Lecture Notes

Thyristors (SCRs)

OUTLINE

- SCR construction and I-V characteristics.
- Physical operation of SCRs.
- Switching behavior of SCRs
- dv/dt and di/dt limitations and methods of improving them.
- SCR drive circuit considerations.

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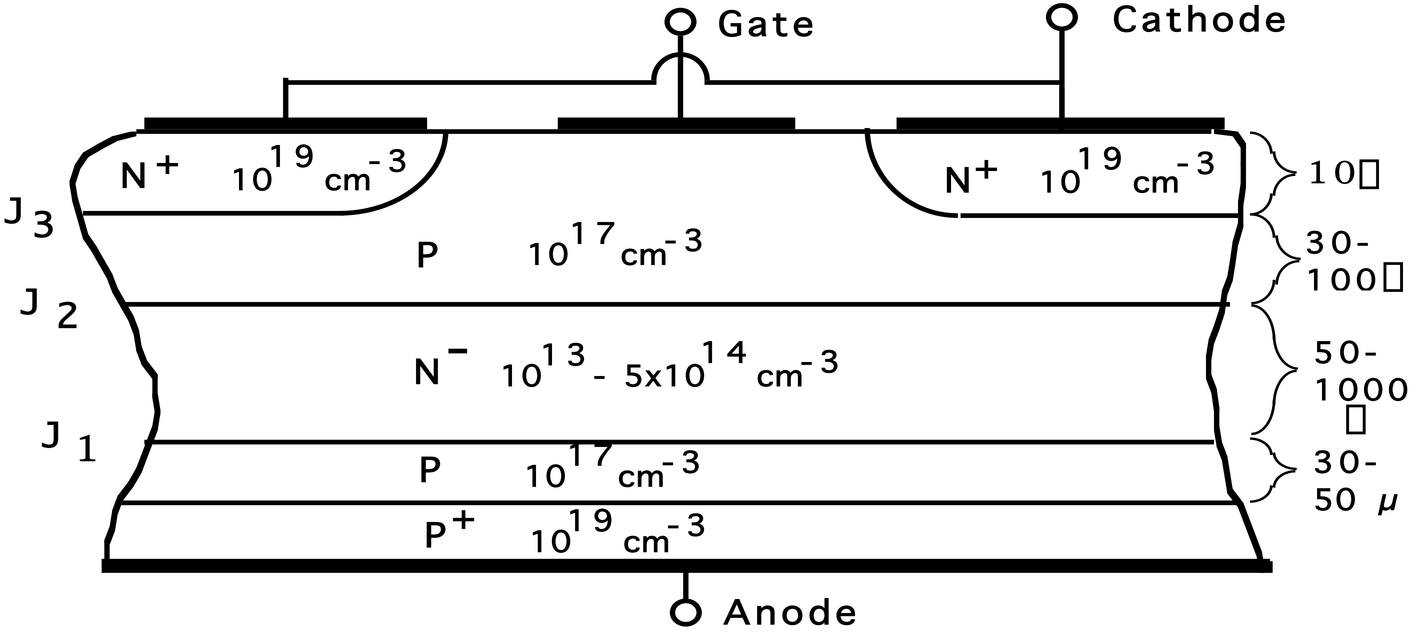
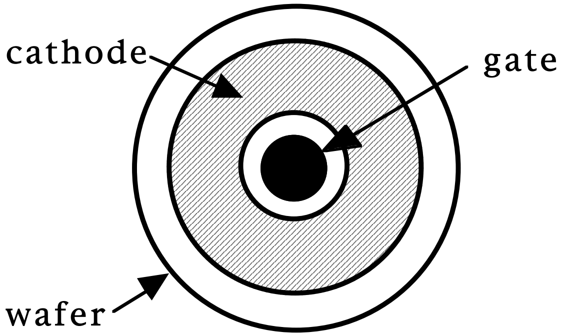
Thyristor (SCR) Geometry

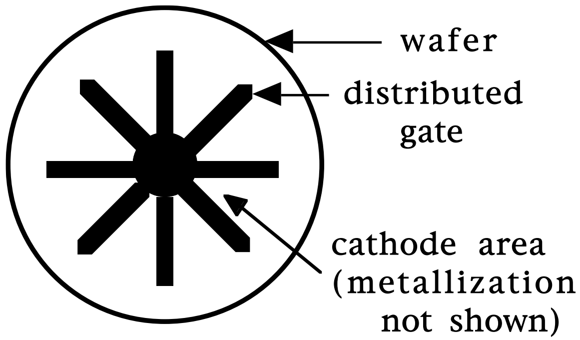


- Cross-sectional view showing vertical orientation of SCR.
- SCRs with kiloamp ratings have diameters of 10 cm or greater.

Gate and cathode metallization for slow (phase control) thyristor.



