Power Semiconductor Devices Study notes For Electrical Engineering

These study notes on Power Semiconductor which will cover the topics such as Basic Principle of Power Converter,Classification of Power Semiconductor,Power Diodes,Application of Power Semiconductor Three/Four Layer Power Diodes,HVT,SCR,J-FET,MOSFET,GTO,IGBT & TRIAC.

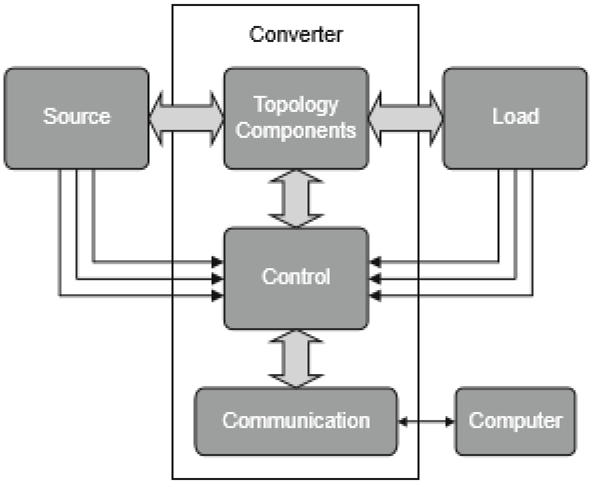
Power electronic systems convert and control electrical energy in an efficient manner between a source and a load. Sensor interfaces to the source and load, as well as information and communication links, are often integrated.

IEEE Power Electronics Society defines the field of power electronics as “This technology encompasses the effective use of electronic components, the application of circuit theory and design techniques, and the development of analytical tools toward efficient electronic conversion, control, and conditioning of electric power”.

Power Semiconductor

Power semiconductors are electronic devices that are specifically designed to handle high power levels and currents. They are used in a variety of applications that require the control and conversion of electrical power, such as power electronics, motor drives, energy storage systems, renewable energy systems, and electric vehicles.

Power semiconductors come in various forms, including power diodes, power transistors, insulated gate bipolar transistors (IGBTs), and thyristors (such as silicon-controlled rectifiers or SCR). These devices are made from semiconductor materials, typically silicon (Si) or gallium nitride (GaN) and silicon carbide (SiC) for high-power and high-frequency applications.



Basic Principles of Power Converters

- **Active Components:** The power semiconductor components that turn on and off the power flow within the converter. The devices are either in the off-state (forward or reverse blocking) or in the on-state (conducting).
- **Passive Components:** Like transformers, inductors, and capacitors, which temporarily store energy within the converter system. Based on the operating frequency, voltage, cooling method, and level of integration, different magnetic, dielectric and insulation materials are used. For a given power rating of the converter, higher operating (switching) frequencies enable smaller passive components.
- **Control Unit:** Analog and digital electronics, signal converters, processors, and sensors, to control the energy flow within the converter such that the internal variables (voltage, current) follow computed reference signals that guarantee proper behavior of the converter according to the external commands.

Classification of power semiconductor switches

Power devices is divided into terms of their number of terminals:

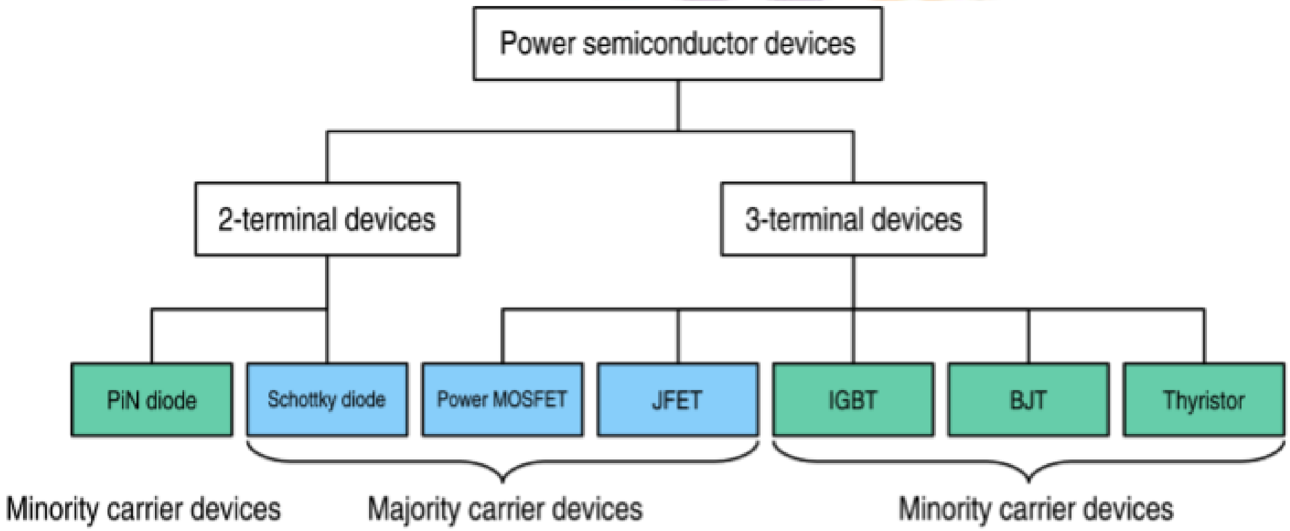
- **The two-terminal devices:** whose state is completely dependent on the external power circuit they are connected to.
- **The three-terminal devices:** whose state is not only dependent on their external power circuit, but also on the signal on their driving terminal (gate or base).

