Lecture 1
Devices Overview

Objectives

- To give a brief review of some key devices used in power electronics
- Such a review is intended to provide a smooth introduction to the applications part of the course

Semiconductors

- Power Electronics devices are made from semiconductors.
- Semiconductors may be
  - intrinsic (or undoped) or
  - they may be doped n-type or p-type.
- An intrinsic semiconductor
  - resistivity lies between that of insulators and conductors.
  - Silicon is the principal semiconductor material used for power electronic devices.
  - Silicon is a member of Group IV of the periodic table of elements, i.e., four electrons in its outer orbit.

Doping

Two types of doping

N-type semiconductor

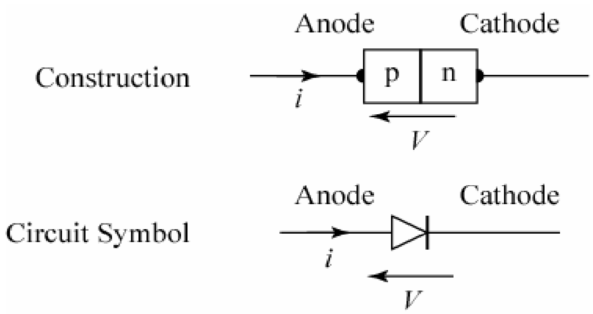
- an element of group V with 5 electrons in its outermost orbit, such as phosphorus, is added to the intrinsic Silicon,
- each phosphorus atom forms a covalent bond within the silicon lattice leaving a loosely bound electron.
- these electrons, or majority carriers, greatly increase conductivity of the n-type material.
- In an n-type material there is a small population of holes called minority carriers.

P-type semiconductor

- by introducing an element from Group III such as Boron, as impurity.
- a vacant bonding location or hole is introduced into the lattice.
- this hole will be filled by an adjacent electron, which in its turn leaves a hole behind.
- Holes (positive charges) are the majority carriers in the p-type semiconductor.
- In a p-type material there also exists a small population of electrons, the minority carriers.

Diode

- Diode consists of a single piece of intrinsic silicon with adjacent regions doped n-type and p-type semiconductor



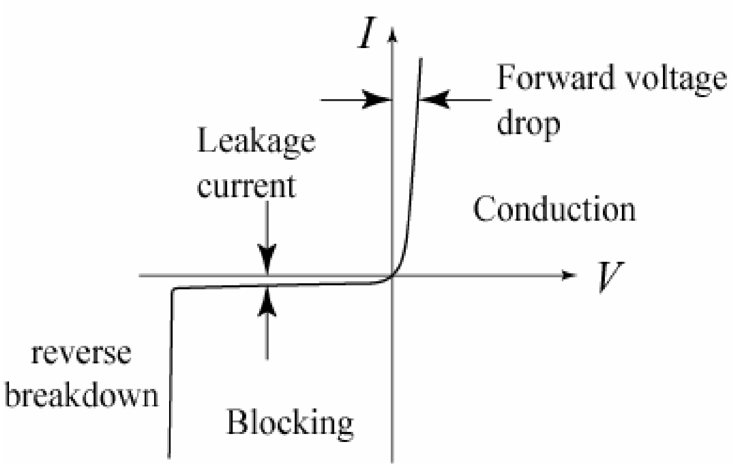
- With no external applied voltage
  - the redistribution of charges in the region of the junction results in a potential barrier across a narrow region - **the depletion region**, depleted of charge carriers on each side of the junction.

Reverse biased

- cathode positive with respect to anode is applied,
- the electric field at the junction is reinforced,
- increasing the height of the potential barrier and
- increasing the energy required by a majority carrier to cross this barrier.
- The small reverse leakage current is due to the flow of minority carriers across the junction.
- When reverse biased, the magnitude of the leakage current is about a few milliamps for a power diode
- would be several thousand amps in the forward direction.
- The very small reverse leakage current will be maintained with increasing reverse voltage up to the point at which reverse breakdown occurs, typically 1000 V for a power diode.

