UNIT I
POWER SEMI-CONDUCTOR DEVICES

SUBJECT CODE : EE6503
SUBJECT NAME : Power Electronics
STAFF NAME : Ms.M.Uma Maheswari
SEMICONDUCTOR DEVICES

- POWER DIODE
- POWER TRANSISTORS
  - POWER BJT
  - POWER MOSFET
  - IGBT
- THYRISTORS
  - SCR
  - TRIAC
  - GTO
POWER DIODE

(a) Symbol: $I_F$

(b) and (c) Types of packaging:

Power diode: (a) symbol; (b) and (c) types of packaging.
STRUCTURAL FEATURES OF POWER DIODE AND ITS SYMBOL.
V-I CHARACTERISTICS OF SIGNAL DIODE, POWER DIODE AND IDEAL DIODE

(a) Forward biased Power Diode

(b) V-I Characteristics of Signal Diode

(c) V-I Characteristics of Power Diode

(d) V-I Characteristics of Ideal Diode
REVERSE RECOVERY CHARACTERISTICS

(a) Variation of Forward Current $I_f$ (b) Forward Voltage Drop $V_f$ (c) Power loss in the Diode
POWER TRANSISTORS

FOUR TYPES

- Bipolar junction Transistor (BJT)
- Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
- Insulated Gate Bipolar Transistors (IGBT) and
- Static Induction Transistor (SIT)
POWER BJT

• Three layer, Two Junction npn or pnp type

• Bipolar means current flow in the device is due to the movement of BOTH holes and Electrons.
POWER BJT

(a) npn type

(b) pnp type
V-I CHARACTERISTICS OF POWER BJT

(a) npn Transistor circuit

(b) Input Characteristics

(c) Output Characteristics
SWITCHING CHARACTERISTICS CIRCUIT FOR BJT

nbn transistor with resistive load
SWITCHING CHARACTERISTICS OF POWER BJT

Switching waveforms of Power BJT
SAFE OPERATING AREA FOR POWER BJT

FBSOA - Forward biased Safe Operating Area

RBSOA - Reverse Block Safe Operating Area
POWER MOSFET
POWER MOSFET
• THREE TERMINALS – DRAIN, SOURCE AND GATE
• VOLTAGE CONTROLLED DEVICE
• GATE CIRCUIT IMPEDANCE IS HIGH (OF THE ORDER OF MEGA OHM). HENCE GATE CAN BE DRIVEN DIRECTLY FROM MICROELECTRONIC CIRCUITS.
• USED IN LOW POWER HIGH FREQUENCY CONVERTERS, SMPS AND INVERTERS
BASIC STRUCTURE OF n-CHANNEL POWER MOSFET
MOSFET TRANSFER CHARACTERISTICS
MOSFET OUTPUT CHARACTERISTICS
MOSFET SWITCHING

Diagram showing the voltage and current waveforms over time.

- $V_G$: Gate voltage
- $V_D$: Drain voltage
- $V_GS$: Gate-to-source voltage
- $V_GSP$: Gate-to-source peak voltage
- $V_GST$: Gate-to-source threshold voltage
- $I_D$: Drain current
- $t_{on}$: Turn-on time
- $t_{df}$: Dead time
- $t_{f1}$: Propagation delay
- $t_1$: Transition time
<table>
<thead>
<tr>
<th>S.No</th>
<th>BJT</th>
<th>MOSFET</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BIPOLAR DEVICE</td>
<td>UNIPOLAR DEVICE</td>
</tr>
<tr>
<td>2</td>
<td>LOW INPUT IMPEDANCE (KILO OHM)</td>
<td>HIGH INPUT IMPEDANCE (MEGA OHM)</td>
</tr>
<tr>
<td>3</td>
<td>HIGH SWITCHING LOSSES BUT LOWER CONDUCTION LOSSES</td>
<td>LOWER SWITCHING LOSSES BUT HIGH ON-RESISTANCE AND CONDUCTION LOSSES</td>
</tr>
<tr>
<td>4</td>
<td>CURRENT CONTROLLED DEVICE</td>
<td>VOLTAGE CONTROLLED DEVICE</td>
</tr>
<tr>
<td>5</td>
<td>NEGATIVE TEMPERATURE COEFFICIENT OF RESISTANCE. PARALLEL OPERATION IS DIFFICULT. CURRENT SHARING RESISTORS SHOULD BE USED.</td>
<td>POSITIVE TEMPERATURE COEFFICIENT OF RESISTANCE. PARALLEL OPERATION IS EASY</td>
</tr>
<tr>
<td>6</td>
<td>SECONDARY BREAKDOWN OCCURS.</td>
<td>SECONDARY BREAKDOWN DOES NOT OCCUR.</td>
</tr>
<tr>
<td>7</td>
<td>AVAILABLE WITH RATINGS</td>
<td>AVAILABLE WITH RATINGS</td>
</tr>
</tbody>
</table>
INSULATED GATE BIPOLAR TRANSISTOR (IGBT)

