor (SCR) – Static Behavior: On-State

- The anode current is determined by the external circuit and is essentially independent of the gate current once the SCR has latched into conduction. It must remain above the holding current to prevent the thyristor from turning off spontaneously.
- The anode-to-cathode voltage typically remains around 1.5–2 V while the device is conducting.
- Current ratings analogous to those of a power diode are specified:
  - **Average On-State Current** *(in some datasheets, RMS On-State Current is also specified)*.
  - Repetitive Peak On-State Current.
  - Non-Repetitive Peak On-State Current (Surge Current).
- Conduction Losses: $P_c = 1{,}3 * I_{Am} + rI_A{}^2$
  - 1.3V: Threshold Voltage.
  - I_{Am}: Average Anode Current.
  - r: Dynamic On-State Resistance.
  - I_A: RMS Anode Current.



Thyristor (SCR) – Triggering

- Triggering is the transition of the thyristor from the blocking state to a stable conducting state.
- Unintentional Triggering:
  - Overvoltage Triggering: If the forward anode-to-cathode voltage exceeds the forward breakover voltage, the SCR may switch into conduction without a gate signal.
  - High dVAK/dt Triggering: Even if the anode-to-cathode voltage is below the forward breakover voltage, a sufficiently rapid increase in voltage may cause unintended turn-on due to capacitive current within the device. The critical rate of rise of off-state voltage depends on the applied voltage and junction temperature. Manufacturers typically specify a maximum permissible dVAK/dt under defined test conditions.
- Gate Triggering: Gate-pulse triggering is the normal method used to turn on an SCR. A suitable gate current pulse is applied while the anode is positive with respect to the cathode.
  - **Delay Time (td):** Time interval from the application of the gate pulse until the anode current reaches 10% of its final value..
  - **Rise Time (tr):** Time required for the anode current to rise from 10% to 90% of its final value.
  - **Turn-On Time (ton):** Sum of the delay time and rise time.
- During turn-on, the rate of rise of anode current must not exceed the specified maximum value, (diA/dt)max. Immediately after triggering, conduction initially occurs over a relatively small area of the junction close to the gate region. An excessively rapid increase in anode current therefore produces a very high local current density, which may damage or destroy the thyristor.