A second classification has to do with the type of charge carriers they use:

- Some devices are majority carrier devices (Schottky diode, MOSFET, JFET) - use only one type of charge carriers (i.e., either electrons or holes)
- Others are minority carrier devices (p-n diode, Thyristor, BJT, IGBT) - use both charge carriers (i.e. electrons and holes).

A third classification is based on the degree of controllability:

- Uncontrollable switches (**diodes**)
- Semi-Controllable Switches (**thyristors**)
- Fully-Controllable Switches (**BJT, MOSFET, JFET, IGBT, GTO, MCT**)



Power Diode

Types of power diodes

- **General purpose diode (rectifier diode):** standard recovery.
- **Fast recovery diode:** Reverse recovery time and charge specified. t_{rr} is usually less than 1μs, for many less than 100 ns,ultra-fast recovery diode.
- **Schottky diode (Schottky barrier diode barrier diode-SBD):** Essentially no recovered charge, and lower forward voltage.Restricted to low voltage (less than 200V),they are majority carrier device.

An ideal diode should have the following characteristics:

- **When forward-biased:** The voltage across the end terminals of the diode should be zero, whatever the current that flows through.
- **When reverse-biased:** the leakage current should be zero,whatever the voltage .The transition between on and off states should be instantaneous.

Practical Power Diode

Static Parameters

- Forward voltage V_F (threshold + linear incr.)
- Reverse current I_R
- Reverse breakdown voltage V_B
- Forward current I_F (avg. and surge)

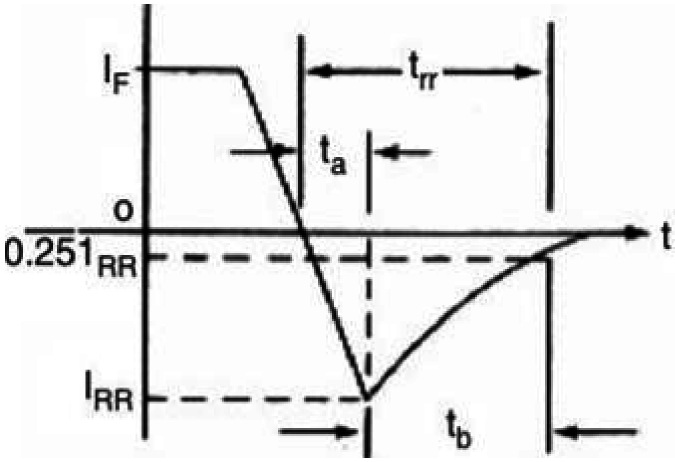
Dynamic Parameters

- Forward recovery time t_{fr}
- Reverse recovery time t_{rr}
- Peak reverse recovery current I_{RR}
- Diode capacitance C_d
- Rate of voltage and current: di/dt, dv/dt
- Transient thermal resistance (high frequency)