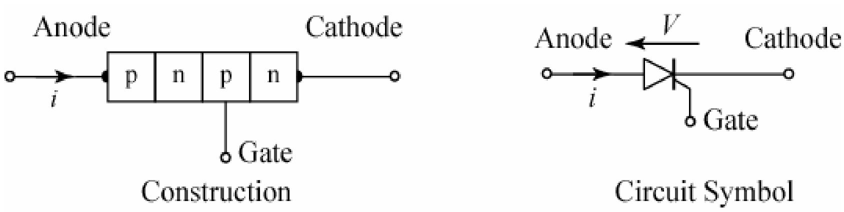
Forward voltage biased

- anode positive with respect to cathode – is applied
- the height of the potential barrier is reduced,
- giving rise to a forward current resulting from the flow of majority carriers across the junction.
- As the forward voltage is increased, the forward current through the diode increases exponentially. and the diode has high conductivity.
- The forward voltage drop is of the order of 0.7 V but
- because of internal resistances in series with the junction, the voltage (V) across the terminals of a practical power diode will be of the order of 1 V with the actual value being determined by the magnitude of the forward current and device temperature.



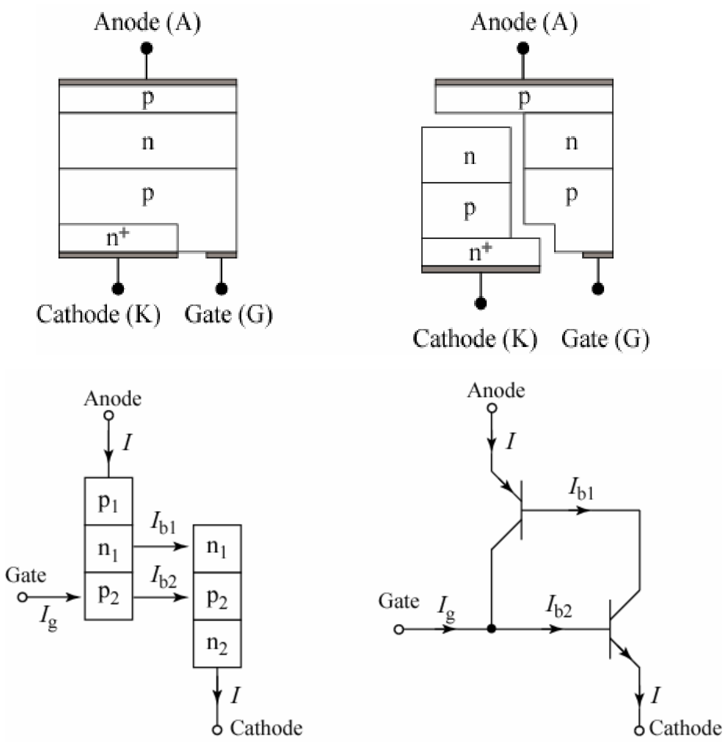
Diode characteristics

Thyristor



- The thyristor is a four-layer, three-terminal device.
- The complex interactions between the three p-n junctions in the device govern its characteristics,