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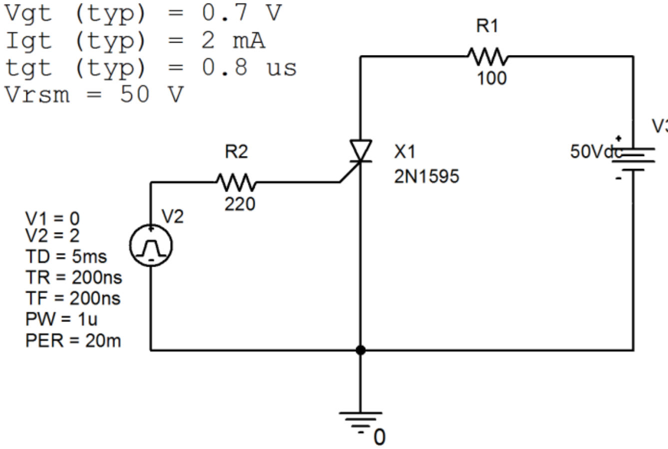
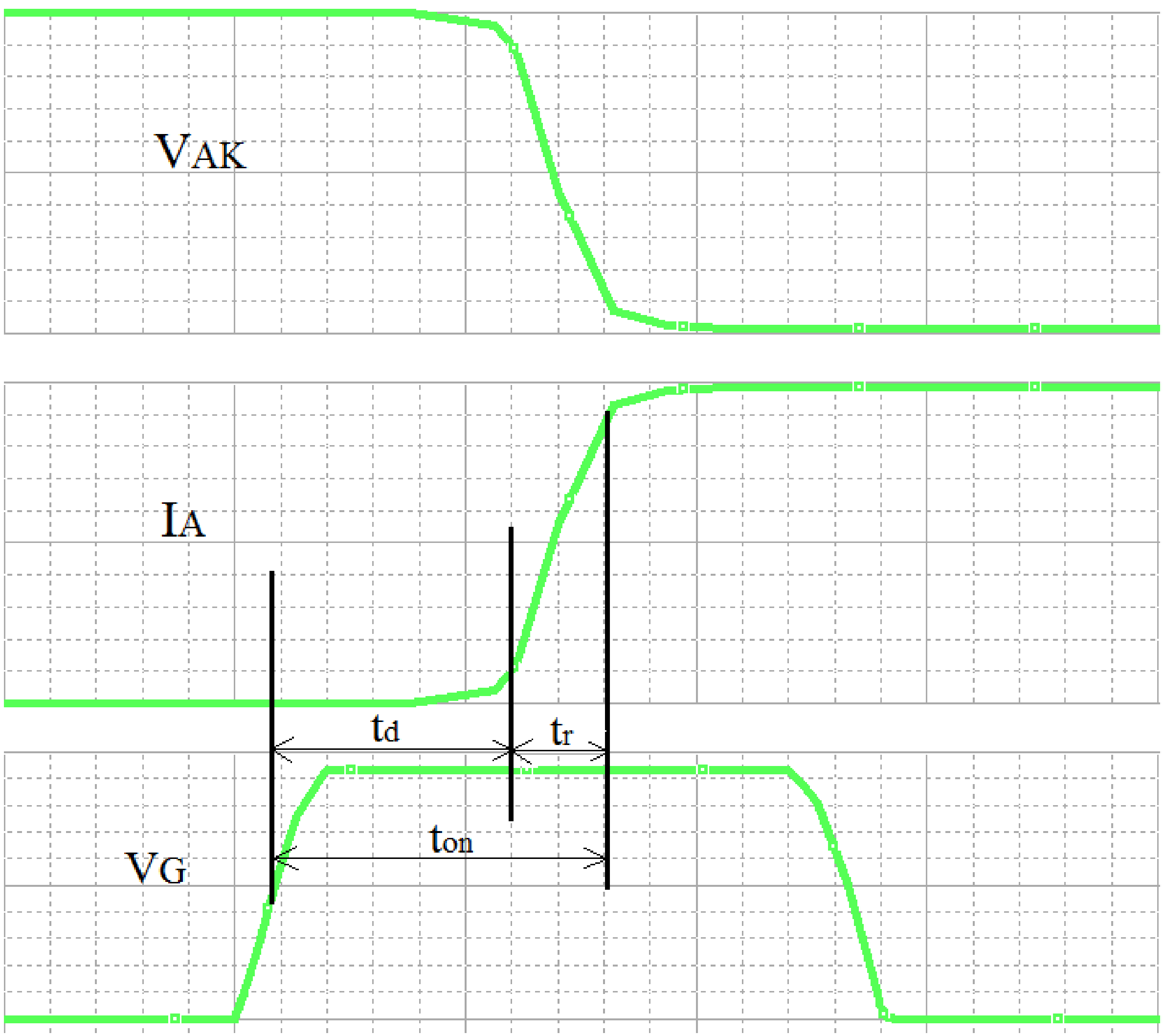
