EE 330
Lecture 29

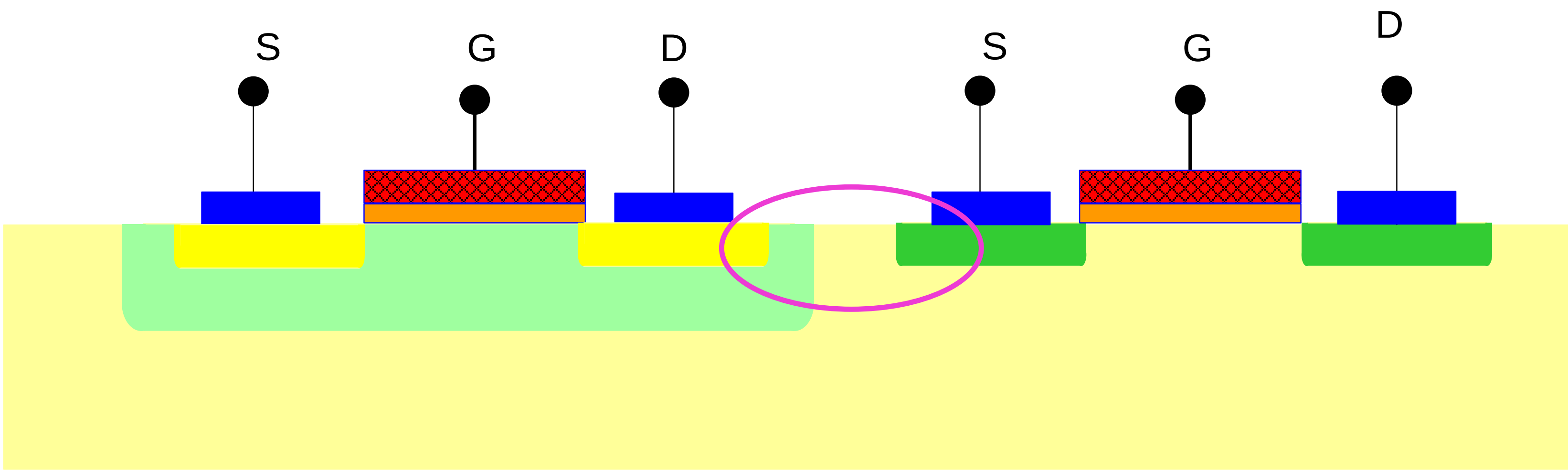
Thyristors

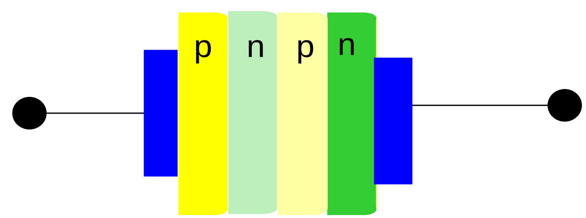
- SCR – Basic circuits and limitations
- Triacs
- Other thyristor types

The Thyristor

A bipolar device in CMOS Processes

Consider a Bulk-CMOS Process

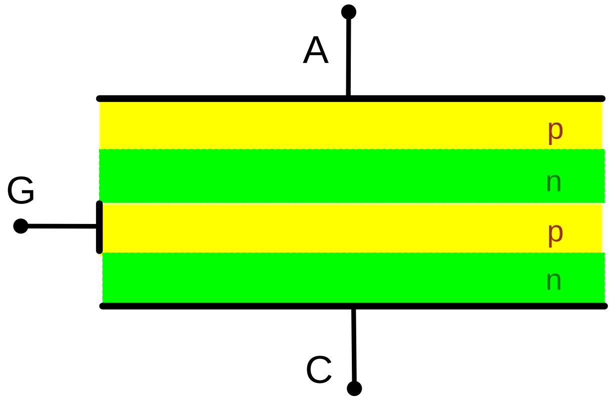


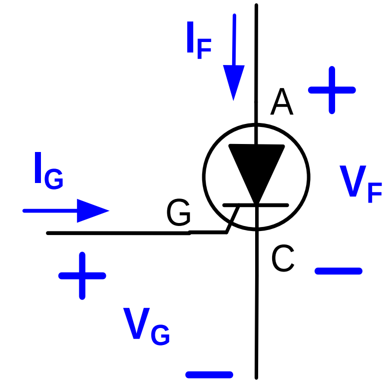


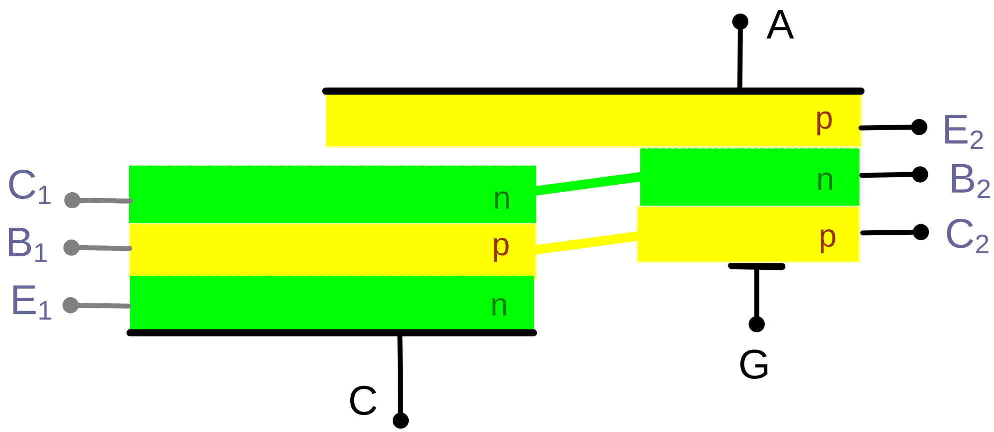
Have formed a lateral pnpn device !

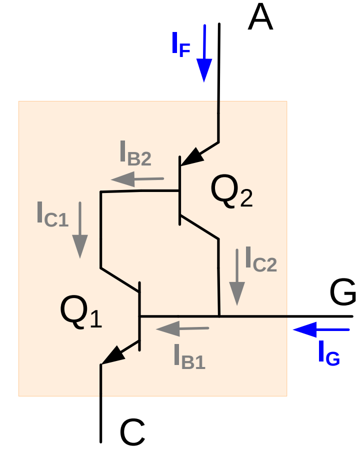
Will spend some time studying pnpn devices

Operation of the SCR





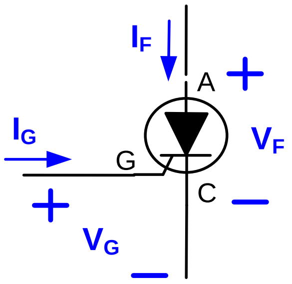




Not actually separated but useful for describing operation

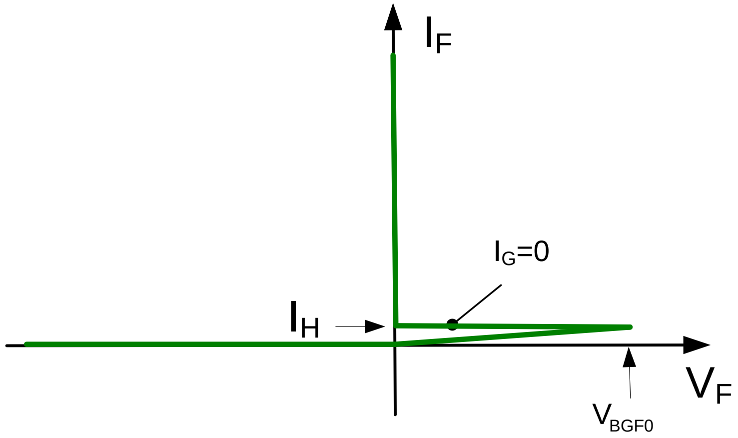
Review from Last Lecture

Operation of the SCR

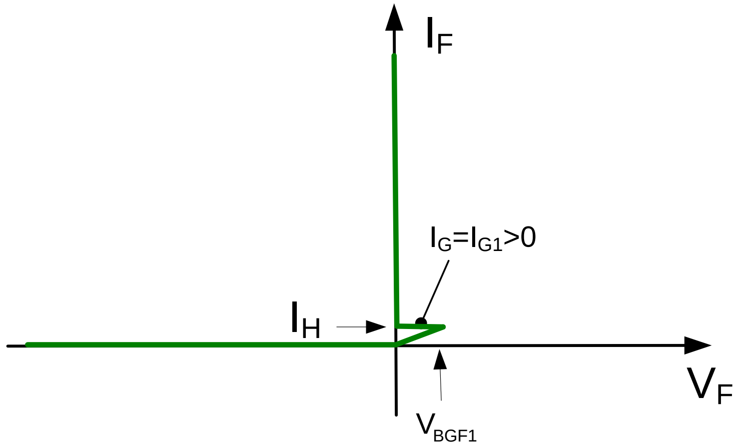


Consider the Ideal SCR Model

$$\left.\begin{aligned} I_F &= f_{1I}\left(V_F, I_G\right) \\ I_G &= f_{2I}\left(V_G\right) \end{aligned}\right\}$$



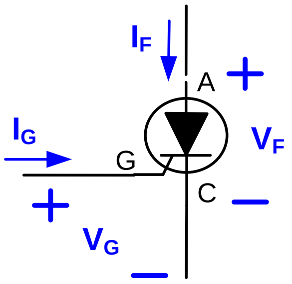
I_H is very small



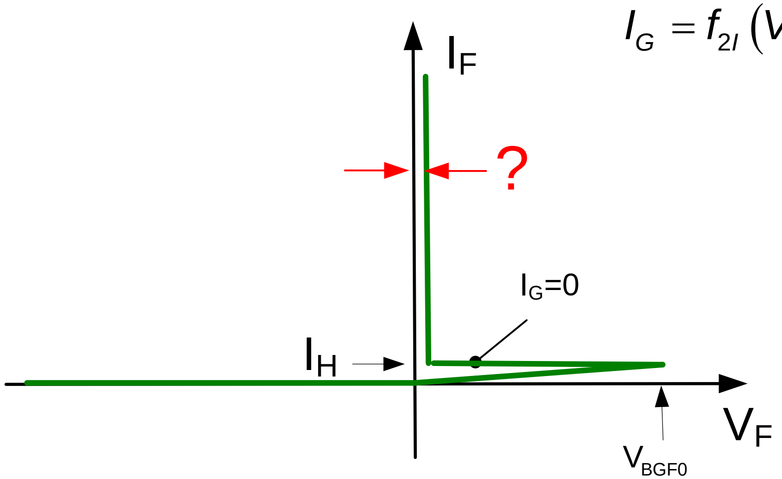
I_{G1} is small (but not too small)

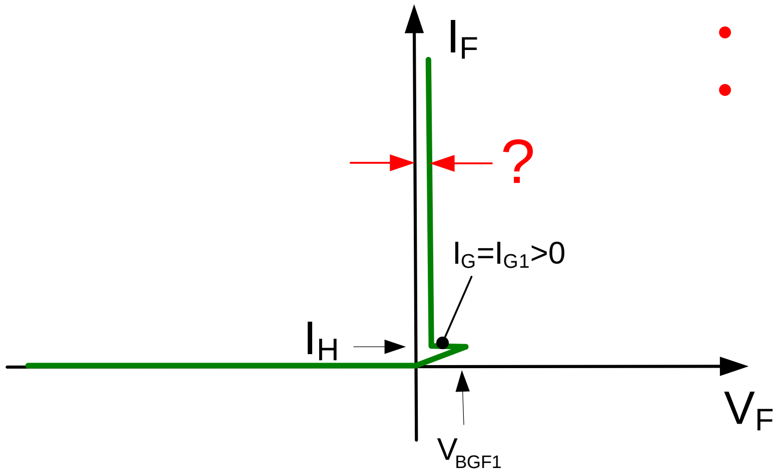
Operation of the SCR

Consider nearly Ideal SCR Model



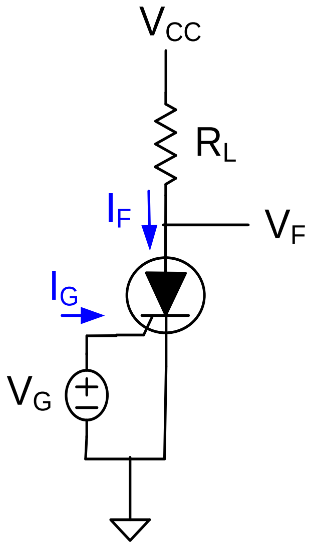
$$\left.\begin{aligned} I_F &= f_{1I}\left(V_F, I_G\right) \\ I_G &= f_{2I}\left(V_G\right) \end{aligned}\right\}$$





- On voltage approximately 0.9V
- Major contributor to ON-state power dissipatio
- Even with large currents, P_{ON} is quite small

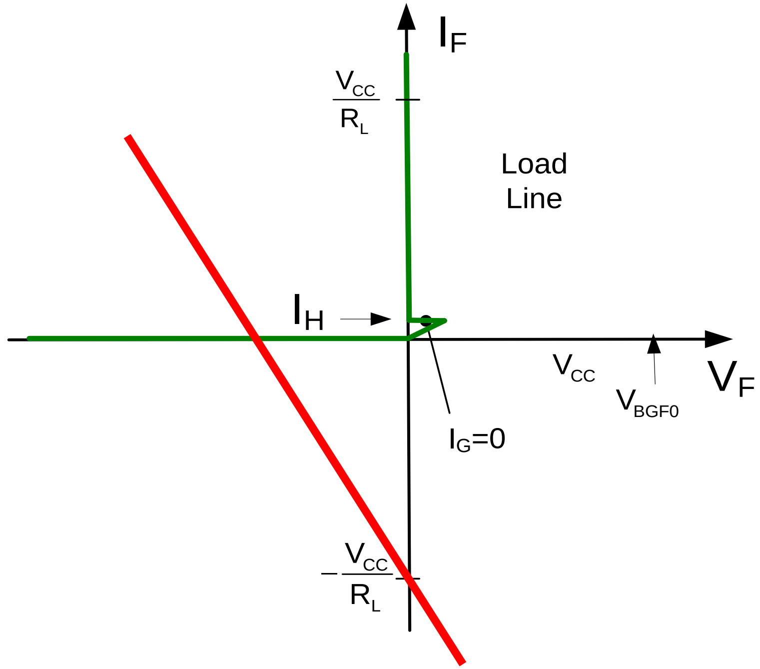
Operation of the SCR



Operation with the Ideal SCR

Often V_{CC} is an AC signal (often 110V)

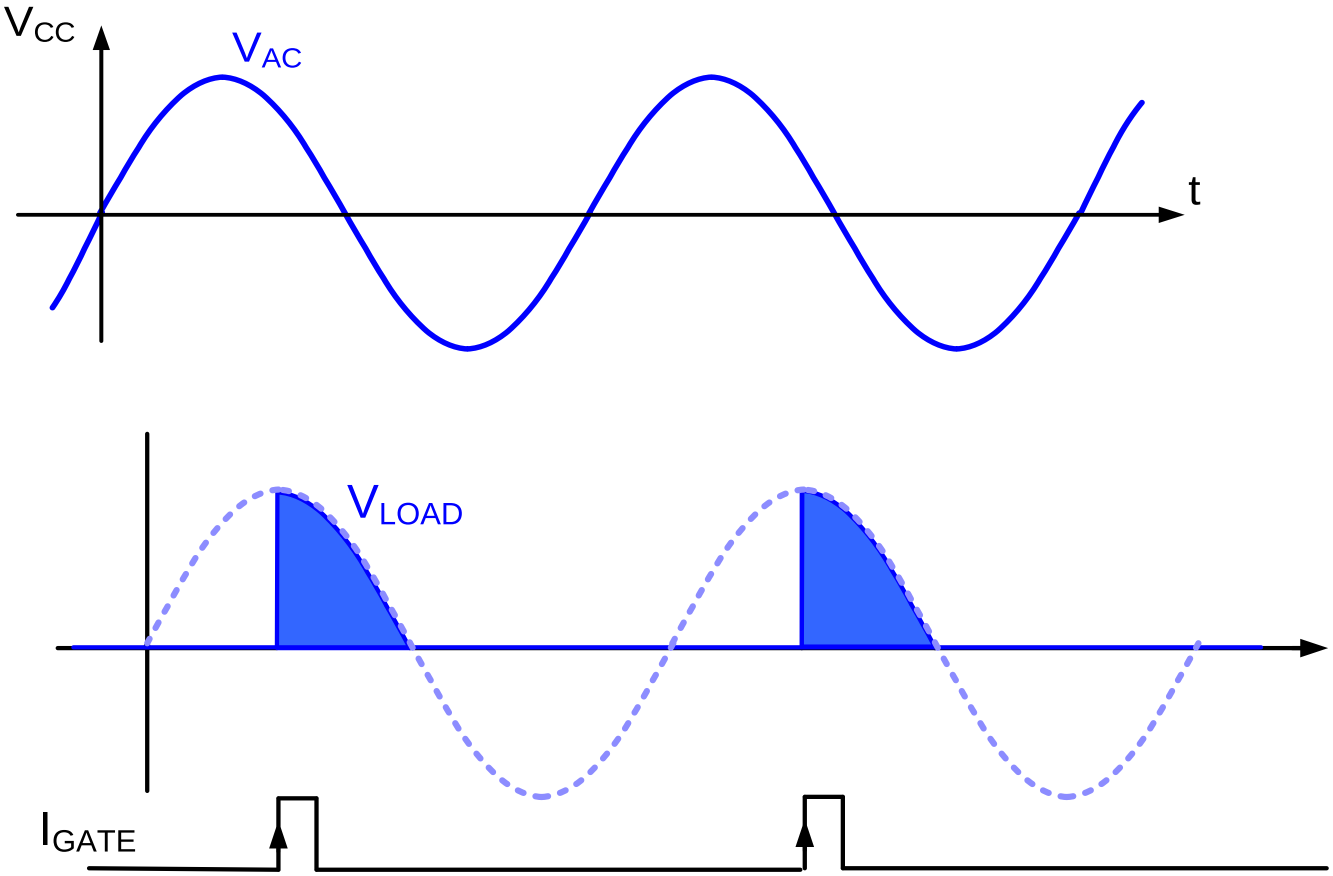
SCR will turn off whenever AC signal goes negative