- The 2-transistor model

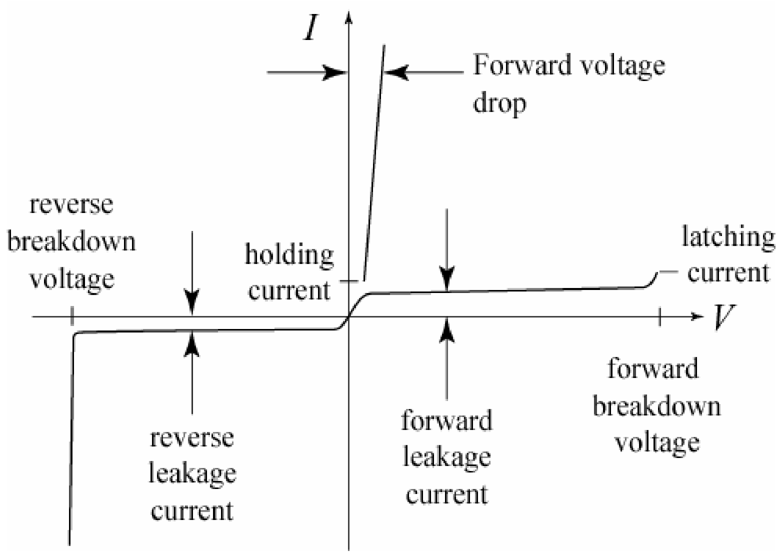


In reverse voltage biased

- p1-n1 and p2-n2 junctions are reverse biased ; hence only leakage current (very low) exists as for diode.

In forward biased with no gate current

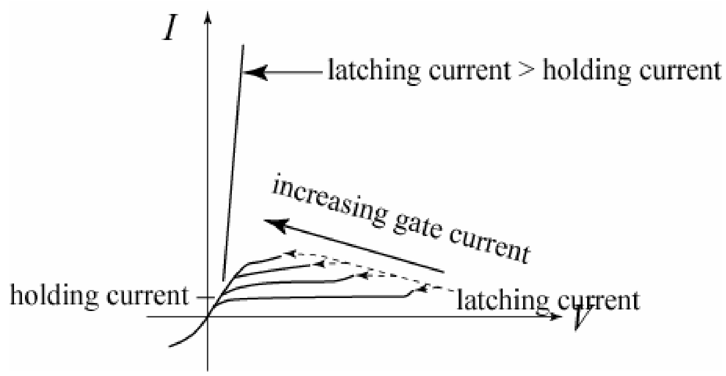
- it is the forward blocking mode of the thyristor.
- the base-emitter junctions of the two transistors are now forward biased but no conduction
- as the applied voltage is increased, the leakage current through the transistors increases.
- the positive feedback between the bases/collectors drives both transistors into saturation and turning the thyristor on.



Thyristor characteristics (with no gate current)

In forward biased with finite gate current

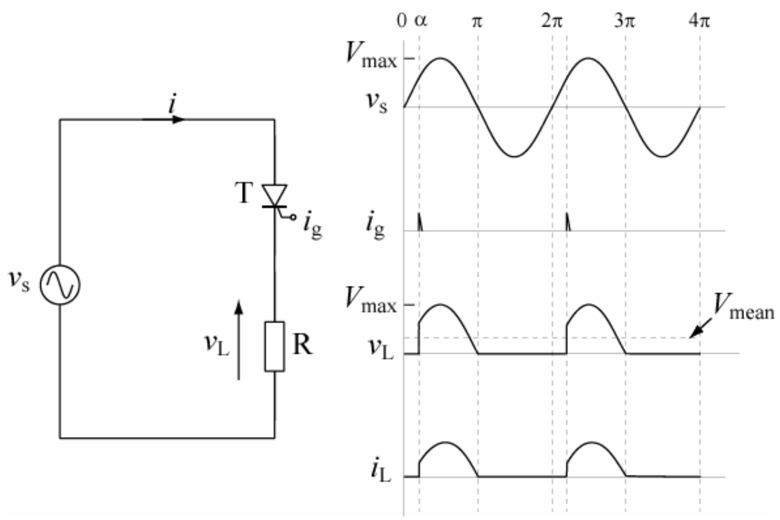
- npn transistor is turned on
- increases base current in pnp transistor
- positive feedback causes both transistors to turn hard on and remain saturated.
- Once conduction is established, gate current may be removed.
- Effect of gate current is to reduce the forward breakover voltage .



