

# EE 330

## Lecture 30

### Thyristors

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

# Exam Schedule

Exam 2 will be given on Friday March 11

Exam 3 will be given on Friday April 15

Photo courtesy of the director of the National Institute of Health ( NIH)



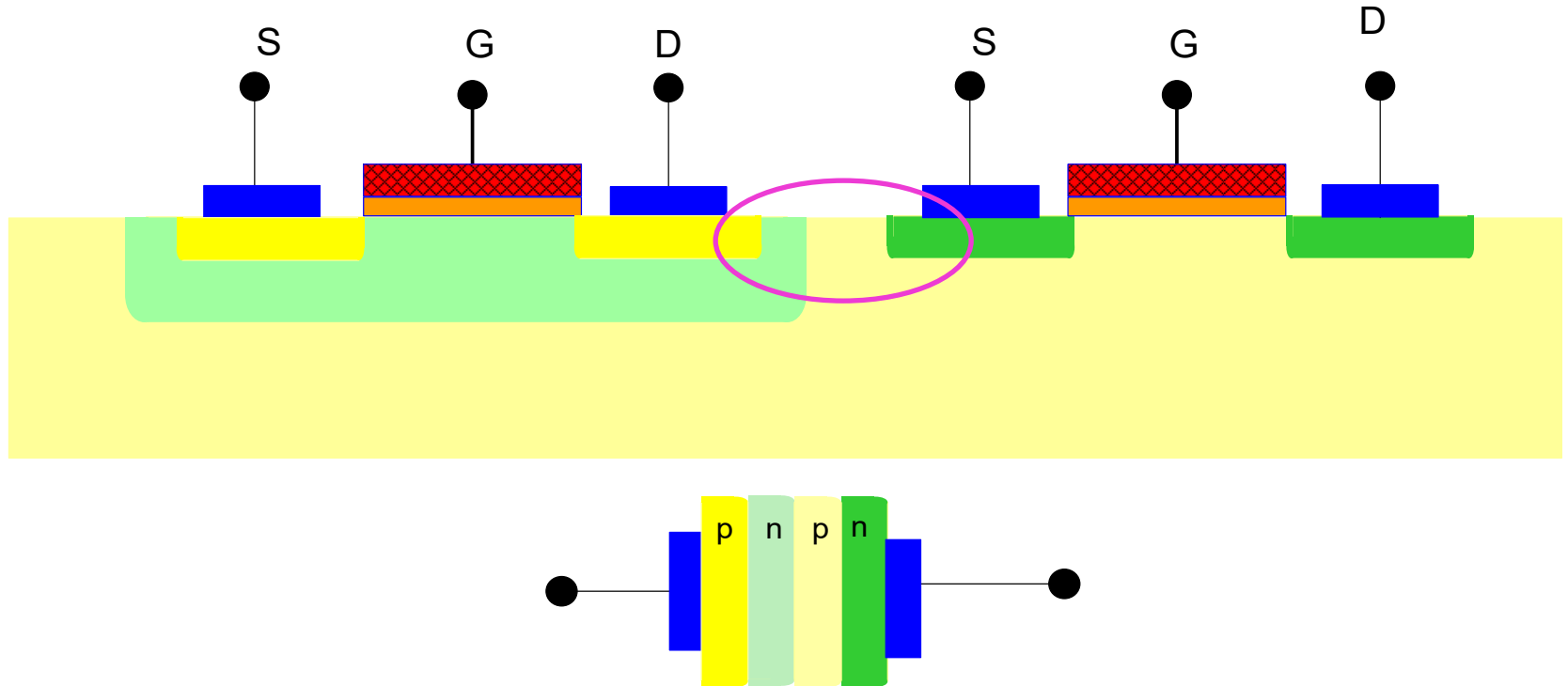
As a courtesy to fellow classmates, TAs, and the instructor

**Wearing of masks during lectures and in the laboratories for this course would be appreciated irrespective of vaccination status**

# The Thyristor

A bipolar device in CMOS Processes

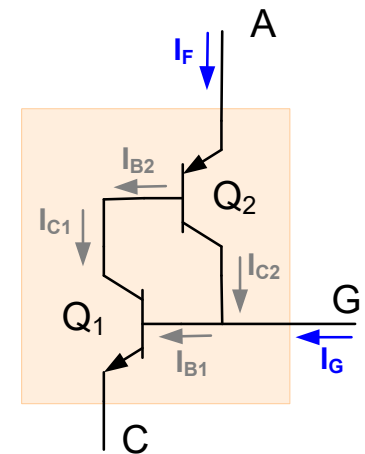
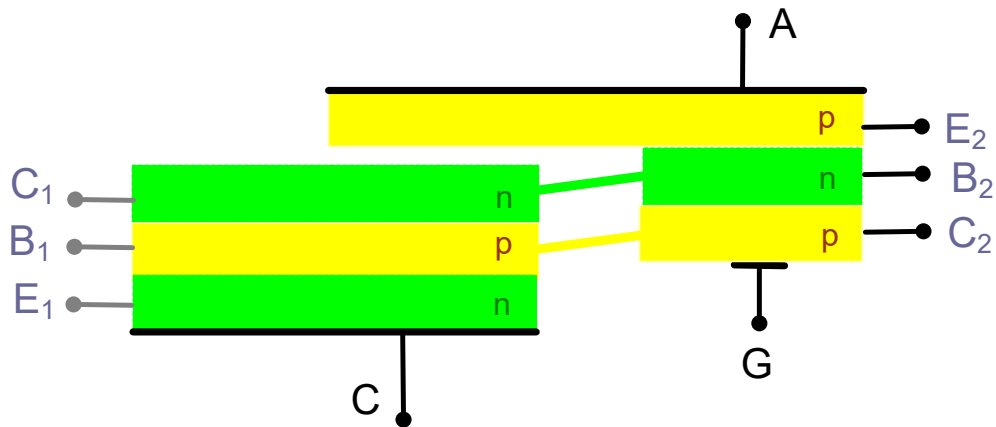
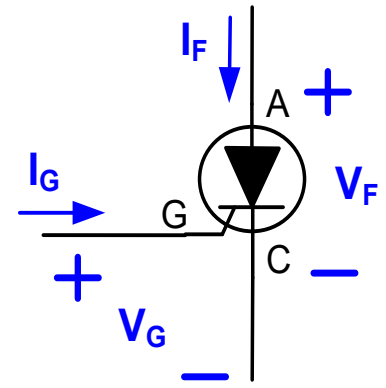
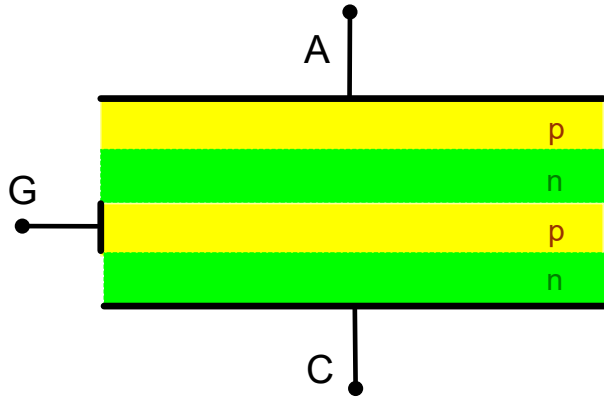
Consider a Bulk-CMOS Process



