EEE6206 Power Semiconductor Devices:

Section 2e: Thyristors

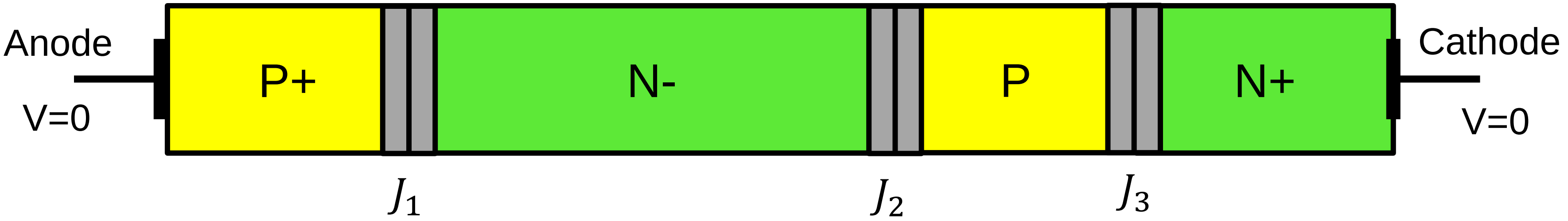
Thyristors

- Originally developed as a replacement for thyratron
  - Vacuum tube used for power applications prior to the advent of solid-state devices
- The thyristor exhibits bistable characteristics allowing operating in either blocking modes with low off-state current or a current conduction state with low forward voltage drop
- The device can be triggered into the on state by using a relatively small gate control current
  - Once triggered the device remains stable in the on state even without the gate signal
  - Device automatically switches to the reverse-blocking state upon reversal of the voltage in a AC circuit

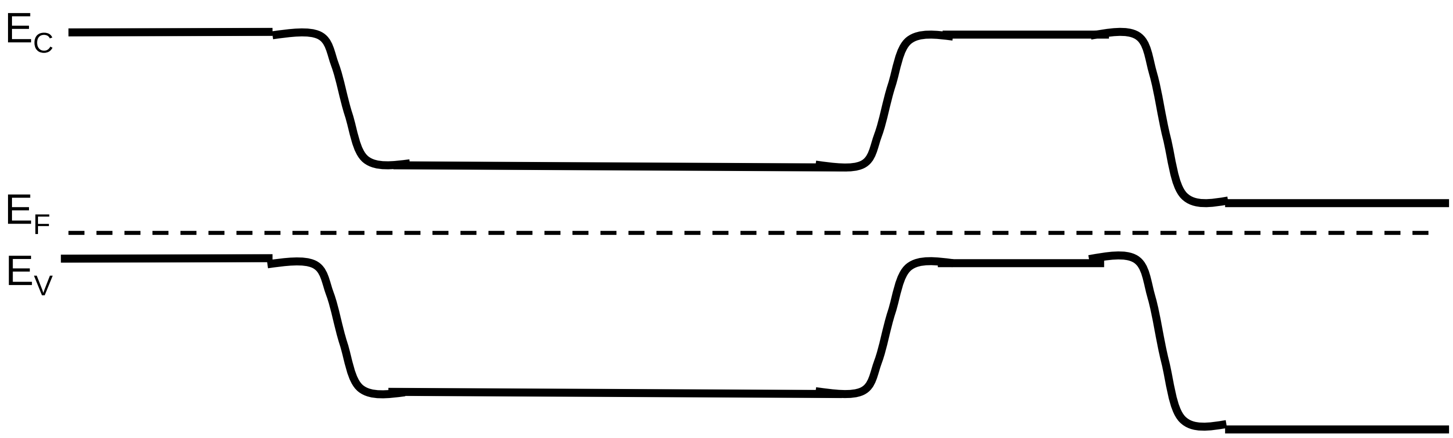
Thyristors Cont.

- With the demands of motor drives operating from DC supplies the Gate turn-off thyristor was developed
  - This modification to the basic thyristor structure enables switching the device from the on state to the off-state while operating in the first quadrant
- Today single thyristors are available with a capability to block 8000V and conduct 5000A in the on state
  - 40MW of power in a single device
  - Such devices are attractive for power distribution networks to reduce the total number of devices connected in series and parallel

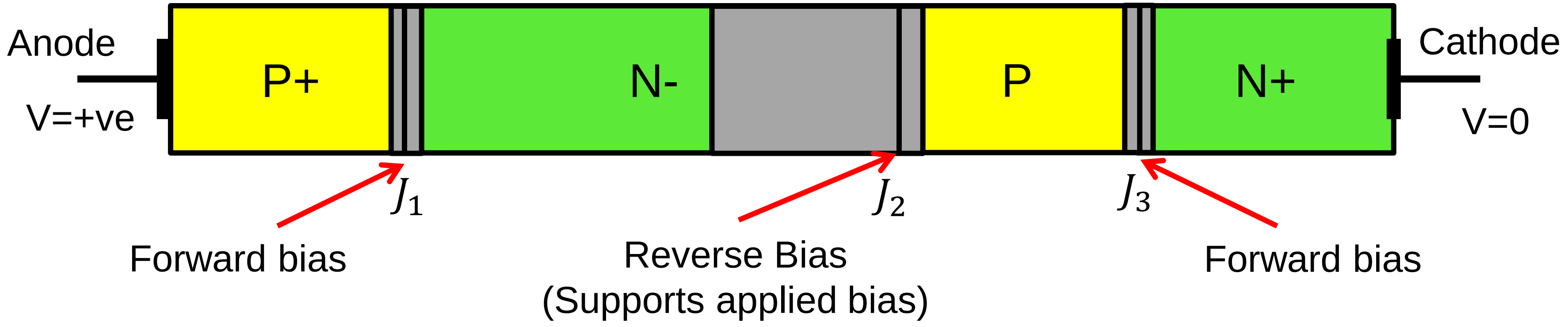
Four layer p-n-p-n thyristor: Zero potential



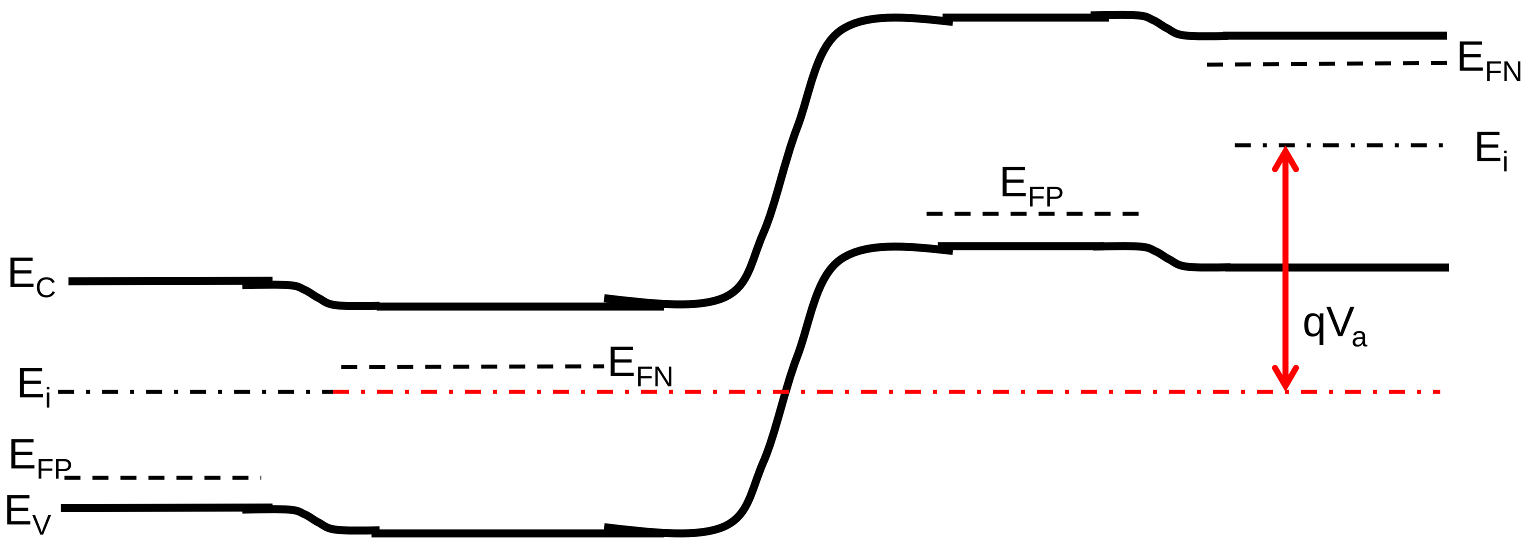
Energy Band Diagram of a thyristor under zero bias



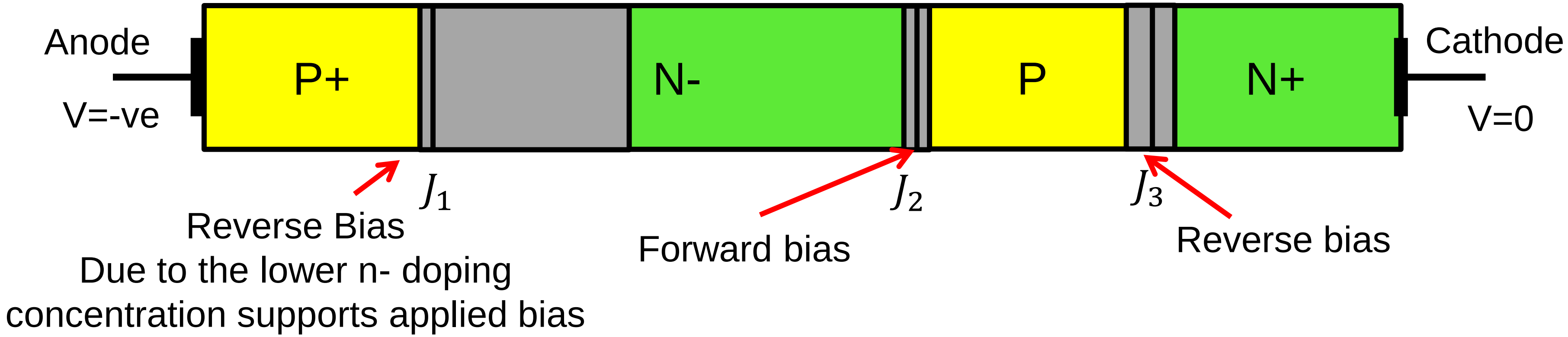
Four layer p-n-p-n thyristor: Positive anode potential (Forward Blocking)