Gate and cathode metallization for fast (inverter grade) SCR



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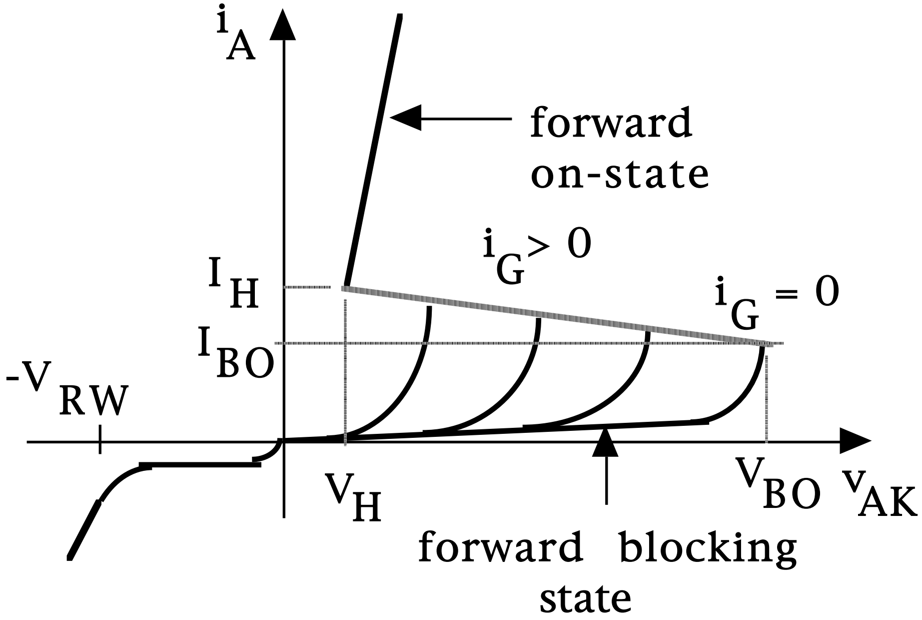
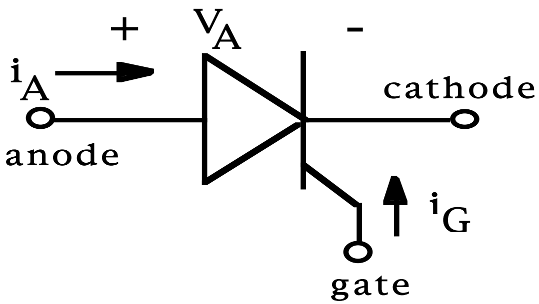
Thyristor I-V Characteristics



Thyristor circuit symbol.



- SCR triggerable from forward blocking state to on-state by a gate current pulse.
- Thyristor latches on and gate cannot turn it off. External circuit must force SCR off.
- Current to several kiloamps for V(on) of 2-4 volts.
- Blocking voltages to 5-8 kilovolts.
- V_{BO} = breakover voltage ; I_{BO} = breakover current
- V_H = holding voltage I_H = holding current
- Maximum junction temperature = 125 °C - limited by temperature dependence of V_{BO}.

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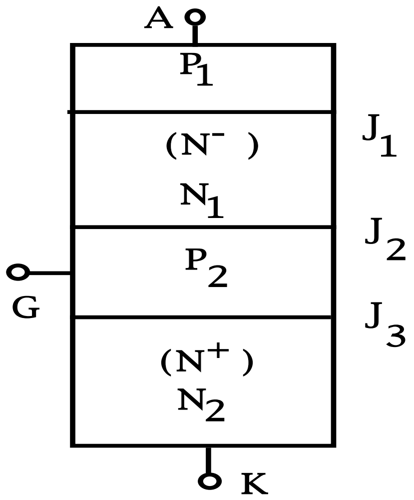
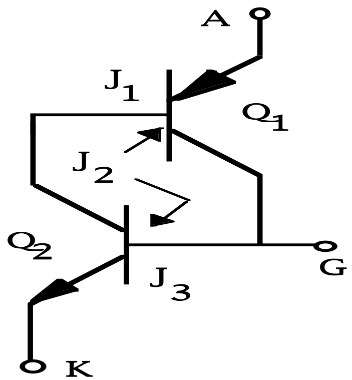
SCR Model and Equivalent Circuit

One dimensional SCR model.



Two transistor equivalent circuit



- BJTs in equivalent circuit in active region.
- Use Ebers-Moll equations for BJTs
- $I_{C1} = -\alpha_1 I_{E1} + I_{CO1}$; $I_{C2} = -\alpha_2 I_{E2} + I_{CO}$
- $I_A = I_{E1}$; $I_K = -I_{E2} = I_A + I_G$
- $I_{C1} + I_{B1} + I_{E1} = 0$
- $I_A = \dfrac{\alpha_2 I_G + I_{CO1} + I_{CO2}}{1 - (\alpha_1 + \alpha_2)}$
- Blocking state $\alpha_1 + \alpha_2 << 1$
- At breakover $\alpha_1 + \alpha_2 \approx 1$