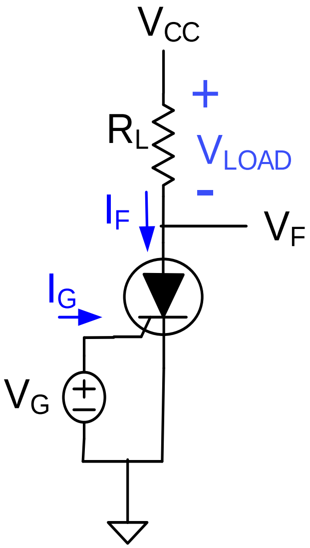


Operation of the SCR

Operation with the Ideal SCR

Duty cycle control of load R_L

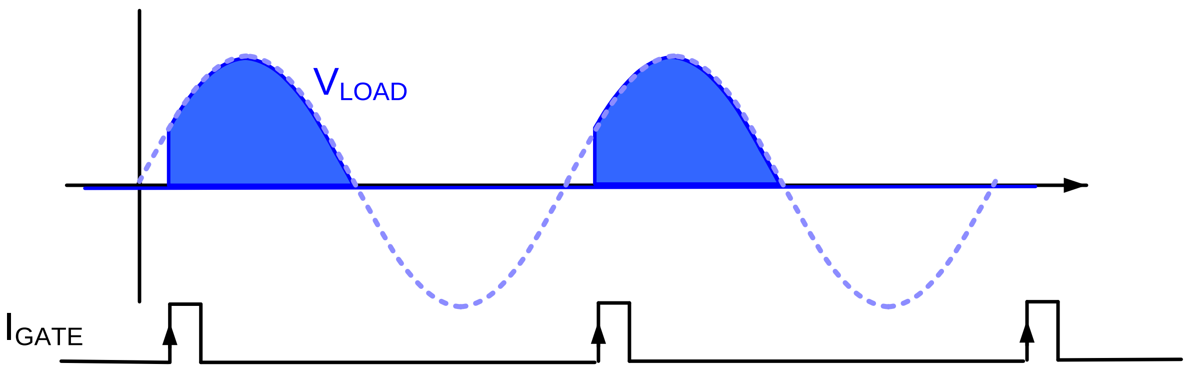


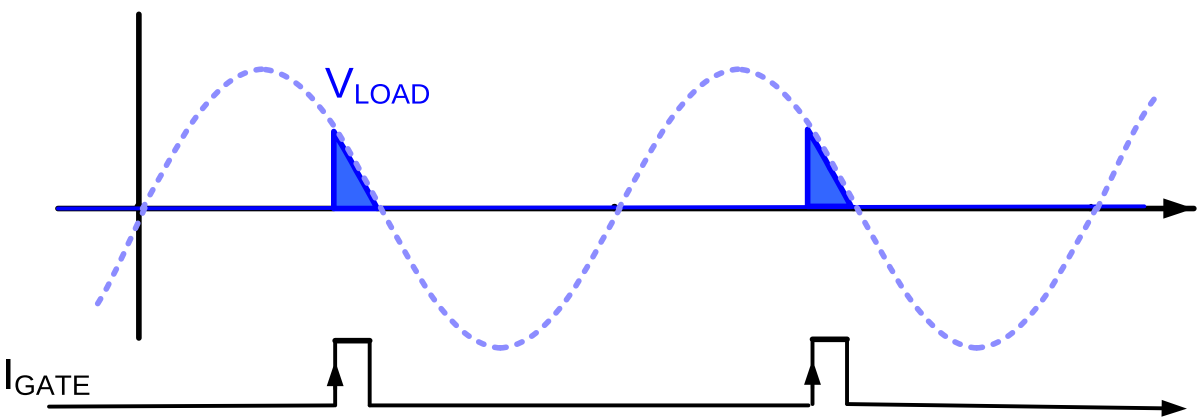


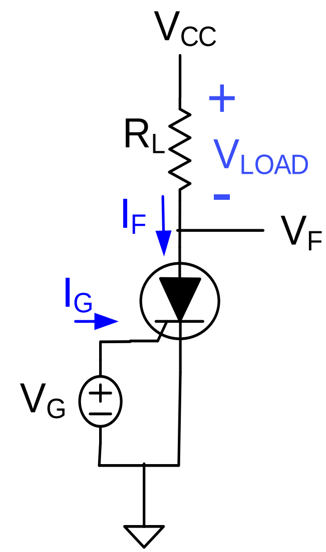
Operation of the SCR

Operation with the Ideal SCR

Duty cycle control of load R_L



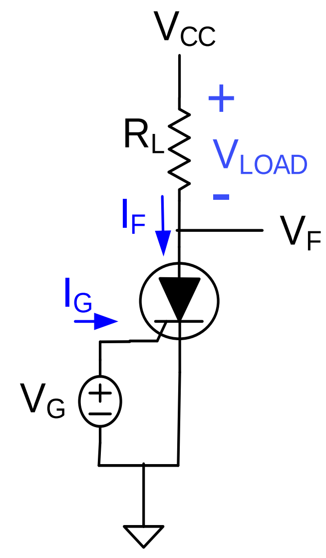


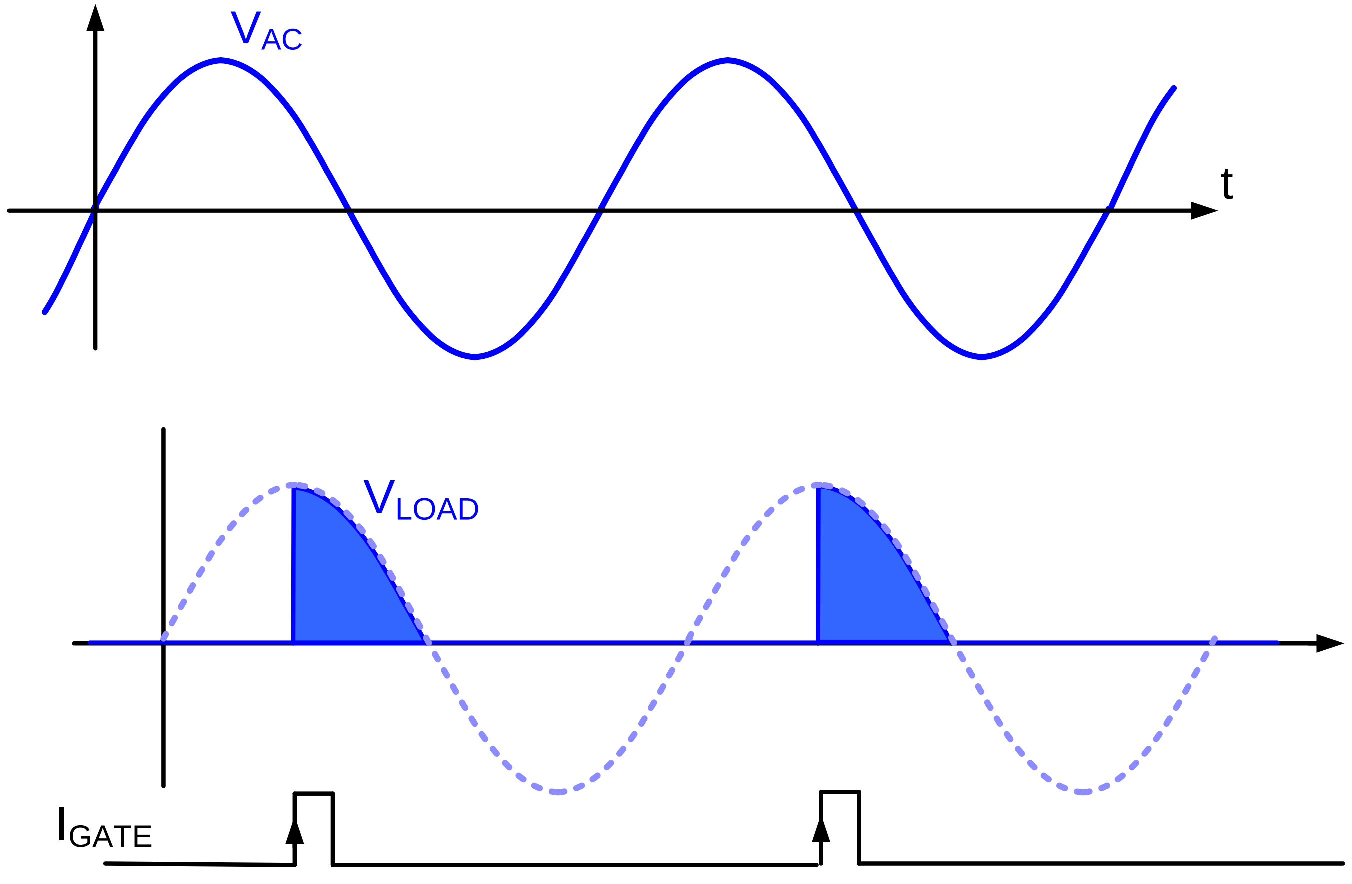


Operation of the SCR

Operation with the Ideal SCR

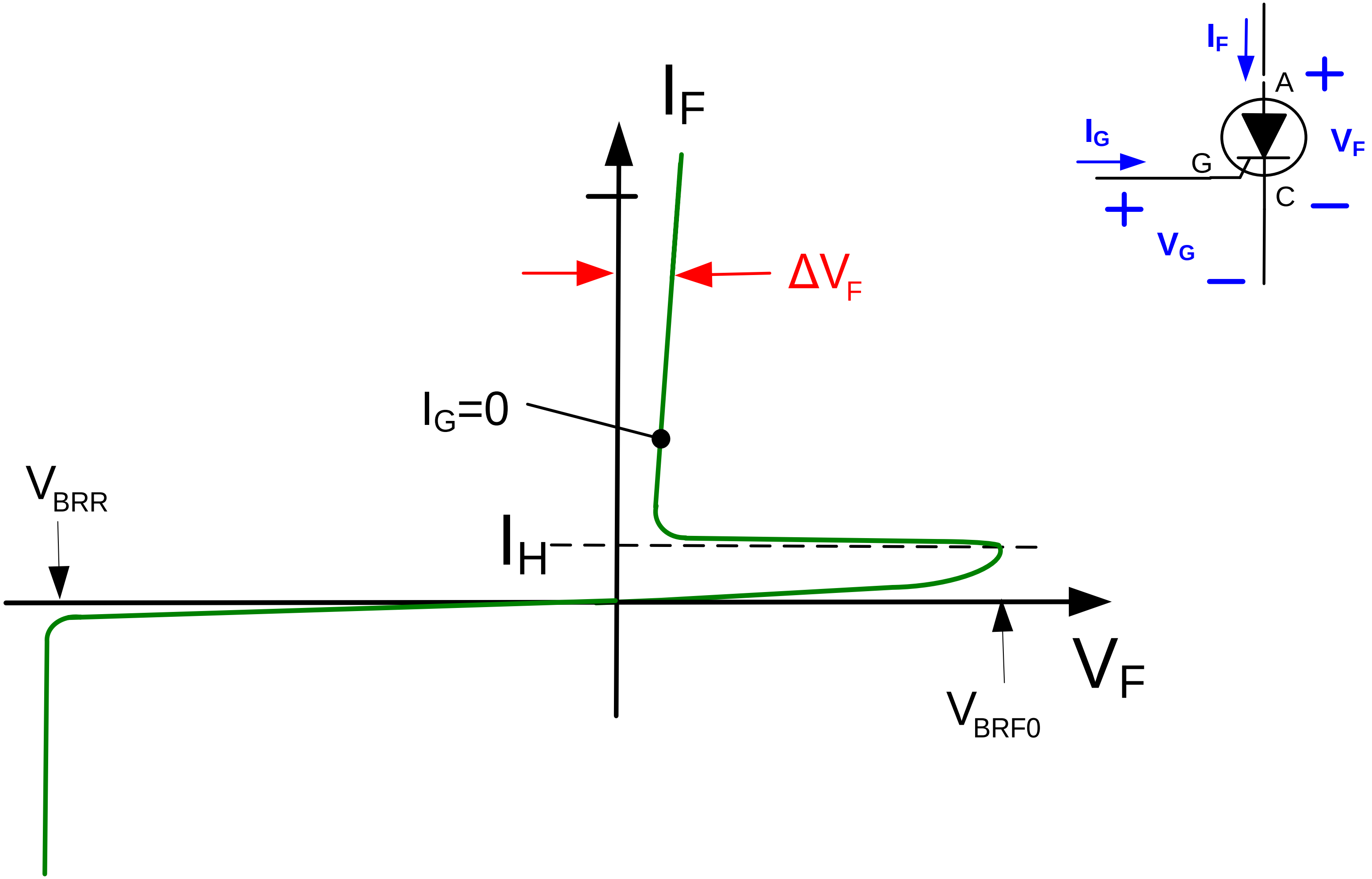
Duty cycle control of load R_L





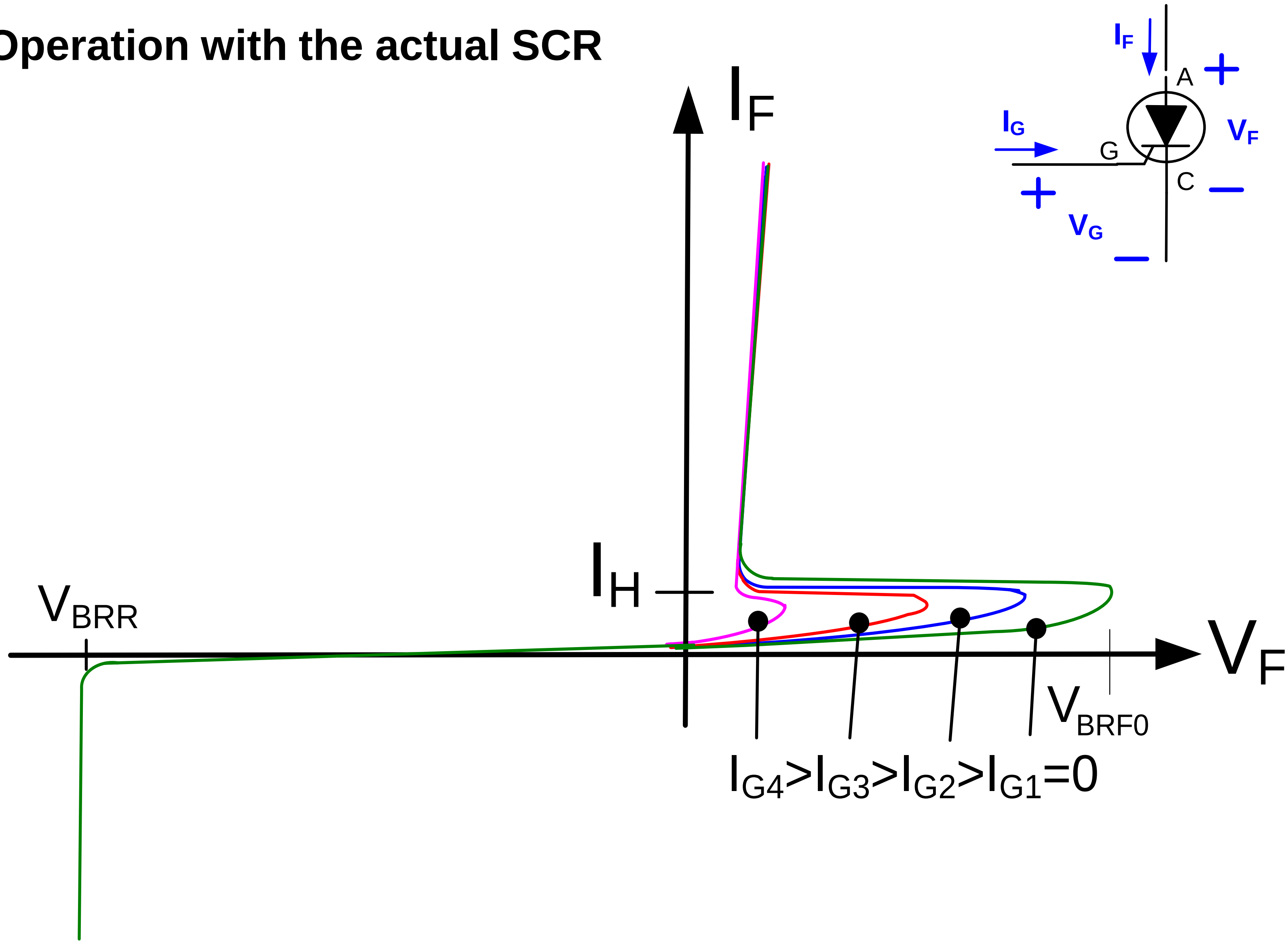
Operation of the SCR

Operation with the actual SCR



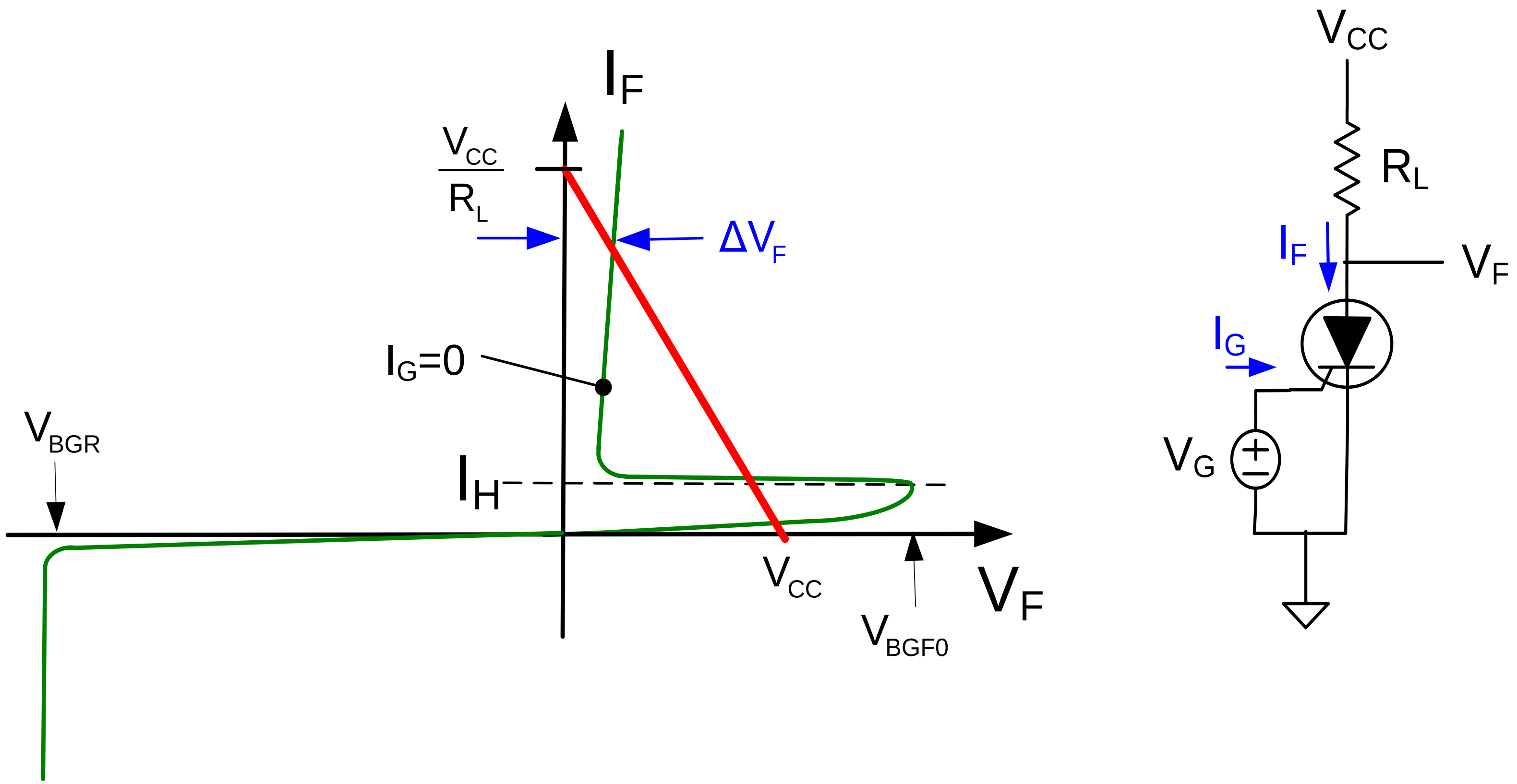
Operation of the SCR

Operation with the actual SCR



Operation of the SCR

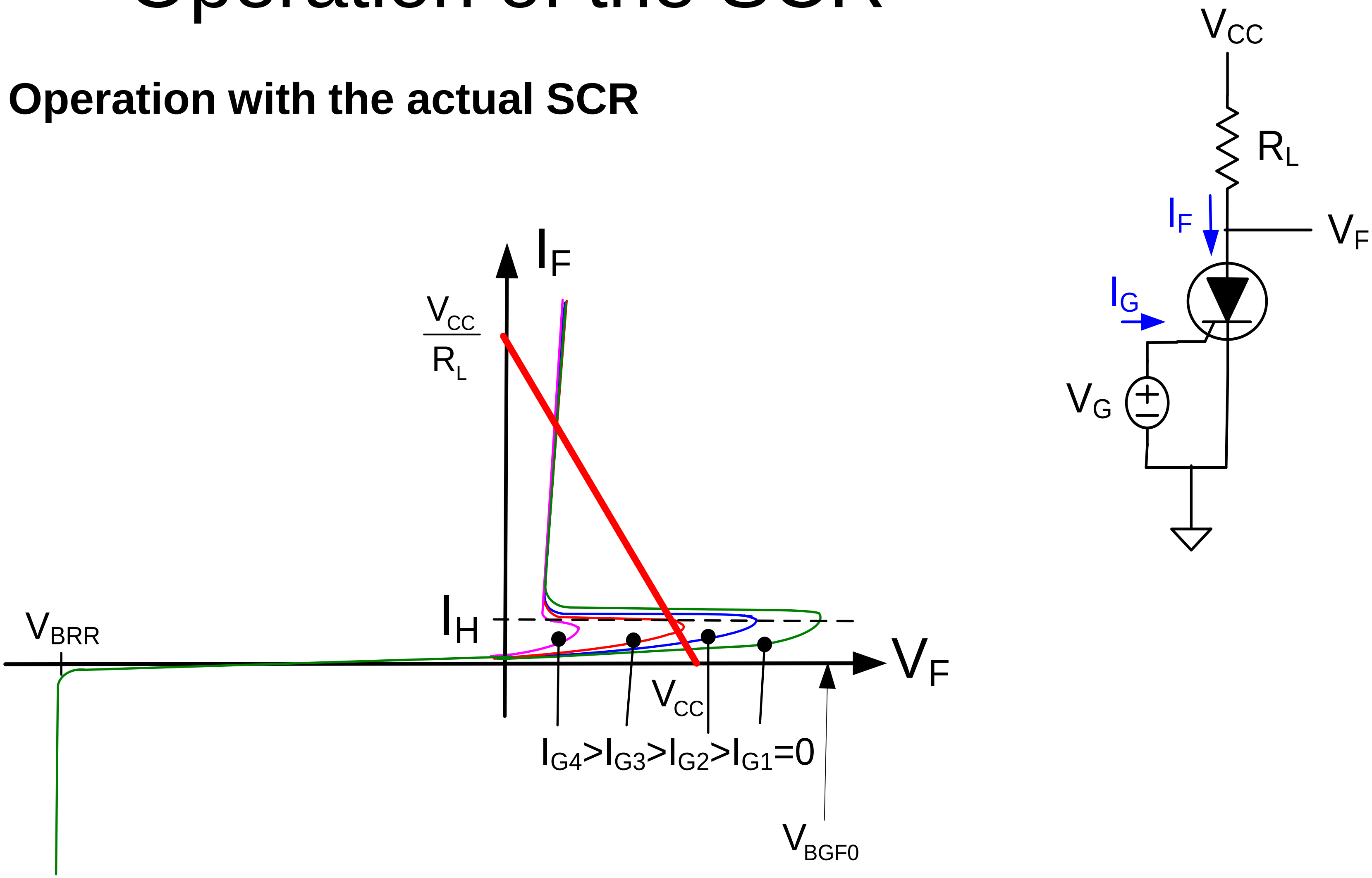
Operation with the actual SCR



- Still two stable equilibrium points and one unstable point
- ΔV_F is quite constant and small (around 1V)
- If large current is flowing, power in anode can be large ($P_A \approx I_F \bullet 1V$)
- Power in gate is usually very small

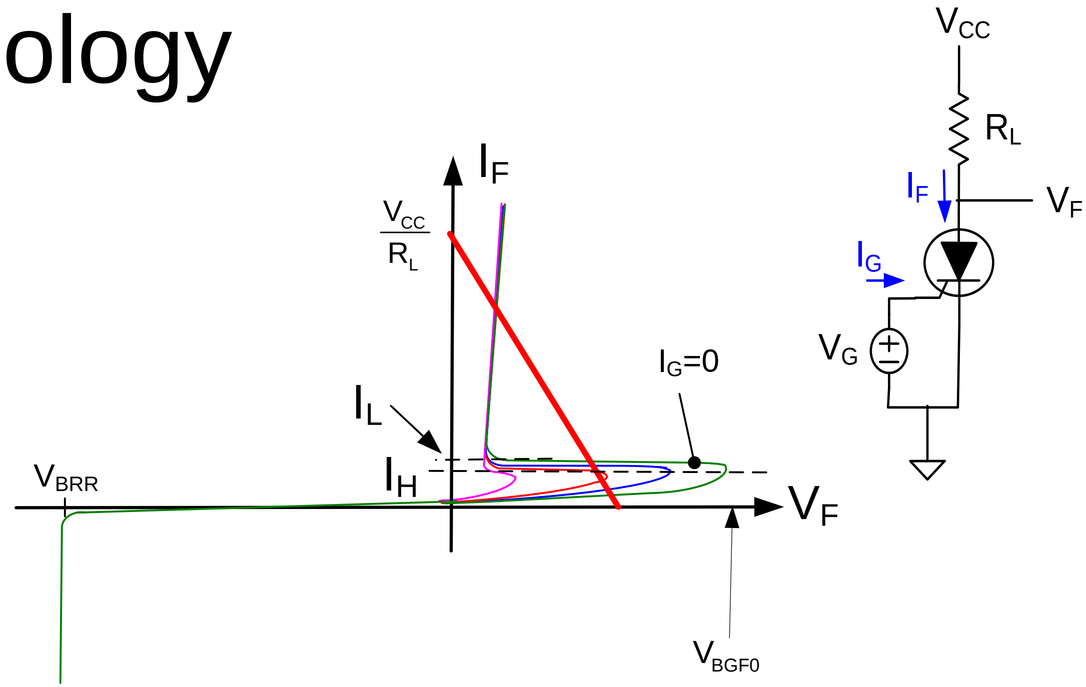
Operation of the SCR

Operation with the actual SCR



To turn on, must make I_G large enough to have single intersection point

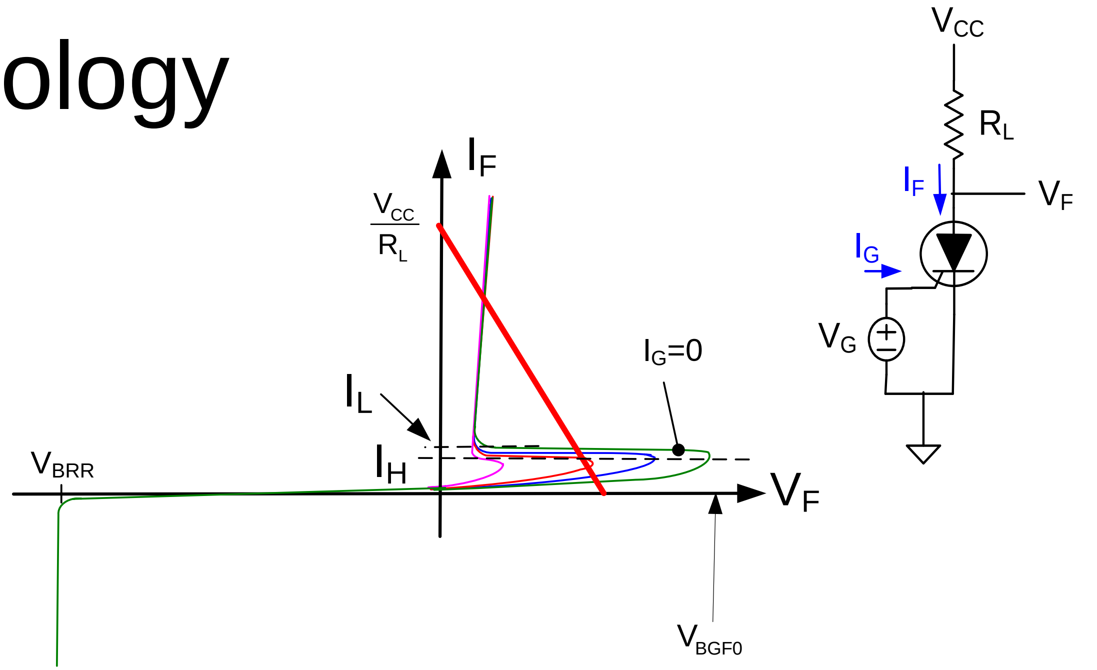
SCR Terminology



I_H is the holding current