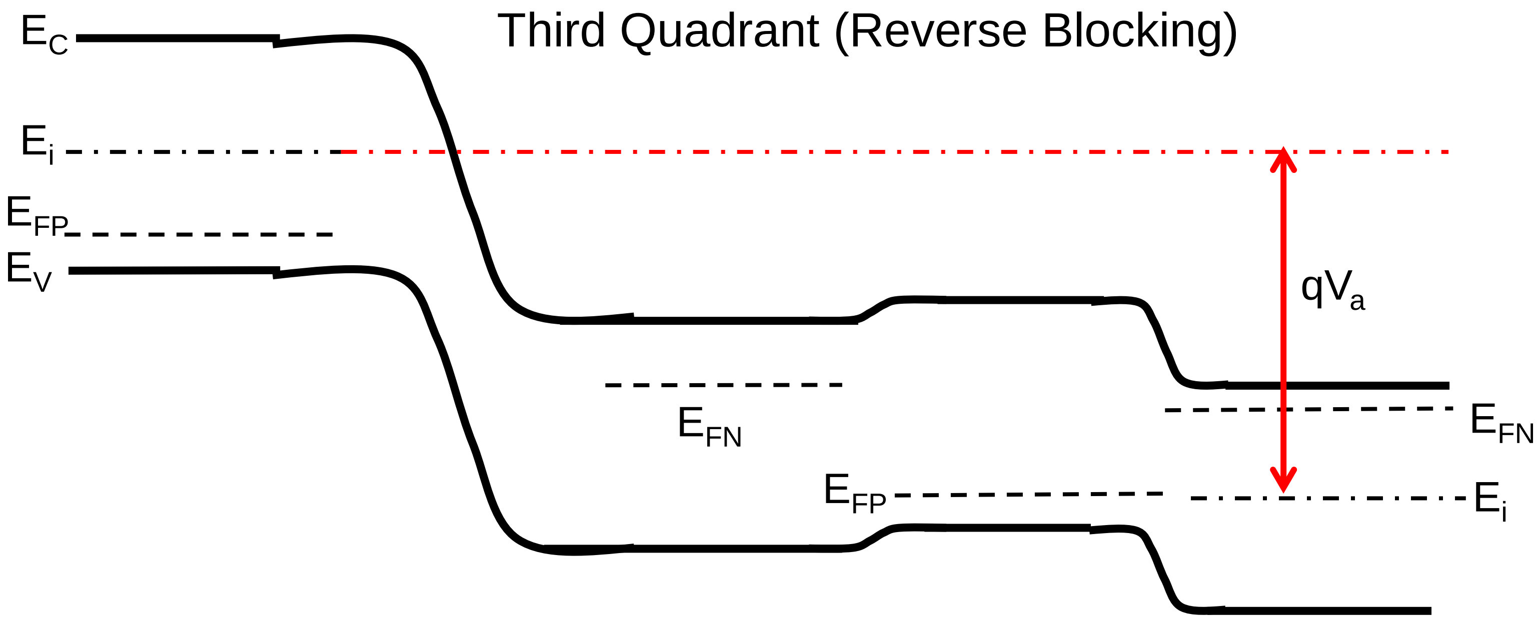
Energy Band Diagram of a thyristor under positive anode bias
First Quadrant (Forward Blocking)



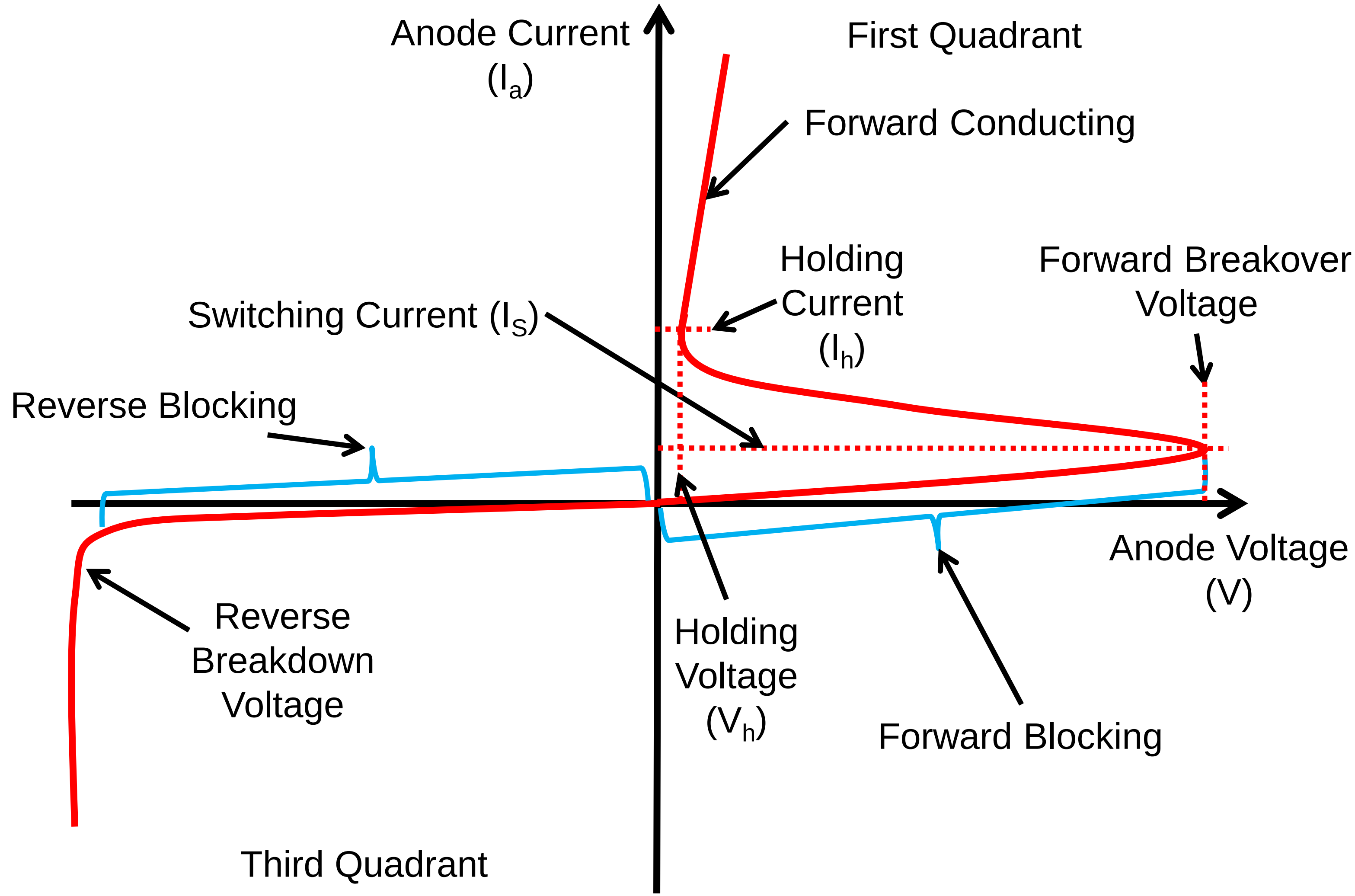
Four layer p-n-p-n thyristor: Negative anode potential (Reverse Blocking)



Energy Band Diagram of a thyristor under negative anode bias
Third Quadrant (Reverse Blocking)



Thyristor current voltage characteristics

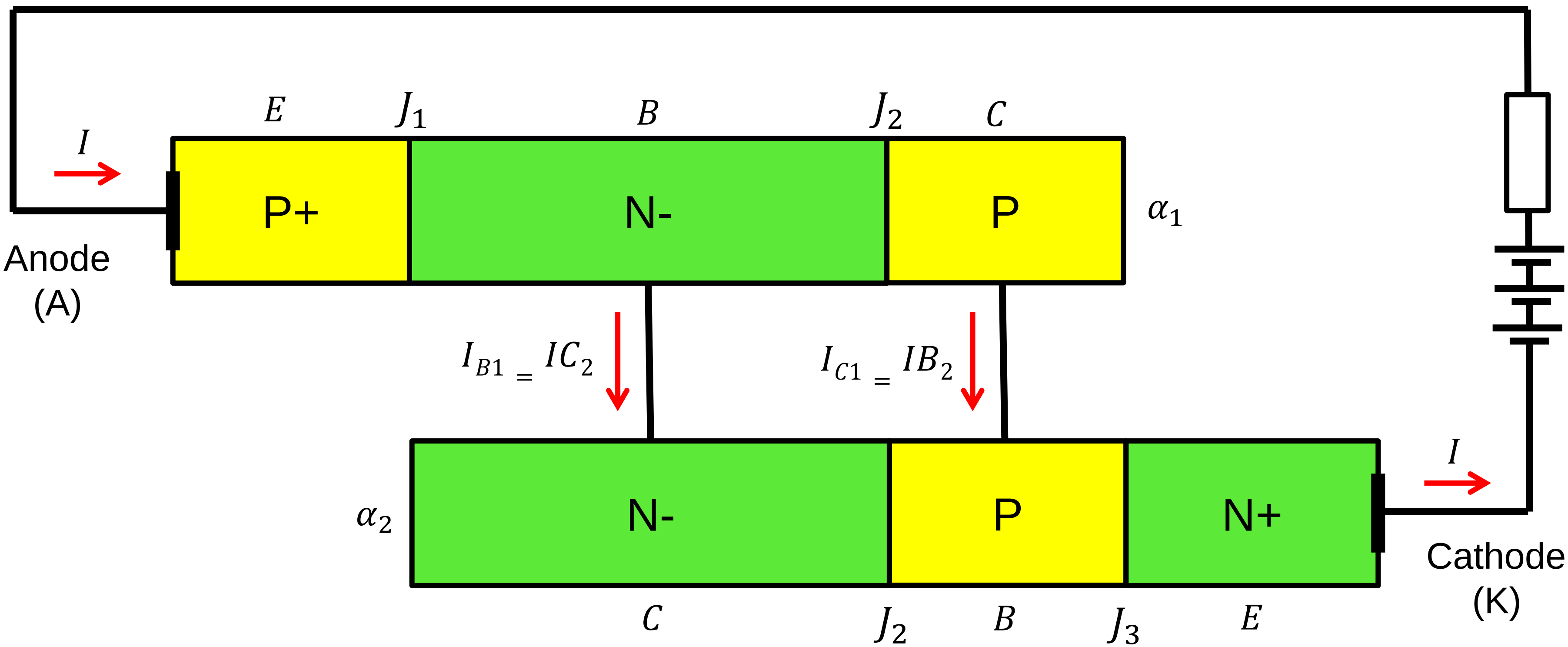


Holding and latching currents

- Switching current
  - Minimum anode current that must flow through the SCR in order for it to switch from forward blocking to forward conducting
  - Voltage at which this occurs
    - Forward break over voltage
- Holding current or latching current
  - Minimum value of anode current required to maintain the SCR in the conducting state
  - Voltage at which this occurs
    - Holding voltage

Thyristor forward blocking characteristic

- To understand the forward blocking characteristics
  - Consider the thyristor as n configuration of a NPN and PNP
    - These are connected with the base of one transistor attached to the collector of the other and visa versa



PNP transistor base current

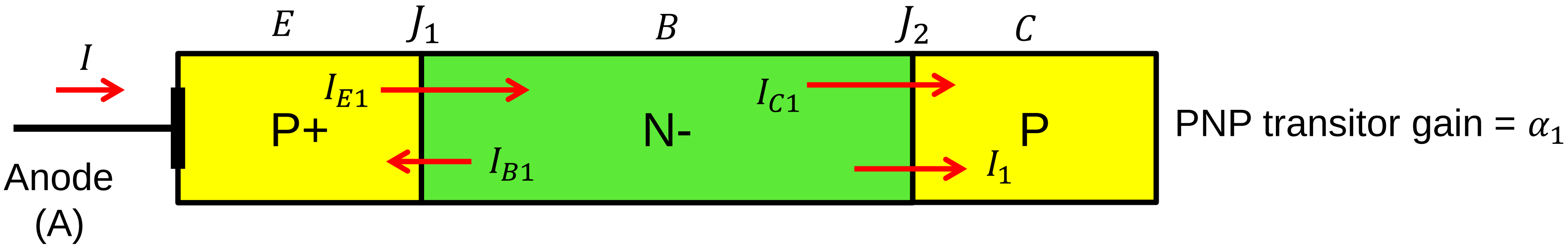
- The base current of the PNP transistor is given by

$$I_{B1} = I_{E1} - I_{C1}$$

$$I_{B1} = (1 - \alpha_1)I_{E1} - I_1$$

$$I_{B1} = (1 - \alpha_1)I - I_1$$

  – Where α_1 is the transistor gain, I_1 is the leakage current of the transistor and I is the anode current