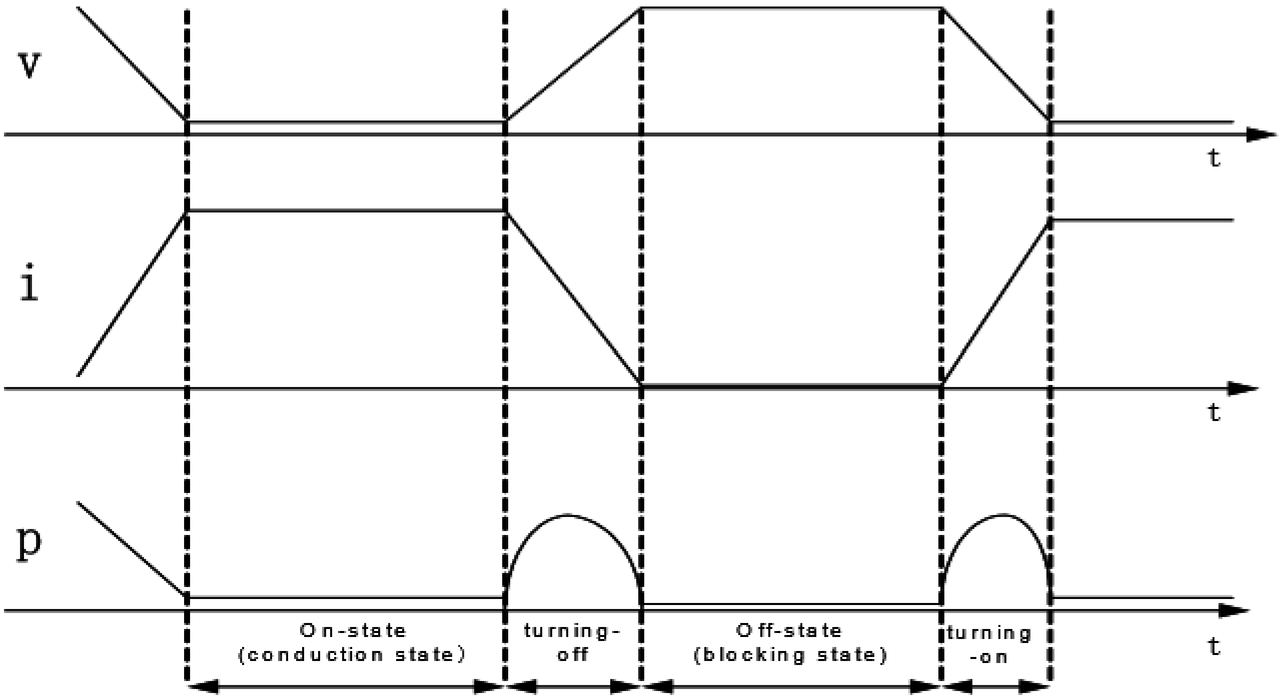
Approximate relation between storage Q_{rr}, t_{rr} and I_{RR}

$$Q_{rr} = \frac{1}{2} t_{rr} I_{rr}, \qquad t_{rr} \frac{di}{dt} = I_{rr}$$

$$t_{rr} = \sqrt{\frac{2Q_{rr}}{di/dt}}, \qquad I_{rr} = \sqrt{2Q_{rr}(di/dt)}$$



Power losses on power semiconductor devices



Total power loss on power semiconductor = (conduction loss + turn-off loss) + (off-state loss + + turn-on loss)

- **Where conduction loss is the On State Loss ,**
- **Turn Off & Turn On Losses are the Switching Loss**

Operating and Selecting Power Semiconductors

Typical design specifications of Power Semiconductor devices are low cost, high efficiency, or high power density (low weight, small size). Ultimately, thermal considerations, i.e. device losses, cooling, and maximum operating temperature, determine the physical limits of a converter design. When devices are operated within their (electrical) **safe operation area (SOA)**, conduction and switching losses dominate device losses. In general, the outcome of the design depends greatly on the selection of the following:

- Device type (unipolar, bipolar, transistor, thyristor) and rating (voltage and current margins, frequency range)
- Switching frequency
- Converter layout (minimizing parasitic stray inductances, capacitances, and skin effects)
- Topology (two level, multi-level, hard switching, or soft switching)
- Gate control (switching slew rate)
- Control (switching functions, minimizing filters, EMI).

Applications of Power Semiconductors

- Since All the electric power not only passes through copper, dielectric, or magnetic materials but also passes through the semiconductors,because most applications require energy conversions or because increased efficiency is required in these energy conversion processes.
- Depending on the required voltage and current ratings of the power semiconductors, different types of power semiconductors are being used.
- At the low power end (1 VA up to 1 kVA), switched-mode power supplies for battery chargers, mostly for portable communication devices and power tools, as well as for electronic systems (audio, video, and controllers).
- Drive applications span a power range from a few 10VA up to 100 MVA. In automotive applications, many small drives (100VA up to 1kVA) are fed from the onboard power source, nominally 12 or 24V.
- As transistor-type devices offer short-circuit protection at low cost, IGBTs are predominantly being used in drives fed from power grids. Medium-voltage drives (grid voltage from 1000V up to 36kV) use, depending on drive rating, transistor

(IGBTs), and turn-off thyristor (GTO or GCT)-type devices. Above 3kV, i.e. at higher voltage and power ratings (above 5MW).