I_L is the latching current (current immediately after turn-on)
V_{BGF0} is the forward break-over voltage
V_{BRR} is the reverse break-down voltage
I_{GT} is the gate trigger current
V_{GT} is the gate trigger voltage

SCR Terminology

Issues and Observations



- Trigger parameters (V_{GT} and I_{GT}) highly temperature dependent
- Want gate “sensitive” but not too sensitive (to avoid undesired triggering)
- SCRs can switch very large currents but power dissipation is large
- Heat sinks widely used to manage power
- Trigger parameters affected by both environment and application
- Trigger parameters generally dependent upon VF
- Exceeding V_{BRR} will usually destroy the device
- Exceeding V_{BGF0} will destroy some devices
- Lack of electronic turn-off unattractive in some applications
- Can be used in alarm circuits to attain forced reset
- Maximum 50% duty cycle in AC applications is often not attractive

Thyristors

The good

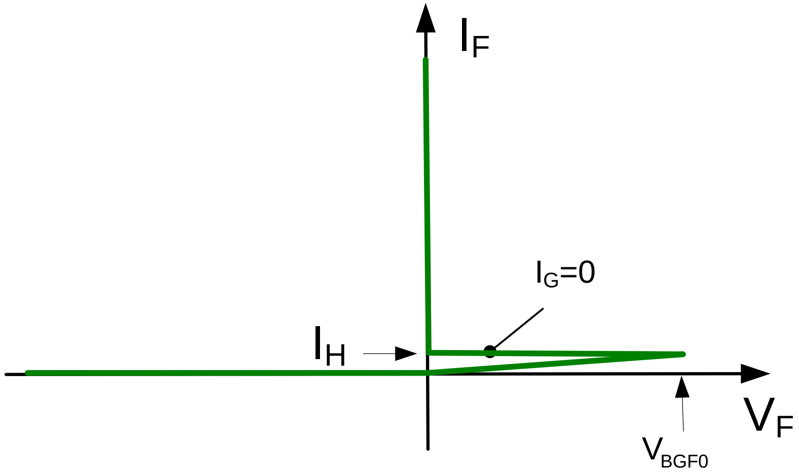
SCRs

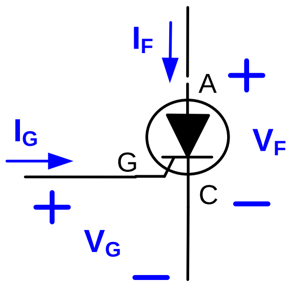
→ Triacs

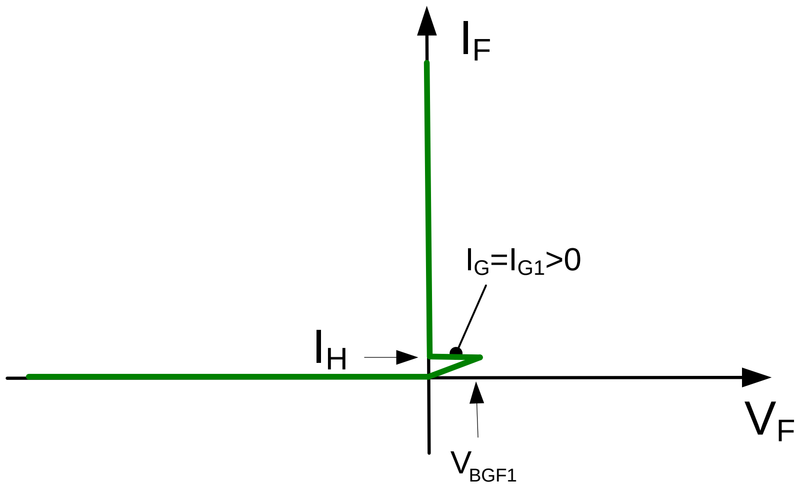
The bad

Parasitic Device that can destroy integrated circuits

Limitations of the SCR





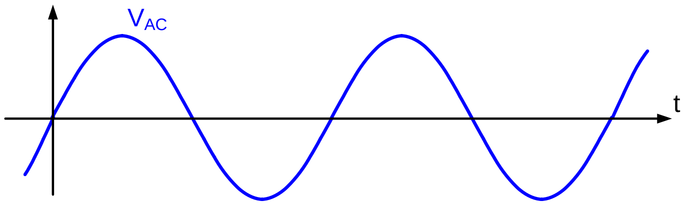


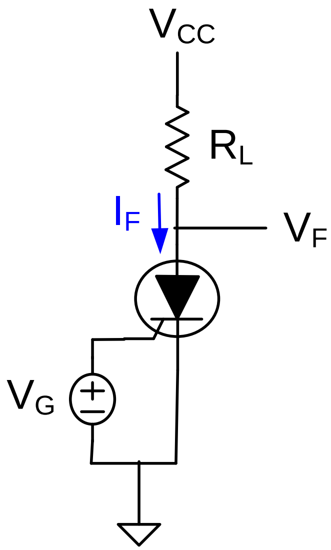
1. Only conducts in one direction
2. Can't easily turn off (though not major problem in AC switching)