**Have formed a lateral pnpn device !**

Will spend some time studying pnpn devices

# Operation of the SCR

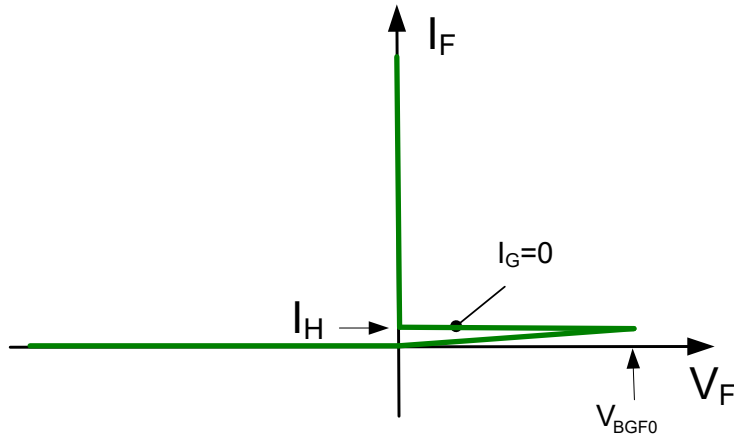
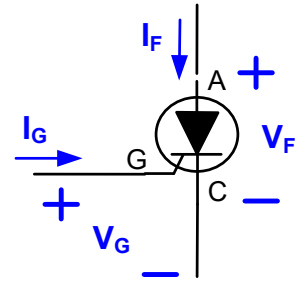


Not actually separated but useful for describing operation

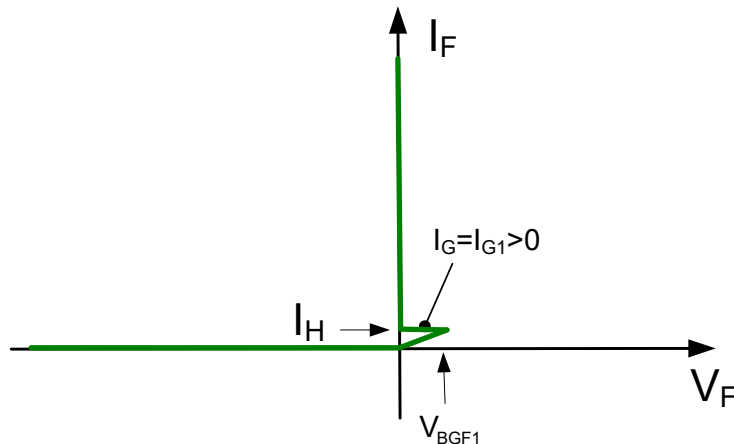
# Operation of the SCR

Consider the Ideal SCR Model

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



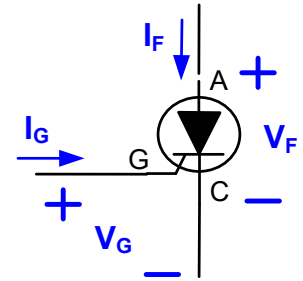
$I_H$  is very small



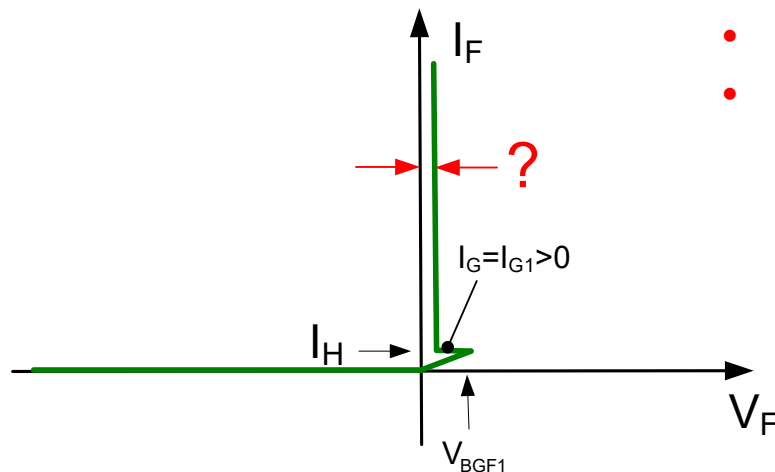
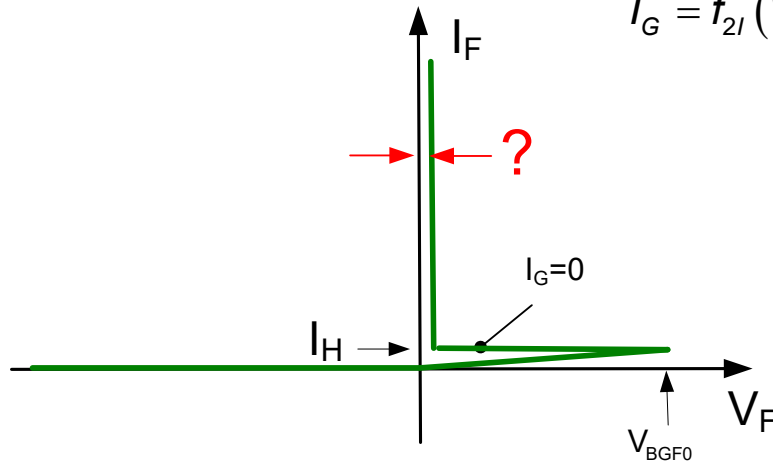
$I_{G1}$  is small (but not too small)