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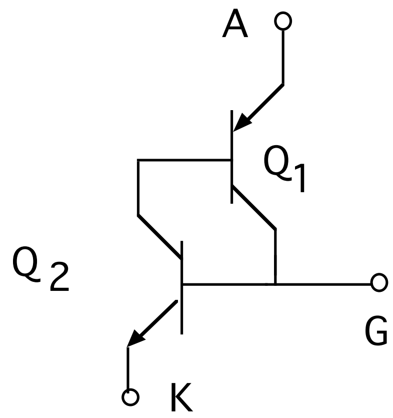
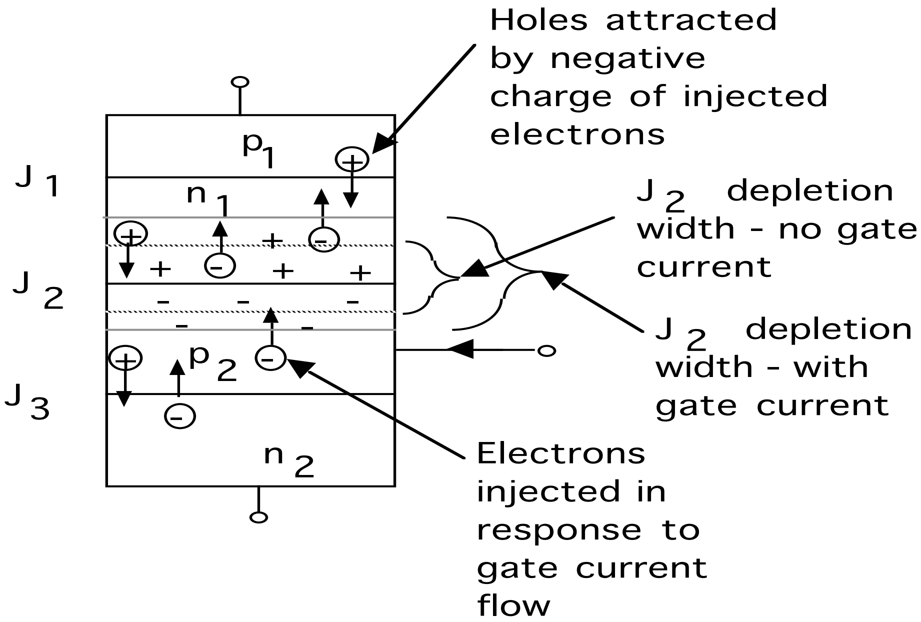
Thyristor Turn-on Process

- In forward blocking state, both BJTs active.
- If $\alpha_1 + \alpha_2 < 1$, connection is stable.
- If $V_{AK} = V_{BO}$ or if positive gate current pulse is applied $\alpha_1 + \alpha_2$ becomes equal to unity and circuit connection becomes unstable and SCR switches on.





- Negative charge of electrons swept into n_1 layer partially compensate positive charge of ionized donors exposed by growth of depletion of junction J_2.
- Growth of depletion reduces width of bases of Q_{npn} and Q_{pnp} and thus increases α_1 and α_2.
- Holes attracted by first wave of injected elctrons attract additional electrons and so on - regenerative action.

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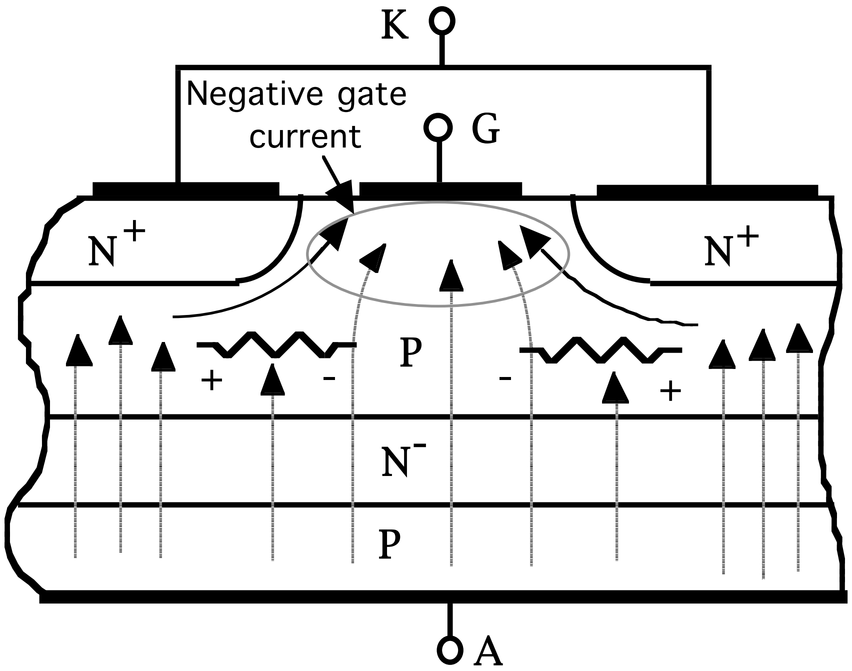
Thyristor On-state Latchup

SCR with negative gate current



- Negative gate current causes lateral voltage drops as indicated which lead to current crowding in center of cathode.
- Conventional SCRs (phase control) have large area cathodes - negative gate current cannot remove stored charge from center of large cathode area.
- SCR stays latched on in spite of negative gate current.
- External circuit must force anode current to negative values in order that enough stored charge be removed from SCR so that it can turn off.