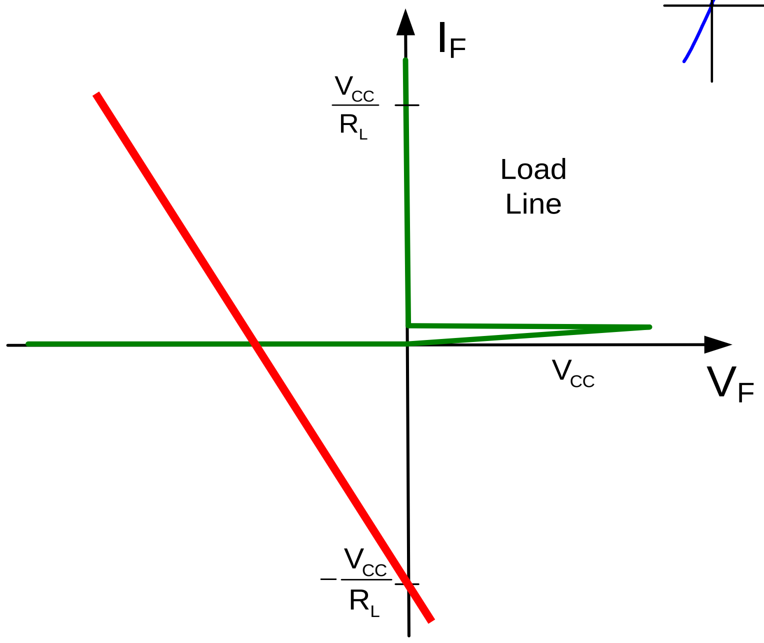
Operation of the SCR

Performance Limitations with the SCR

Assume V_{CC} is an AC signal (often 110V) and V_G is static





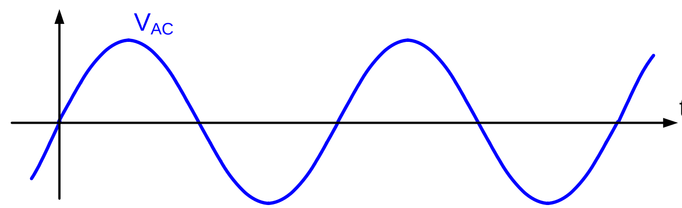


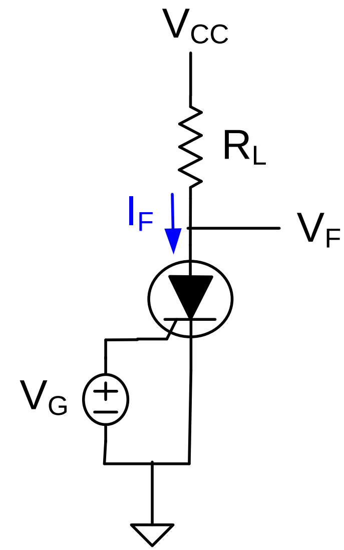
SCR is always off

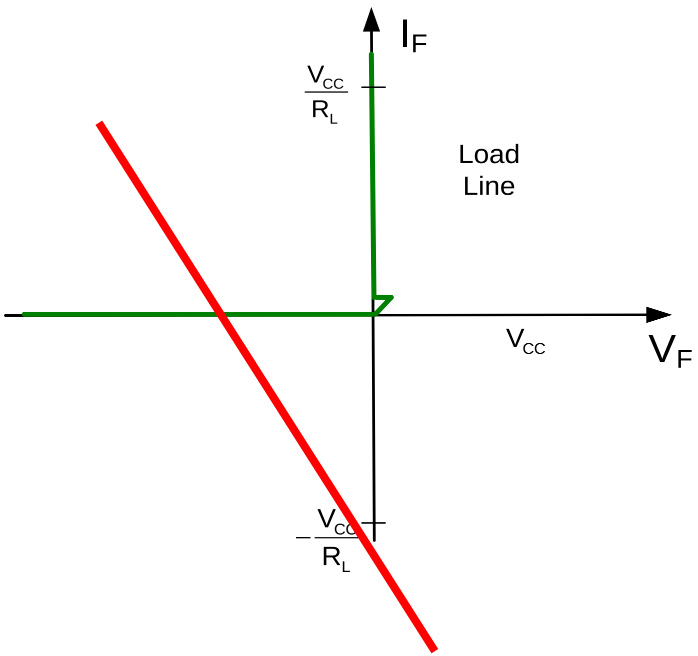
Operation of the SCR

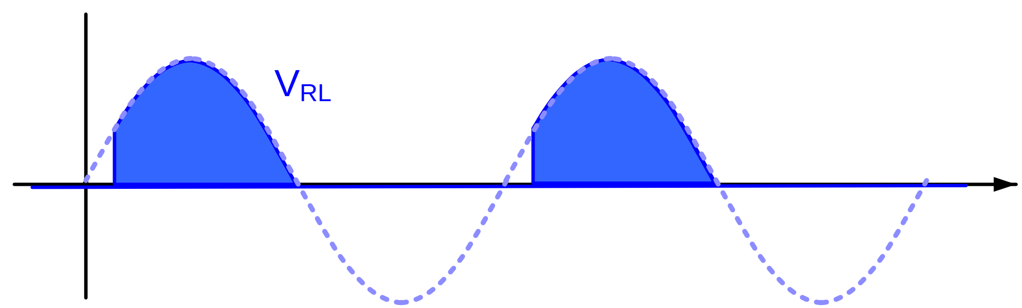
Performance Limitations with the SCR

Assume V_{CC} is an AC signal (often 110V) and V_G is static







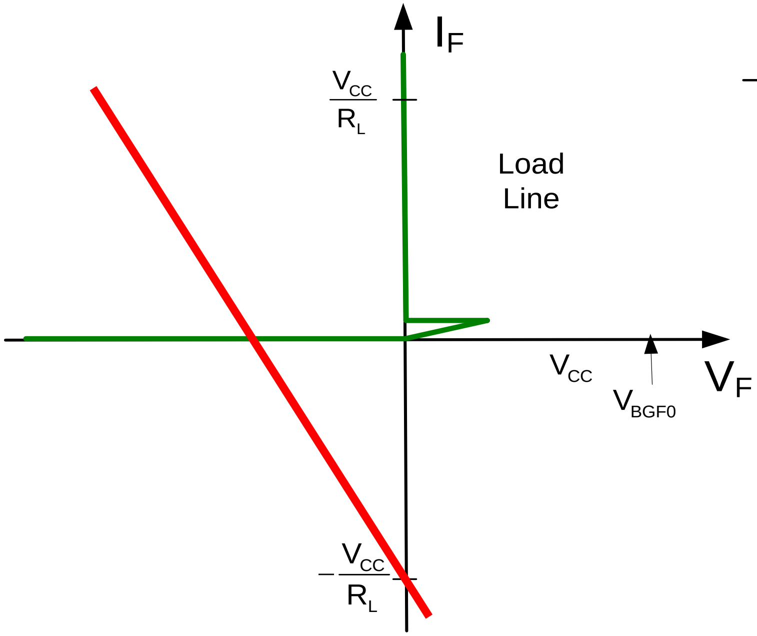


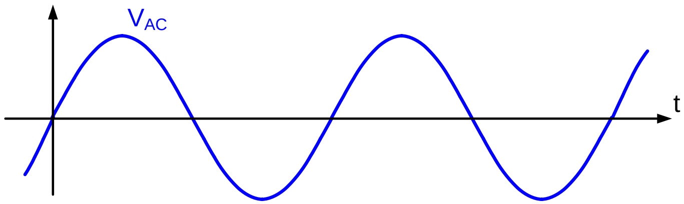
SCR is ON about
50% of the time

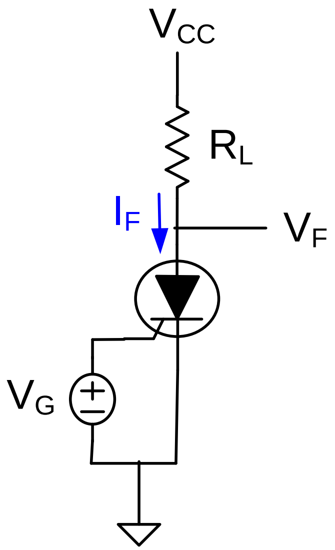
Operation of the SCR

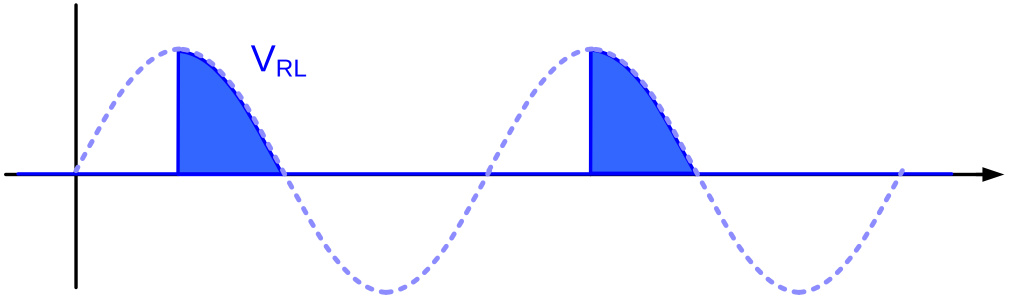
Performance Limitations with the SCR

Assume V_{CC} is an AC signal (often 110V) and V_G is static





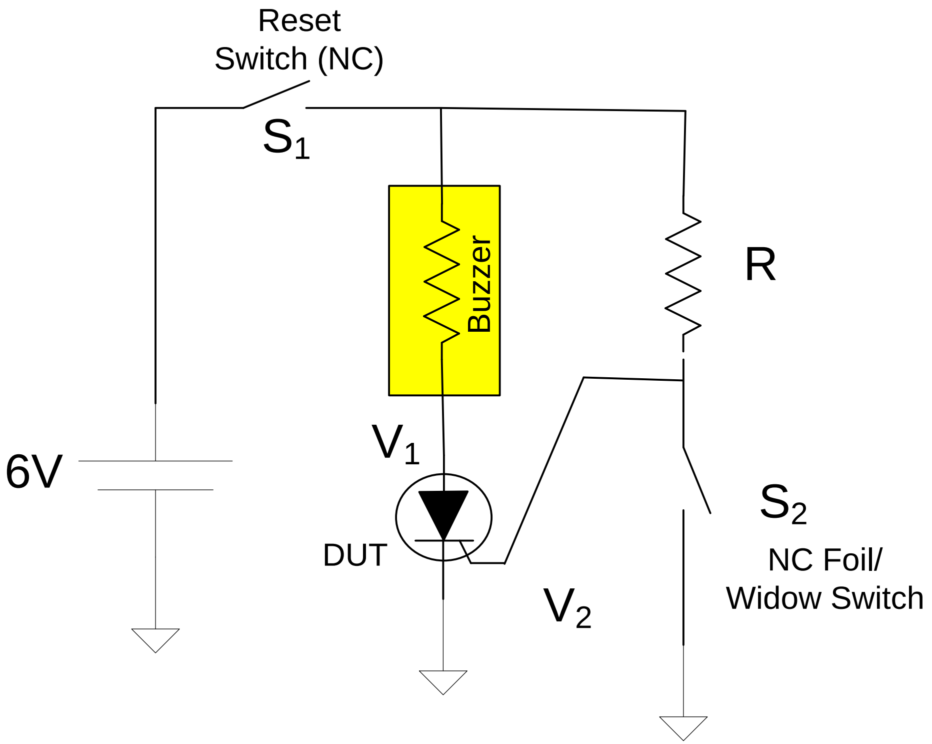




SCR is ON less than 50% of the time (duty cycle depends upon V_G)

Often use electronic circuit to generate V_G

Alarm Application



Outline

Two-Port Amplifier Models

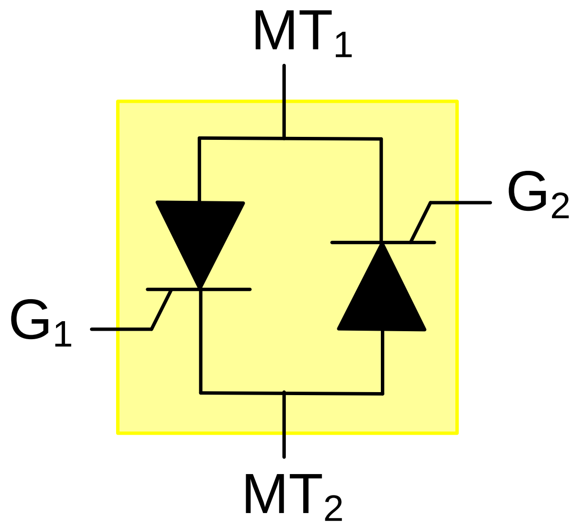
Bipolar Processes

- Comparison of MOS and Bipolar Process
- Parasitic Devices in CMOS Processes
- JFET

Special Bipolar Processes

- Thyristors
  - SCR
  - TRIAC

Bi-directional switching

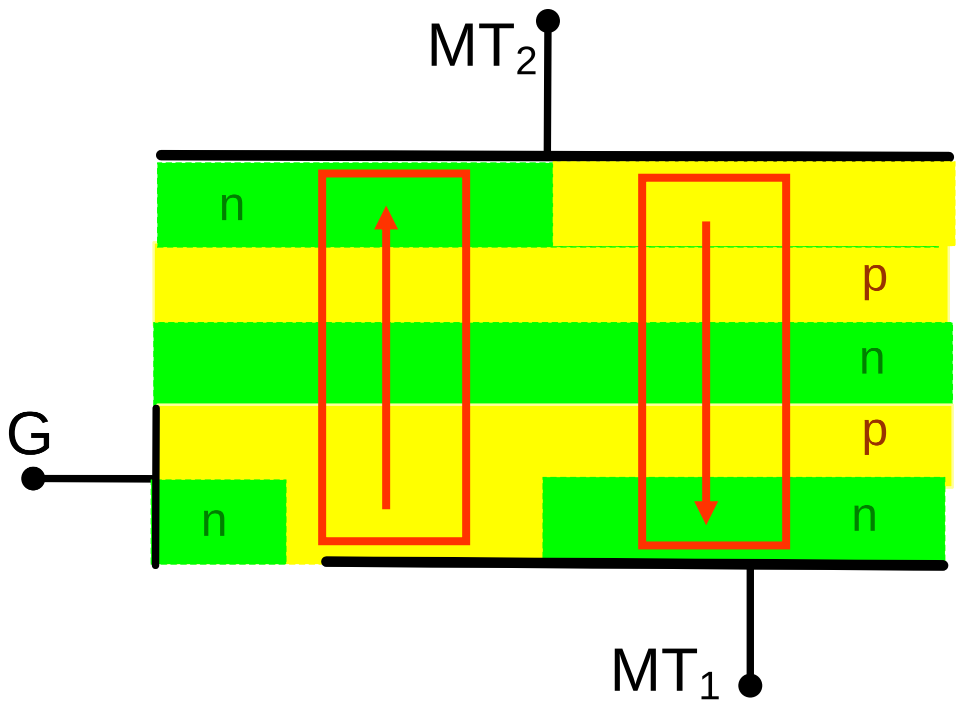


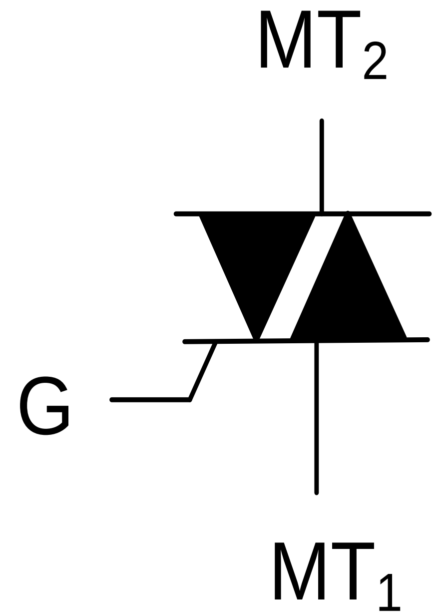
Use two cross-coupled SCRs

Limitations

Size and cost overhead with this solution
Inconvenient triggering since G_1 and G_2 WRT different terminals

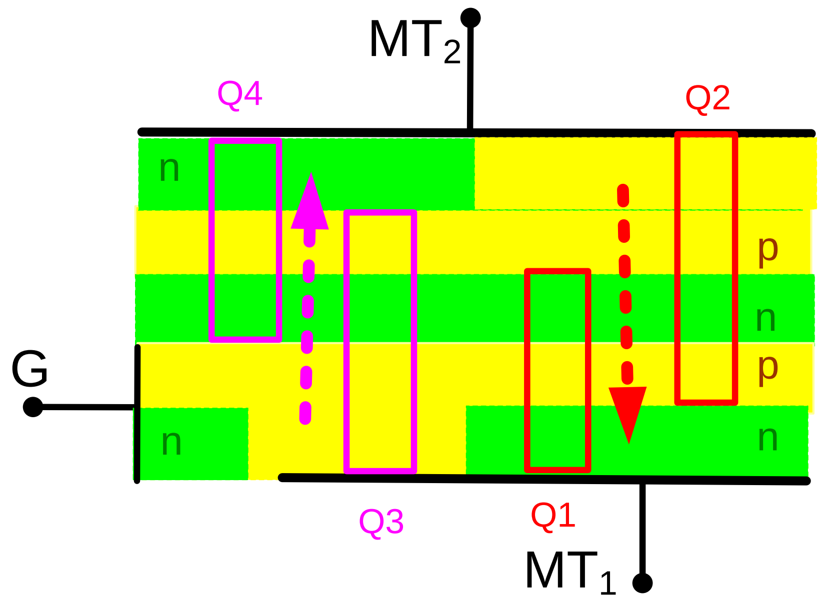
Bi-directional switching with the Triac

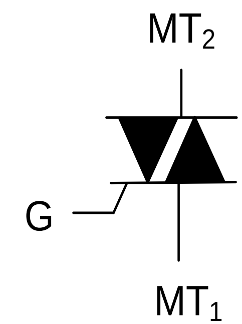




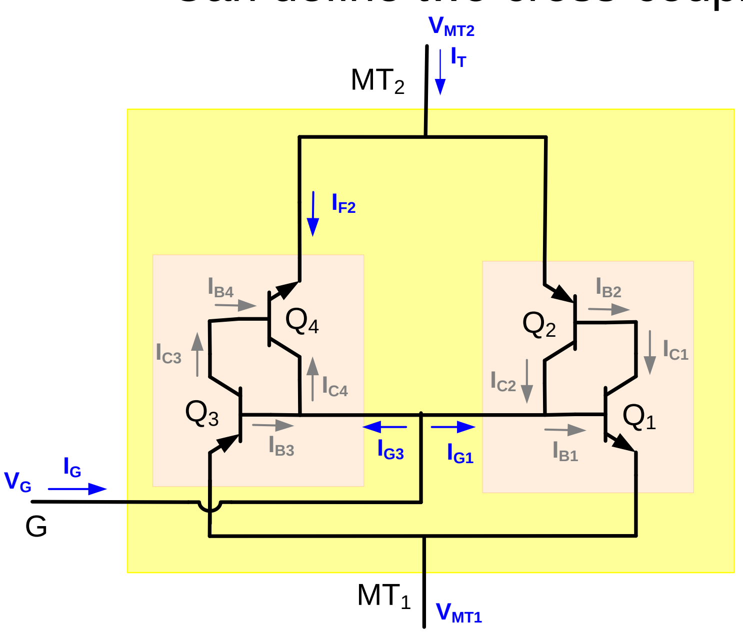
- Has two cross-coupled SCRs !
- Manufactured by diffusions
- Single Gate Control

The Triac





- Can define two cross-coupled transistor pairs in each side



Model for Quadrants 1 and 4
(n-diffusion for gate not shown)

As for SCR, both circuits have regenerative feedback

Can turn ON in either direction with either positive or negative current

Defines 4 quadrants (in V_{MT21}-$V_{G\text{-}MT1}$ plane) for operation

$V_{MT2}>V_{MT1}$	$V_{G\text{-}MT1}>0$	Quadrant 1
$V_{MT2}>V_{MT1}$	$V_{G\text{-}MT1}<0$	Quadrant 2
$V_{MT2}<V_{MT1}$	$V_{G\text{-}MT1}<0$	Quadrant 3
$V_{MT2}<V_{MT1}$	$V_{G\text{-}MT1}>0$	Quadrant 4