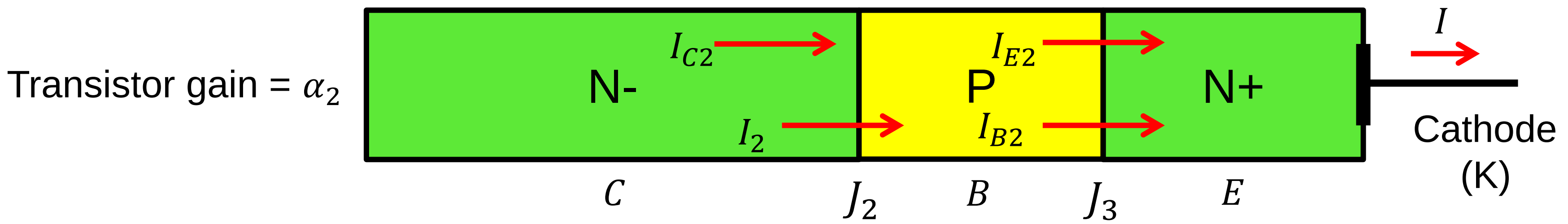


NPN transistor collector current

- The PNP transistor base current is supplied to the collector of the NPN transistor with the current gain of α_2
- The collector current of the NPN transistor is give by

$$I_{C2} = \alpha_2 I_{E2} + I_2 = \alpha_2 I + I_2$$

- Where α_2 is the transistor gain, I_2 is the leakage current of the transistor and I is the cathode current

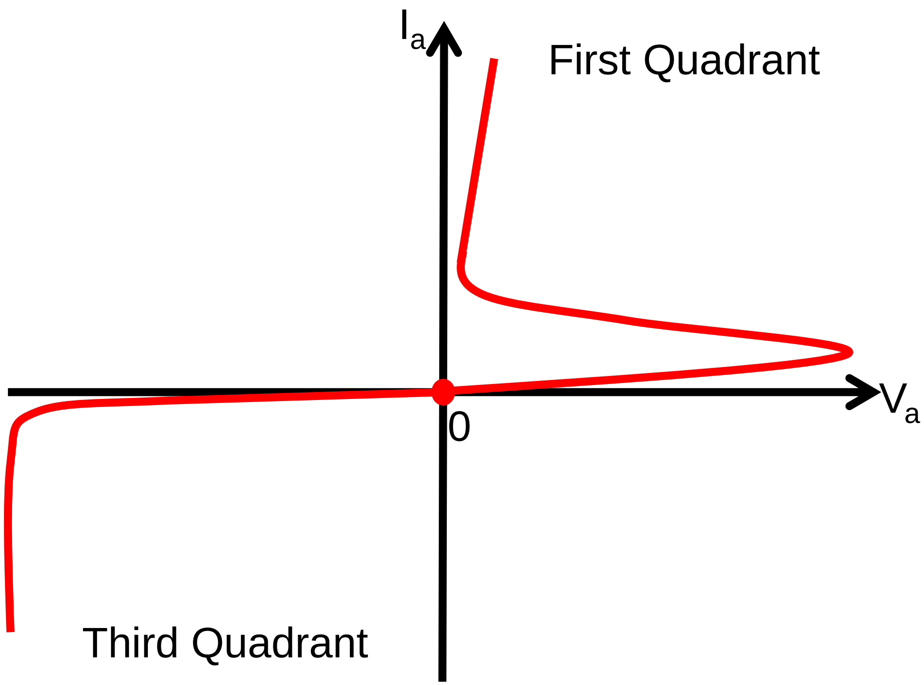


- Equating I_{B1} to I_{C2} we obtain:

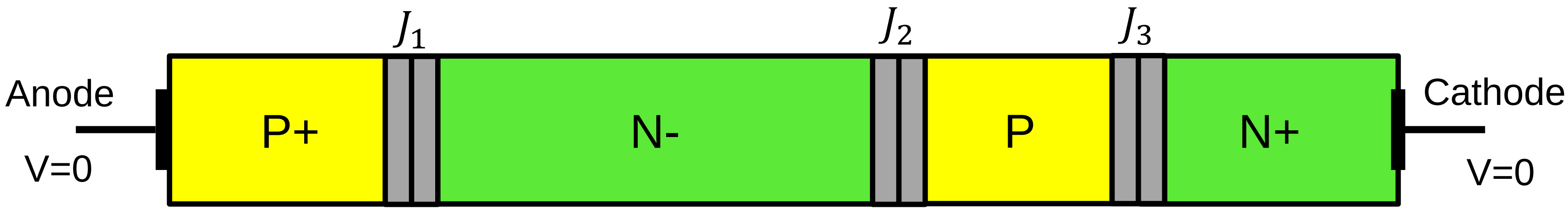
$$I = \frac{I_1 + I_2}{1 - (\alpha_1 + \alpha_2)}$$

- If $\alpha_1 + \alpha_2$ approaches 1, the thyristor would latch and enter its forward conducting state

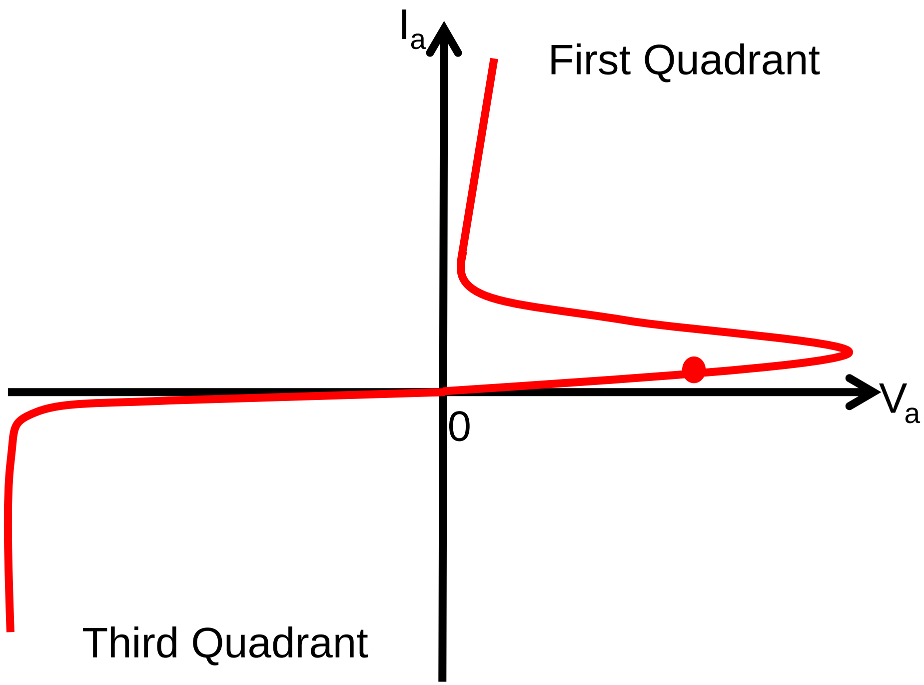
Biased Thyristor: Thermal Equilibrium



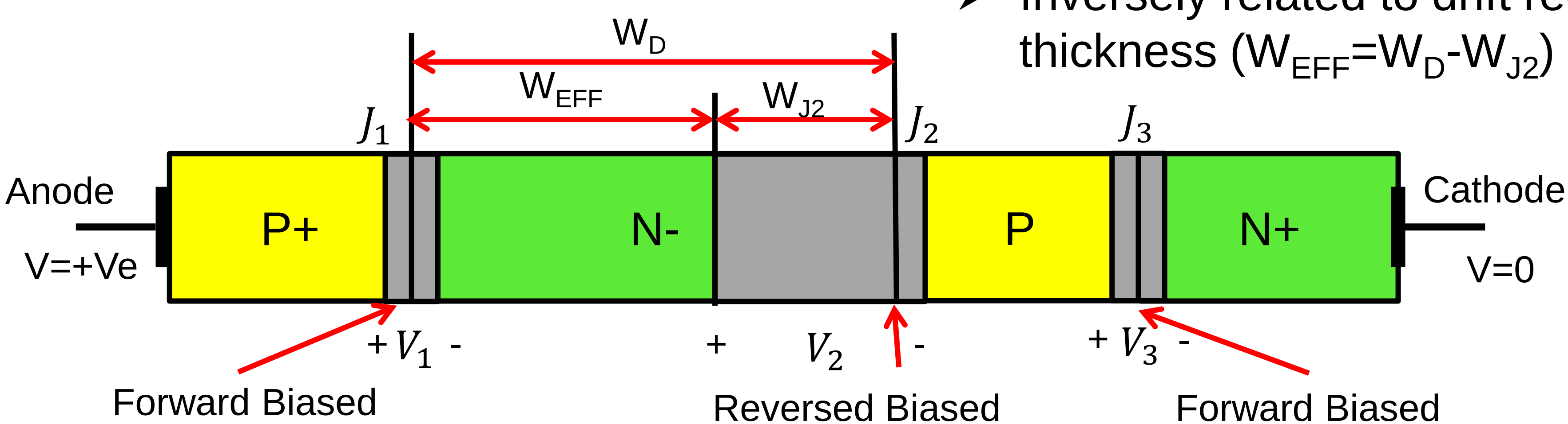
- At zero bias thermal equilibrium, no current flowing through the device
- Depletion widths determined by the impurity doping profiles



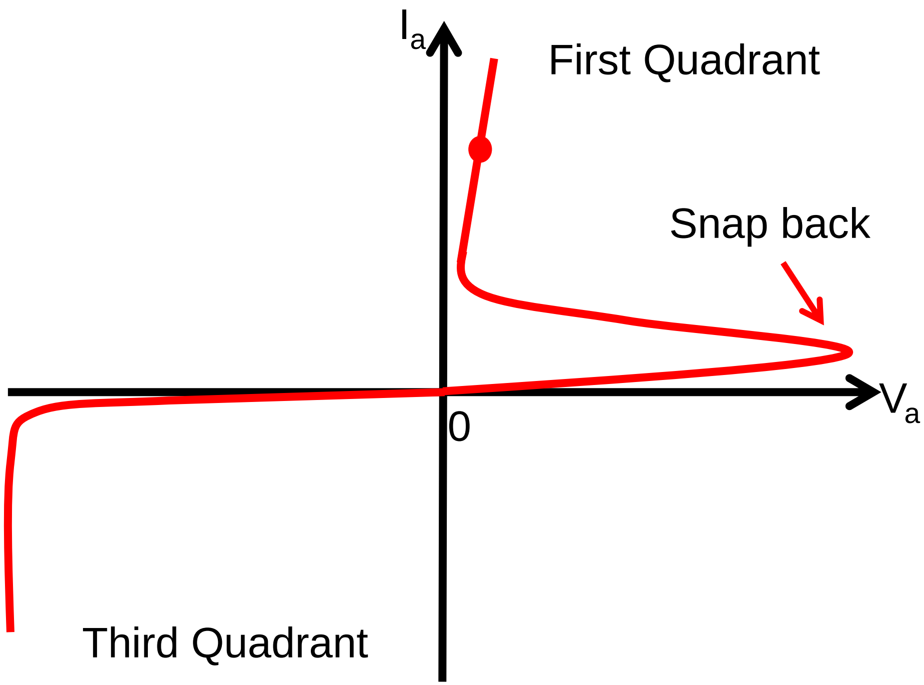
Biased Thyristor: Forward blocking



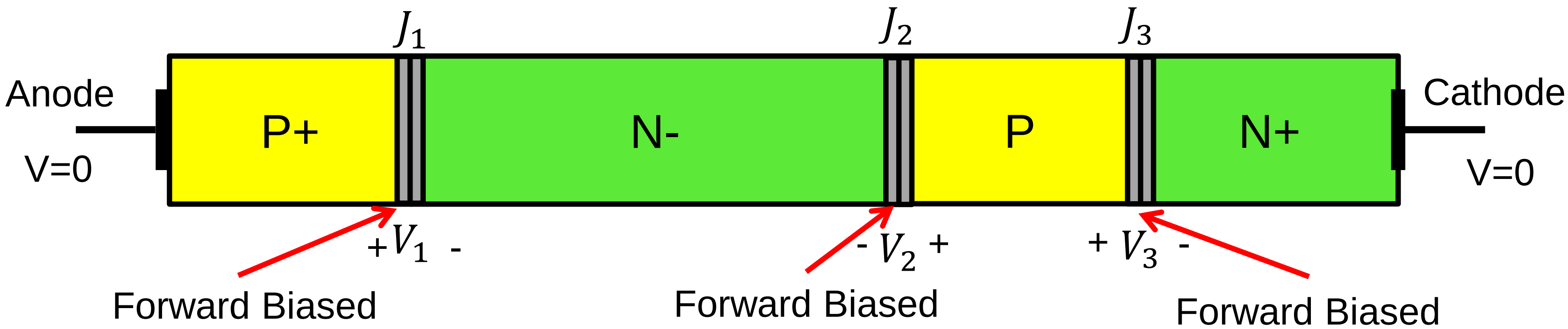
- Under forward blocking conditions
- J_1 an J_3 are forward biased J_2 is reverse biased
- The majority of the voltage is dropped across the reverse biased junction J_2
- As voltage increases PNP transistor gain (α_1) increases are a result of increased base transit time (α_T)
  - Inversely related to drift region thickness (W_{EFF}=W_D-W_{J2})