• COMBINES THE BEST QUALITIES OF BOTH BJT AND MOSFET

• HAS HIGH INPUT IMPEDANCE AS MOSFET AND HAS LOW ON-STATE POWER LOSS AS IN BJT

• OTHER NAMES
  ✓ MOSIGT (METAL OXIDE INSULATED GATE TRANSISTOR),
  ✓ COMFET (CONDUCTIVELY-MODULATED FIELD EFFECT TRANSISTOR),
  ✓ GEMFET (GAIN MODULATED FIELD EFFECT TRANSISTOR),
BASIC STRUCTURE OF IGBT
BASIC STRUCTURE OF IGBT
EQUIVALENT CIRCUIT OF IGBT
BASIC STRUCTURE OF IGBT
EQUIVALENT CIRCUIT OF IGBT
V-I AND TRANSFER CHARACTERISTICS OF IGBT
SWITCHING CHARACTERISTICS OF IGBT

[Diagram showing the switching characteristics of an IGBT with labels for various voltage and current levels and time intervals.]
APPLICATIONS OF IGBT

• DC AND AC MOTOR DRIVES
• UPS SYSTEMS, POWER SUPPLIES
• DRIVES FOR SOLENOIDS, RELAYS AND CONTACTORS
### COMPARISON OF IGBT WITH MOSFET

<table>
<thead>
<tr>
<th>S.No</th>
<th>MOSFET</th>
<th>IGBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>THREE TERMINALS ARE GATE, SOURCE AND DRAIN</td>
<td>THREE TERMINALS ARE GATE, EMITTER AND COLLECTOR</td>
</tr>
<tr>
<td>2.</td>
<td>HIGH INPUT IMPEDANCE</td>
<td>HIGH INPUT IMPEDANCE</td>
</tr>
<tr>
<td>3.</td>
<td>VOLTAGE CONTROLLED DEVICE</td>
<td>VOLTAGE CONTROLLED DEVICE</td>
</tr>
<tr>
<td>4.</td>
<td>RATINGS AVAILABLE UPTO 500V, 140A</td>
<td>RATINGS AVAILABLE UPTO 1200V, 500A</td>
</tr>
<tr>
<td>5.</td>
<td>OPERATING FREQUENCY IS UPTO 1 MHz</td>
<td>OPERATING FREQUENCY IS UPTO 50KHz</td>
</tr>
<tr>
<td>6.</td>
<td>WITH RISE IN TEMPERATURE, THE INCREASE IN ON-STATE RESISTANCE IN MOSFET IS MORE PRONOUNCED THAN IGBT. SO, ON-STATE VOLTAGE DROP AND LOSSES RISE RAPIDLY IN MOSFET THAN IN IGBT. WITH RISE IN TEMPERATURE.</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>WITH RISE IN VOLTAGE, THE INCREMENT IN ON-STATE VOLTAGE DROP IS MORE DOMINANT IN MOSFET THAN IT IS IN IGBT. THIS MEANS IGBTs CAN BE DESIGNED FOR HIGHER VOLTAGE RATINGS THAN MOSFETs.</td>
<td></td>
</tr>
</tbody>
</table>
THYRISTORS
SILICON CONTROLLED
RECTIFIER (SCR)

• Three terminal, four layers (P-N-P-N)

• Can handle high currents and high voltages, with better switching speed and improved breakdown voltage.