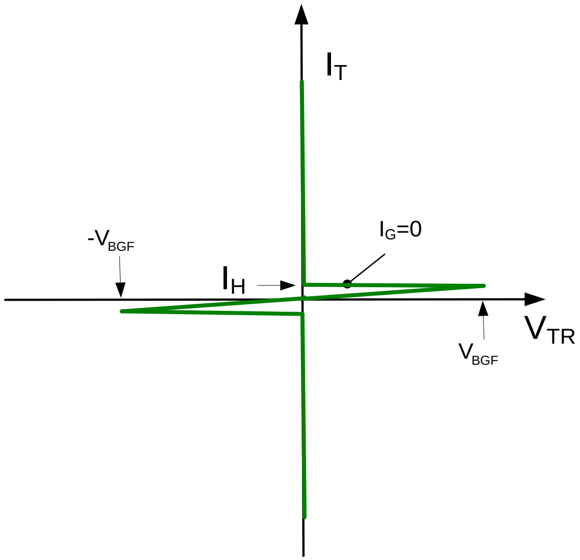
Usually use only one V_G:V_{MT} for control

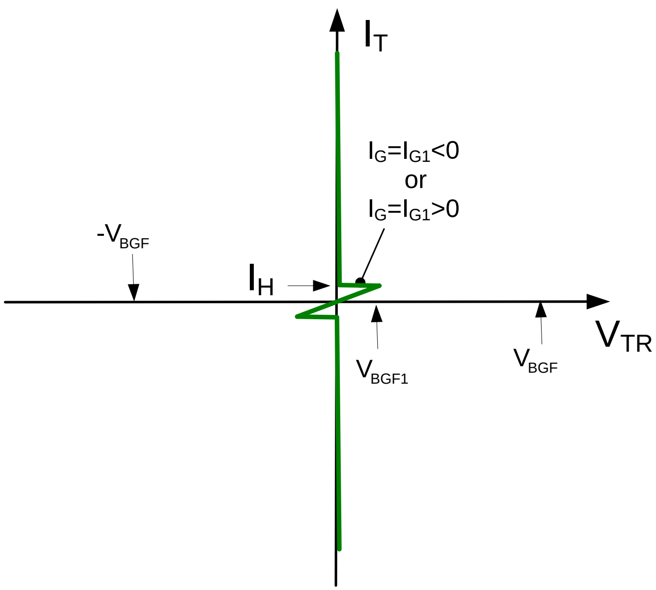
Different voltage, duration strategies exist for triggering

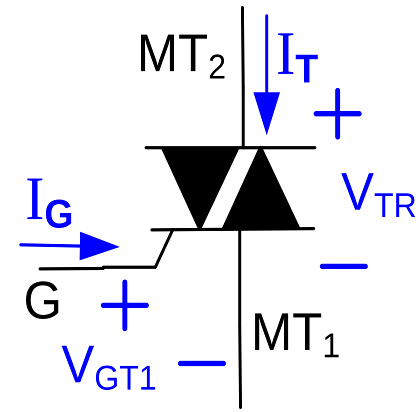
Can't have single V_G:V_{MT} control with two SCRs

The Triac

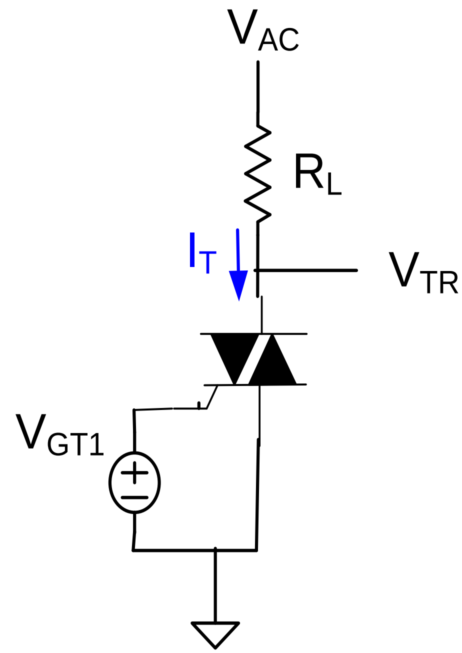
The ideal Triac





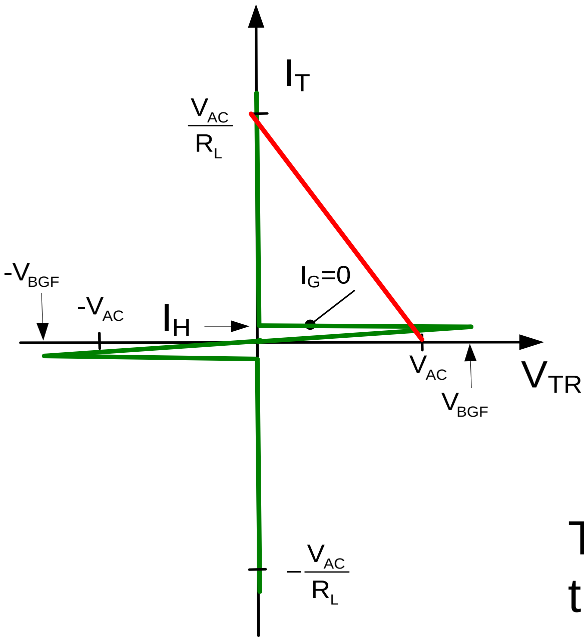


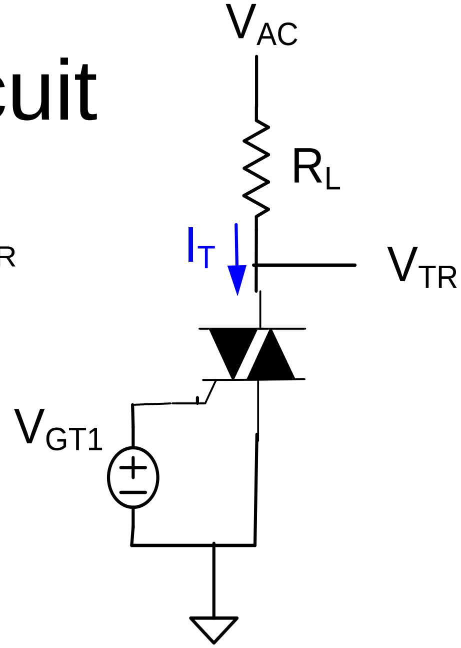
Consider the basic Triac circuit



The Basic Triac Circuit

Assume ideal Triac



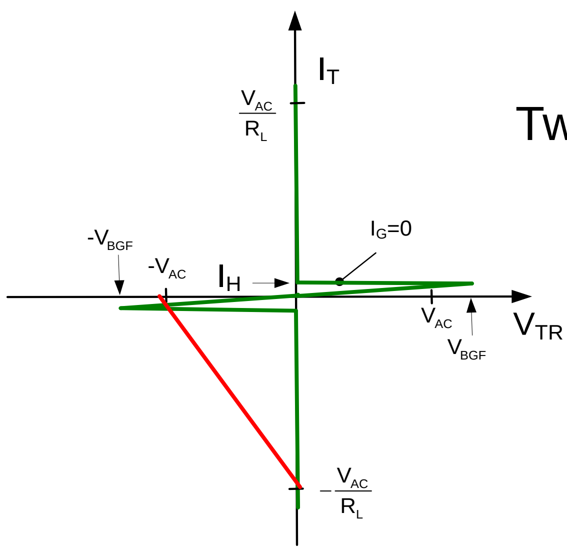


Load Line: $V_{AC} = I_T R_L + V_{TR}$

Analysis:

$$\left.\begin{aligned} V_{AC} &= I_T R_L + V_{TR} \\ I_T &= f_A\left(V_{TR}, V_{GT1}\right) \end{aligned}\right\}$$

The solution of these two equations is at the intersection of the load line and the device characteristics

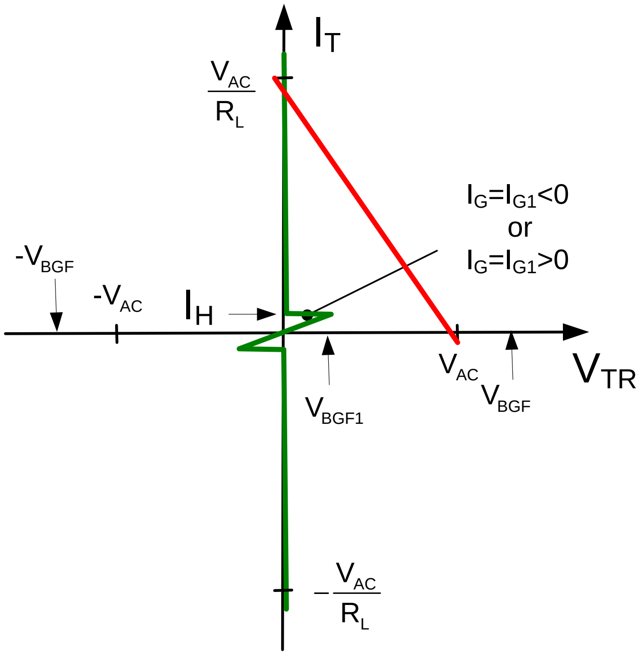


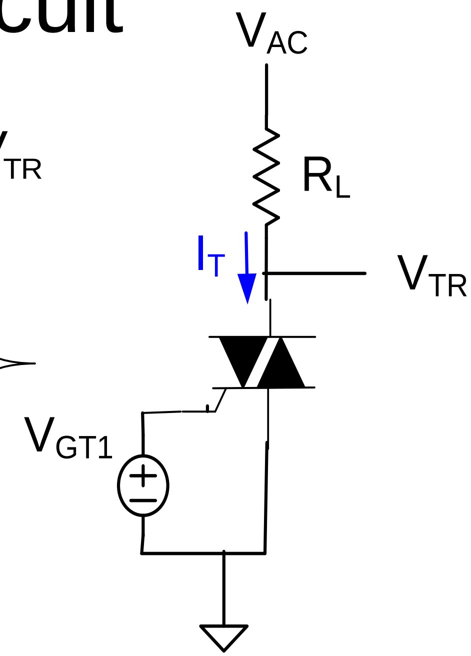
Two stable operating points for both positive and negative V_{AC}

If V_{AC} is a sinusoidal signal, will stay OFF

Assume ideal Triac

The Basic Triac Circuit

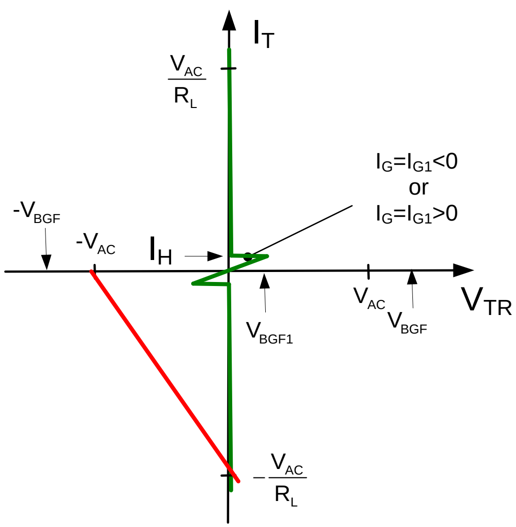




Load Line: $V_{CC} = I_T R_L + V_{TR}$

Analysis:
$$\left.\begin{aligned} V_{AC} &= I_T R_L + V_{TR} \\ I_T &= f_A\left(V_{TR}, V_{GT1}\right) \end{aligned}\right\}$$

Single solution for both positive and negative V_{AC}

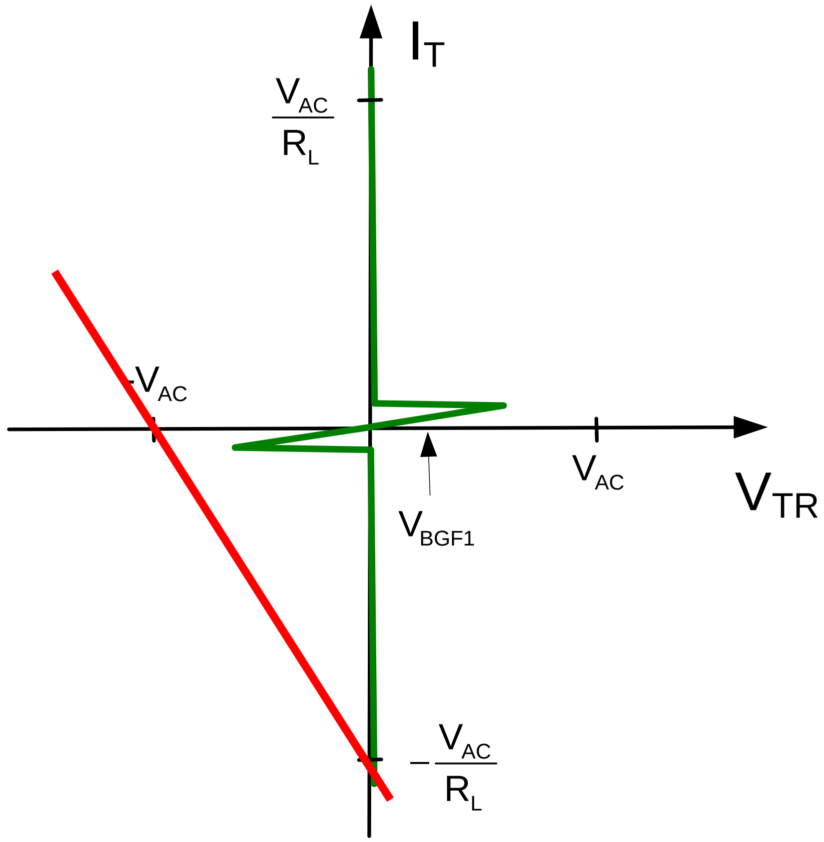


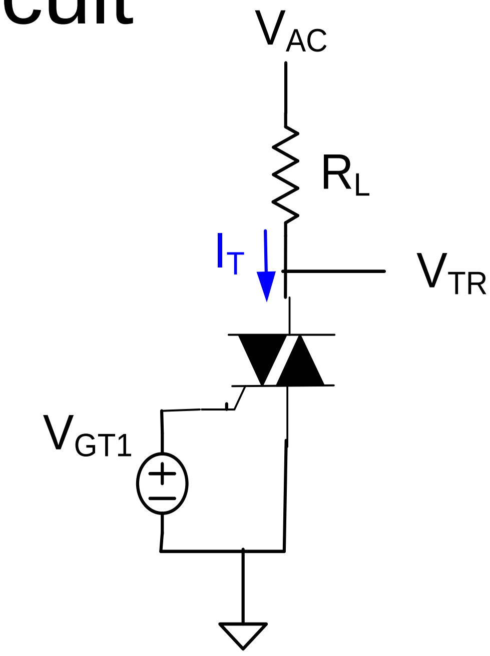
If V_{AC} is a sinusoidal signal will stay ON

(except for small time when I_T=0 but then ON and OFF state of Triac do not alter current in circuit)