# Operation of the SCR

Consider nearly Ideal SCR Model



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



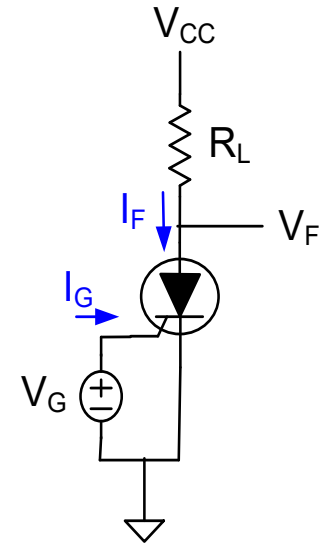
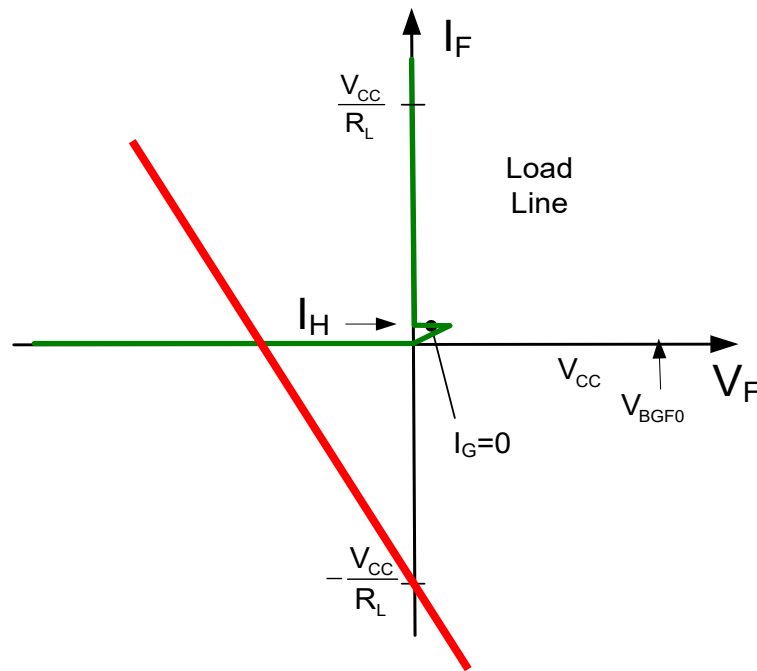
- On voltage approximately 0.9V
- Major contributor to ON-state power dissipation
- Even with large currents,  $P_{ON}$  is quite small

# 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

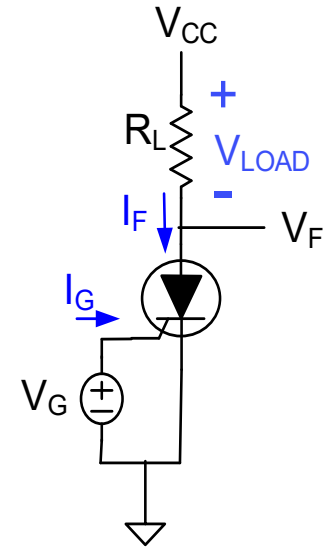
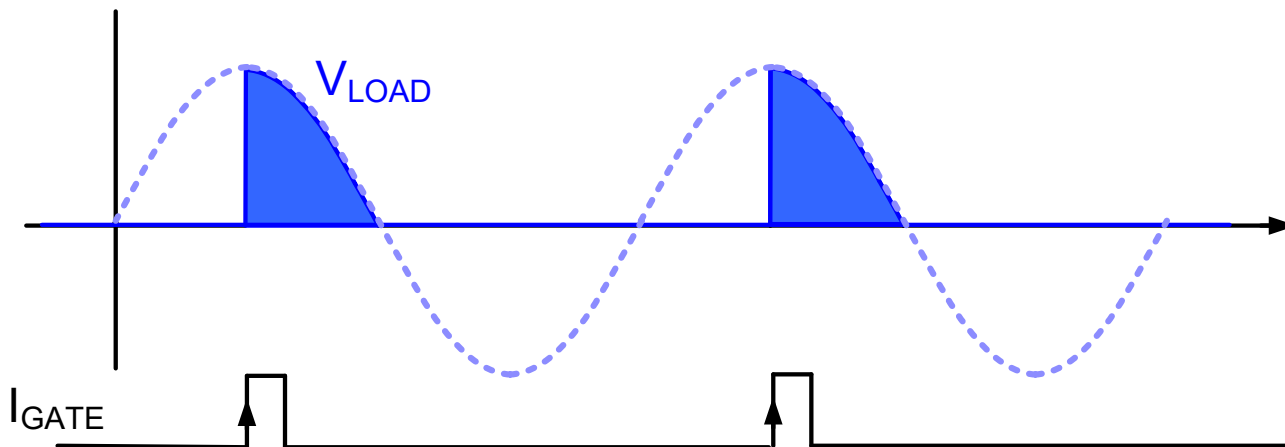
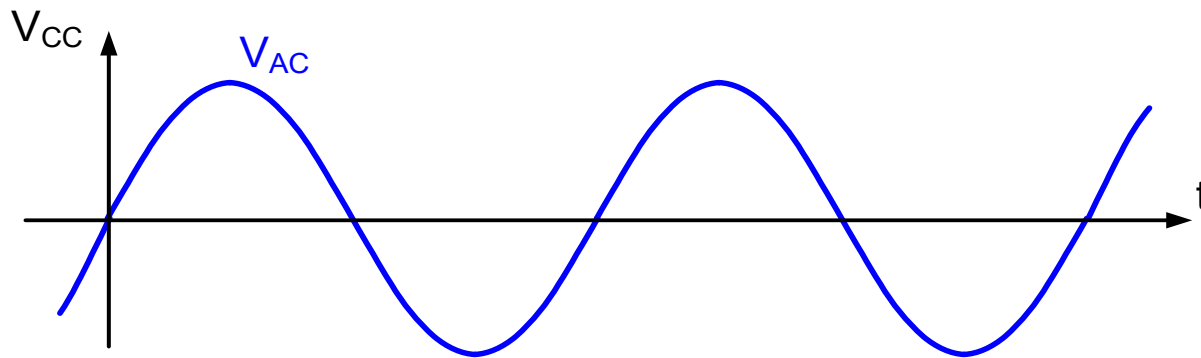