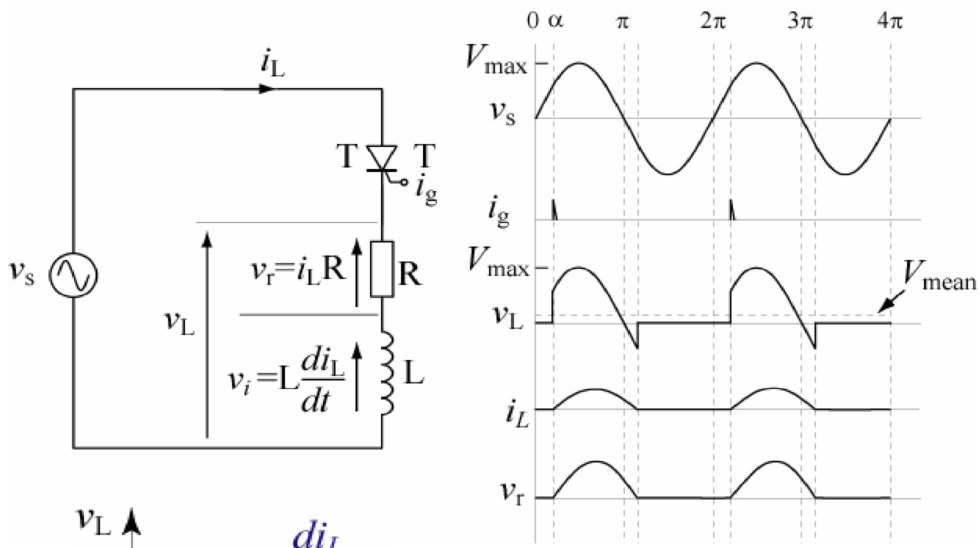
Thyristor characteristics (with gate current)

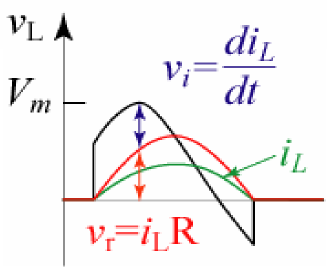
Thyristor Driving Resistive Load

- Thyristor is turned on about 1/8 cycle after the voltage zero.
- Thyristor switches off when current reaches zero.
- Load current follows exactly the load voltage.



Thyristor Driving Inductive Load





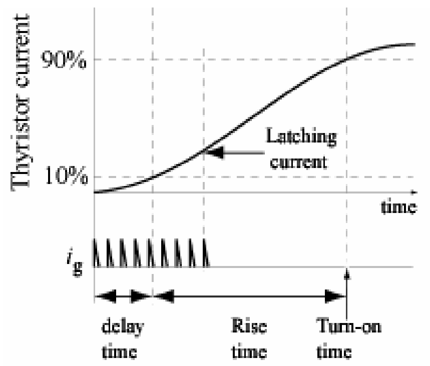
- Thyristor is turned on 1/8 cycle after the voltage zero.
- Load voltage made up of two components:
  - voltage across the inductor (v_i)
  - voltage across the resistor (v_r).
- Current through the thyristor has an initial value of zero (else $\mathrm{d}i_L/\mathrm{d}t$ and hence v_i [$=L\mathrm{d}i_L/\mathrm{d}t$] would be infinite).
- Current rises to a maximum at which point
  - $\mathrm{d}i/\mathrm{d}t = 0$
  - voltage across the inductance (v_i) becomes zero
  - load voltage (V_L) equals the voltage across the resistor (v_r).

- Slope of $\mathrm{d}i/\mathrm{d}t$ then becomes negative, changing the polarity of v_i
- V_L falls to zero and then becomes negative.
- Positive load current maintained by stored energy in inductor.
- When load current reaches zero, thyristor switches off (assuming a thyristor holding current of zero)

Thyristor Turn-on

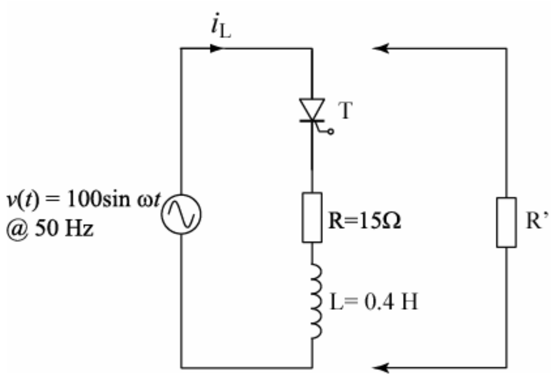
Successful latching

- The thyristor current must have reached the latching current by the time the gate current pulse ceases in order that conduction will be maintained.