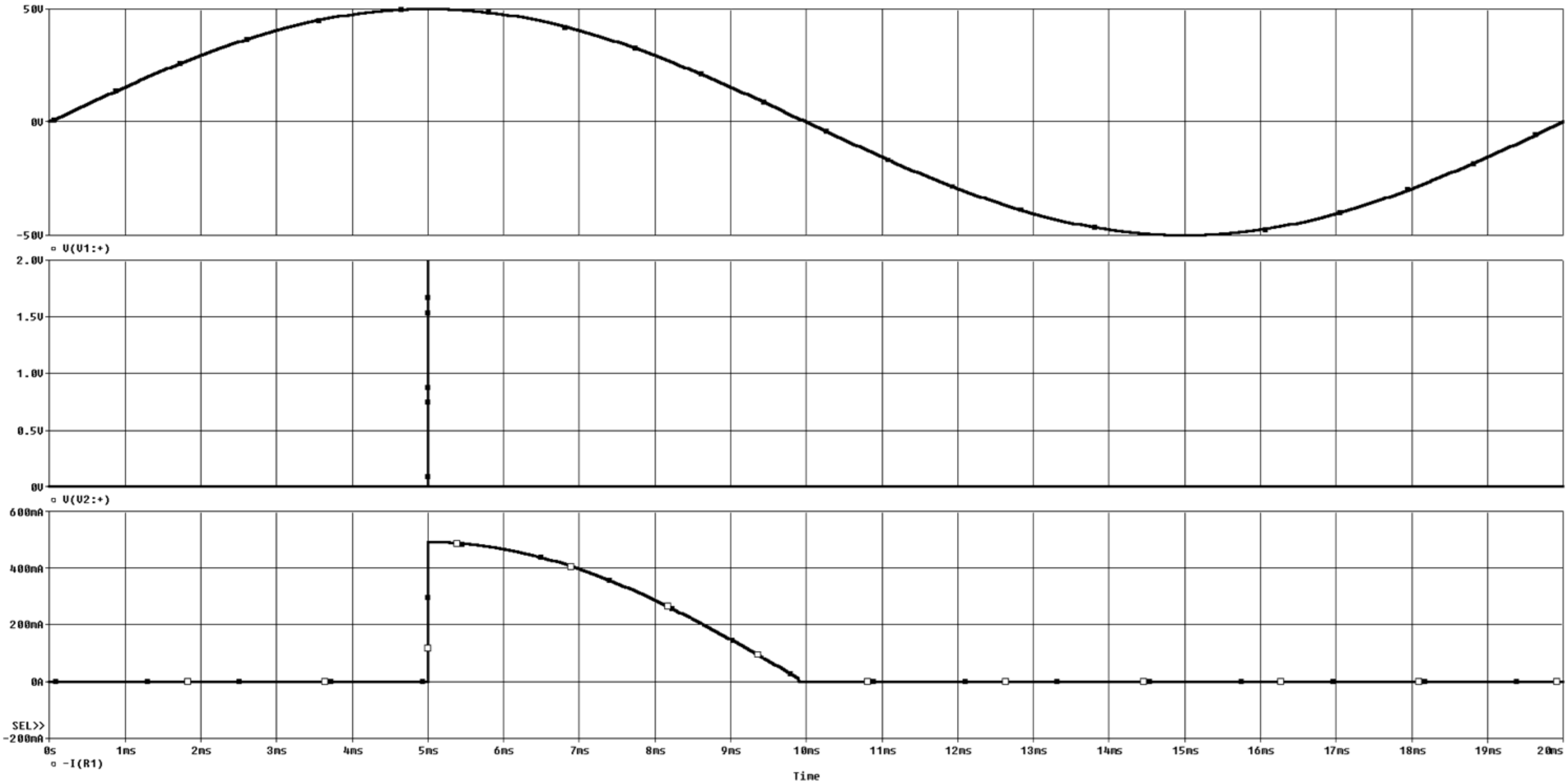
2N1595
Vgt (typ) = 0.7 V
Igt (typ) = 2 mA
tgt (typ) = 0.8 us
Vrsm = 50 V