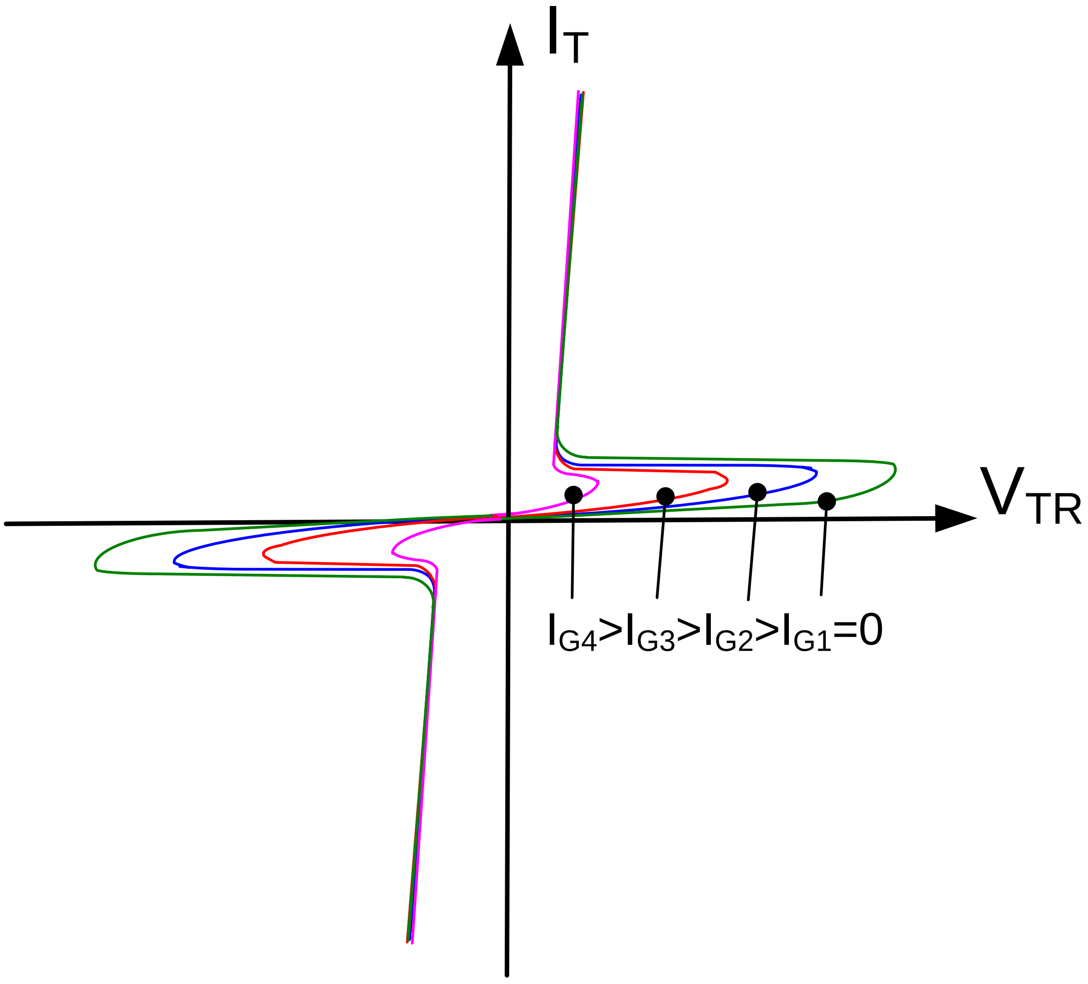
The Basic Triac Circuit

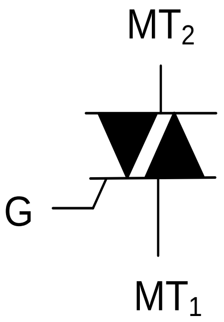
Assume ideal Triac



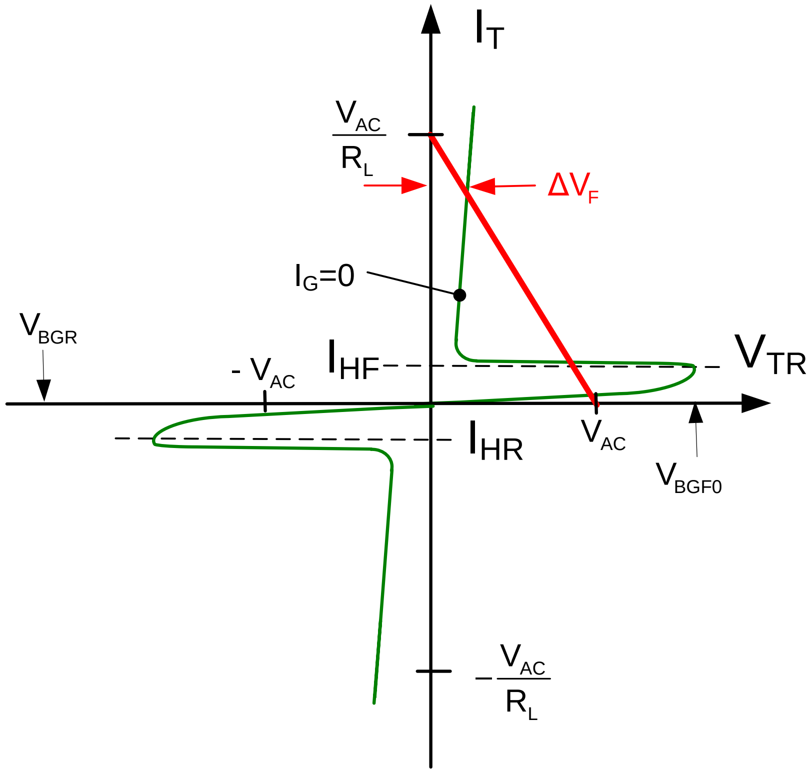


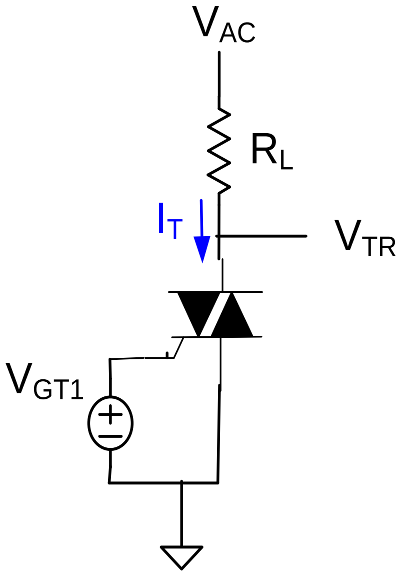
The Actual Triac





The Actual Triac in Basic Circuit

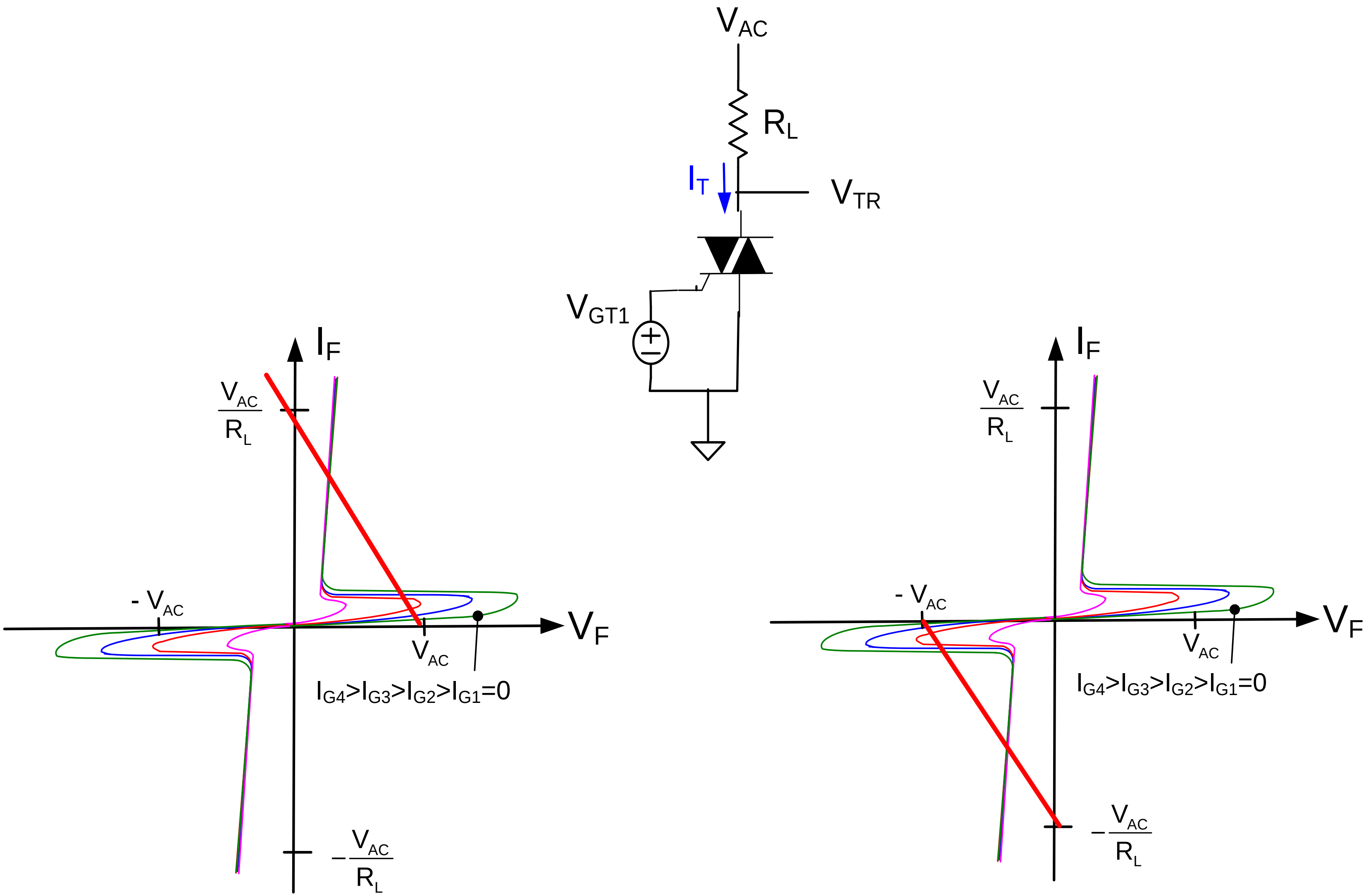




Two stable operating points

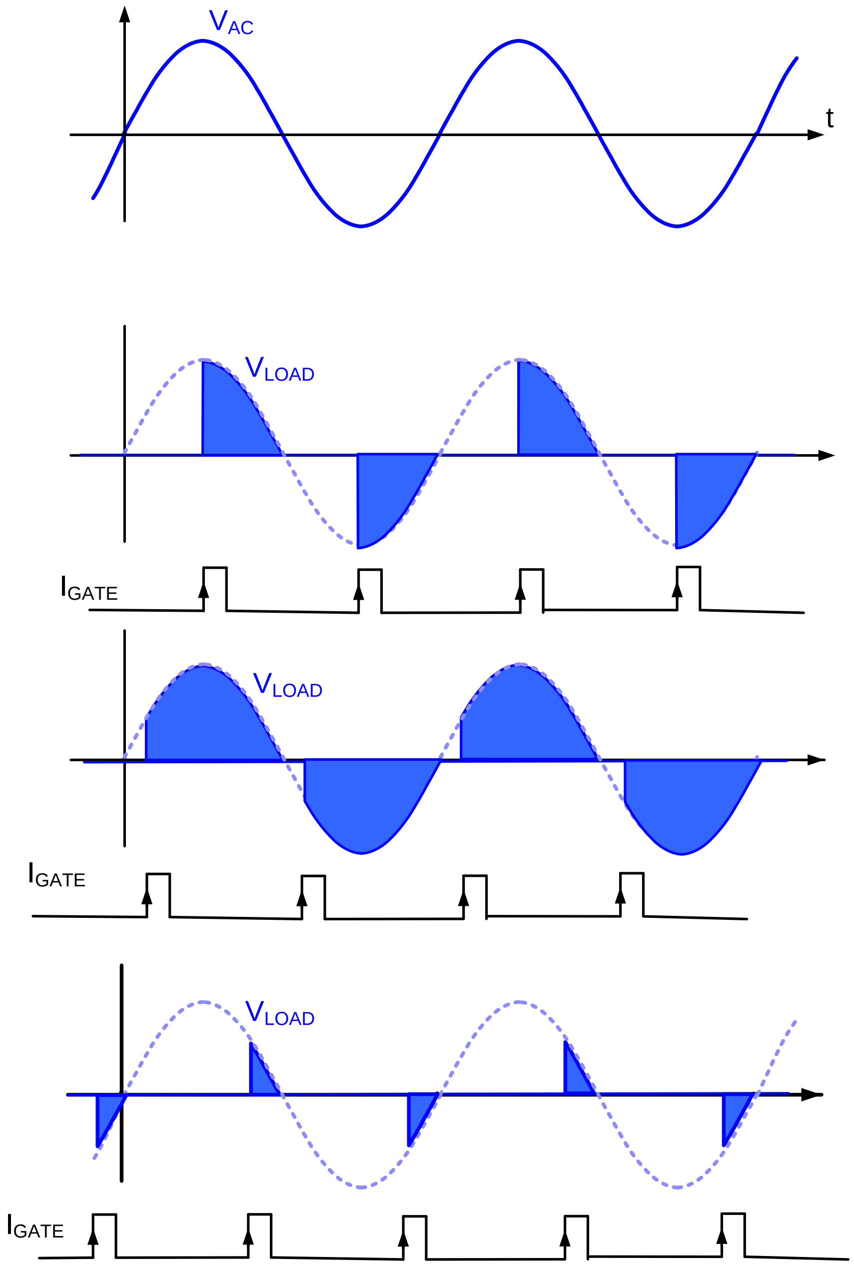
I_G=0 State

The Actual Triac in Basic Circuit



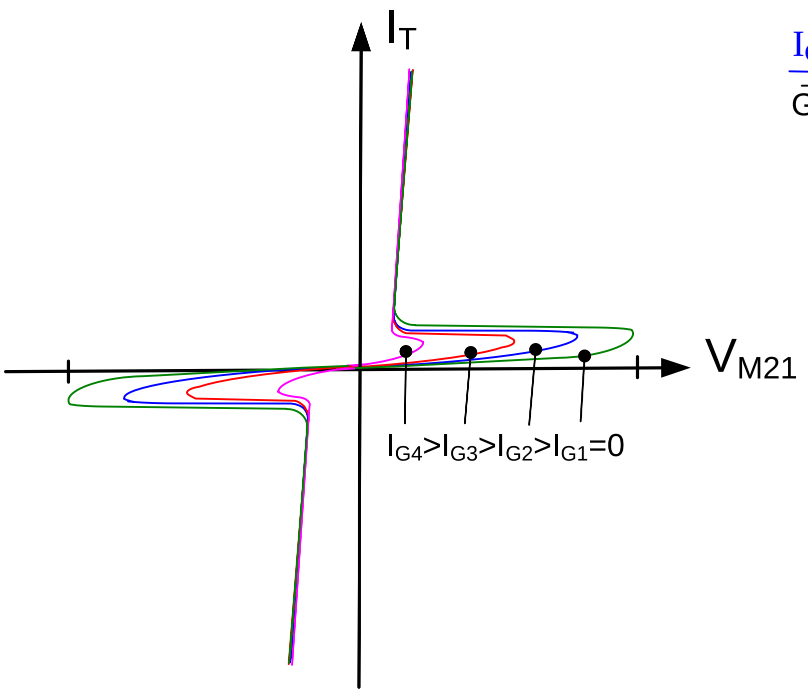
Can turn on for either positive or negative V_{AC} with single gate signal

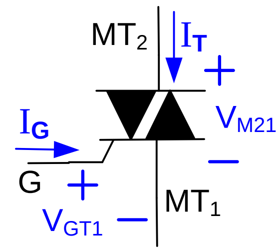
Phase controlled bidirectional switching with Triacs

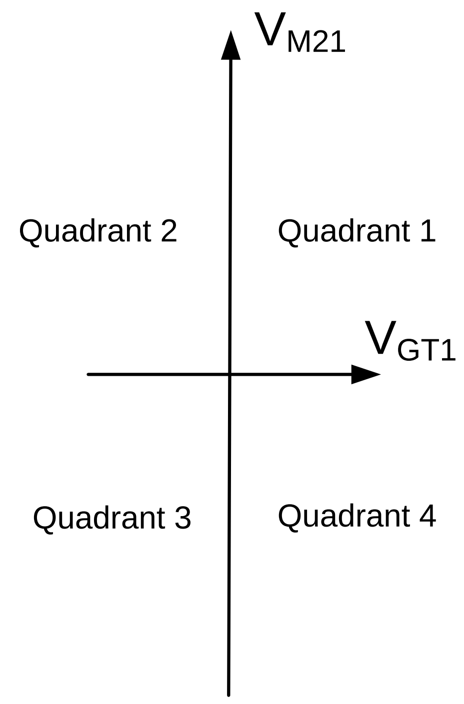


Quadrants of Operation Defined in V_{M21}-V_{GT1} plane

(not in the I_T-V_{M21} plane)

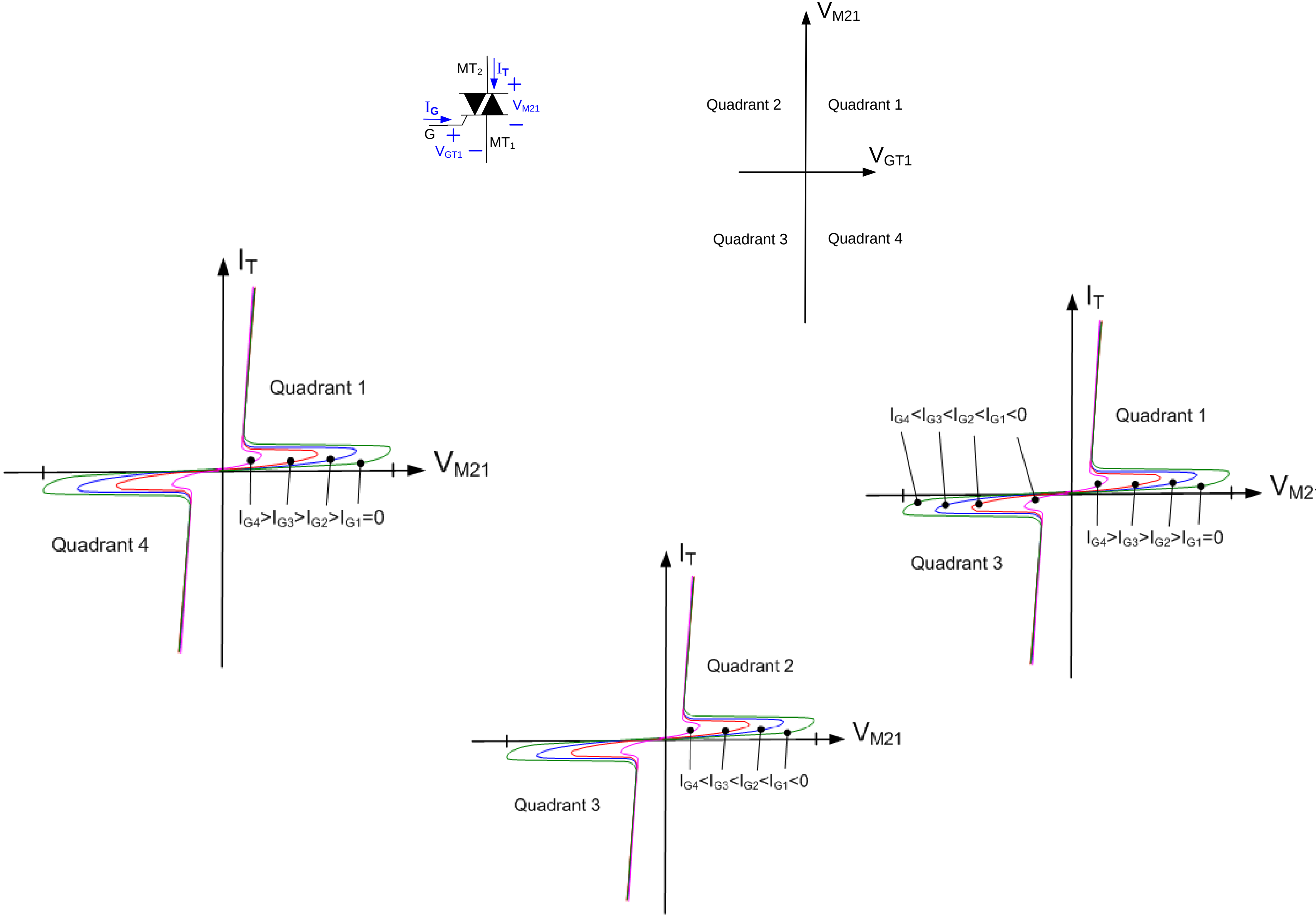




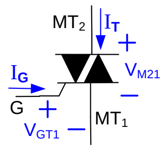


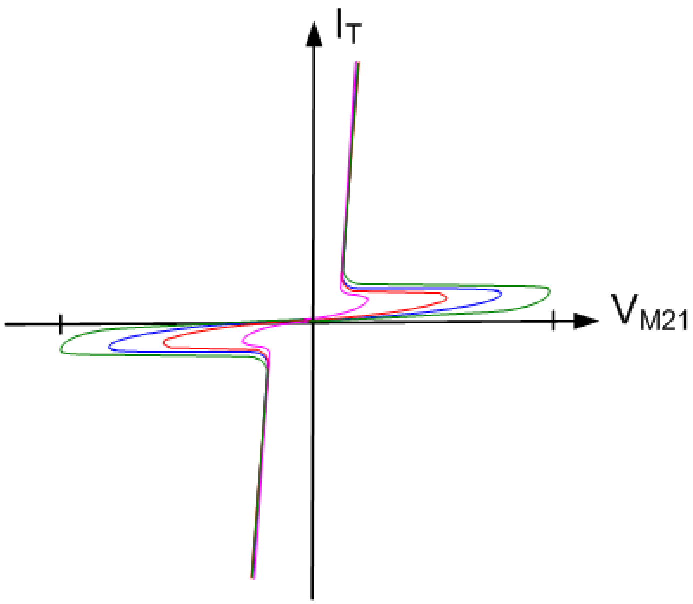
But for any specific circuit, can map quadrants from the V_{M21}-V_{GT1} plane to I_T-V_{M21} plane