# Operation of the SCR

## Operation with the Ideal SCR

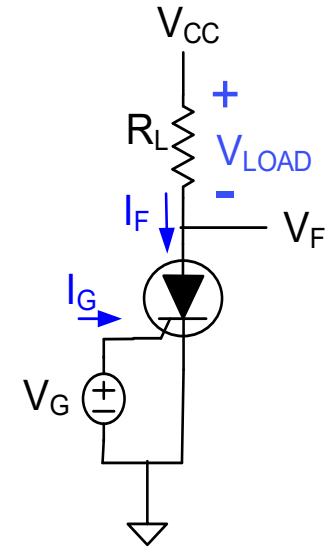
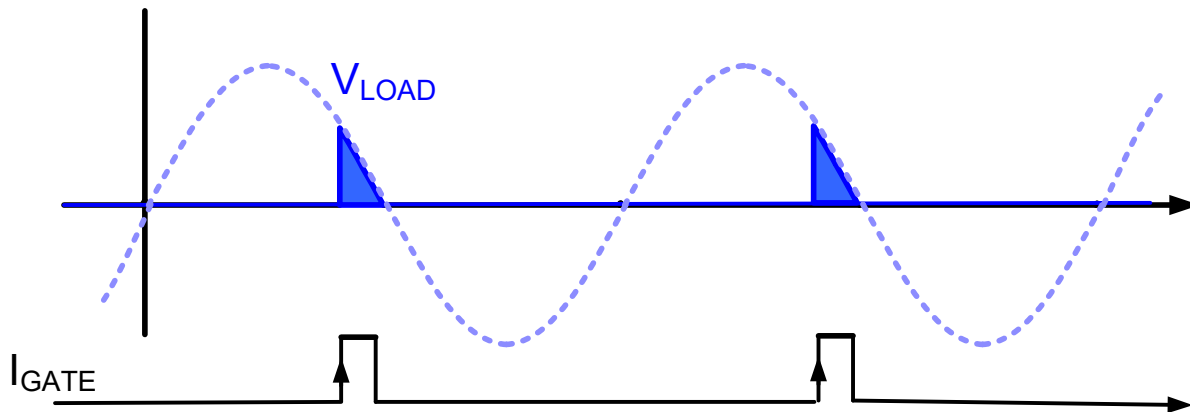
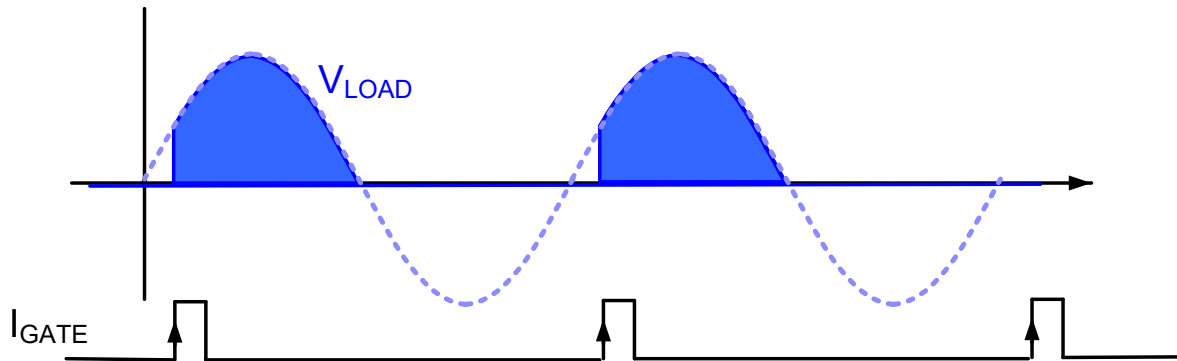
Duty cycle control of load  $R_L$