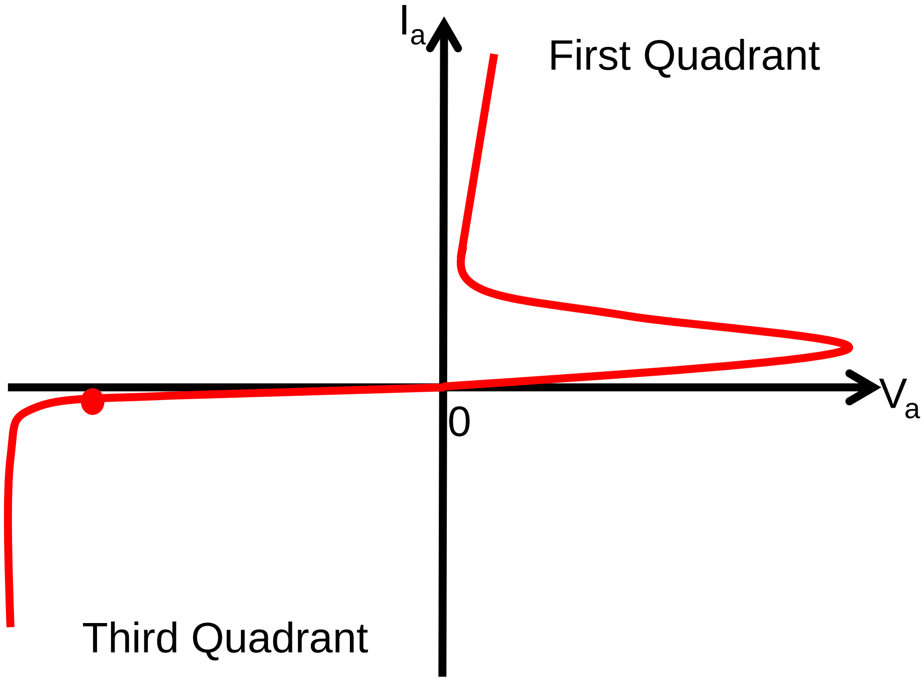
Biased Thyristor: Forward Biased



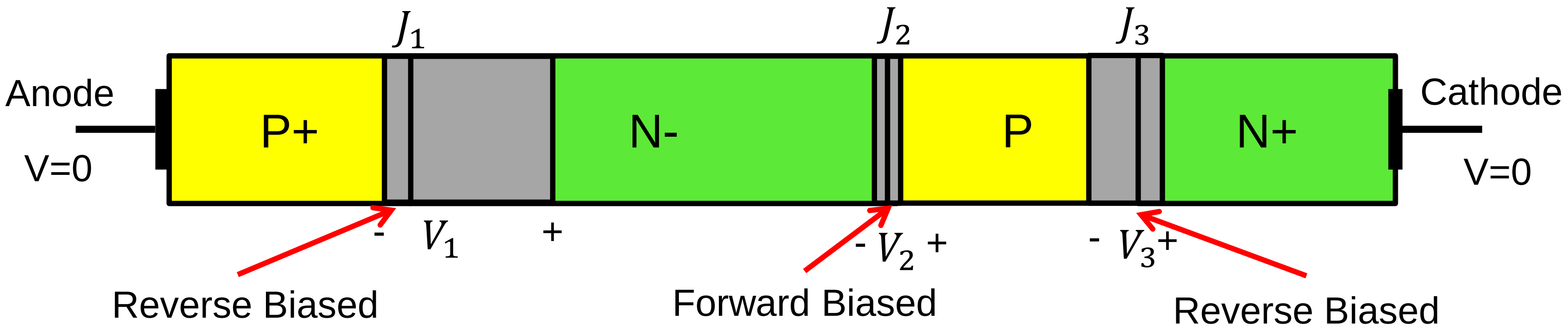
- As PNP transistor gain approaches unity ($\alpha_1 = \alpha_{PNP} = 1$) the thyristor latches
- Causing the anode voltage collapse with a characteristic snap-back
- Under this condition all three junctions are forward biased and the transistors are operating in their saturation mode
- Voltage drop across the device is very low, given by ($V_1 - V_2 + V_3$) which is approximately equivalent to a single forward biased junction



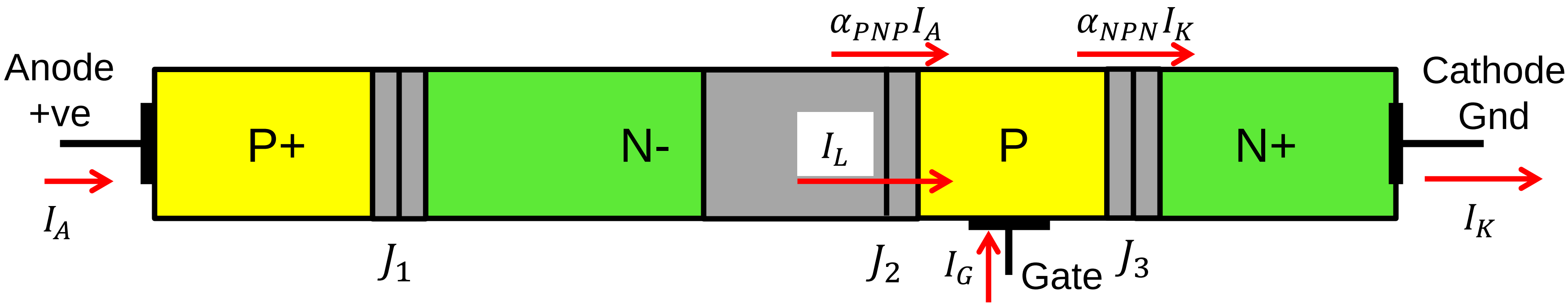
Biased Thyristor: Reverse Blocking



- Under reverse blocking J_1 and J_3 are reverse biased whereas J_2 is forward biased
- Due to the lower doping concentration in the n- region, J_1 supports the applied voltage



Gate triggering: Forward blocking to forward conducting



- To switch the device from its forward blocking state into a forward conducting state a gate current is applied to the gate terminal
  - Connected to the p region between J_2 and J_3
- The anode current constitutes of:

$$I_A = \alpha_{PNP} I_A + \alpha_{NPN} I_K + I_L$$

- Applying Kirchhoff's current law to the thyristor structure:

$$I_K = I_A + I_G$$

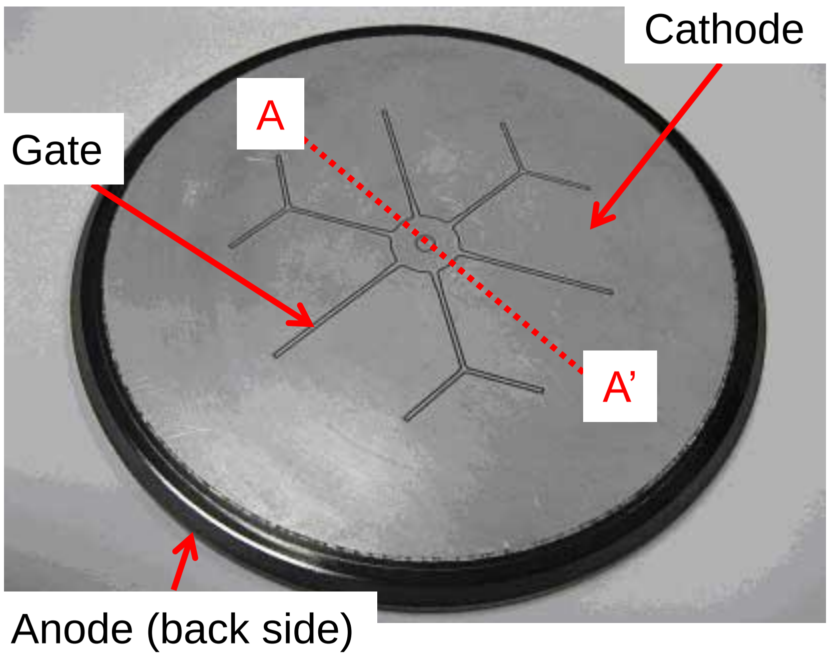
- Therefore:

$$I = \frac{\alpha_{NPN} + I_L}{1 - (\alpha_{PNP} + \alpha_{NPN})}$$

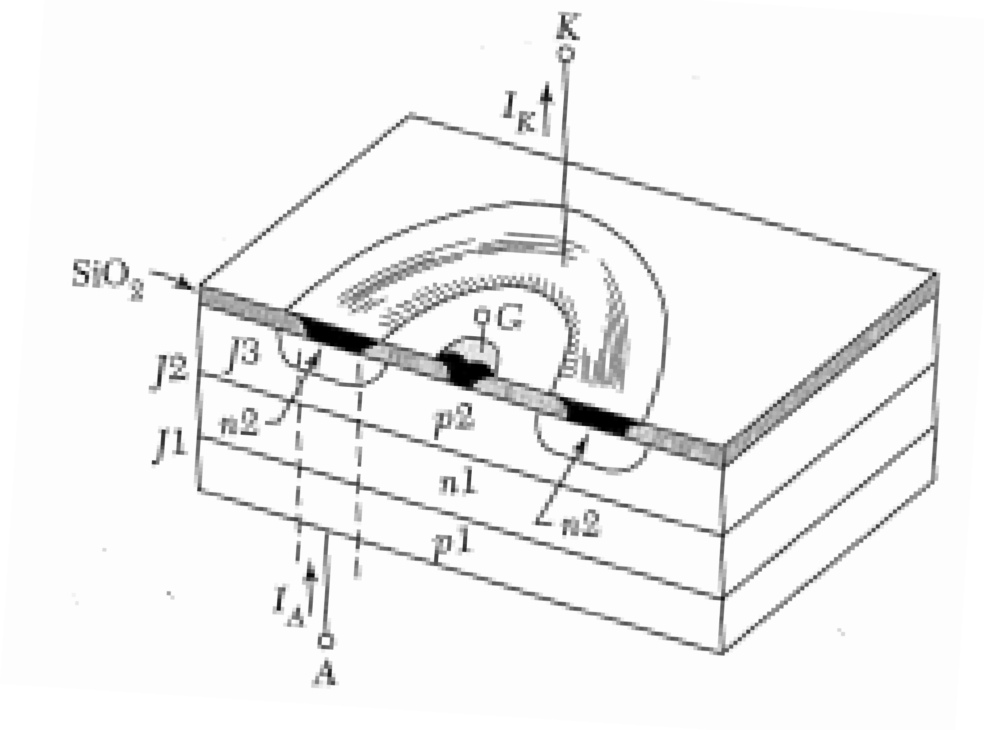
  - Once the holding current has been exceeded the gate supply can be removed and the thyristor is self-sustaining in its on-state