An Introduction To Power Devices

The P-N diode will be considered first since this is the basis of all active switches. This will be followed by a look at both 3 layer and 4 layer switches.Under normal operating conditions the off-state losses in the switch are practically zero. For square wave systems, the on-state losses (occurring during the on-time), are primarily determined by the **On-State Resistance** which gives rise to an on-state voltage drop, V_{ON}.

- The (static) on-state losses may be calculated from

$$P_{STATIC} = \delta.V_{ON}.I_{ON}$$

- The total dynamic power loss is proportional to both the frequency and to the turn-on and turn-off energies.

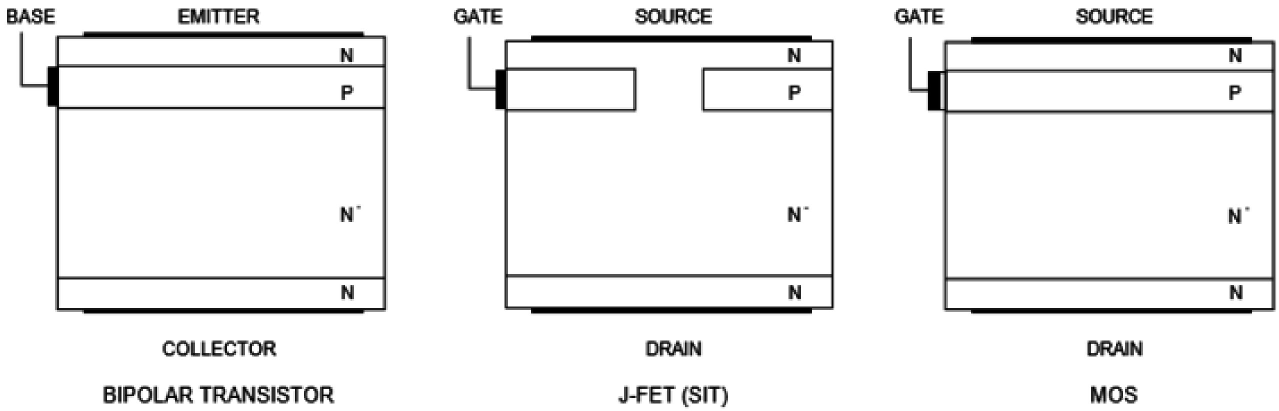
$$P_{DYNAMIC} = f.(E_{ON} + E_{OFF})$$

- The total losses are the sum of the on-state and dynamic losses

$$P_{TOT} = \delta.V_{ON}.I_{ON} + f.(E_{ON} + E_{OFF})$$

- At the other extreme a device whose on-state loss is negligible compared with the switching loss, will be limited in frequency due to the increasing dynamic losses.
- High frequency switching When considering frequency limitation it is important to realize that the real issue is not just the frequency, but also the minimum on-time required. For example, an SMPS working at 100 kHz with an almost constant output power,will have a pulse on-time t_P of about **2-5μs**.

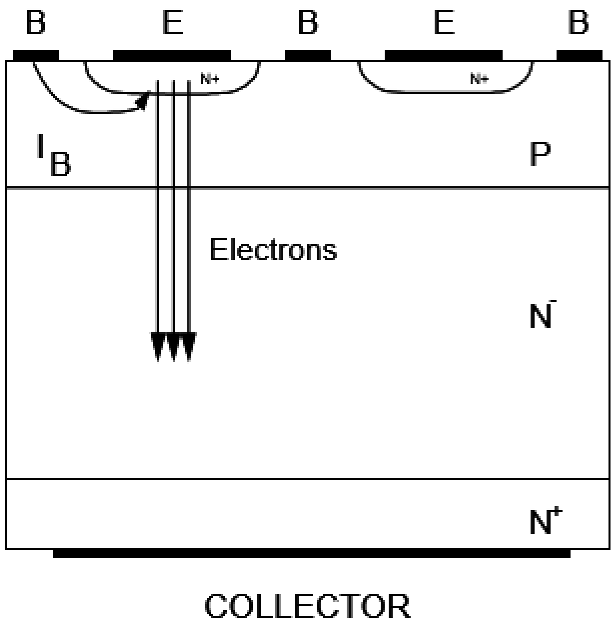
Three Layer devices



- The three basic design of 3-layer devices are shown in the above figuree.It should be emphasized here that the discussion is restricted to high voltage devices only,which means that all relevant devices will have a vertical structure ,characterized by a wide N--layer.
- The figure shows how a three layer device can be formed by adding an N type layer to the P-N diode structure. Two back to back P-N diodes thus form the basis of the device, where the P layer provides a means to control the current when the device is in the on-state.
- There are three ways to use this P-layer as a control terminal. The first is to feed current into the terminal itself. The current through the main terminals is now proportional to the drive current. This device is called a High Voltage Transistor or HVT.