50V
0V
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V(V1:+)
2.0V
1.5V
1.0V
0.5V
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200mA
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16ms
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-I(R1)
Time

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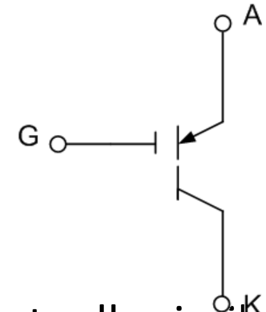
Thyristor (SCR) – Gate Trigger Characteristics

- The pulses applied to the SCR gate must satisfy specific requirements to ensure reliable triggering:
  - They must have sufficient duration for the anode current to reach the latching current **(I_L)**.
  - The gate current must exceed the specified gate trigger current **(I_{GT})** at the operating temperatura
  - The gate-to-cathode voltage must exceed the specified gate trigger voltage **(V_{GT})** at the operating temperature. This voltage produces the gate current that actually initiates the triggering process
- To prevent unintended triggering, manufacturers also specify :
  - Maximum Gate-to-Cathode Non-Trigger Voltage **(V_{GD})**.
  - Maximum Non-Trigger Gate Current **(I_{GD})**.
- Therefore:
  - Gate voltage and current values above the guaranteed trigger thresholds ensure reliable triggering.
  - Gate voltage and current values below the guaranteed non-trigger limits ensure that unintended triggering does not occur.
  - Values between these regions result in an indeterminate triggering condition.

Thyristor (SCR) – Turn-Off

- An SCR cannot normally be turned off through the gate terminal.
- Natural turn-off occurs when the anode current falls below the holding current.
- If the anode current decreases too rapidly, the thyristor may temporarily conduct reverse current due to stored charge, similarly to the reverse recovery process in a diode.
    - The turn-off time (t_q) is the minimum time required after the anode current falls to zero and reverses before a positive forward anode-to-cathode voltage can be reapplied without causing the SCR to turn on again unintentionally.
- Forced turn-off can be achieved by :
    - Applying a sufficient reverse voltage across the anode and cathode.
    - Applying a reverse current that forces the net anode current below the holding current and allows the device to recover its forward-blocking capability.

MCT (MOS-Controlled Thyristor)



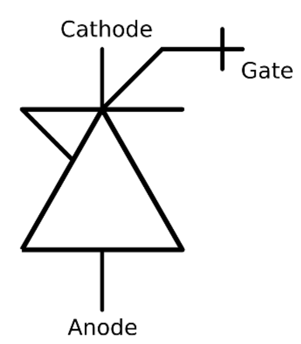
- The MCT is a hybrid power semiconductor device, conceptually similar in this respect to the IGBT.
- It incorporates two MOS-controlled structures: one is used to turn the thyristor on, while the other is used to turn it off.
- In an MCT, the anode serves as the reference terminal for the gate-control voltage.
- In the forward-blocking state, applying a negative gate-to-anode voltage turns the MCT on.
- While the device is conducting, applying a positive gate-to-anode voltage turns the MCT off..
- Turn-off is possible only while the anode current remains below a specified value known as the peak controllable current. Attempting to turn the device off above this limit may damage or destroy it. Under such conditions, the device effectively behaves like a conventional thyristor with respect to turn-off capability.
- The required gate-pulse width depends on the device current. Maintaining the appropriate gate drive throughout the turn-on or turn-off interval is generally recommended.
- MCTs are constructed from many parallel cells, allowing them to withstand relatively high rates of change of current (di/dt).

Other devices

- GTO (Gate Turn-off Thyristor): The GTO is a thyristor specifically designed so that both turn-on and turn-off can be controlled through the gate terminal.
- DIAC: Self-triggering device that switches to the conducting state in either the forward or reverse direction when the breakover voltage is reached.
- TRIAC: A DIAC provided with a control terminal that allows it to switch to the conducting state before the breakover voltage is reached.
- Hybrid devices: In addition to the IGBT and MCT, manufacturers offer a wide range of hybrid devices with similar characteristics

Emerging Technologies

- **Motivation:** Despite significant technological improvements, these devices still have certain limitations..
  - SCRs can only be turned on.
  - IGBTs can be turned off, but exhibit significant losses.
  - GTOs have lower losses, but also a lower switching frequency.
- IGCTs **(Integrated Gate-Commutated Thyristors)** have emerged as a compromise solution for medium- and high-power applications requiring high switching speed.



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