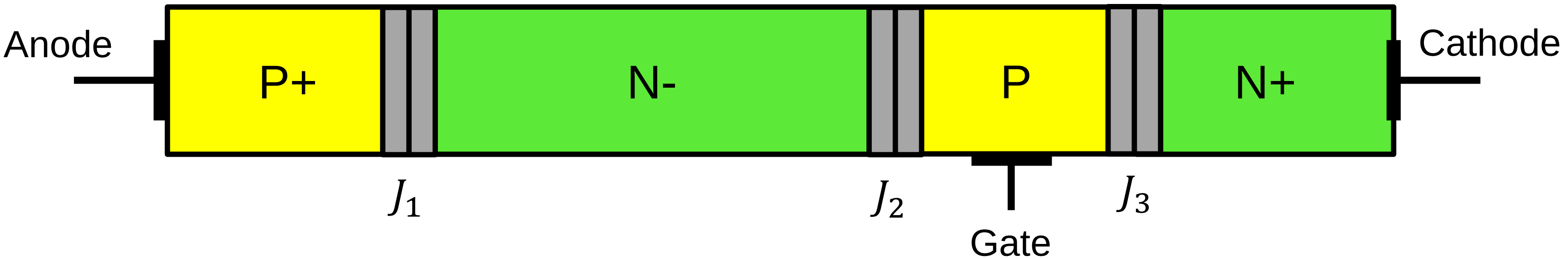
Gate connection of SCR's

Typical thyristor

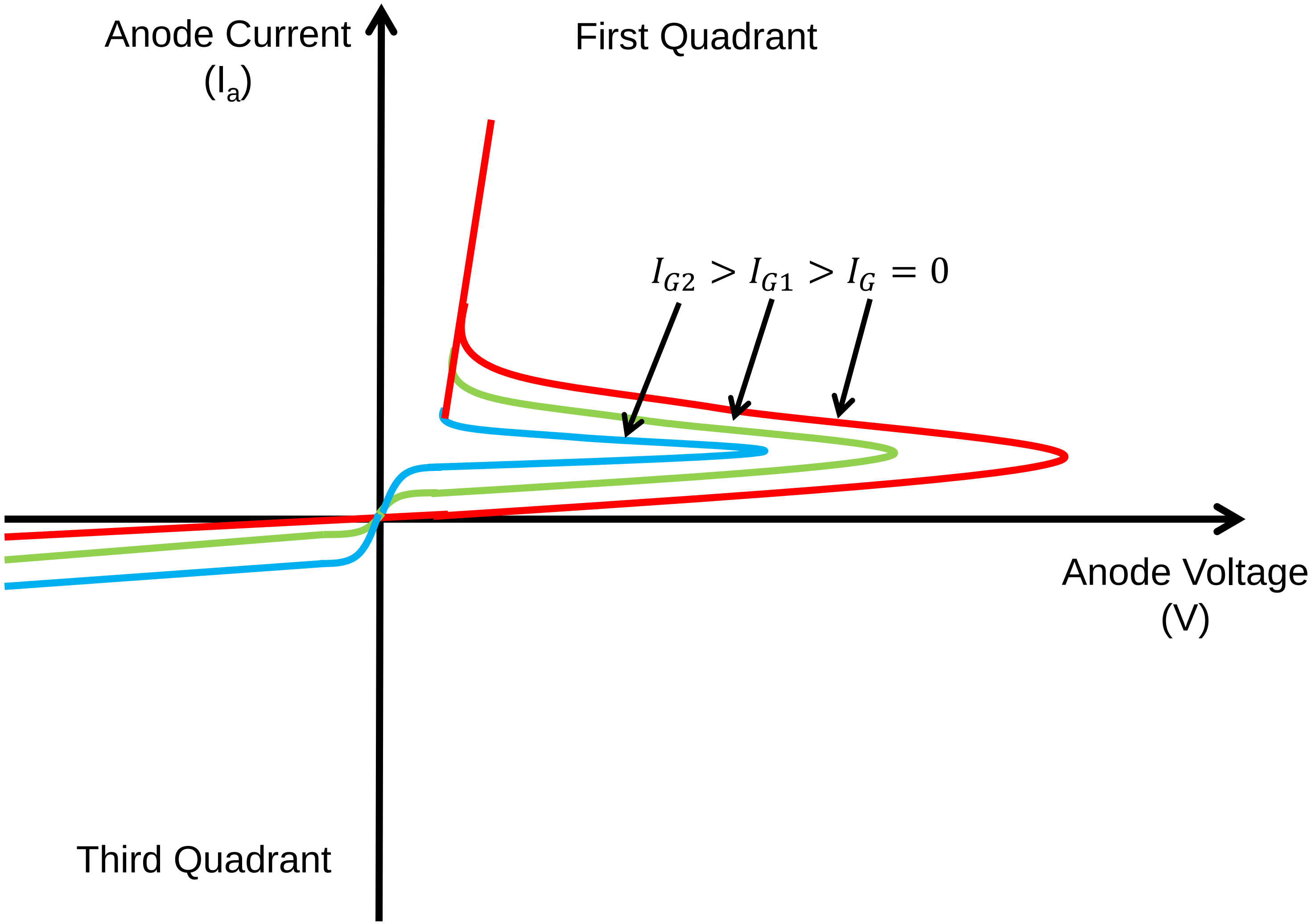


Cross-section through A-A'

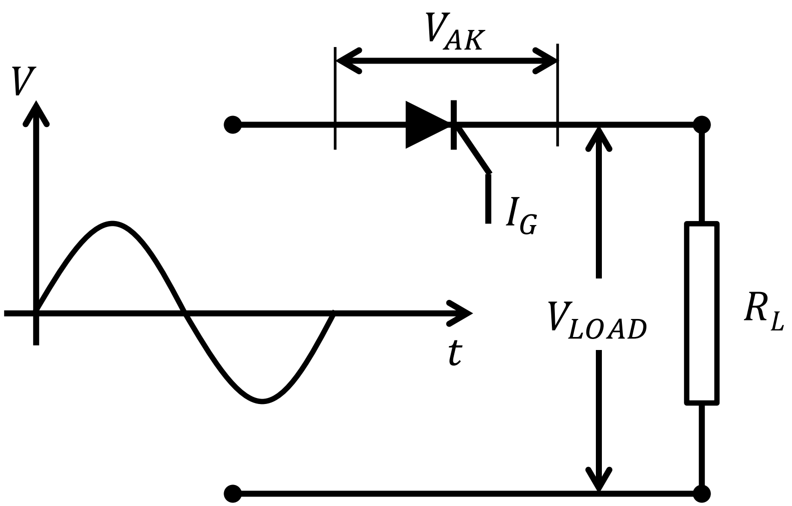




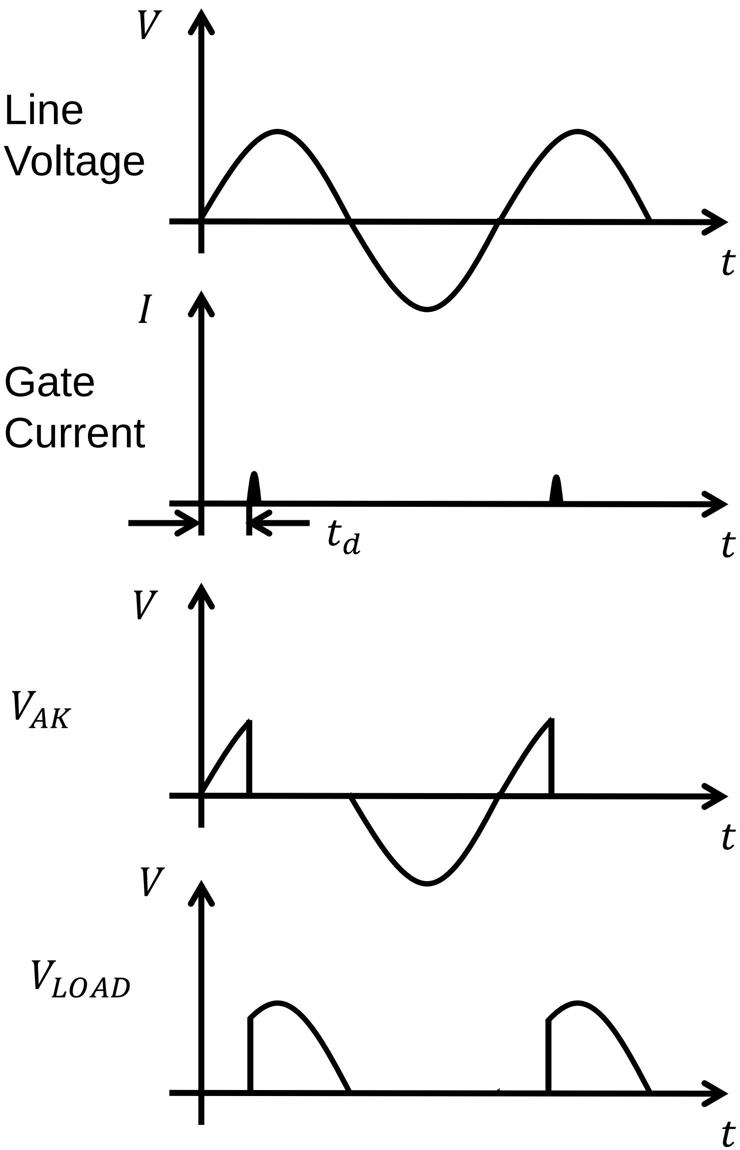
Thyristor current voltage characteristics



Schematic circuit for a thyristor application



Voltage and gate current waveforms



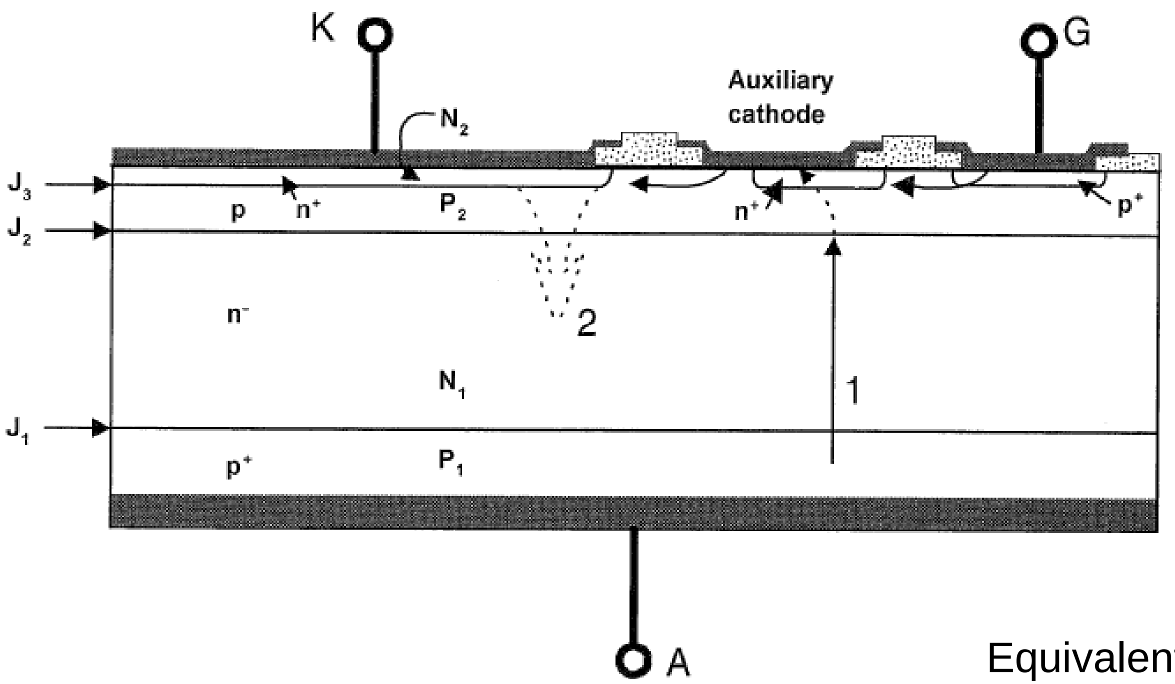
Critical di/dt

- There is a limit to the permissible rise rate of the on-state current if irreversible damage to the electrical characteristics are to be avoided
- The critical rise rate of the on-state current $\left(\frac{di_T}{dt}\right)_{crit}$ is a direct function of the area initially turned on and the spreading velocity
  - Current density for the turned-on area may be much higher than that for the steady state
  - This current density increases with $\frac{di_T}{dt}$ and can be as high as 1000-100,000A/cm^2
  - As a result the voltage dropped across the device can remain high during this ramp in current ~10-100V