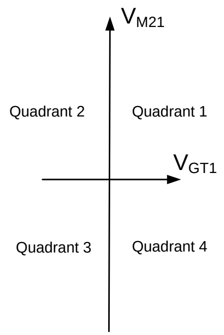
Identification of Quadrants of Operation in I_T -V_{M21} plane



Identification of Quadrants of Operation in I_T-V_{M21} plane







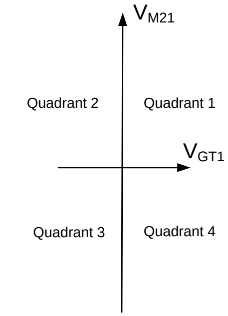
Curves may not be symmetric between Q_1 and Q_3 in the I_T-V_{M21} plane

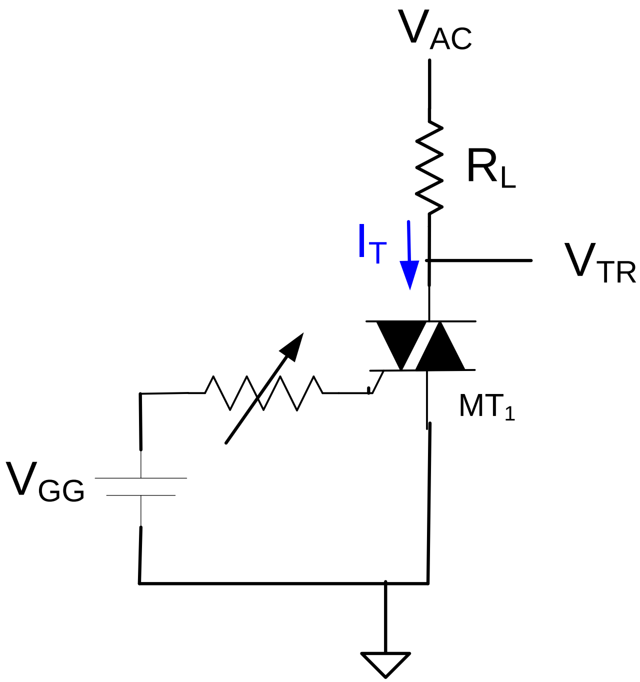
Turn on current may be large and variable in Q_4 (of the V_{M21}-V_{GT1})

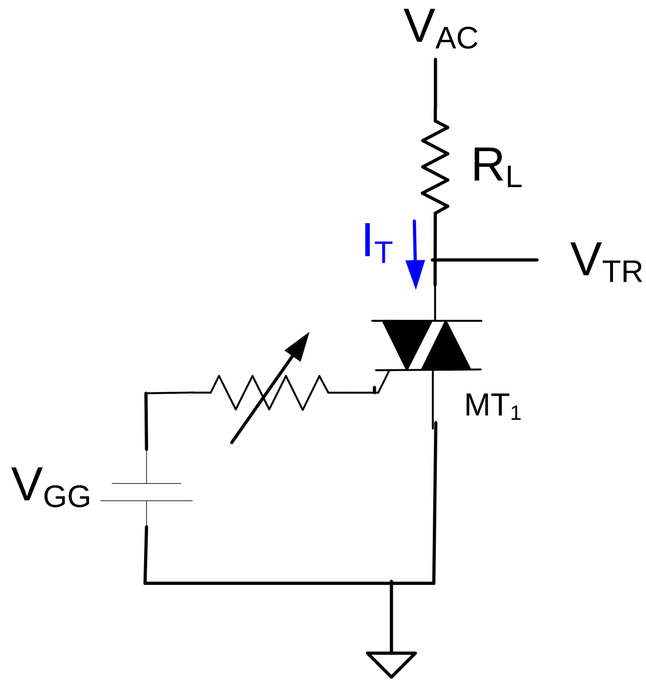
Generally avoid operation in Q_4 (of the V_{M21}-V_{GT1} plane)

Most common to operate in Q2-Q3 quadrants or Q1-Q3 quadrants (of the V_{M21}-V_{GT1} plane)

Some Basic Triac Application Circuits







(V_{GG} often from logic/control circuit)

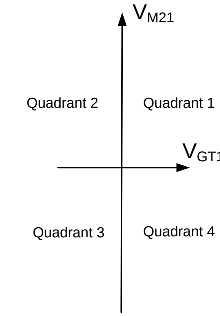
Quad 1 : Quad 4

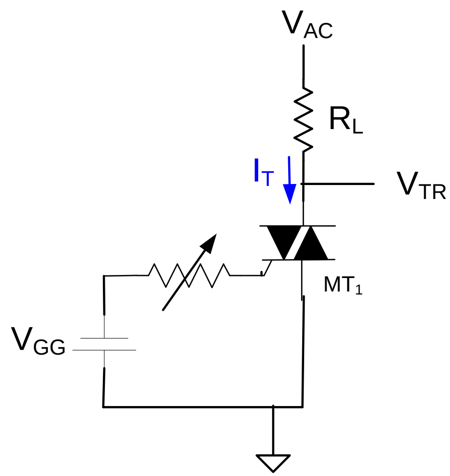
(not attractive because of Quad 4)

(V_{GG} often from logic/control circuit)

Quad 2 : Quad 3

Some Basic Triac Application Circuits



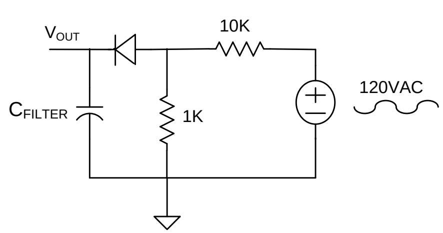


Quad 2 : Quad 3

Limitations ?

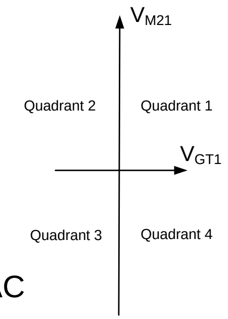
If V_{AC} is the standard 120VAC line voltage, where do we get the dc power supply?

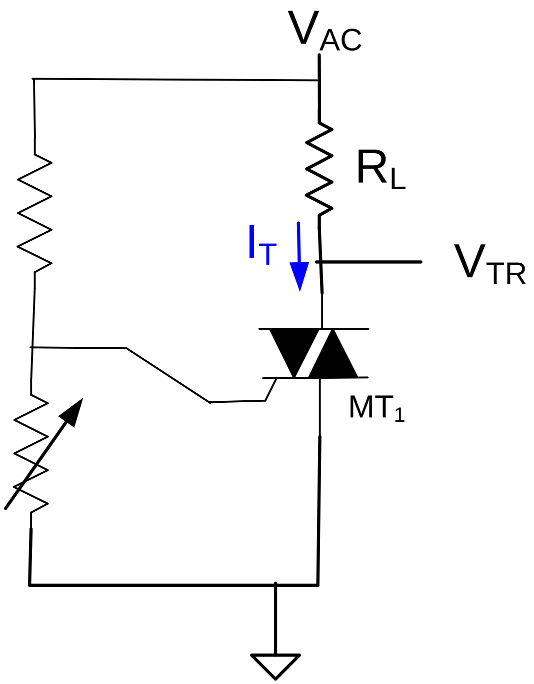
$1,607.00
AGILENT TECHNOLOGIES
E3631A



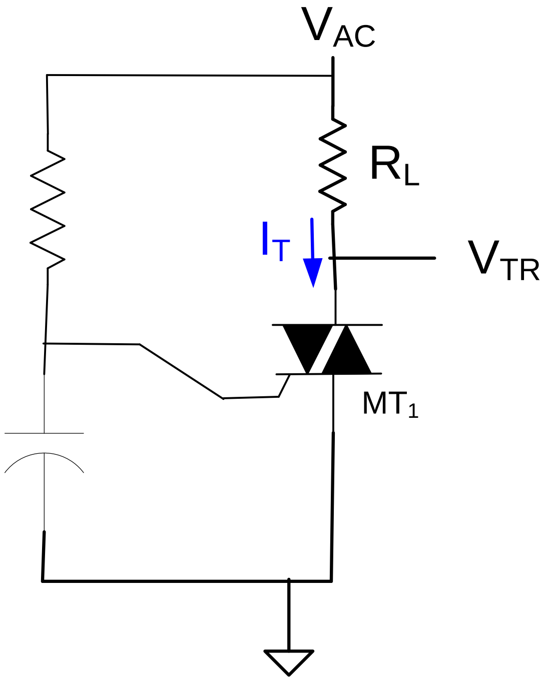
Direct digital control of trigger voltage/current with dedicated IC

Some Basic Triac Application Circuits

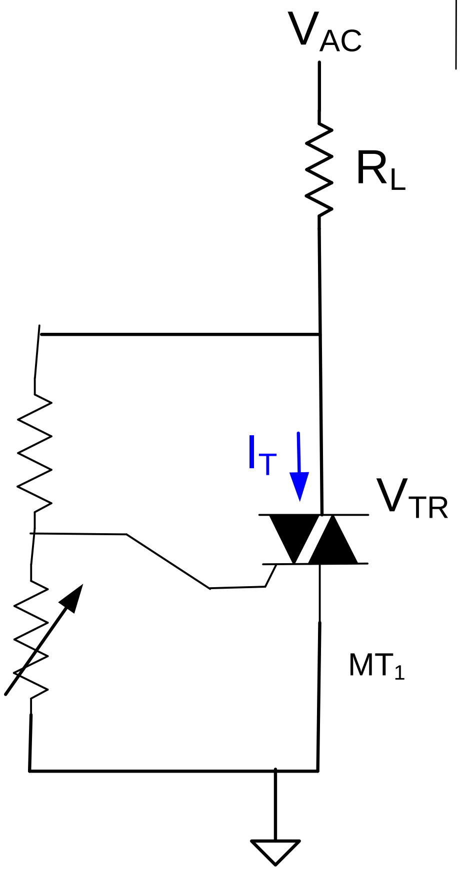




Quad 1 : Quad 3

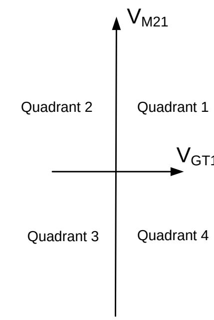


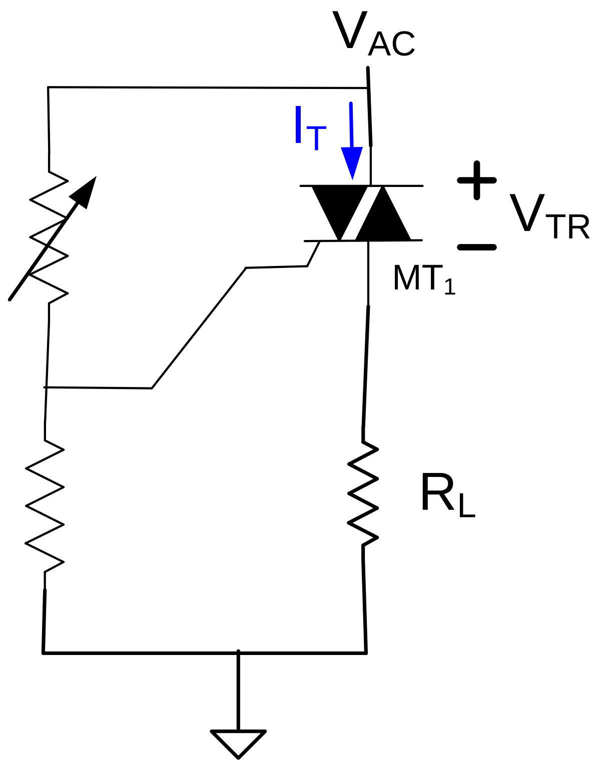
Quad 1 : Quad 3



Quad 1 : Quad 3

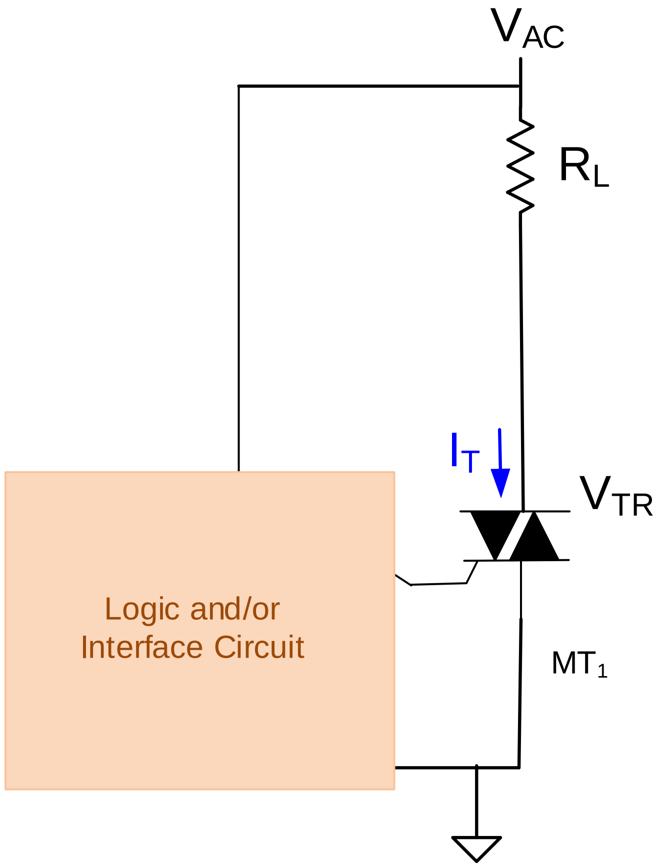
Some Basic Triac Application Circuits





Quad 1/ Quad 2 : Quad 3/Quad 4

Not real popular



Real popular

Thyristor Types

Some of the more major types:

- SCR
- Triac
- Bidirectional Phase-controlled thyristors (BCT)
- LASCR (Light activated SCR)
- Gate Turn-off thyristors (GTO)
- FET-controlled thyristors(FET-CTH)
- MOS Turn-off thyristors (MTO)
- MOS-controlled thyristors (MCT)

Thyristor Applications

Thyristors are available for working at very low current levels in electronic circuits to moderate current levels such is in incandescent light dimmers to very high current levels

I_{TRIAC} from under 1mA to 10000A

Applications most prevalent for moderate to high current thyristors

SCR, rated about 100 amperes, 1200 volts, 1/2 inch stud, photographed by C J Cowie. Uploaded on 4 April 2006.

Thanks to Prof. Ajjarapu for providing the following slides:

DYNEX SEMICONDUCTOR

PT40QPx45

Pulse Power Thyristor Switch

Preliminary Information

Replaces November 1999 version, DS5267-1.1

DS5267-1.4 April 2000

APPLICATIONS

- Pulse Power
- Crowbars
- Ignitron Replacement

KEY PARAMETERS

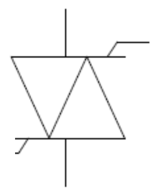
V_{DRM}	4500V
$I_{T(AV)}$	760A
I_{TSM}	13000A
dI/dt	5000A/µs

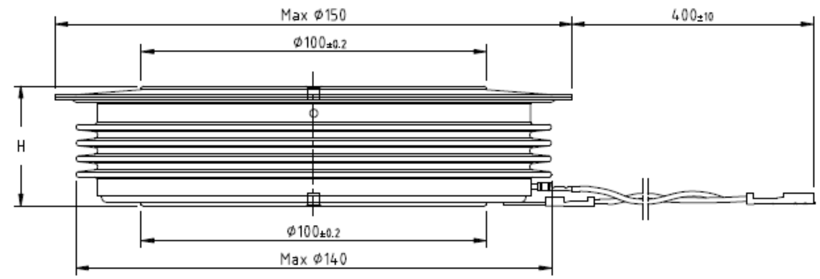
From ABB Web Site

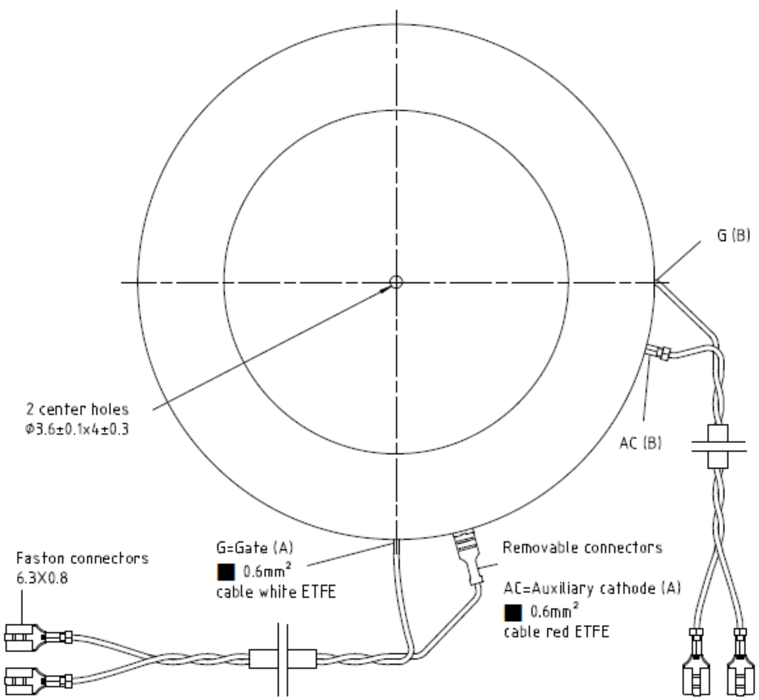
V_{RM}	=	6500 V
$I_{T(AV)M}$	=	1405 A
$I_{T(RMS)}$	=	2205 A
I_{TSM}	=	22×10^{3} A
V_{T0}	=	1.2 V
r_T	=	0.6 mΩ

Bi-Directional Control Thyristor

5STB 13N6500







Diameter = 140mm

Thanks to Prof. Ajjarapu for providing the following slides:

THE BIDIRECTIONAL CONTROL THYRISTOR (BCT)

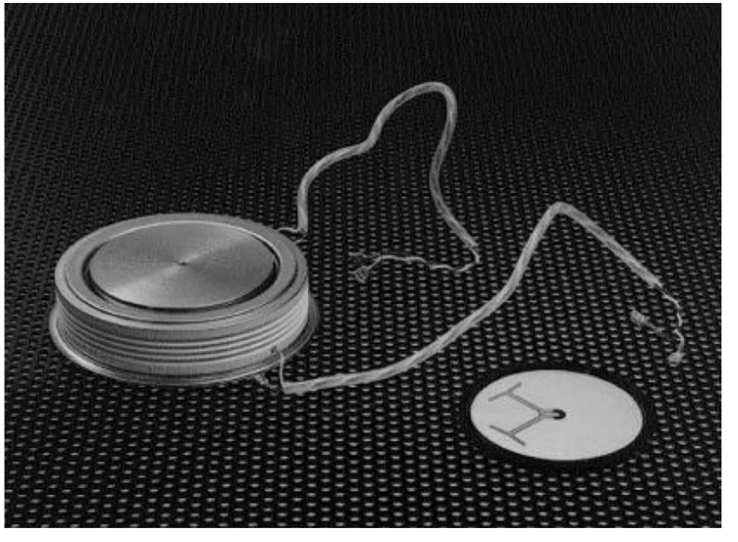
by

Kenneth M. Thomas, Björn Backlund, Orhan Toker
ABB Semiconductors AG, CH5600 Lenzburg, Switzerland

Björn Thorvaldsson
ABB Power Systems AB, S-721 64 Västerås, Sweden

ABSTRACT

The Bidirectional Control Thyristor (BCT) is a new concept for high power thyristors integrated on a single silicon wafer with separate gate contacts. This unique design, based on free-floating silicon technology, successfully overcomes the traditional problems of interference experienced by bidirectional thyristors during dynamic operation which previously prevented the use of such devices. Such components are suitable for applications at high voltages like a normal thyristor but where triacs can no longer be used.