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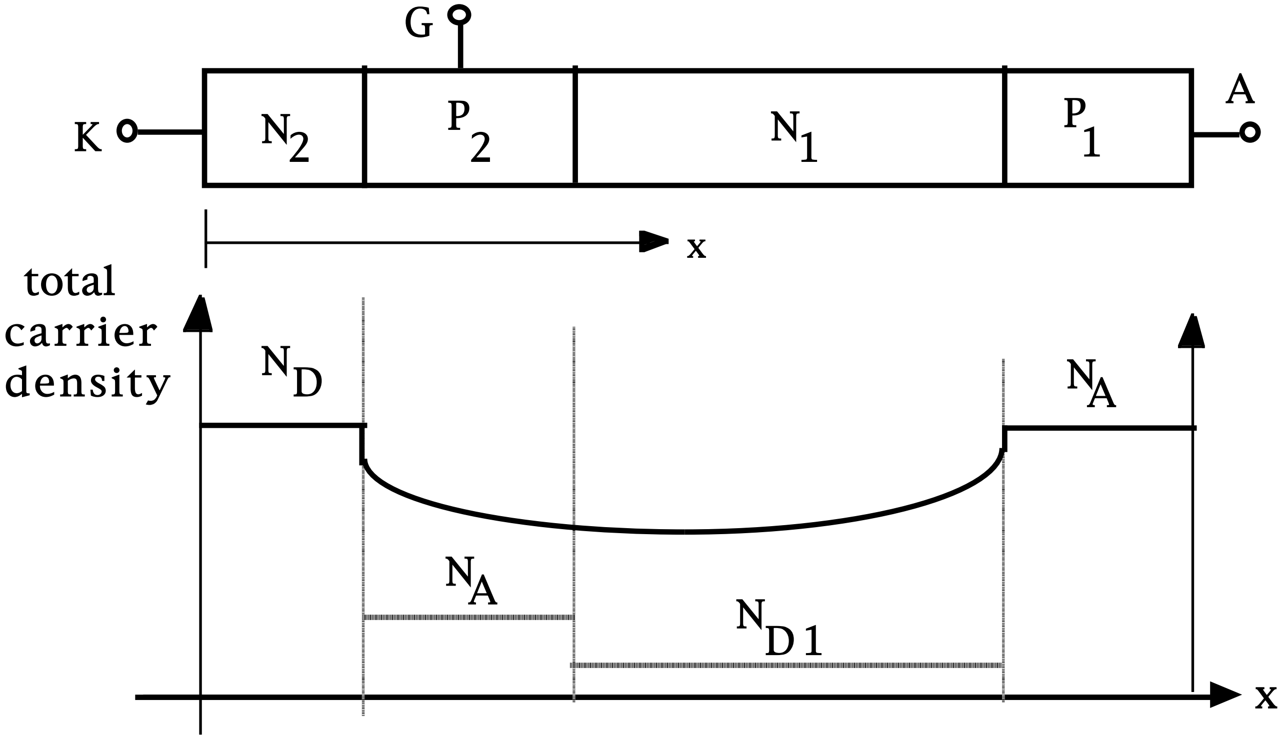
Thyristor On-state Operation



- On-state: all three junctions forward biased and BJTs in equivalent circuit saturated.

- On-state stable because saturated BJTs have $\alpha_1 + \alpha_2 << 1$.

- On-state voltage $V_{AK(on)} = V_{j1} - V_{j2} + V_{j3} + V_n$

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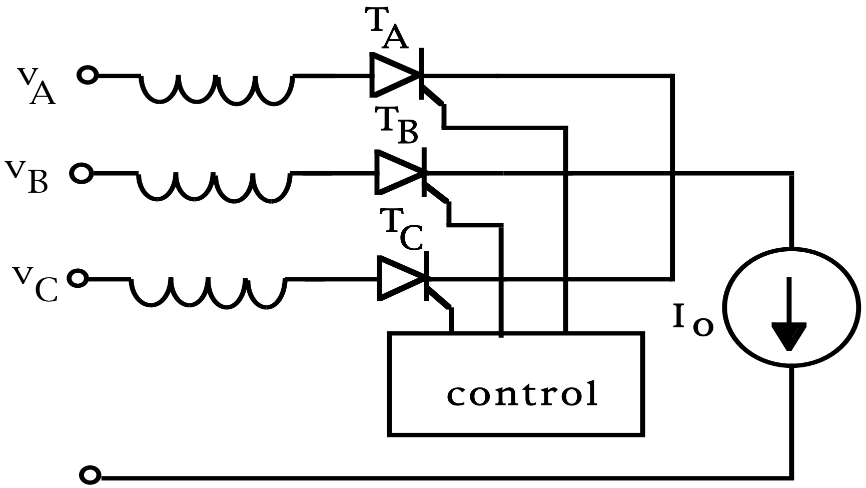
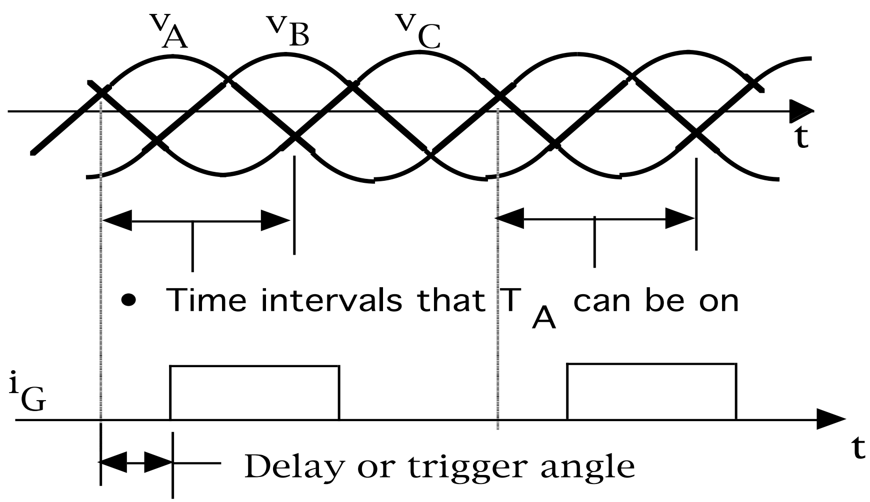
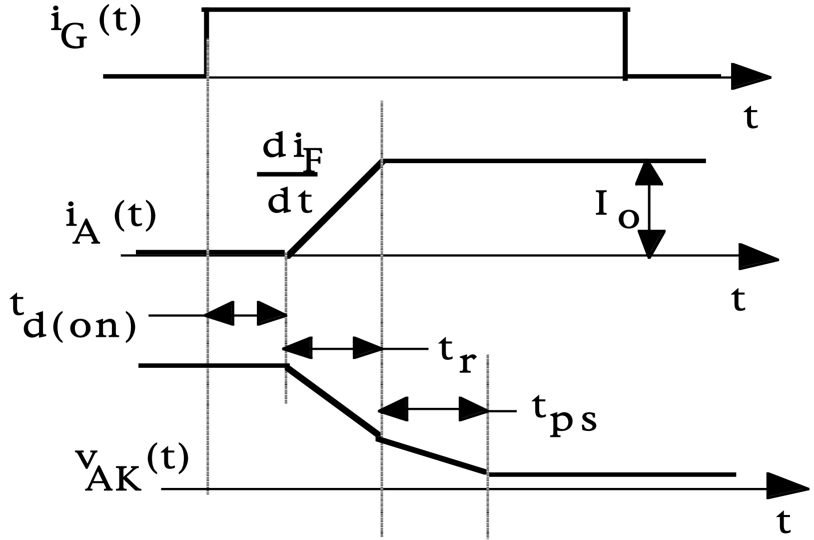
Thyristor Turn-on Behavior