# Operation of the SCR

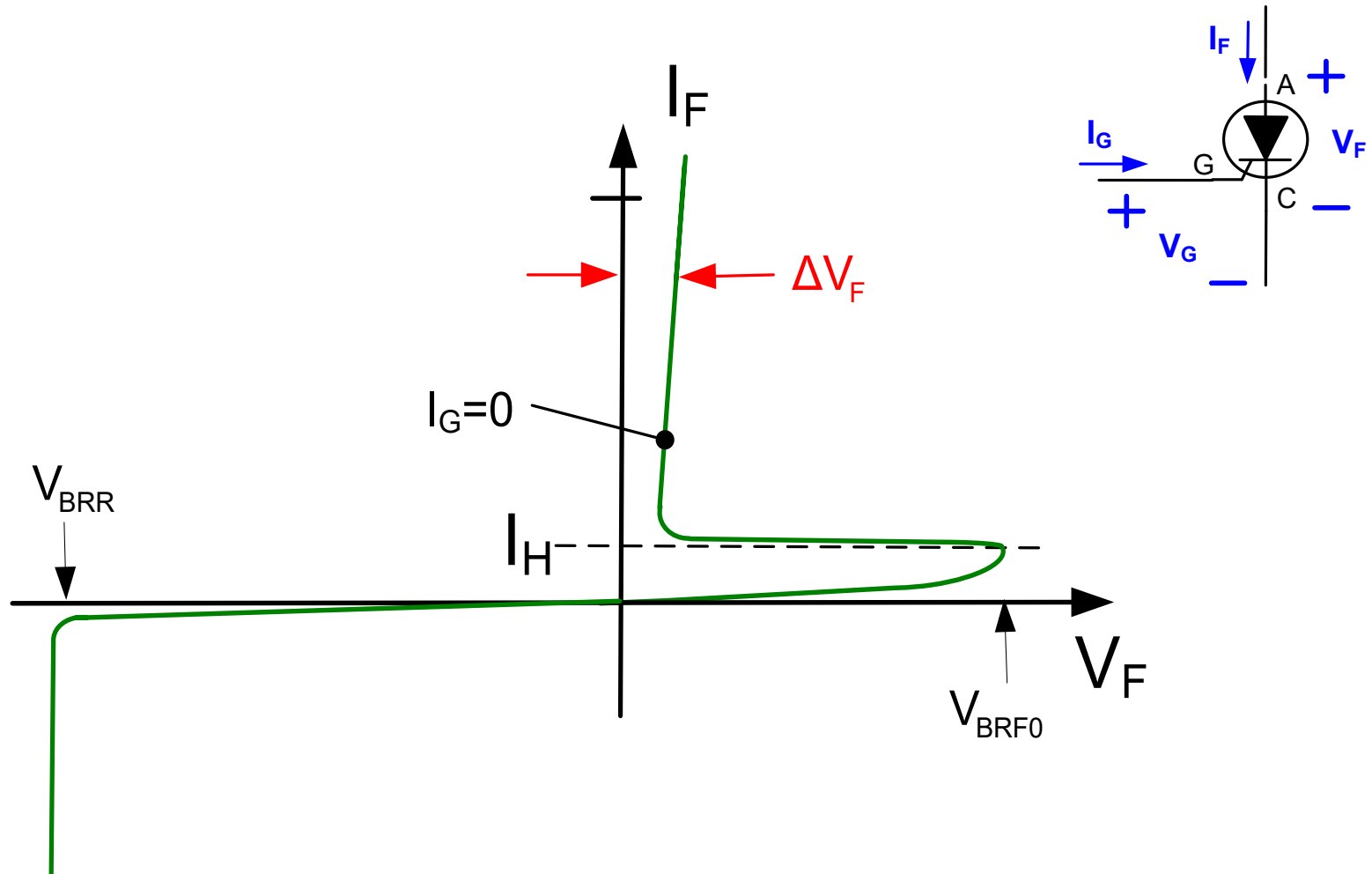
## Operation with the Ideal SCR

Duty cycle control of load  $R_L$



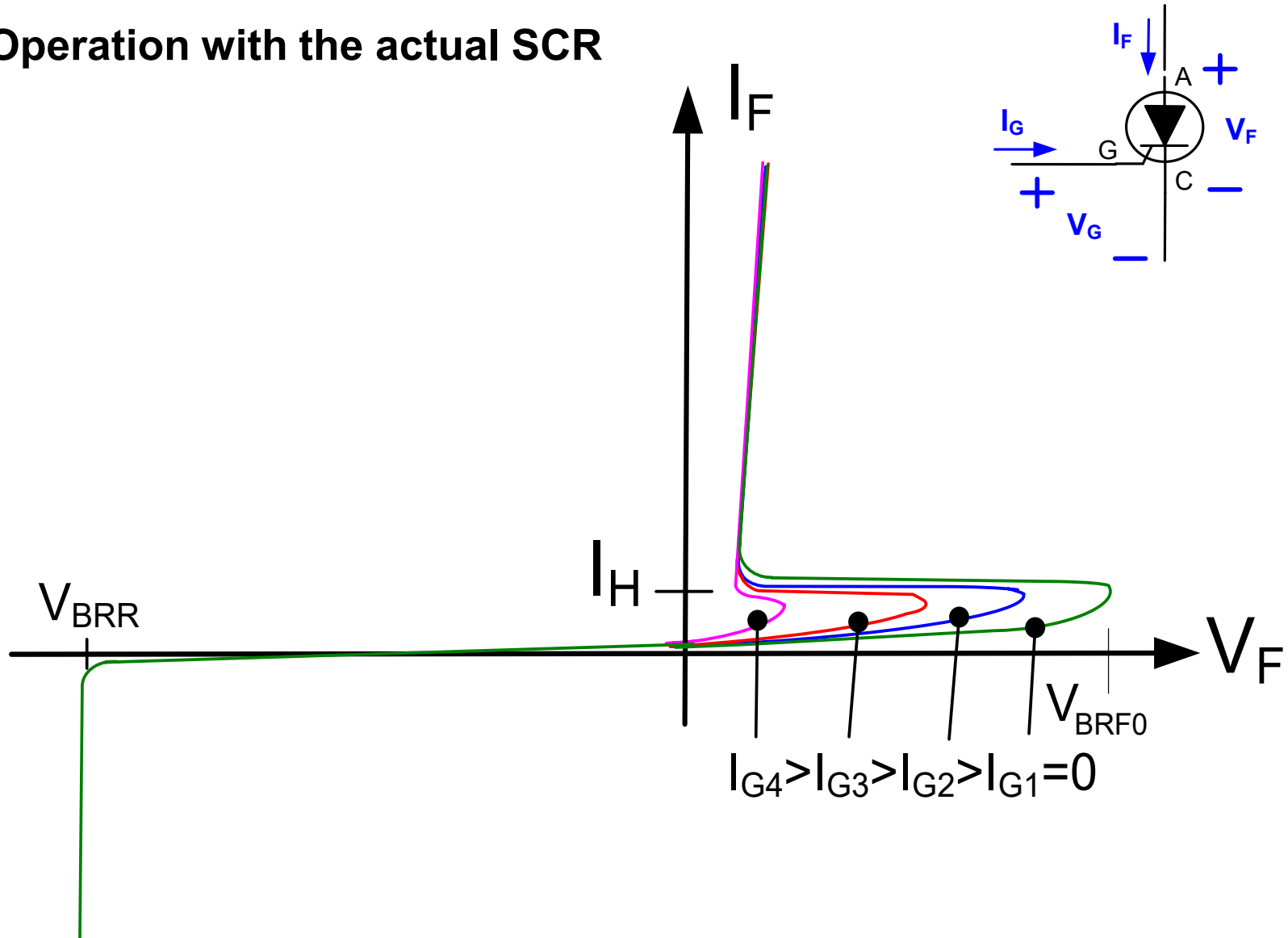
# Operation of the SCR

## Operation with the actual SCR