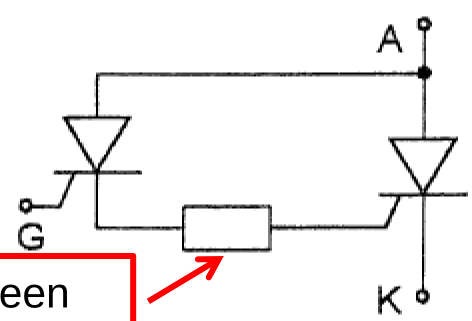
- This energy is concentrated in a small volume within the thyristor structure causing localised overheating
  - Causing significant deterioration to the thyristor electrical characteristics
  - Or device destruction
    - Exceeding the melting point of the semiconductor metal contacts
    - Fracture of the Silicon due to the thermally induces mechanical stress
- The critical rate of rise of the current can be increased by increasing the cross sectional area of the thyristor that is initially turned on
- This can be achieved by the application of a gate current pulse that raises rapidly to a high value
  - The enables condition for triggering to be reaches along the periphery of the cathode emitter surrounding the gate contact

Auxiliary Cathode

Device Cross-section through the active region



Equivalent Circuit

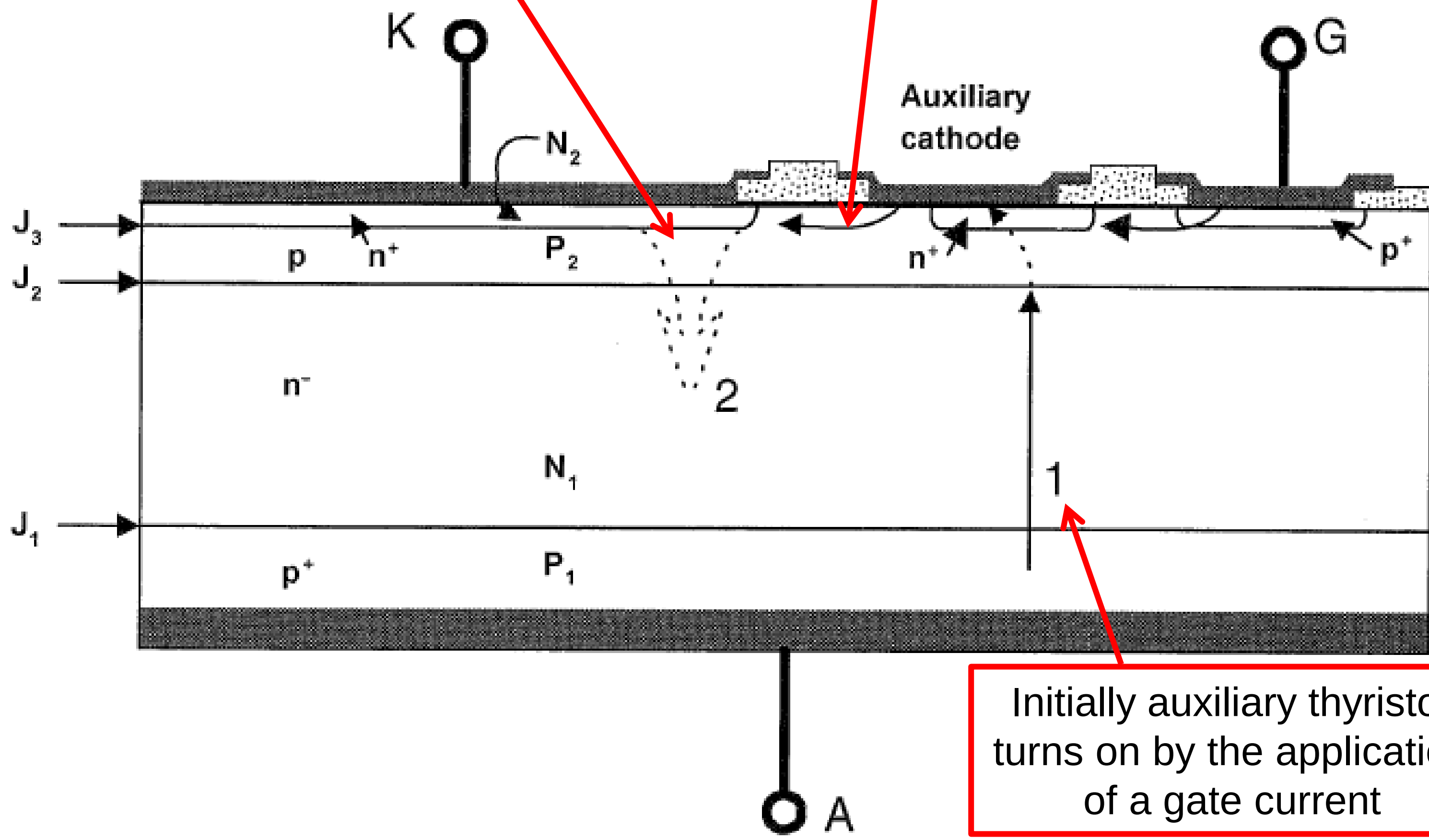


Layout Resistance between Auxiliary and main thyristor gate

Auxiliary Cathode

Almost all of the periphery of the cathode emitter adjacent to the auxiliary contact is triggered

Due to the n+/p+ short
Current flows out of the auxiliary cathode into the gate of the main thyristor amplifying the initial gate current pulse



Initially auxiliary thyristor turns on by the application of a gate current

Cathode view of a amplifying gate thyristor

Cathode view

- The interdigitated gate geometry provides a long gate-cathode periphery
- As long as the gate current in large enough to turn on the whole length the initial turn-on area can be large, minimising turn on losses
- For this reason amplified gate thyristors with interdigitated gate-cathodes designs are used for high frequency applications

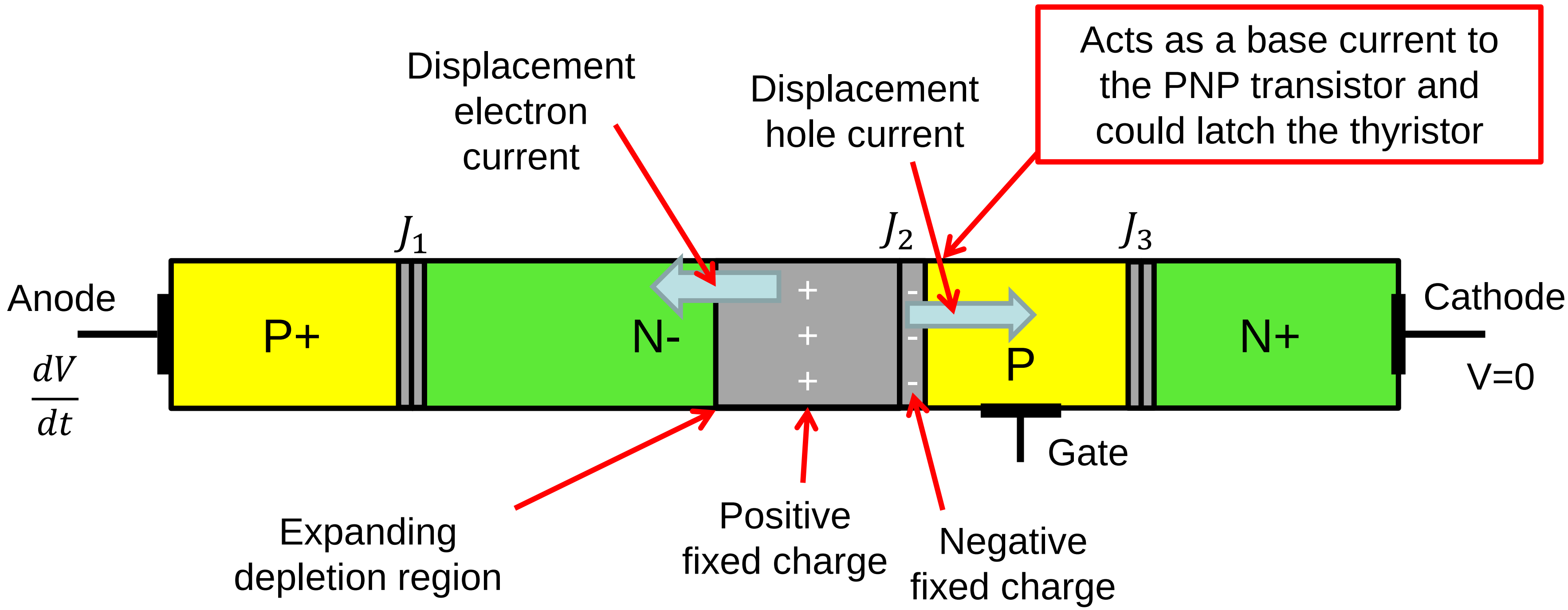
Critical dV/dt

- Another critical dynamic parameter connect with the turn-on process is the critical rate of rise of the blocking voltage $\left(\frac{dV_D}{dt}\right)_{crit}$
- This is the maximum rise rate of the forward voltage that can be sustained by the thyristor in the blocking state under open gate conditions
- The displacement current density needed to charge the differential capacitance (C_j) of the space charge layer at the voltage blocking junction (J_2)

$$J_q = \frac{d}{dt}\left(C_j V_D\right) = \left(C_j + V_D \frac{dC_j}{dV_D}\right)\frac{dV_D}{dt}$$