• Name ‘Thyristor’, is derived by a combination of the capital letters from THYRatron and transISTOR.

• Has characteristics similar to a thyratron tube

But from the construction viewpoint belongs to transistor (pnp or npn device) family.
THYRISTORS

• TYPICAL RATINGS AVAILABLE ARE 1.5KA & 10KV WHICH RESPONDS TO 15MW POWER HANDLING CAPACITY.

• THIS POWER CAN BE CONTROLLED BY A GATE CURRENT OF ABOUT 1A ONLY.
BASIC STRUCTURE OF SCR

\[ p_1 (p^+) \quad 10^{19} \text{cm}^{-3} \]

\[ n_1 (n^-) \quad 10^{13} \text{ to } 5 \times 10^{14} \text{cm}^{-3} \]

\[ p_2 (p^+) \quad 10^{17} \text{cm}^{-3} \]

\[ n_2 (n^+) \]

Anode

Cathode

Gate

J1

J2

J3
BASIC STRUCTURE OF SCR CONT'D...

(a) Vertical cross-section of thyristor
SCR / Thyristor

- Circuit Symbol and Terminal Identification
SCR / Thyristor

• Anode and Cathode terminals as conventional pn junction diode

• Gate terminal for a controlling input signal
SCR/ Thyristor

• An SCR (Thyristor) is a “controlled” rectifier (diode)
• Control the conduction under forward bias by applying a current into the Gate terminal
• Under reverse bias, looks like conventional pn junction diode
SCR / Thyristor

• 4-layer (pnppn) device

• Anode, Cathode as for a conventional pn junction diode

• Cathode Gate brought out for controlling input
Equivalent Circuit

ANODE

GATE

P

N

P

P

N

CATHODE

Q1

BJT_PNP_VIRTUAL

Q2

BJT_NPN_VIRTUAL

ANODE

GATE

CATHODE
Apply Biasing

With the Gate terminal OPEN, both transistors are OFF. As the applied voltage increases, there will be a “breakdown” that causes both transistors to conduct (saturate) making $I_F > 0$ and $V_{AK} = 0$.

$$V_{Breakdown} = V_{BR(F)}$$
V-I CHARACTERISTICS OF SCR
Apply a Gate Current

For $0 < V_{AK} < V_{BB(F)}$,

Turn $Q_2$ ON by applying a current into the Gate

This causes $Q_1$ to turn ON, and eventually both transistors SATURATE

$V_{AK} = V_{CE_{sat}} + V_{BE_{sat}}$

If the Gate pulse is removed, $Q_1$ and $Q_2$ still stay ON!
How do you turn it OFF?

• Cause the forward current to fall below the value if the “holding” current, $I_H$

• Reverse bias the device
SCR Application – Power Control

When the voltage across the capacitor reaches the “trigger-point” voltage of the device, the SCR turns ON, current flows in the Load for the remainder of the positive half-cycle.

Current flow stops when the applied voltage goes negative.
SWITCHING CHARACTERISTICS OF SCR

Turn-on transient
- Delay time $t_d$
- Rise time $t_r$
- Turn-on time $t_{gt}$

Turn-off transient
- Reverse recovery time $t_{rr}$
- Forward recovery time $t_{gr}$
- Turn-off time $t_q$
SCR OPERATING MODES

FORWARD BLOCKING MODE: Anode is positive w.r.t. cathode, but the anode voltage is less than the break over voltage (VBO).

- only leakage current flows, so thyristor is not conducting.

FORWARD CONDUCTING MODE: When anode voltage becomes greater than VBO, thyristor switches from forward blocking to forward conduction state, a large forward current flows.

- If the IG=IG1, thyristor can be turned ON even when anode voltage is less than VBO.
- The current must be more than the latching current (IL).
- If the current reduced less than the holding current (IH), thyristor switches back to forward blocking state.