The High Voltage Transistor (HVT)

- The High Voltage Transistor uses a positive base current to control the main collector current.
- The relation is: $\mathbf{I_C = h_{fe} * I_B}$. The base drive forward biases the base emitter P-N junction and charge (holes and electrons) will pass through it.
- Now the base of a transistor is so thin that the most of the electrons do not flow to the base but into the collector - giving rise to a collector current.
- As we know the ratio between the holes and electrons depend on the doping. So by correctly doping the base emitter junction, the electron current can be made much larger than the hole current, which means that I_C can be much larger than I_B.

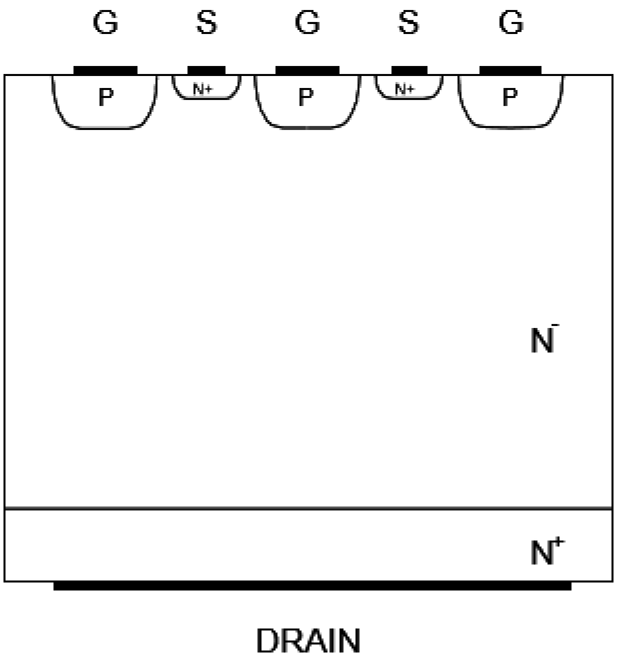


- The on-state voltage of an HVT will be considerably lower than for a MOS or J-FET. This is its main advantage, but the resulting charge stored in the N- layer has to be delivered and also to be removed.
- A serious limitation of the HVT is the occurrence of second breakdown during switch off. The current contracts towards the middle of the emitter finger sand the current density can become very high.
- The **RBSOAR (Reverse Bias Safe Operating Area)** graph specifies where the device can be used safely. Device damage may result if the device is not properly used and one normally needs a snubber (dV/dt network) to protect the device.

The J-FET

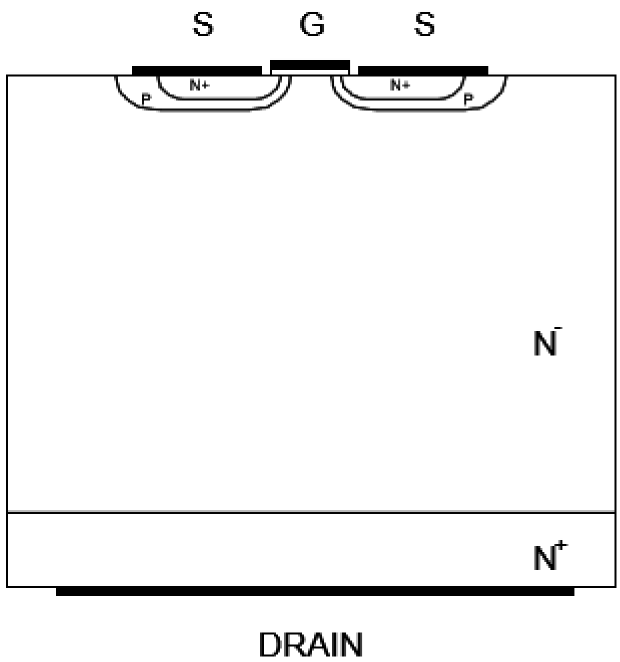
- The J-FET(Junction Field Effect Transistor) has a direct resistance between the Source and the Drain via the opening in the P-layer.
- When the **gate-source voltage is zero** the device is **ON**. Its on-resistance is determined by the resistance of the silicon and no charge is present to make the resistance lower as in the case of the bipolar transistor.
- When a negative voltage is applied between Gate and Source, a depletion layer is formed which pinches off the current path. So, the current through the switch is determined by the voltage on the gate.