1988 Paper

Thanks to Prof. Ajjarapu for providing the following slides:

High Current, High Voltage Solid State Discharge Switches for Electromagnetic Launch Applications

A. Welleman, R. Leutwyler, J. Waldmeyer
ABB Switzerland Ltd, Semiconductors - CH-5600 Lenzburg

***Abstract*—This presentation is about the work done on design, built-up, production and test of ready-to-use solid state switch assemblies using Thyristor- or IGCT technology. The presented thyristor switch assemblies, using 120 mm wafer size, are made to switch 3MJ stored energy into a load. The maximum charge voltage of the assembly is 12 kVdc, current capability more than 260kA@tp=3.3ms and a pulse repetition rate of up to 6 shots per minute with convection air cooling. New very large thyristors with 150 mm wafer diameter will be available from fall 2008. As second a 70 kA/21kVdc switch using IGCT technology will be presented. The switch is designed for fast discharge in the micro-second range and has a very high di/dt capability. Because for** adapted standard products which can fulfill the requirements for pulsed applications. Beside the semiconductor devices, ABB is also in the position to supply complete custom made ready-to-use solid state switch assemblies including clamping, triggering, cooling and with application oriented testing. The presentation describes both, the loose semiconductor components as well as some custom made solid state switches for single pulse or low repetition rate pulsing.

II. Device Technology

2008 Paper

Thanks to Prof. Ajjarapu for providing the following slides:

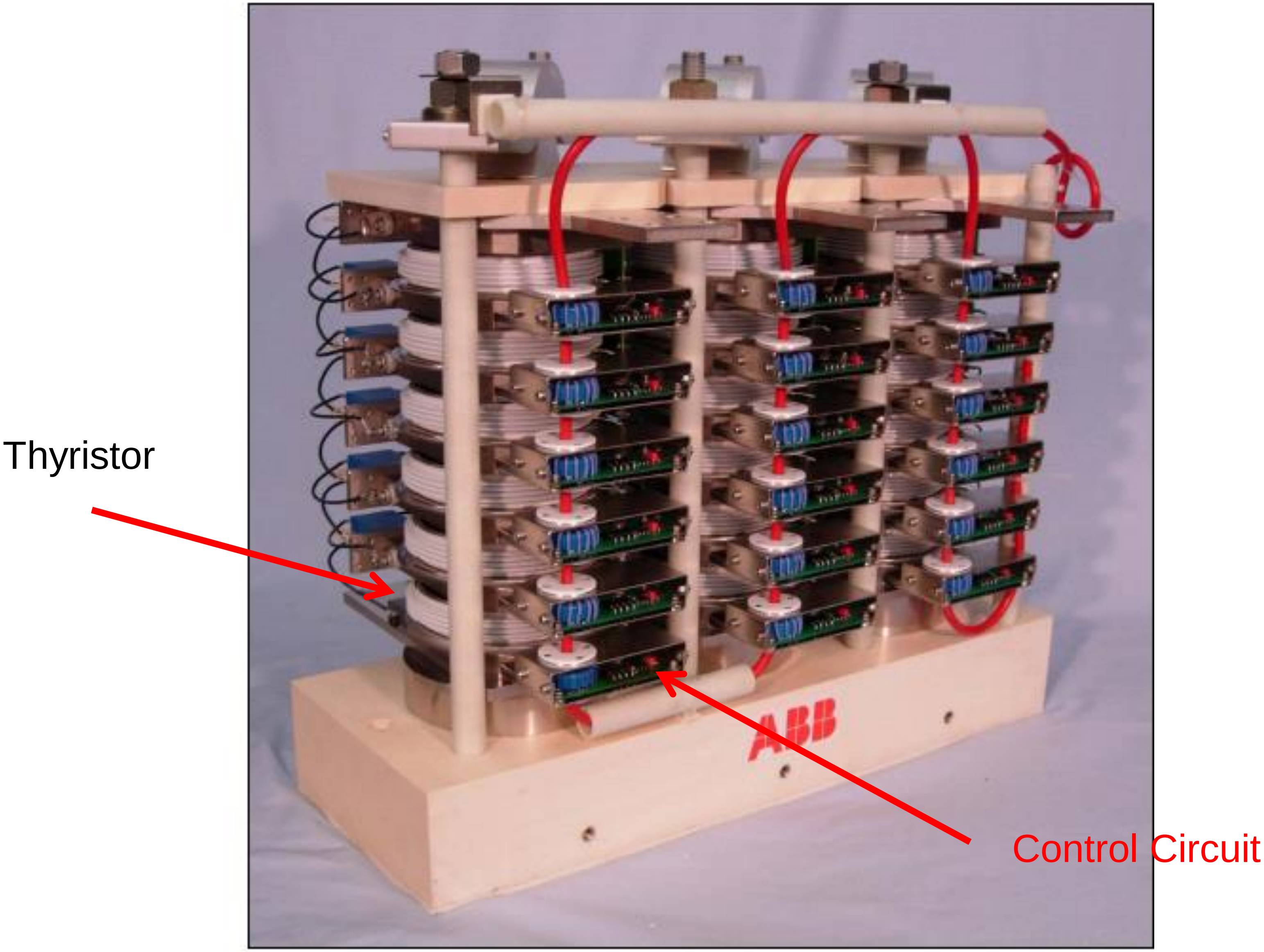
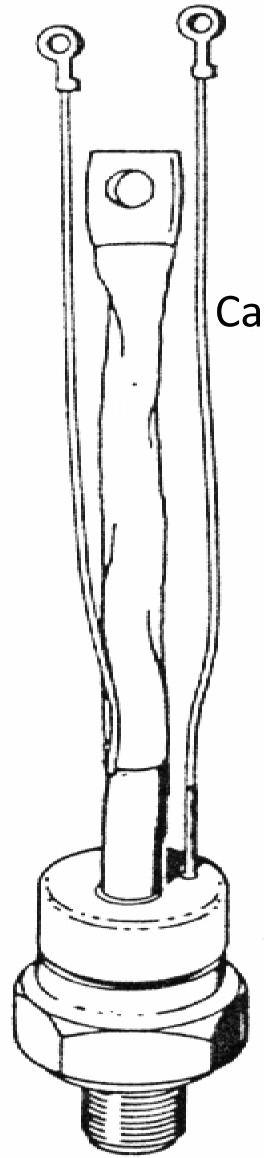


Fig.3: Thyristor Switch Assembly A-STP 5742U-18-CC

Thanks to Prof. Ajjarapu for providing the following slides:

Auxiliary
Cathode Lead
(Red)
Extends cathode
potential to the
control circuit.

Gate Lead
(White)

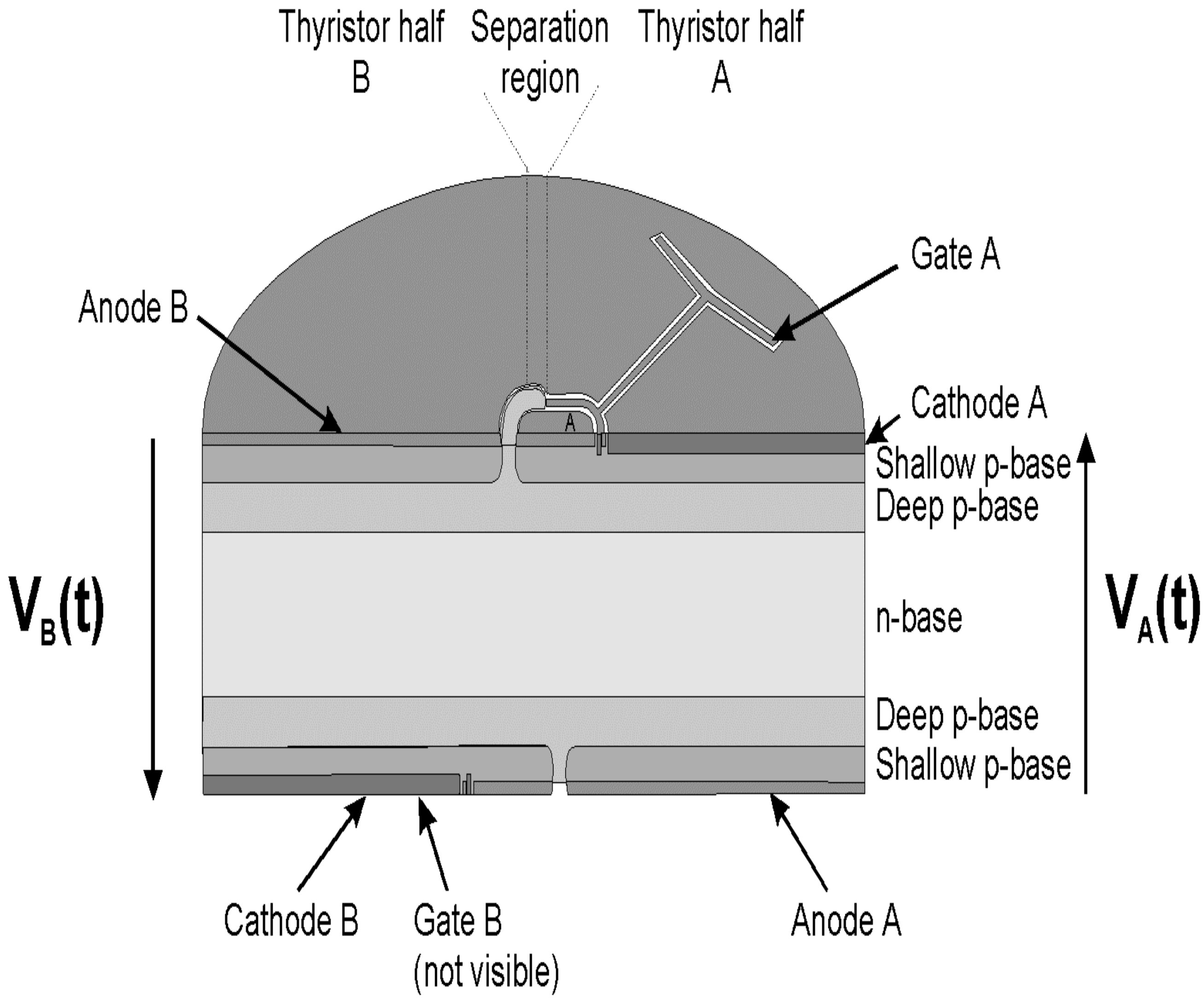


Cathode Lead

Stud Anode

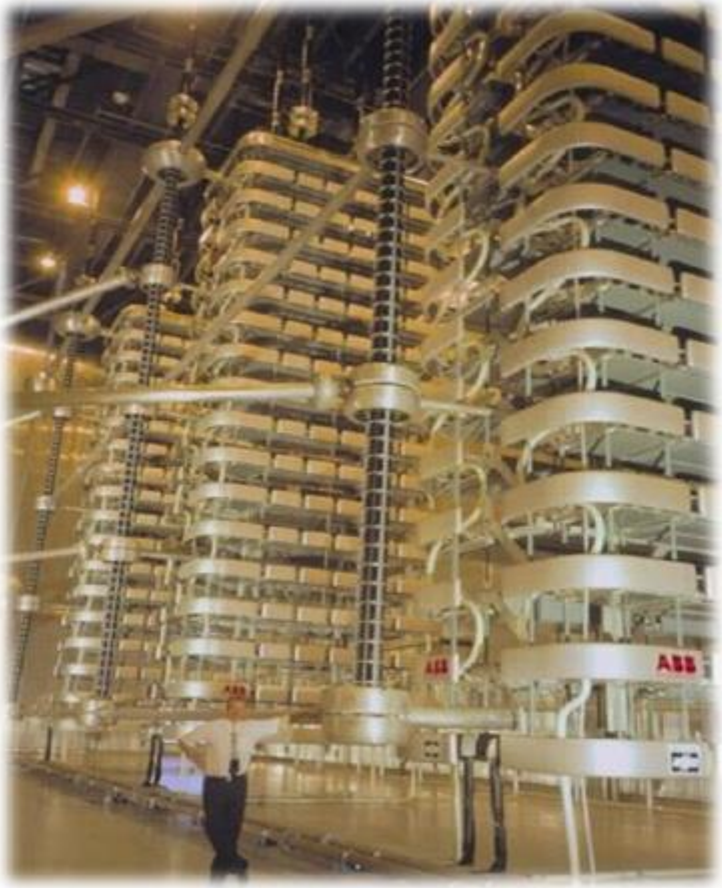
Stud- Mounted SCR
110 Amp RMS Rating

Thanks to Prof. Ajjarapu for providing the following slides:



Cross-section of a BCT wafer showing the antiparallel arrangement of the A and B component thyristors. The arrows indicate the convention of forward blocking for A and B.

Thanks to Prof. Ajjarapu for providing the following slides:



Thyristor Valve - 12 Pulse Converter (6.5Kv, 1568 Amp, Water cooled)

Thyristor Observations

Many different structures used to build thyristors

Range from low power devices to extremely high power devices

Often single-wafer solutions for high power applications

Usually formed by diffusions

Widely used throughout society but little visibility

Applications somewhat restricted

Thyristors

The good

SCRs
Triacs

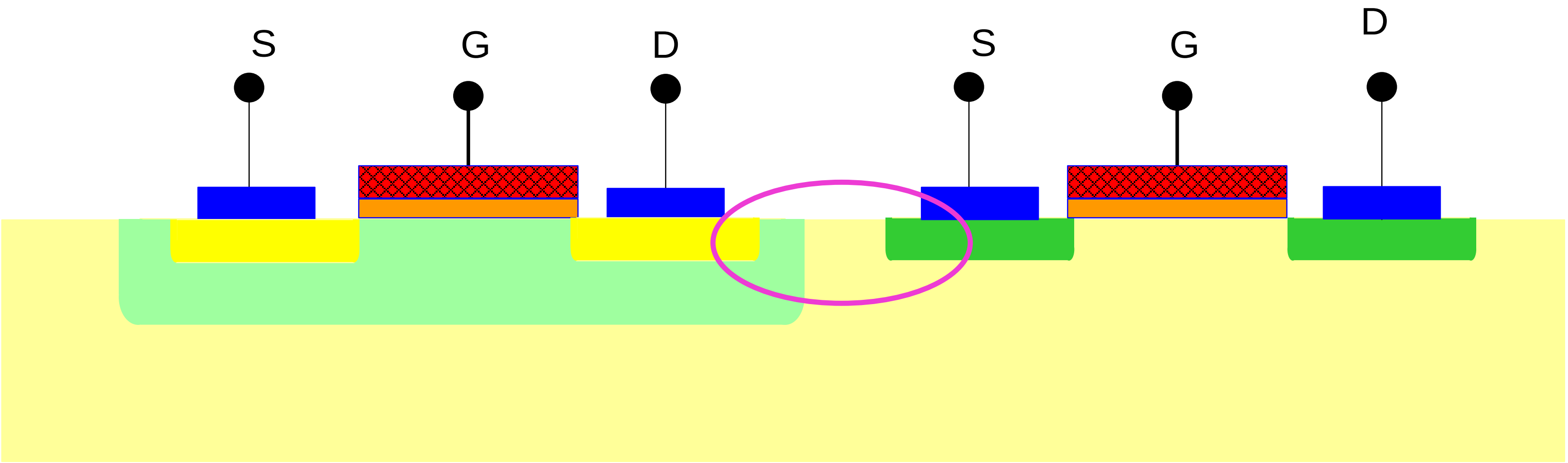
The bad

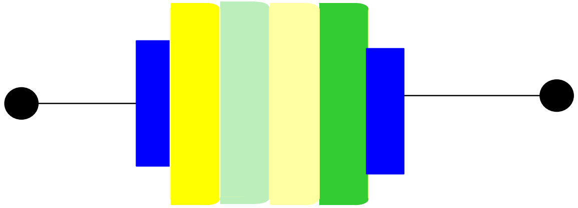
Parasitic Device that can destroy integrated circuits

The Thyristor

A bipolar device in CMOS Processes

Consider a Bulk-CMOS Process





If this parasitic SCR turns on, either circuit will latch up or destroy itself

Guard rings must be included to prevent latchup

Design rules generally include provisions for guard rings

End of Lecture 29