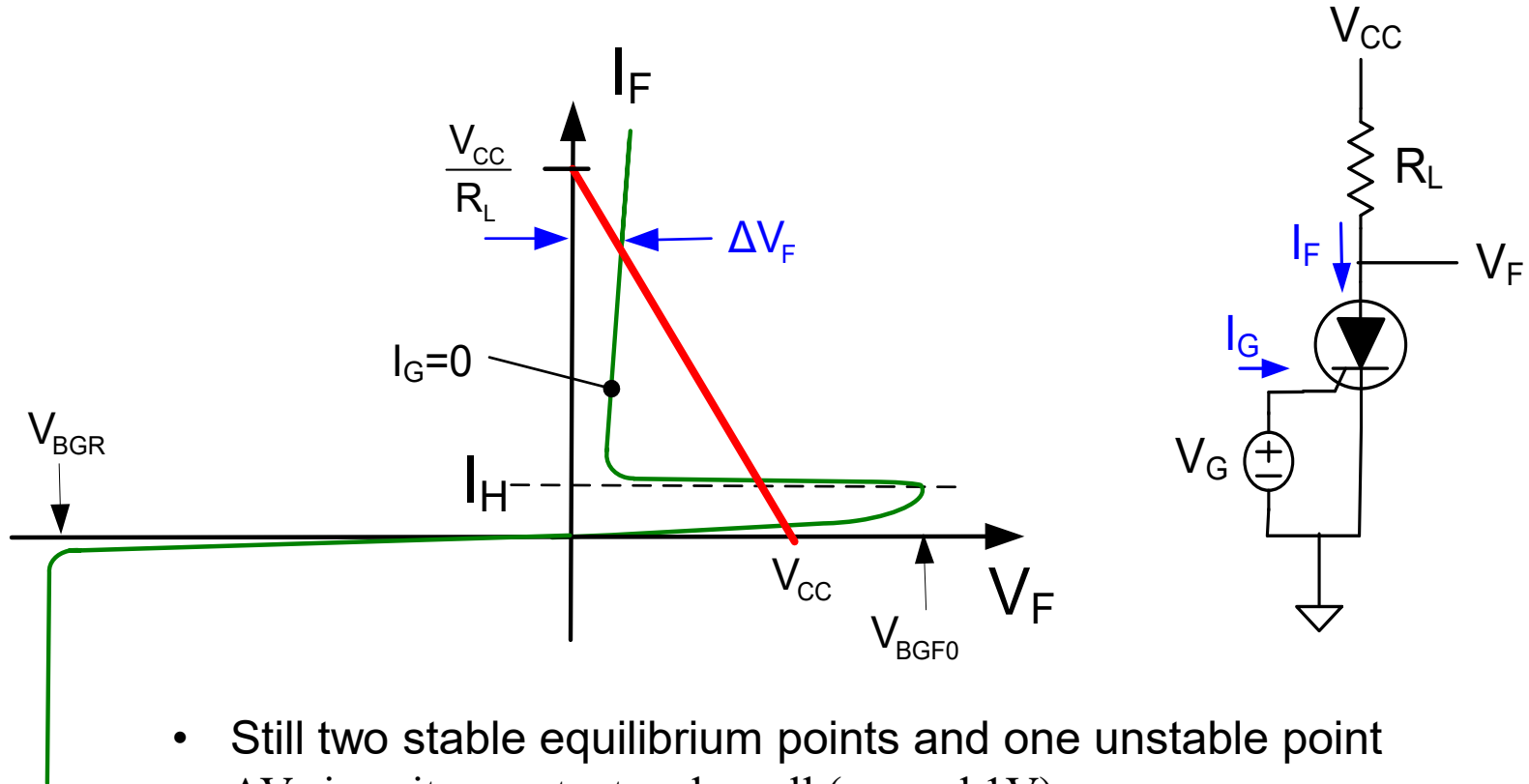
# Operation of the SCR

## Operation with the actual SCR



# Operation of the SCR

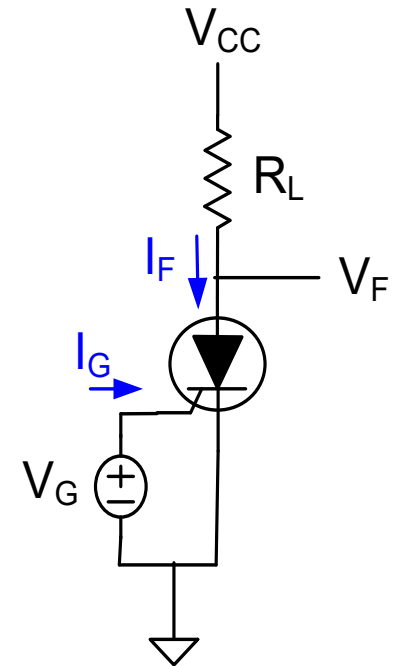
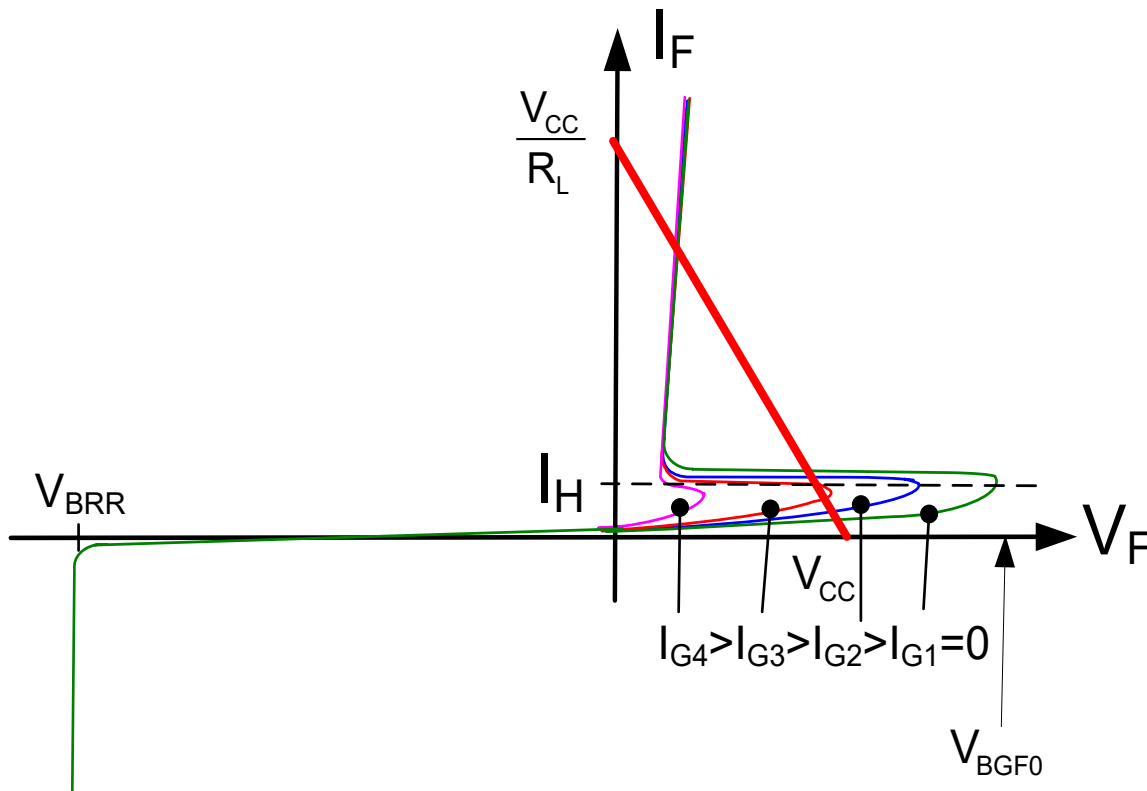
## Operation with the actual SCR