- The drive energy is low, it consists mainly of the charging and discharging of the gate-source diode capacitance. This sort of device is normally very fast.



The MOS transistor

- The **M-O-S (Metal-Oxide-Semiconductor)** transistor is **normally off**: a positive voltage is required to induce a channel in the P-layer.
- When a positive voltage is applied to the gate, electrons are attracted to the surface beneath the gate area. In this way an "inverted" N-type layer is forced in the P-material providing a current path between drain and source.
- The properties are quite like the J-FET with the exception that the charge is now across the (**normally very thin**) gate oxide.
- Unlike the J-FET it does not require a negative voltage although a negative voltage may help switch the device off quicker.
- The MOSFET is the preferred device for higher frequency switching since it combines fast speed,easy drive and wide commercial availability.

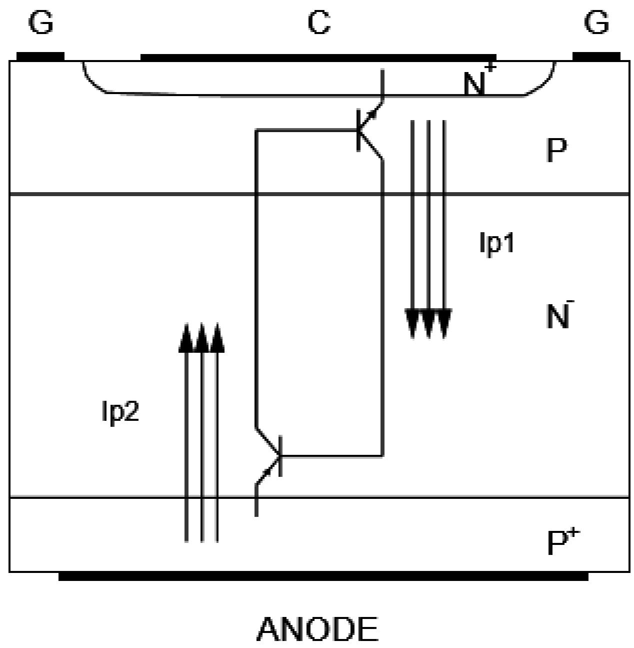


Four layer devices

- The three basic designs from the previous section can be extended with a **P$^+$**-layer at the back, thereby generating three basic Four Layer Devices. The addition of this extra layer creates a PNP transistor from the **P$^+$-N$^-$-P** layers.
- An important point is latching . This happens when the internal currents are such that we are not able to turn off the device using the control electrode. The only way to turn it off is by externally removing the current from the device.

The SCR/Thyristor(Silicon Controlled Rectifier)

A thyristor(or SCR, Silicon Controlled Rectifier) is essentially an HVT with an added **P$^+$**-layer**.** The resulting **P$^-$-N$^-$-P$^+$** transistor is on when the whole device is on and provides enough base current to the **N$^+$-P-N$^-$** transistor to stay on. So after an initial kick-on, no further drive energy is required.



- The classical thyristor is thus a **latching device**. Its construction is normally not very fine and as a result the gate contact is too far away from the centre of the active area to be able to switch it off.

- Also the current density is much higher than in a bipolar transistor.The switching times however are very long. Its turn-on is hampered by its structure since it takes quite a while for the whole crystal to become active. This seriously limits its dI/dt.

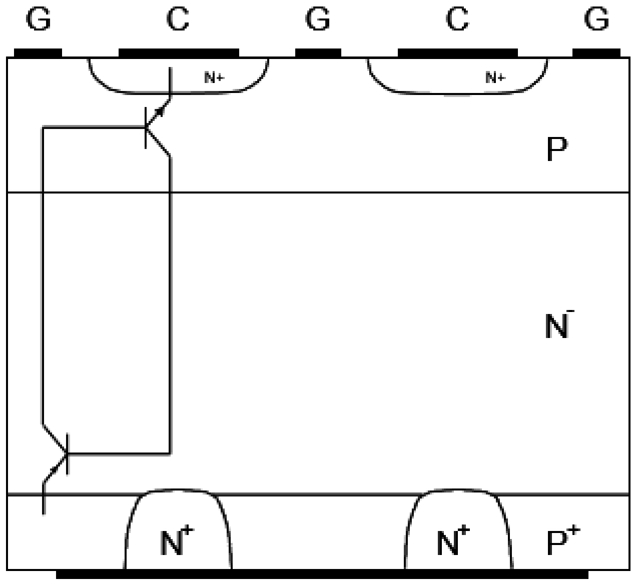
- Once a thyristor is on it will only turn-off after having zero current fora few microseconds. This is done by temporarily forcing the current via a so-called **commutation circuit**.