REVERSE BLOCKING MODE: When cathode is more positive than anode, small reverse leakage current flows.
Thyristor- Operation Principle

• Thyristor has three p-n junctions (J1, J2, J3 from the anode).

• When anode is at a positive potential (VAK) w.r.t cathode with no voltage applied at the gate, junctions J1 & J3 are forward biased, while junction J2 is reverse biased.
  – As J2 is reverse biased, no conduction takes place, so thyristor is in forward blocking state (OFF state).
  – Now if VAK (forward voltage) is increased w.r.t cathode, forward leakage current will flow through the device.
  – When this forward voltage reaches a value of breakdown voltage (VBO) of the thyristor, forward leakage current will reach saturation and reverse biased junction (J2) will have avalanche breakdown and thyristor starts conducting (ON state), known as forward conducting state.

• If Cathode is made more positive w.r.t anode, Junction J1 & J3 will be reverse biased and junction J2 will be forward biased.

• A small reverse leakage current flows, this state is known as reverse blocking state.
TRIGGERING METHODS

• THYRISTOR TURNING ON IS ALSO KNOWN AS TRIGGERING.

• WITH ANODE POSITIVE WITH RESPECT TO CATHODE, A THYRISTOR CAN BE TURNED ON BY ANY ONE OF THE FOLLOWING TECHNIQUES:
  ▪ FORWARD VOLTAGE TRIGGERING
  ▪ GATE TRIGGERING
  ▪ DV/DT TRIGGERING
  ▪ TEMPERATURE TRIGGERING
  ▪ LIGHT TRIGGERING
Forward Voltage Triggering

• When breakover voltage (VBO) across a thyristor is exceeded than the rated maximum voltage of the device, thyristor turns ON.

• At the breakover voltage the value of the thyristor anode current is called the latching current (IL).

• Breakover voltage triggering is not normally used as a triggering method, and most circuit designs attempt to avoid its occurrence.

• When a thyristor is triggered by exceeding VBO, the fall time of the forward voltage is quite low (about 1/20th of the time taken when the thyristor is gate-triggered).

• However, a thyristor switches faster with VBO turn-ON than with gate turn-ON, so permitted $\frac{di}{dt}$ for breakover voltage turn-on is lower.
dv/dt triggering

- With forward voltage across anode & cathode of a thyristor, two outer junctions (A & C) are forward biased but the inner junction (J2) is reverse biased.

- The reversed biased junction J2 behaves like a capacitor because of the space-charge present there.

- As p-n junction has capacitance, so larger the junction area the larger the capacitance.

- If a voltage ramp is applied across the anode-to-cathode, a current will flow in the device to charge the device capacitance according to

\[ i_c = C \cdot \frac{dv}{dt} \]

- If the charging current becomes large enough, density of moving current carriers in the device induces switch-on.
Temperature Triggering

• During forward blocking, most of the applied voltage appears across reverse biased junction J2.

• This voltage across junction J2 associated with leakage current may raise the temperature of this junction.

• With increase in temperature, leakage current through junction J2 further increases.

• This cumulative process may turn on the SCR at some high temperature.

• High temperature triggering may cause Thermal runaway and is generally avoided.
Light Triggering

• In this method light particles (photons) are made to strike the reverse biased junction, which causes an increase in the number of electron hole pairs and triggering of the thyristor.

• For light-triggered SCRs, a slot (niche) is made in the inner p-layer.

• When it is irradiated, free charge carriers are generated just like when gate signal is applied b/w gate and cathode.

• Pulse light of appropriate wavelength is guided by optical fibers for irradiation.

• If the intensity of this light thrown on the recess exceeds a certain value, forward-biased SCR is turned on. Such a thyristor is known as light-activated SCR (LASCR).

• Light-triggered thyristors is mostly used in high-voltage direct current (HVDC) transmission.
Thyristor Gate Control Methods

• An easy method to switch ON a SCR into conduction is to apply a proper positive signal to the gate.