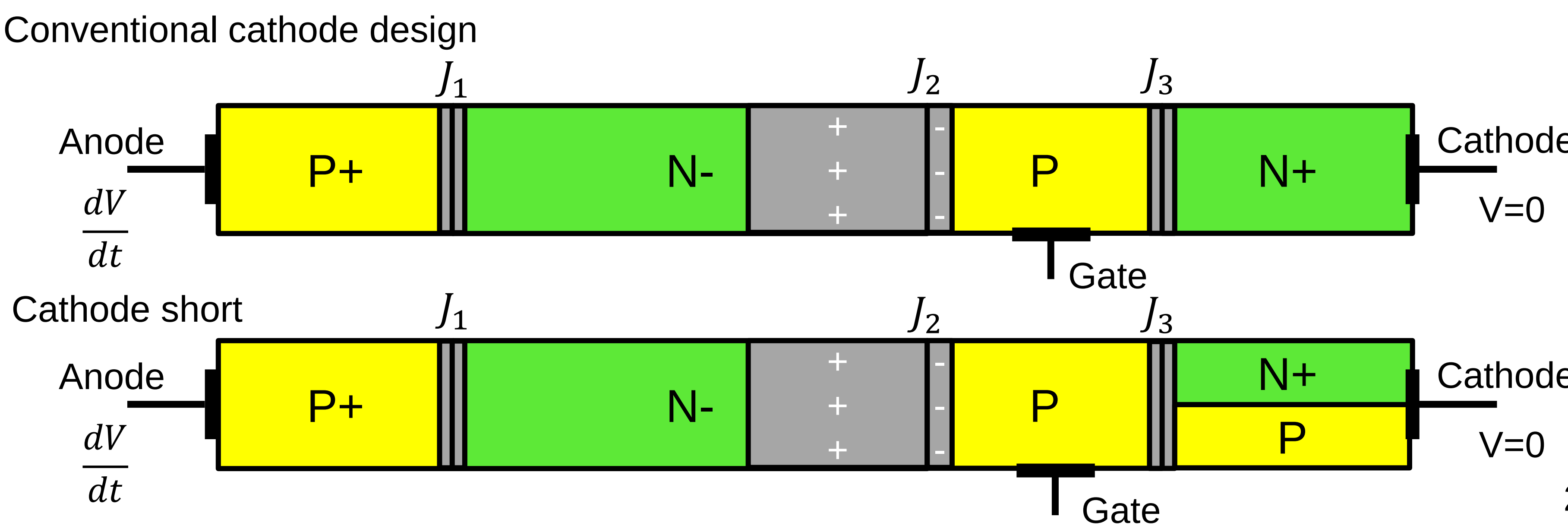
- In the P2 layer this current density represents the current of holes that are displaced by the expansion of the depletion region towards J_3
- This has an effect similar to a positive gate current and it is possible for J_q to fulfil the triggering condition

Displacement current triggering



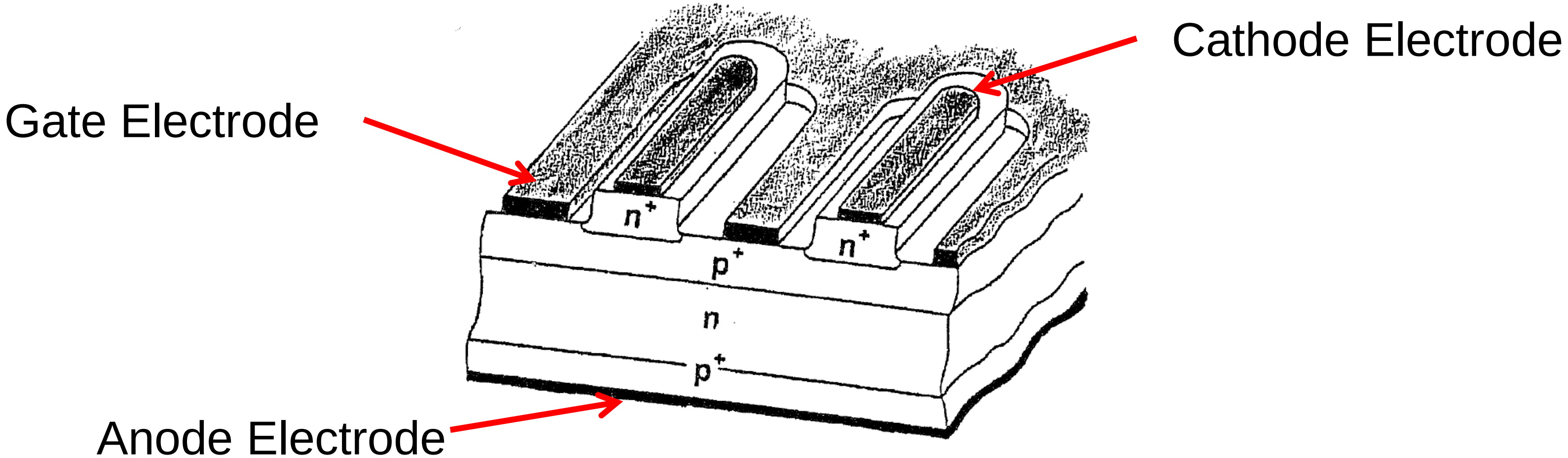
Cathode short

- Cathode shorts enable the displacement current to be removed from the thyristor without electron injection from the cathode emitter
- These enable values of $\frac{dV_D}{dt}$ to exceed 1000V/μs
  – Limited to a few volts/μs without cathode short
- However cathode shorts can reduce the spreading velocity following turn on and so may increase turn on losses
  – They may also increase static on-state losses due to the reduced transistor gain



Gate turn off thyristor structure

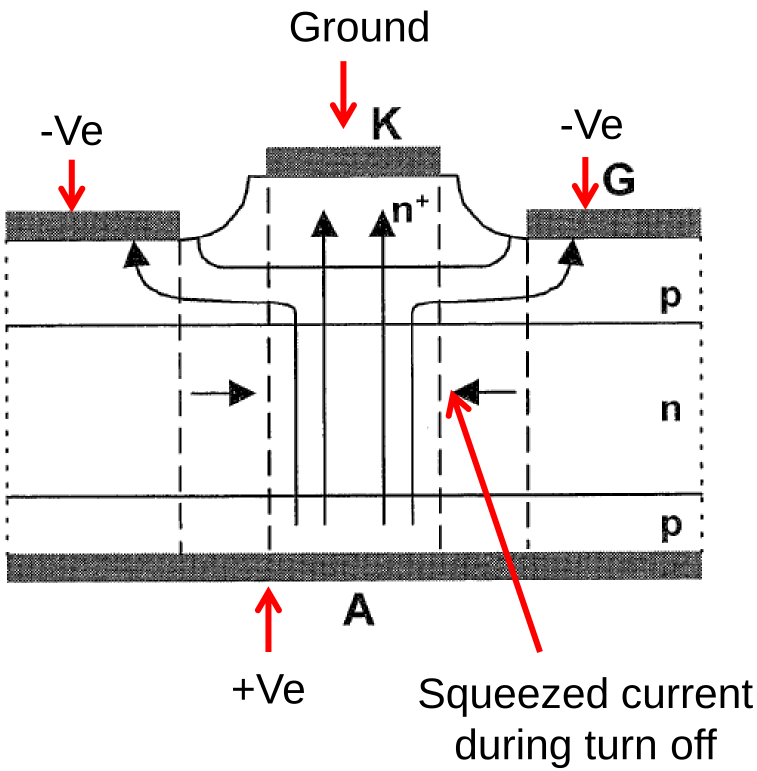
- For normal thyristors the only method to achieve turn off is to reverse the polarity of the anode/cathode voltage
  - Generally devices are used for AC applications
  - Due to the injected carriers within the drift region the device turns off similar to a high voltage diode with a characteristic reverse recovery
- Provided there are no cathode shorts it is possible for a thyristor in the on-state to be turned off by applying a negative voltage to the gate electrode
- To make gate turn off feasible, the cathode cell needs to be modified
  - The cathode is re-designed to form a mesa region surrounded by the gate contact