A GTO (Gate-Turn-Off Thyristor)

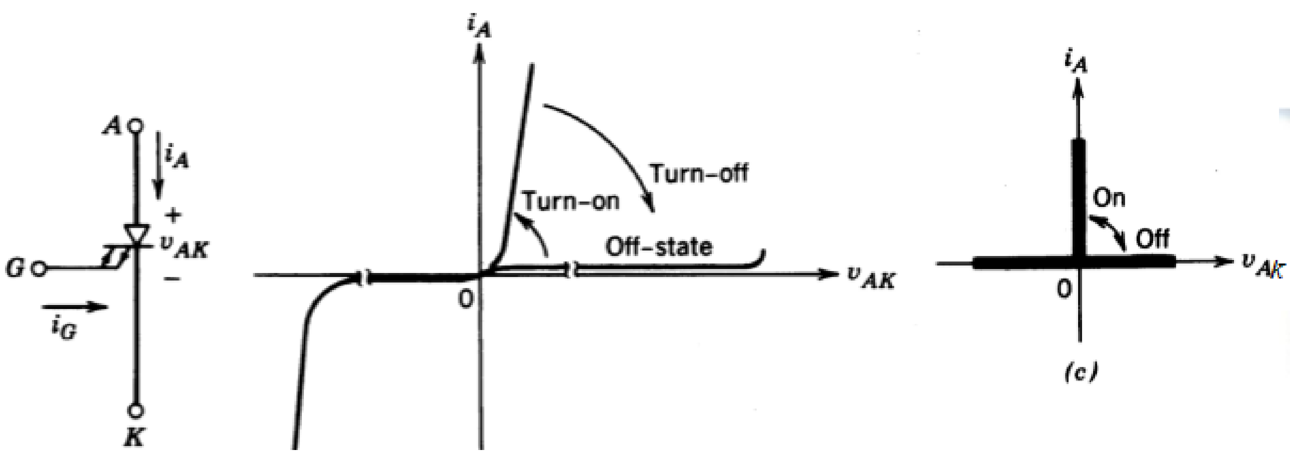
- A major variation on the thyristor is the GTO (Gate Turn Off Thyristor).

- This is a thyristor where the structure has been tailored to give better speed by techniques such as accurate lifetime killing, fine finger or cell structures and "anode shorts" (short circuiting P+ and N- at the back in order to decrease the current gain of the PNP transistor).

- As a result, the product of the gain of both NPN and PNP is just sufficient to keep the GTO conductive. A negative gate current is enough to sink the hole current from the PNP and turn the device off.



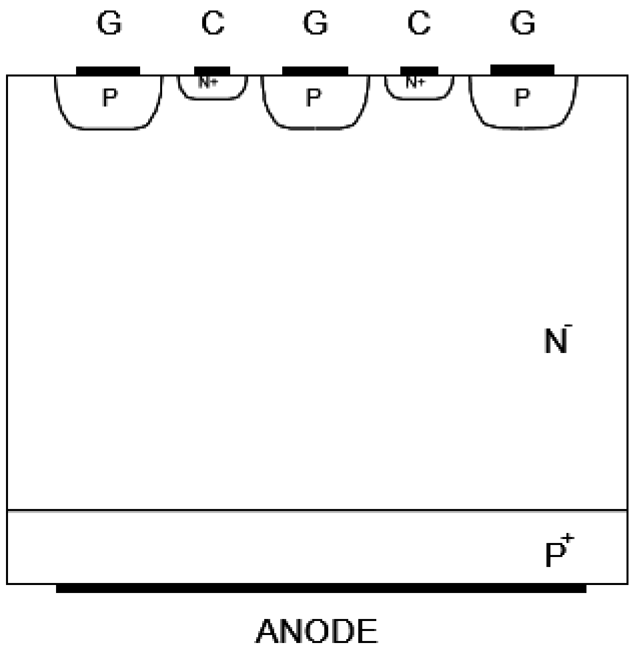
The lower terminal is also the **Anode.**



The SITh (Static Induction Thyristor)