- $t_{d(on)}$ = turn-on delay time; time required for charge injection by gate current to make $\alpha_1 + \alpha_2 = 1$.
- t_r = time required for anode current to reach on-state value. Anode current rate-of-rise di_F/dt limited by external inductance.
- t_{ps} = time required for plasma to spread over whole cathode area from cathode periphery near gate.
- V_{AK} does not attain on-state value until complete area of cathode is conducting.

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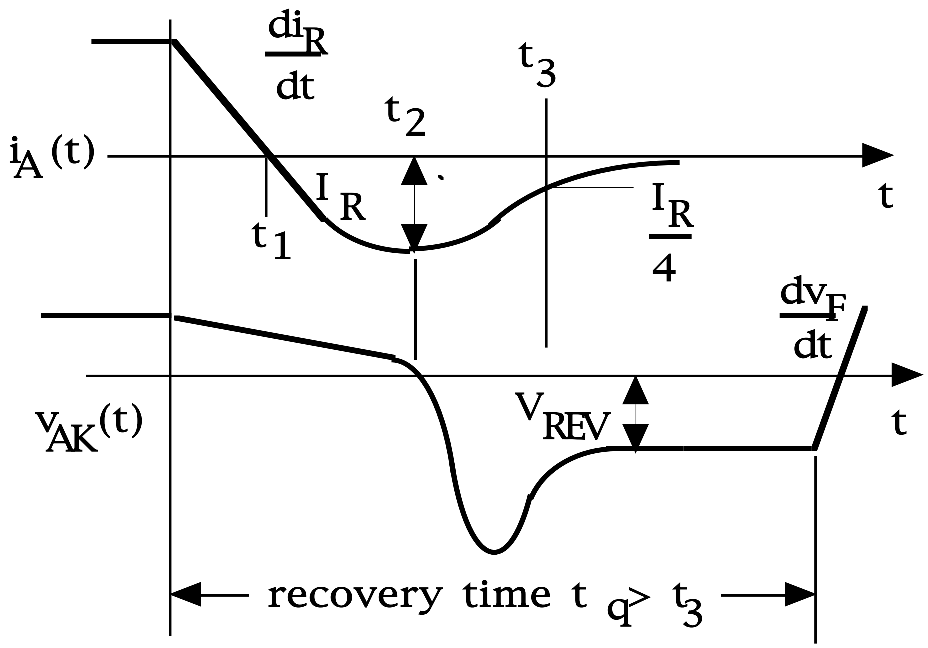
Thyristor Turn-off Behavior



Turn-off waveforms

- SCR turn-off quite similar to power diode turn-off.
- Anode current rate-of-fall controlled by external inductance.
- Reverse voltage overshoot caused by external inductance.
- Junction J_1 is blocking junction in reverse bias. J_3 has low breakdown voltage (20-40 volts) because of the heavy doping on both sides of the junction.