- Still two stable equilibrium points and one unstable point
- $\Delta V_F$  is quite constant and small (around 1V)
- If large current is flowing, power in anode can be large ( $P_A \approx I_F \bullet 1V$ )  
(but usually much less than power in the controlled load)
- Power in gate is usually very small

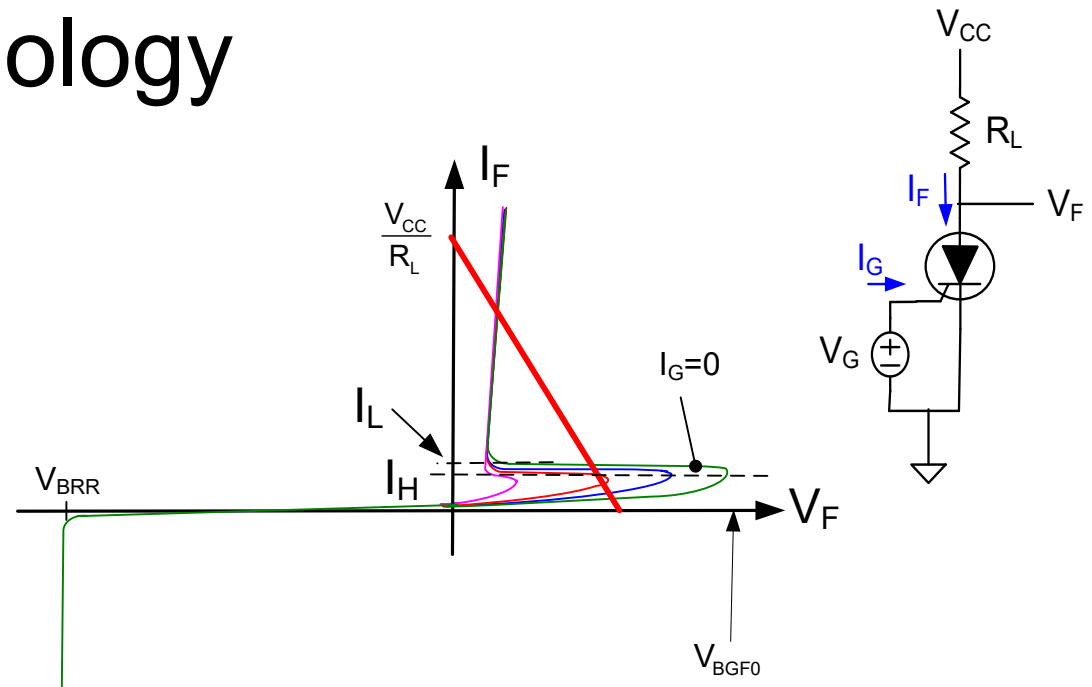
# Operation of the SCR

## 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

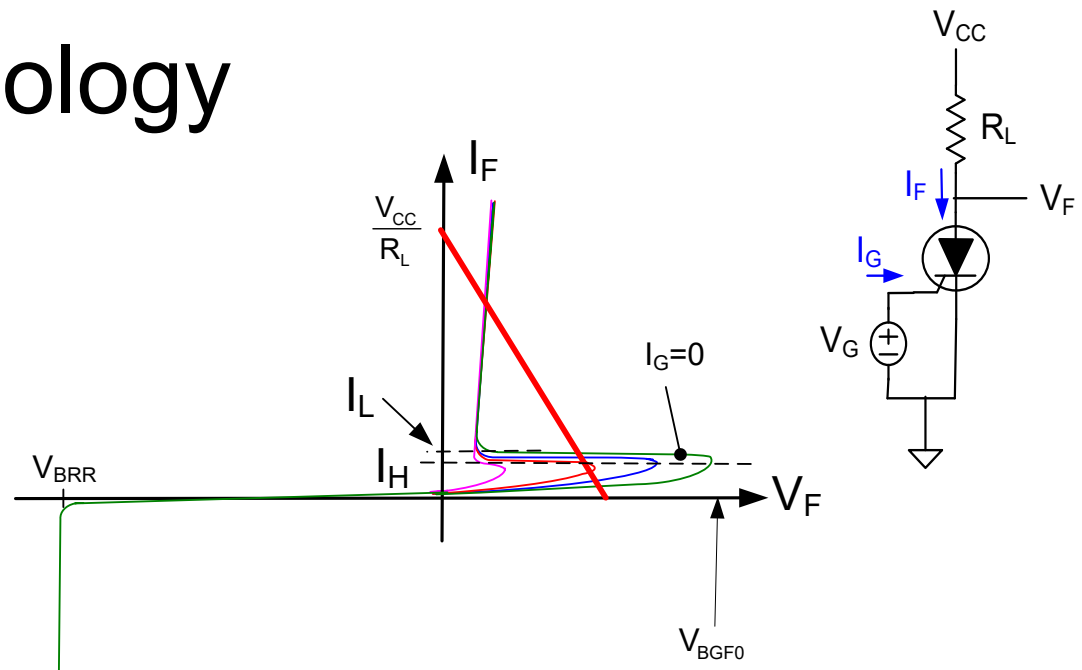
$V_{BRR}$  is the reverse break-down voltage