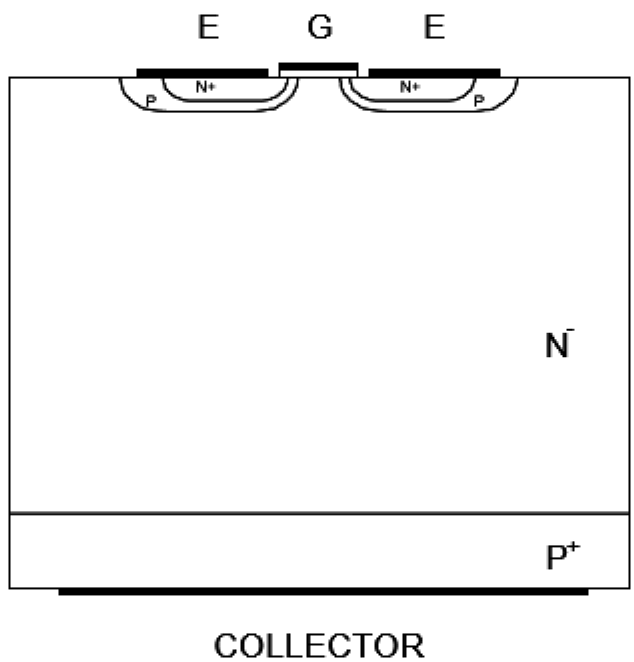
- Sometimes also referred to as **FCT (Field Controlled Thyristor)** is essentially a J-FET with an added P+ back layer.
- In contrast to the standard thyristor, charge is normally only injected from the back, so the total amount of charge is limited. However, a positive gate drive is possible which will reduce on-state resistance.
- Active extraction of charge via the gate contact is possible and switching speeds may be reduced considerably by applying an appropriate negative drive as in the case of an HVT. As for the SIT the technological complexity is a severe drawback, as is its negative drive requirements. Consequently mass production of this device

is not available yet.



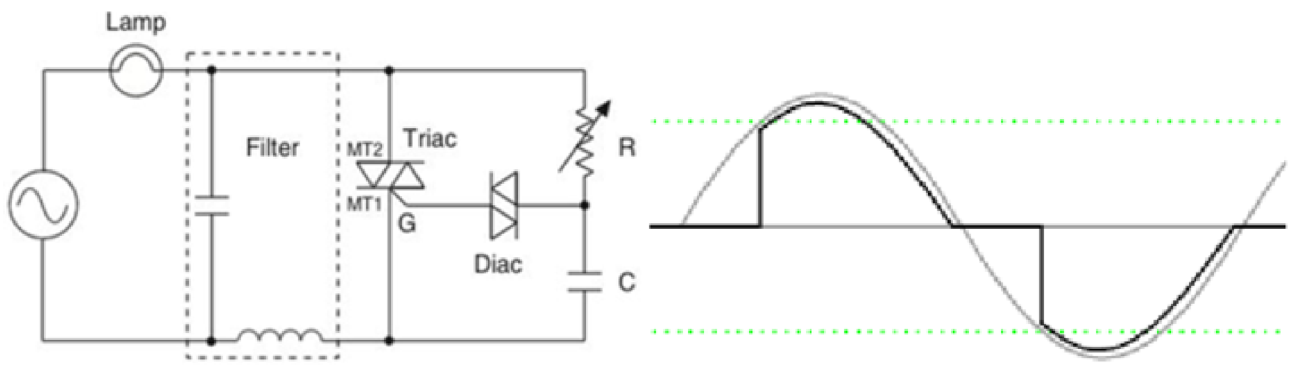
The IGBT (Insulated Gate Bipolar Transistor)

- An IGBT (Insulated Gate Bipolar Transistor) is an MOS transistor with **P^+** at the back. Charge is injected from the back only, which limits the total amount of charge.
- Active charge extraction is not possible, so the carrier lifetime τ should be chosen carefully, since that determines the switching losses.Again two ranges are available with both fast and slow IGBTs.
- The speed of the fast IGBT is somewhat better than that of a GTO because a similar technology is used to optimize the IGBT but only the back **P^+**-layer is responsible for the charge.
- The IGBT is gaining rapidly in popularity since its manufacturing is similar to producing Power MOS and an increasing market availability exists. Although the latching of IGBTs was seen as a problem,modern optimized devices don’t suffer from latch-up in practical conditions.



Triac

- A Tirac belongs to the thyristor (or SCR) family. However, unlike SCRs, which are unidirectional devices (i.e.,can conduct current only in one direction), a Triac is bidirectional and so current can flow through them in either direction.
- Another difference from SCRs is that TRIACs can be triggered by either a positive or a negative current applied to its gate electrode, whereas SCRs can be triggered only by currents going into the gate.
- Once triggered, the device continues to conduct until the current drops below the "holding current".



Light Dimmer Circuit

Thanks!