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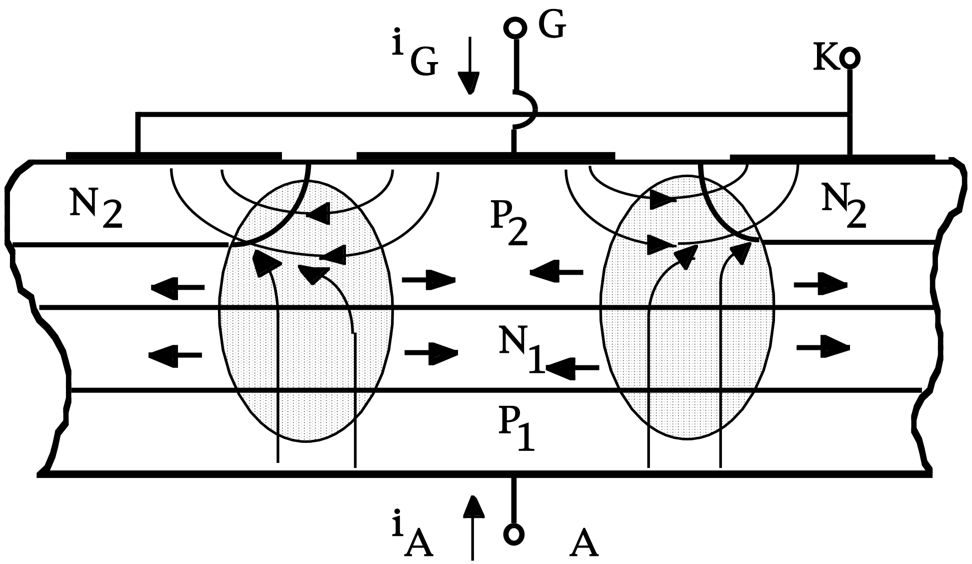
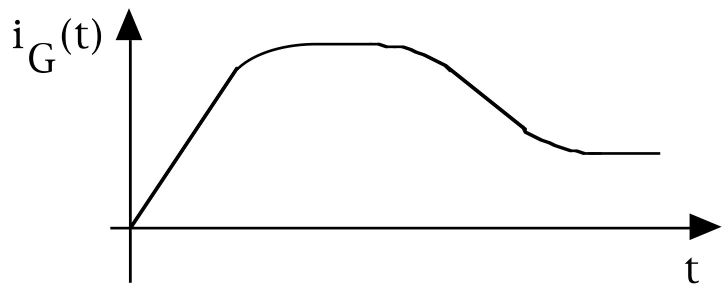
Thyristor di/dt Limit at Turn-on





- SCR first turns on at cathode periphery nearest gate.
- Current constricted to small areas during initial phases of turn-on, $t_{d(on)}$ and t_r.
- If anode current rate-of-rise, di_F/dt, not kept less than some specified maximum, current density in constricted area will be too large.
- Localized power dissipation too high and thermal runaway likely.

- Use shaped gate current pulse for rapid turn-on.

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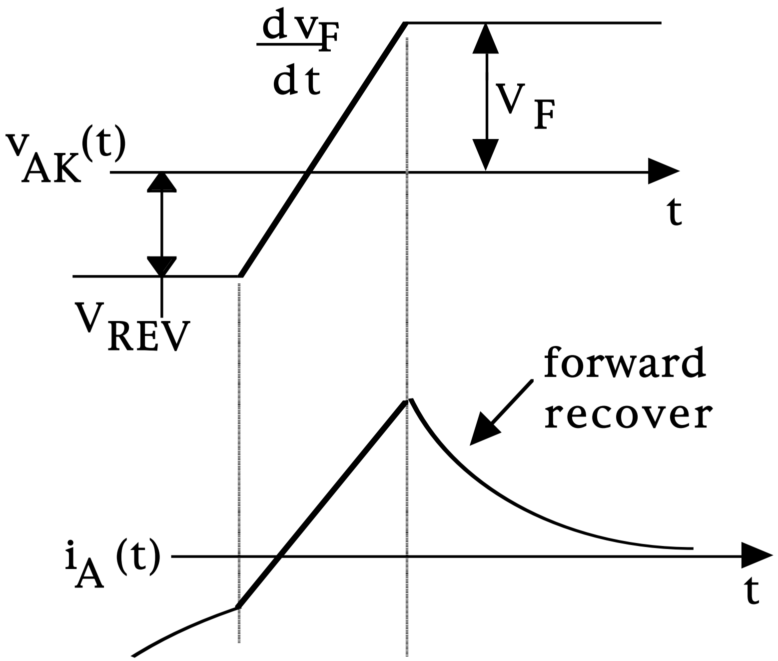
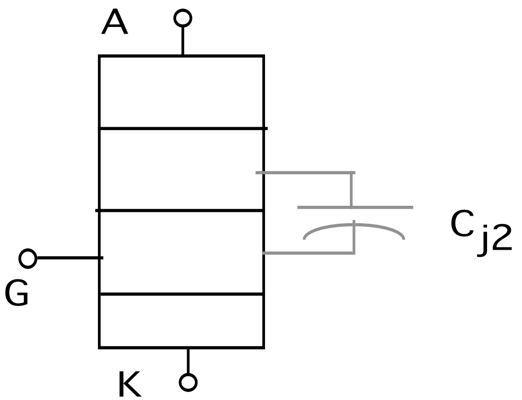
Thyristor Re-applied dv/dt Limits



- Removal of all stored charge in SCR requires a minimum time t_q.
- Application of positive dV_F/dt larger than a specified value before t_q results in a pulse of positive anode current which may produce unintentioned turn-on of the SCR.
- Avoidance of unintentioned turn-on requires $dV_F/dt < dV_{F,max}/dt$ and remaining in reverse bias for a minimum time t_q.