Typical thyristor current turn-on characteristic

Example



- A thyristor with a latching current of 40 mA is used in the circuit shown.
- If a firing pulse of 50 μs is applied at the instant of maximum source voltage, show whether the thyristor would stay on or not.
- What value of R' connected as shown can ensure the turn on?

- As the gate pulse is applied at the instant of the maximum source voltage

$$v(t) = 100 \sin 50t$$

$$= iR + L\frac{di}{dt}$$

- The time constant of the circuit τ is,

$$\tau = \frac{L}{R} = \frac{0.4}{15} = 26.67 \quad \text{ms}$$

- The supply period is 20 ms (f = 50Hz) and the circuit time constant 26.67 ms,
- so after only 50 μs, we can make the following assumptions:
  - The supply voltage is still at its maximum value of 100 V
  - The current is negligible and therefore the term iR = 0

  - The rate of change of i with time is approximately linear and given by:

$$\frac{di}{dt} = \frac{\Delta i}{\Delta t}$$

- Hence,

$$V_{max} = L\frac{\Delta i}{\Delta t}$$

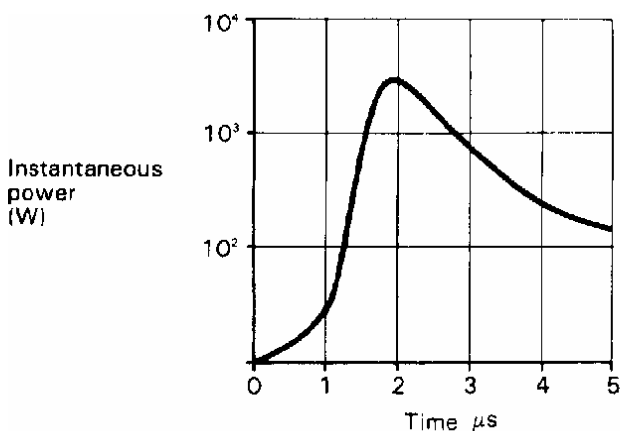
$$\Delta i = \frac{V_{max}}{L}\Delta t = \frac{100}{0.4} \times 50 \times 10^{-6} = 12.5 \times 10^{-3} \quad \text{A}$$

- which is below the latching current of 40 mA, so thyristor fails to stay on.

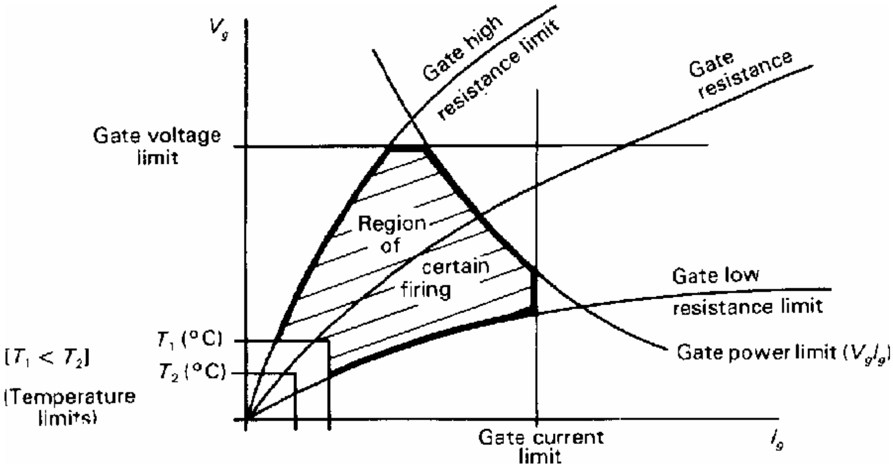
- Current needed = 40 – 12.5 = 27.5 mA.
- Maximum value of R' is thus
- R' = 100/0.0275 = 3636 Ω
- A full analysis without making the above approximations and using Laplace transforms gives Δi = 12.4 mA

Power Limitations And Aspects Of Gate Drive

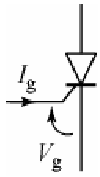
- Thyristor can be damaged by thermal effects due to high rate of rise of current at high forward voltage levels. Effective cooling systems sometimes are necessary.