• This signal should be applied when the thyristor is forward biased and should be removed after the device has been switched ON.

• Thyristor turn ON time should be in range of 1-4 micro seconds, while turn-OFF time must be between 8-50 micro seconds.

• Thyristor gate signal can be of three varieties.
  – D.C Gate signal
  – A.c Gate Signal
  – Pulse
**Thyristor Gate Control Methods**

**D.C Gate signal:** Application of a d.c gate signal causes the flow of gate current which triggers the SCR.

– Disadvantage is that the gate signal has to be continuously applied, resulting in power loss.
– Gate control circuit is also not isolated from the main power circuit.

**A.C Gate Signal:** In this method a phase - shifted a.c voltage derived from the mains supplies the gate signal.

– Instant of firing can be controlled by phase angle control of the gate signal.

**Pulse:** Here the SCR is triggered by the application of a positive pulse of correct magnitude.

– For Thyristors it is important to switched ON at proper instants in a certain sequence.
– This can be done by train of the high frequency pulses at proper instants through a logic circuit.

A pulse transformer is used for circuit isolation.
Thyristor Commutation

- **Commuation:** Process of turning off a conducting thyristor
  - Current Commutation
  - Voltage Commutation

- A thyristor can be turned ON by applying a positive voltage of about a volt or a current of a few tens of milliamps at the gate-cathode terminals.

- But SCR cannot be turned OFF via the gate terminal.

- It will turn-off only after the anode current is negated either naturally or using forced commutation techniques.

- These methods of turn-off do not refer to those cases where the anode current is gradually reduced below Holding Current level manually or through a slow process.
Thyristor Turn-off Mechanism

• In all practical cases, a negative current flows through the device.

• This current returns to zero only after the reverse recovery time \( (trr) \), when the SCR is said to have regained its reverse blocking capability.

• The device can block a forward voltage only after a further \( t_{fr} \), the forward recovery time has elapsed.

• Consequently, the SCR must continue to be reverse-biased for a minimum of \( t_{fr} + trr = tq \), the rated turn-off time of the device.

• The external circuit must therefore reverse bias the SCR for a time \( toff > tq \).

• Subsequently, the reapplied forward biasing voltage must rise at a \( dv/dt < dv/dt \text{ (reapplied)} \) less than the static counterpart.
Thyristor Commutation Classification

• Commutation can be classified as
  – Natural commutation
  – Forced commutation
GATE TURN OFF THYRISTORS (GTO)
The basic operation of GTO is the same as that of the conventional thyristor.

The principal differences lie in the modifications in the structure to achieve gate turn-off capability.

- Large $\alpha_2$
- $\alpha_1+\alpha_2$ is just a little larger than the critical value 1.
- Short distance from gate to cathode makes it possible to drive current out of gate.
TRIAC
(TRIODE FOR ALTERNATING CURRENT)

• TRIAC is a five layer device that is able to pass current bidirectionally and therefore behaves as an a.c. power control device.

• The main connections are simply named main terminal 1 (MT1) and main terminal 2 (MT2).

• The gate designation still applies, and is still used as it was with the SCR.
TRIAC (CONTD....)

• it not only carries current in either direction, but the gate trigger pulse can be either polarity regardless of the polarity of the main applied voltage.

• The gate can inject either free electrons or holes into the body of the triac to trigger conduction either way.
  – So triac is referred to as a "four-quadrant" device.

• Triac is used in an ac environment, so it will always turn off when the applied voltage reaches zero at the end of the current half-cycle.

• If a turn-on pulse is applied at some controllable point after the start of each half cycle, we can directly control what percentage of that half-cycle...
TRIAC SYMBOL AND BASIC STRUCTURE
TRIAC OPERATION

- TRIAC can be considered as two thyristors connected in antiparallel. The single gate terminal is common to both thyristors.

- The main terminals MT1 and MT2 are connected to both p and n regions of the device and the current path through the layers of the device depends upon the polarity of the applied voltage between the main terminals.

- Device polarity is usually described with reference to MT1, where the term MT2+...