$$\left.\frac{dv_F}{dt}\right|_{max} < \frac{I_{BO}}{C_{j2}}$$

<u>Rate effect</u>

$$100\ \text{V}/\mu\text{s} < \left.\frac{dv_F}{dt}\right|_{max} < 2000\ \text{V}/\mu\text{s}$$

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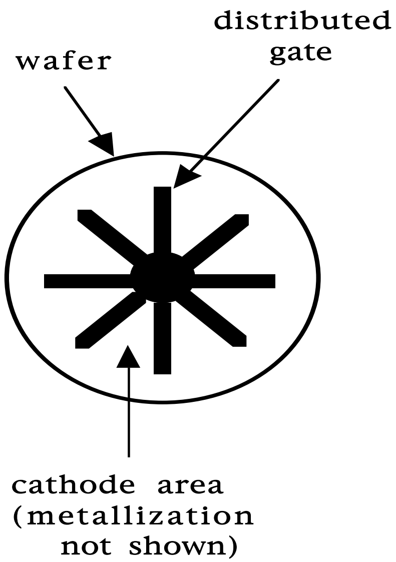
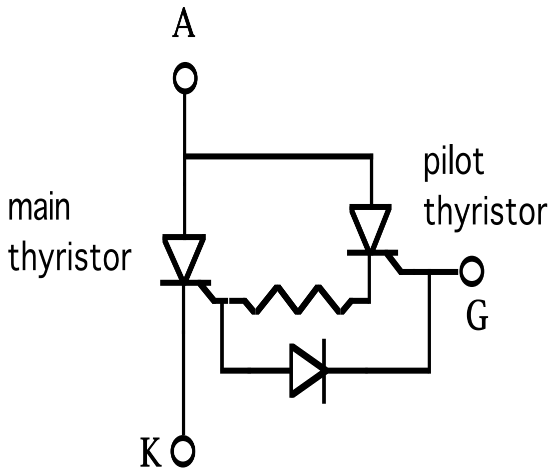
Methods of Improving Thyristor di/dt Rating



- Interdigitated gate-cathode structure used to greatly increase gate-cathode periphery.
- Distance from periphery to center of any cathode region significantly shortened.
- Ability of negative gate current to break latching condition in on-state increased.
- Combination of pilot thyristor, diode, and iterdigitated gate-cathode geometry tgermed a gate-assisted turn-off thyristor or GATT



- Use of pilot thyristor to increase turn-on gate current to main thyristor.
- Larger gate current increases amount of initial conducting area of cathode and thus improves di_F/dt capabiities.
- Diode allowes negative gate current to flow from main SCR.

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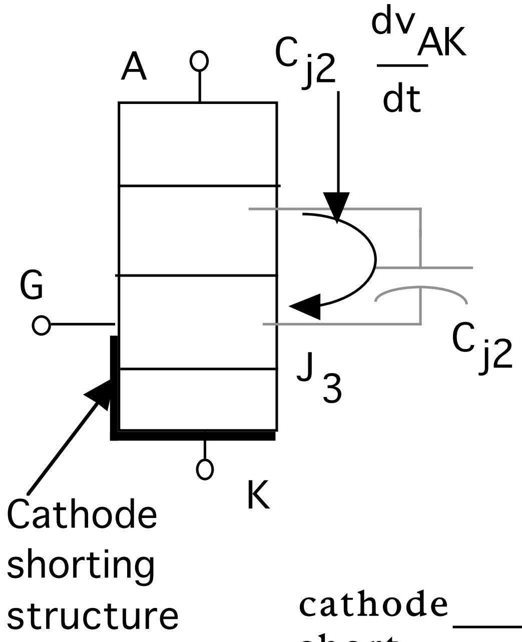
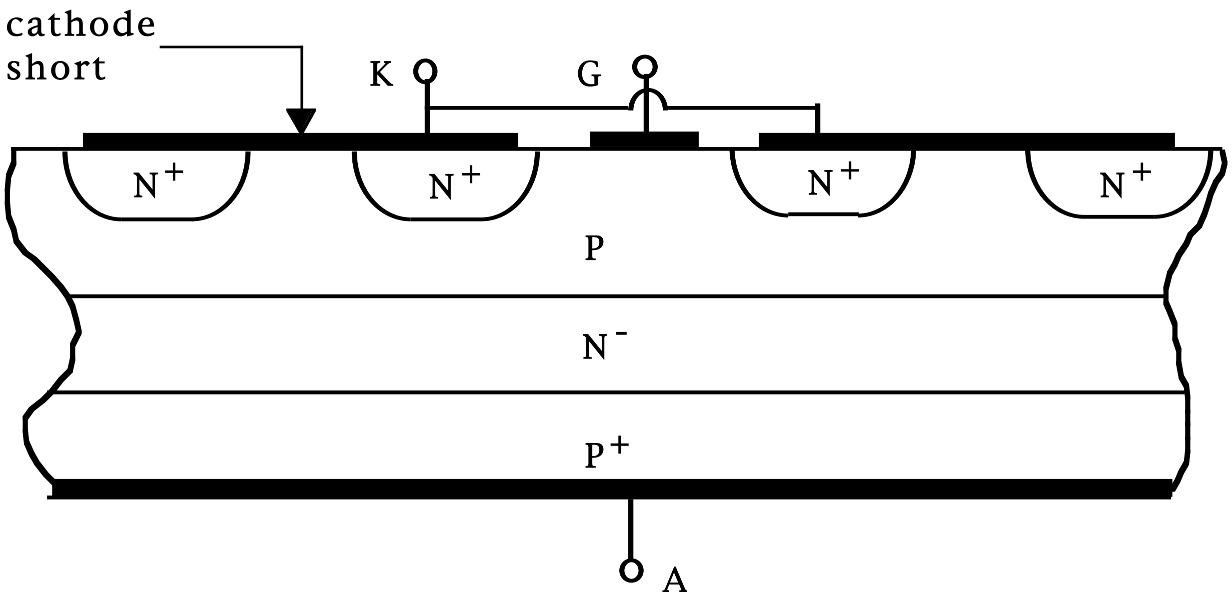
Improvement in dv/dt Rating Via Cathode Shorts