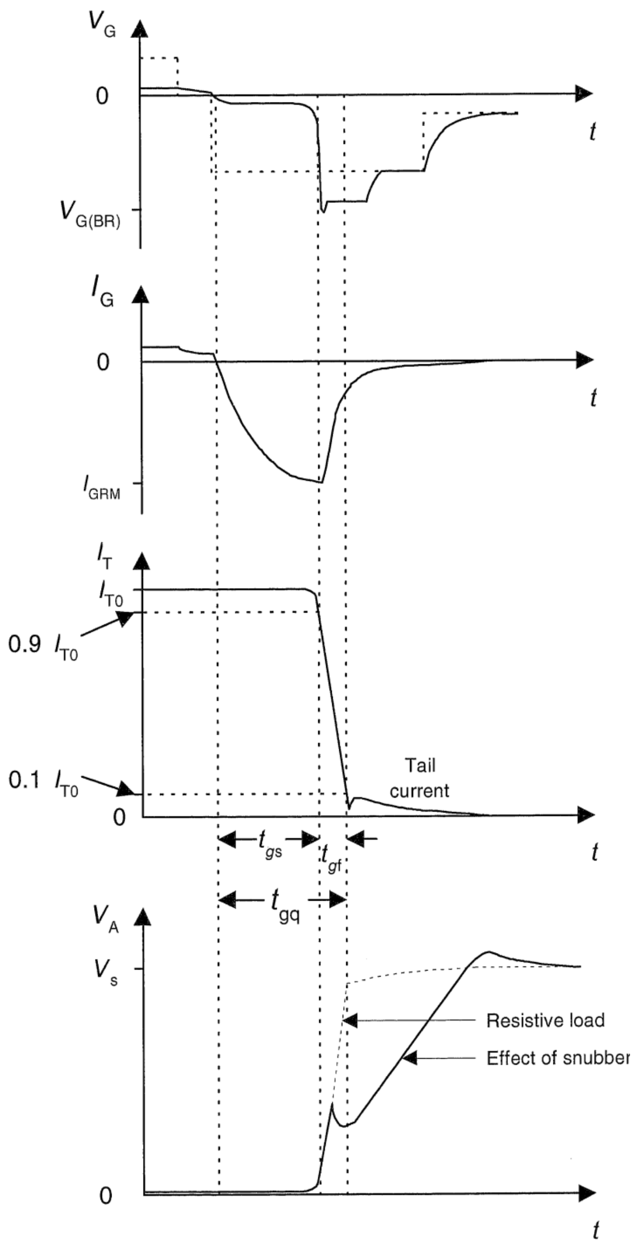


GTO Turn off process

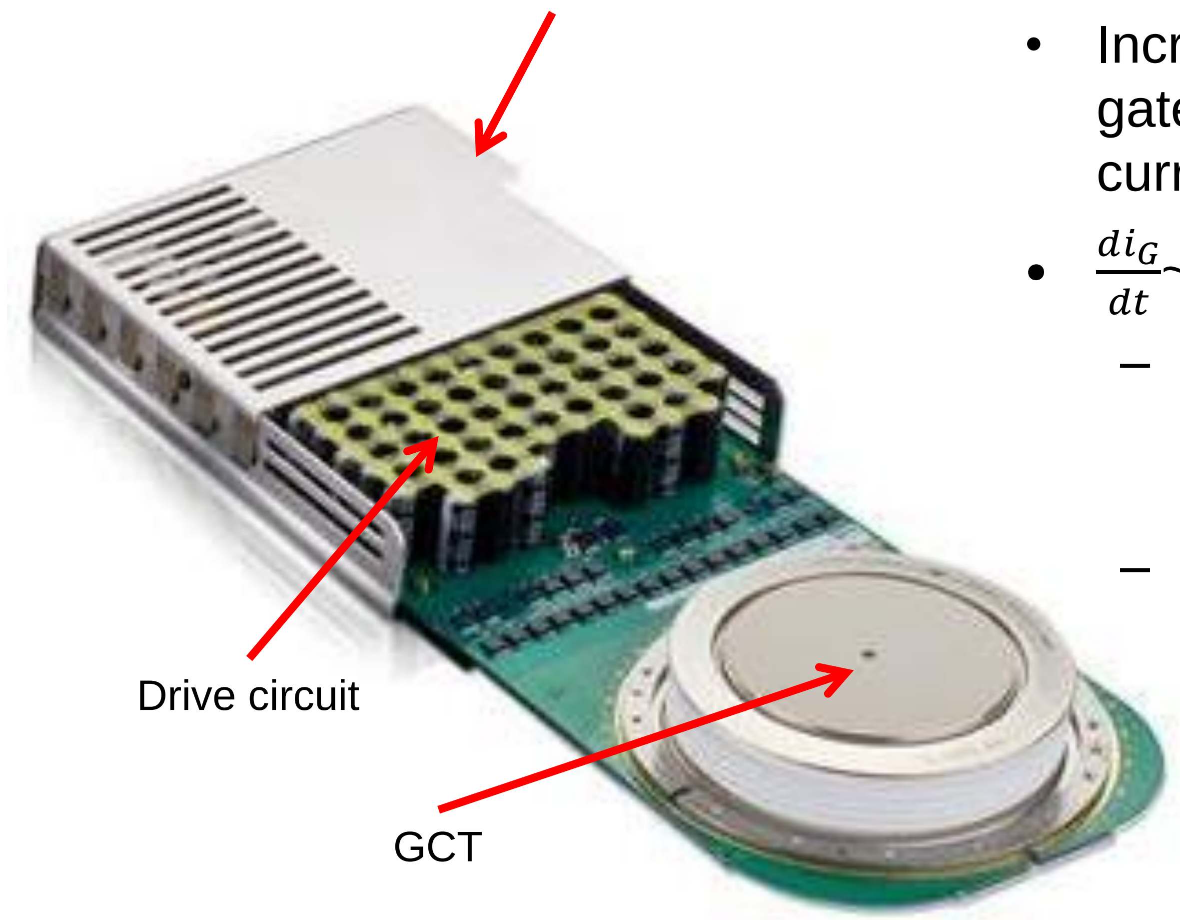
- In the on-state the inner layers of the thyristor are flooded with excess carriers injected from both the anode and cathode emitters
- Using the two-transistor model, these are in saturation with
$$\alpha_{pnp} + \alpha_{npn} = 1$$
- A negative gate voltage draws the holes current away from the cathode emitter (J_3)
  - Decreasing the electron injection into the gate layer from the n+ emitter
- Initially the turned on area of the n+ emitter is squeezed from the gate contact sides, reducing α_{npn}
  - With sufficient negative gate current $\alpha_{pnp} + \alpha_{npn} \neq 1$ and the thyristor unlatches
- Electron hole plasma decays away as the thyristor turns off into its forward blocking mode
  - Observed as a tail current in the turn off characteristic

Current flow through the GTO during turn off and typical switching transient



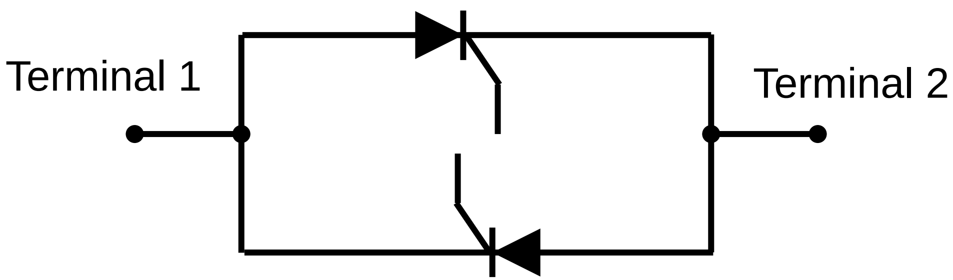


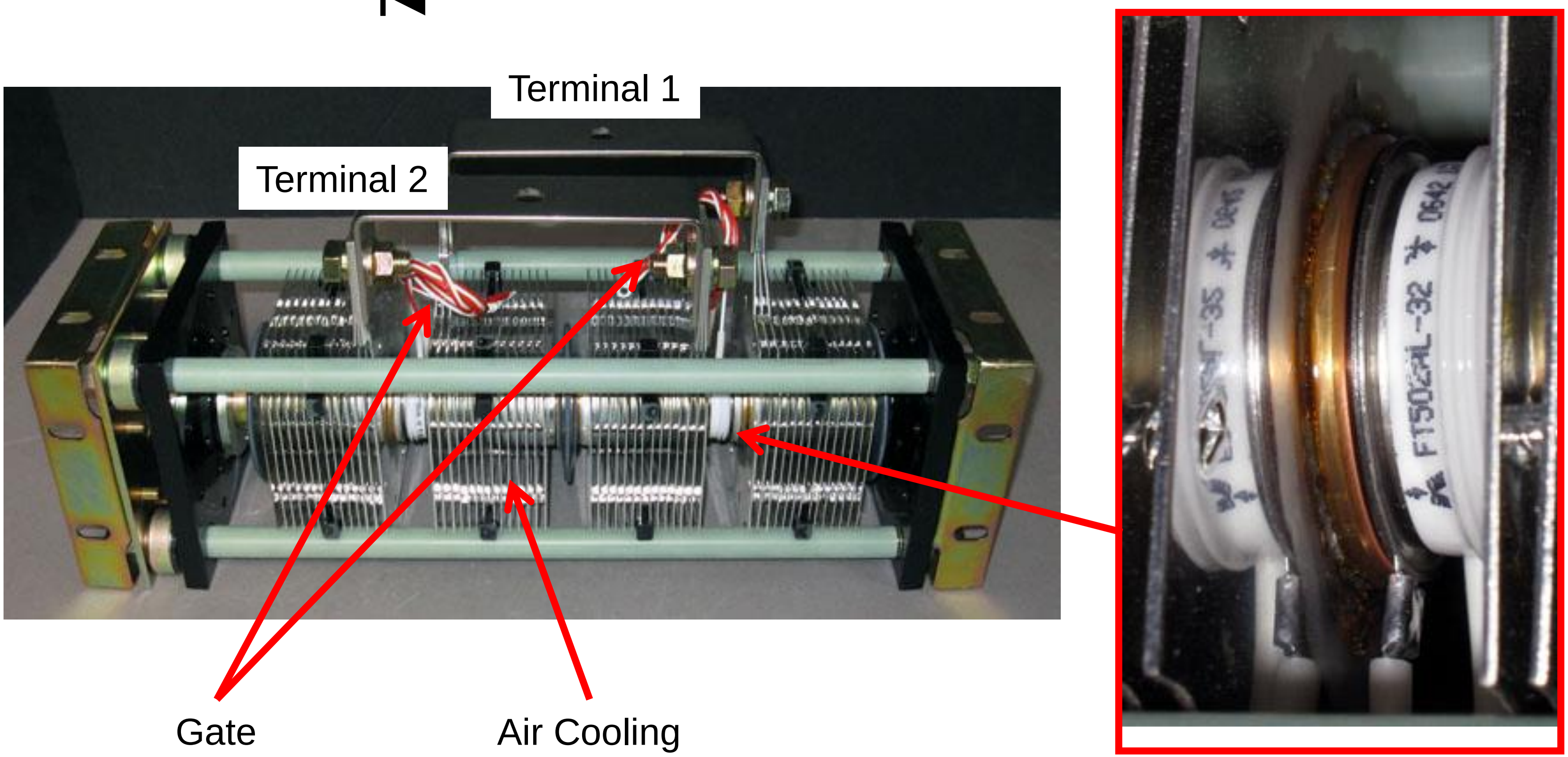
Integrated Gate-Commutated Thyristor (IGCT)



- Integrated Gate Commutated Thyristor (GCT) with the gate drive unit
- Increase rate of change of the gate drive turning the cathode current of in 1us
- $\frac{di_G}{dt}$~ 3000A/us for a 3kA GCT
  - Reduced gate leakage inductance to 6nH or less ($1/50^{th}$) of the usual GTO
  - Coaxial multi-layer configuration of device conductions

Typical Thyristor stacks: 440V 1015A bi-directional





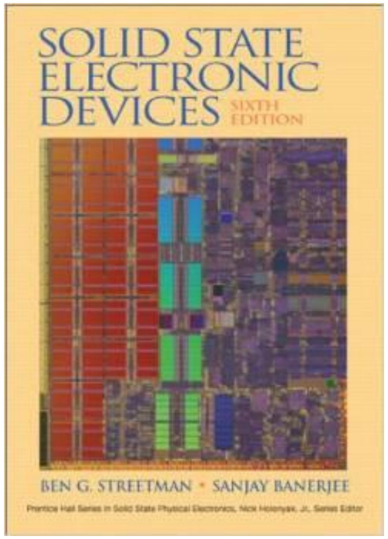
Summary

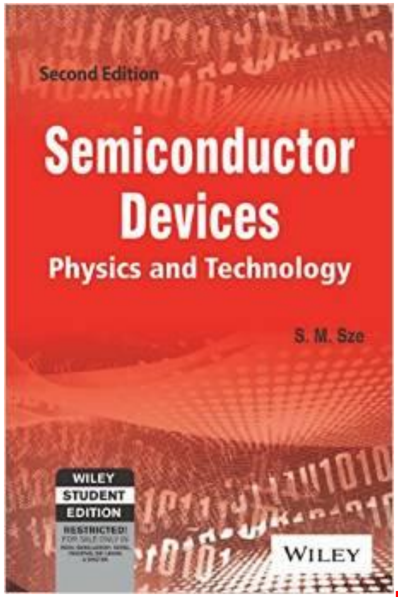
- Thyristor structures are formed by a combination of NPN and PNP transistor which can latch from a blocking state into a self-sustaining on-state
  - Once device has latched gate supply currents can be removed
- Electrical characteristics share similar limitations to transistors and diodes
  - Breakdown voltage can be limited by internal transistor gain
  - Once device enters its on-state drift region flooded with carries
    - Conductivity modulation occurs with the same injected carrier densities to that to high voltage diodes
- These device show the lowest forward voltage drops for bipolar device and are seen in low frequency high power applications

Summary cont.

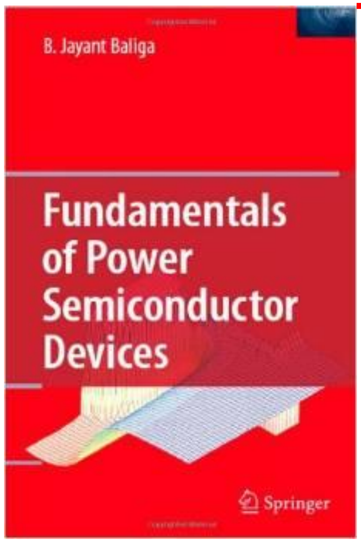
- Standard Thyristors are turned off in a similar manor to that of a diode
  - Reversal of the anode/cathode voltage polarities breaking the regulative action
  - Device re-enters forward blocking state after a reverse recovery process
- Modification to the cathode enables the device to be switched off with an application of a negative gate voltage
  - Diverting current away from the cathode junction and breaking the regenerative action
- With their superior on-state performance many alternative thyristor structures are being investigated
  - MOS Controlled: Monolithic integration of a MOSFET into the GTO process to facilitate voltage controlled turn on/off of the thyristor structures
  - MOS Gated: Integration of MOSFETs into the structure to **continuously** control the current through all operating conditions

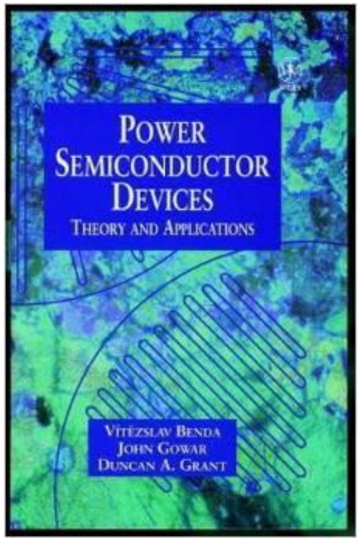
Further reading





Source material for introduction to semiconductor device technologies and principles of operation for traditional device technologies





Source material for high voltage and power device technologies