Typical power in 150A thyristor during turn-on

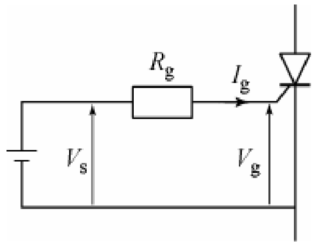


- To turn on a thyristor, we need to consider
  - The relation between the gate voltage and gate current for particular thyristor
  - The limiting values of
    - gate voltage,
    - gate current,
    - gate power and
    - temperature

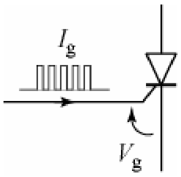


Definition of thyristor gate current and voltage

- Equivalent circuit for gate drive circuit,



- In practice, reliance is not usually placed on a single pulse to fire a thyristor but a train of pulses is frequently used,

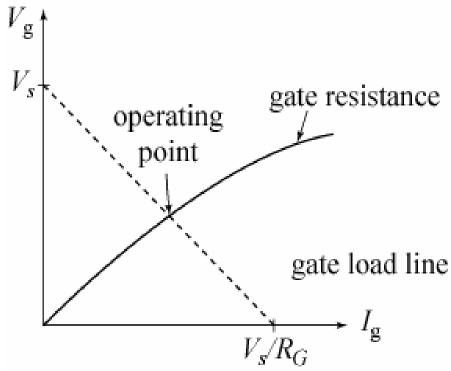


Determination of Operation Point

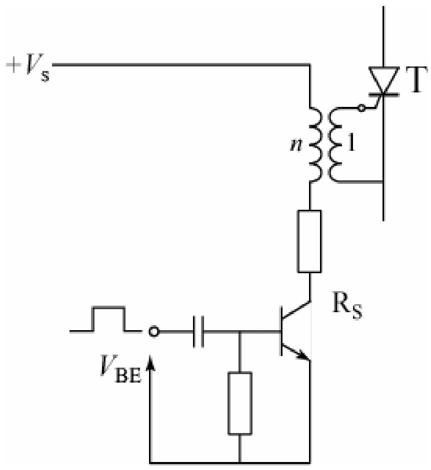
- Consider the $V_g - I_g$ plane,
- The operating point must lie on the gate resistance curve.
- V_g and I_g are also related via the source resistance R_G.

$$V_g = V_s - I_g R_G$$

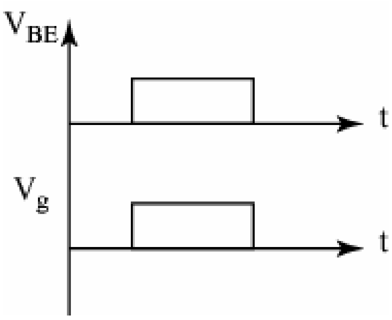
- Hence for a given device V_s and R_G determine the gate operating point.



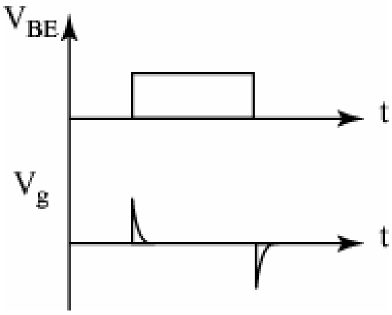
- The pulse transformer is often used to provide isolation and remove the need for a floating gate power supply.