- Current thru C_{j2} indistinguishable from positive gate current with respect to turn-on of SCR.
- If current thru C_{j2} bypasses junction J_3, then SCR will not be turned on by the large displacement currents.
- Cathode shorts provide this desirable bypass. Most effective with interdigitaated gate-cathode geometry.
- $\left.\frac{dV_F}{dt}\right|_{max}$ significantly increased.



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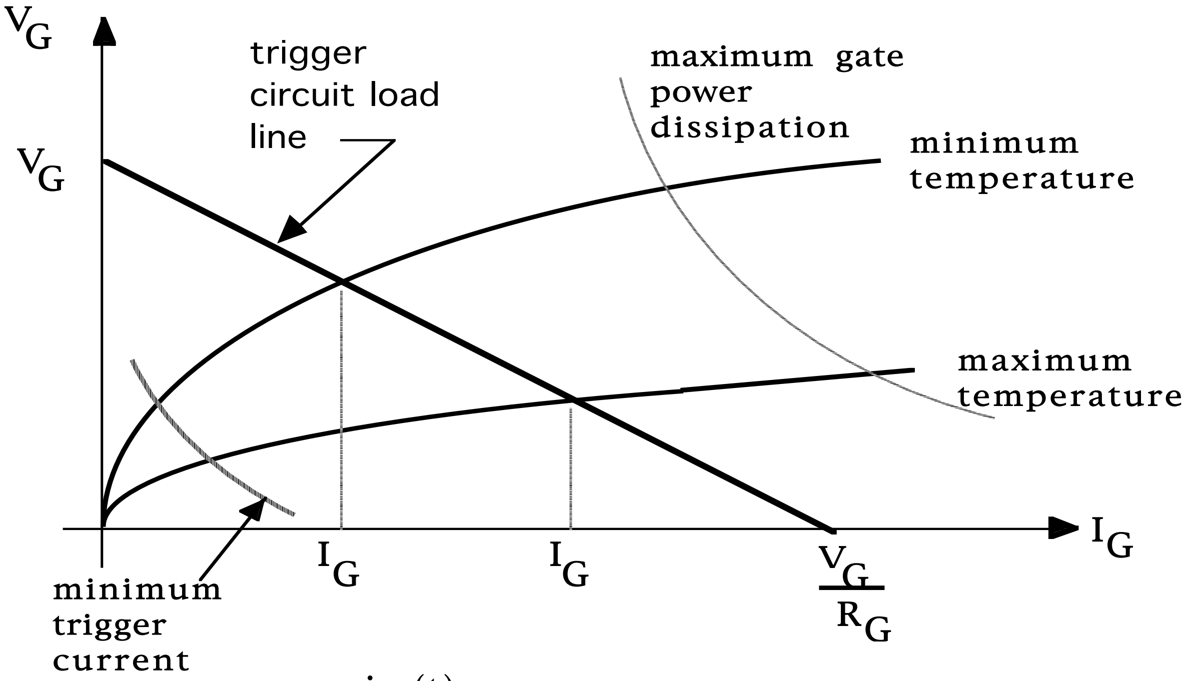
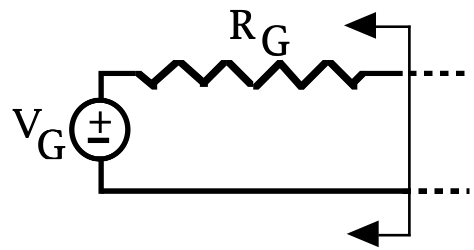
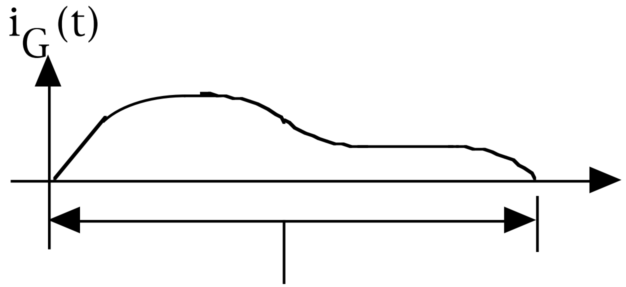
Thyristor Gate Trigger Requirements







Gate current must be on for a specified minimum time interval (few tens of microseconds) to guarantee SCR turn-on

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