- When the system time constant is much larger than the pulse width T, the pulse will be correctly transmitted.

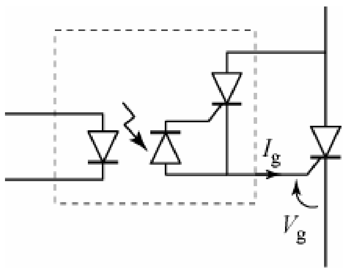


- When the system time constant is much less than the pulse width the response will be as shown.

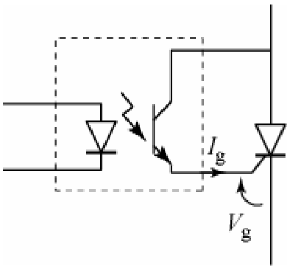


Opto-isolation

- Isolation is required when a thyristor gate signal is derived from a microprocessor or other low voltage drive circuitry.
- Thyristor with optically coupled gate can be used.



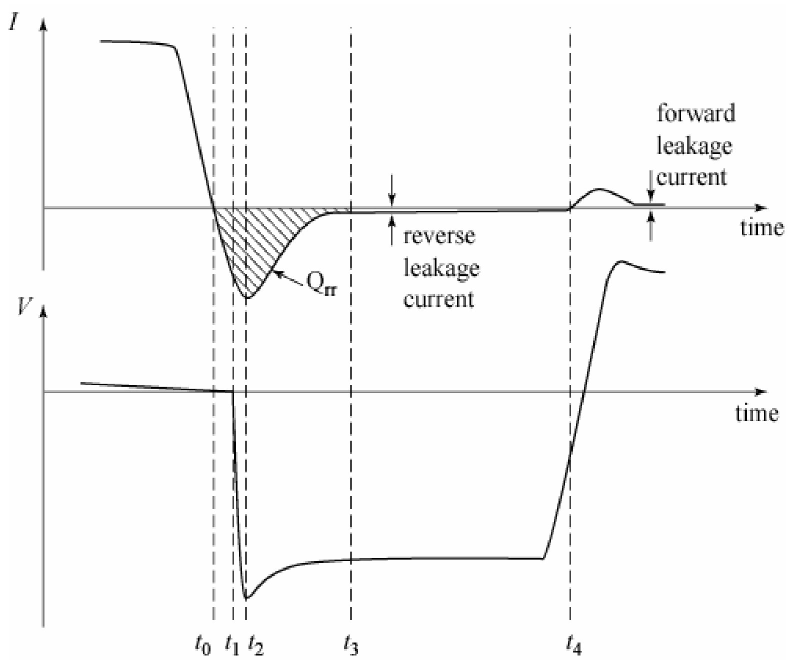
- or an optically coupled transistor.



Thyristor Turn-off

- Turn-off occurs when is forward current of a thyristor falls to less than the holding current.
- Once the current has fallen to zero the thyristor must be placed into the reverse blocking state with a reverse voltage applied across the thyristor for sufficient time to allow the potential barriers to be re-established, completing the turn-off (usually 10 - 100 μs).
- Turn-off performance depends on
  - device characteristics
  - forward current prior to turn-off
  - peak reverse current
  - rate of rise of forward voltage
  - temperature

Dynamic Behaviour Of The Thyristor During Turn-off



- t_0 – the forward current reaches zero, and then reversed
- t_0 to t_1 – reverse current sustained by carriers; voltage drop is small.
- t_1 to t_2 – carriers exhausted, current reduces, voltage increases; slight overshoot due to load conductance
- t_2 – the reverse current cannot be sustained and begins to reduce
- t_3 – the reverse recovery period is completed.
- t_2 to t_4 – negative voltage maintained until all carriers dispelled to prevent turn-on when positive voltage applied

Summary

- We have presented two key devices used in power electronics, i.e., the diode and the thyristor
- These devices will be examined in much greater detail in the devices part of the course
- Other important devices to be covered include the gate turn-off thyristor, the triac, the bipolar junction transistor and the power MOSFET