$I_{GT}$  is the gate trigger current

$V_{GT}$  is the gate trigger voltage

# SCR Terminology

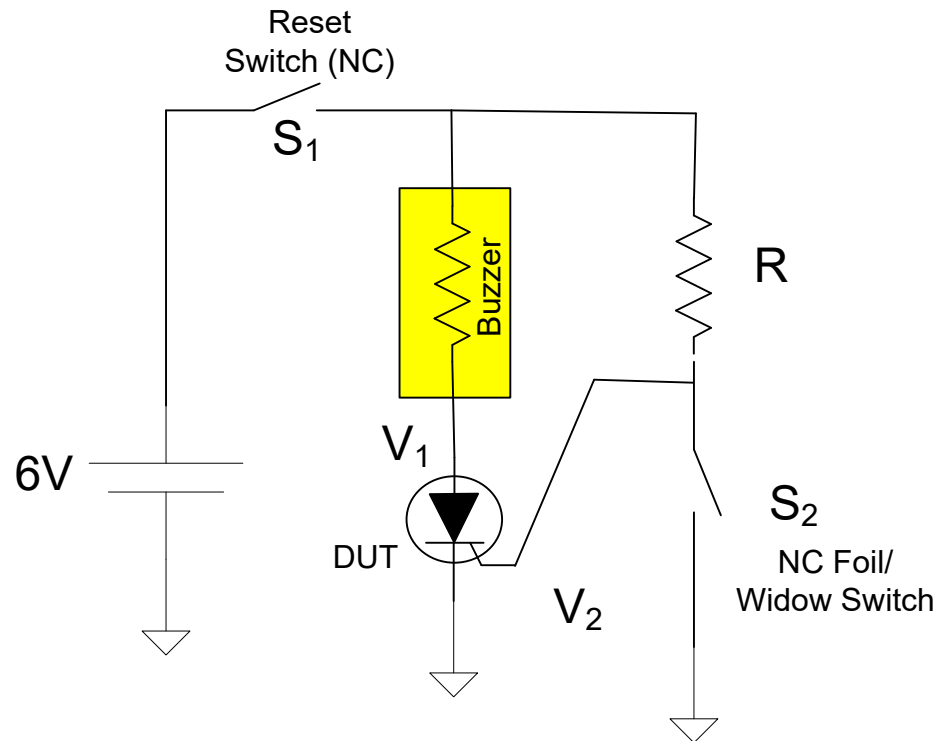
## Issues and Observations



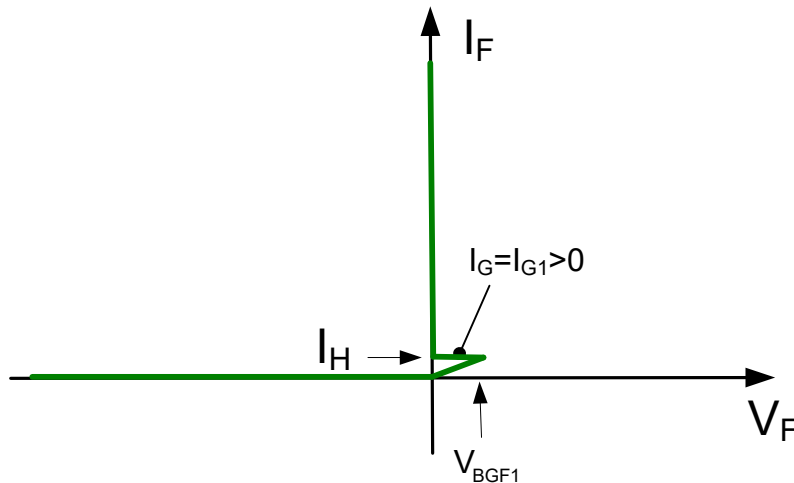
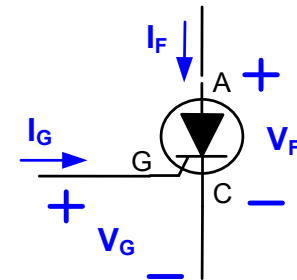
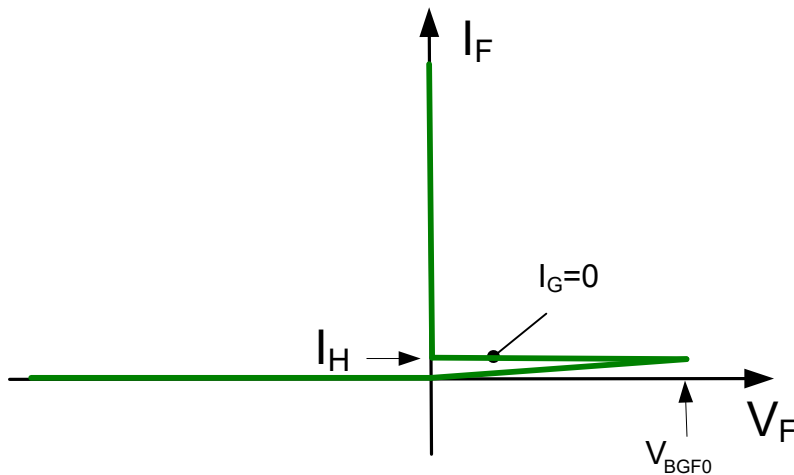
- Trigger parameters ( $V_{GT}$  and  $I_{GT}$ ) highly temperature dependent
- Want gate “sensitive” but not too sensitive (to avoid undesired triggering)
- SCRs can switch very large currents but power dissipation is large
- Heat sinks widely used to manage power
- Trigger parameters affected by both environment and application
- Trigger parameters generally dependent upon  $V_F$
- 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



# Alarm Application



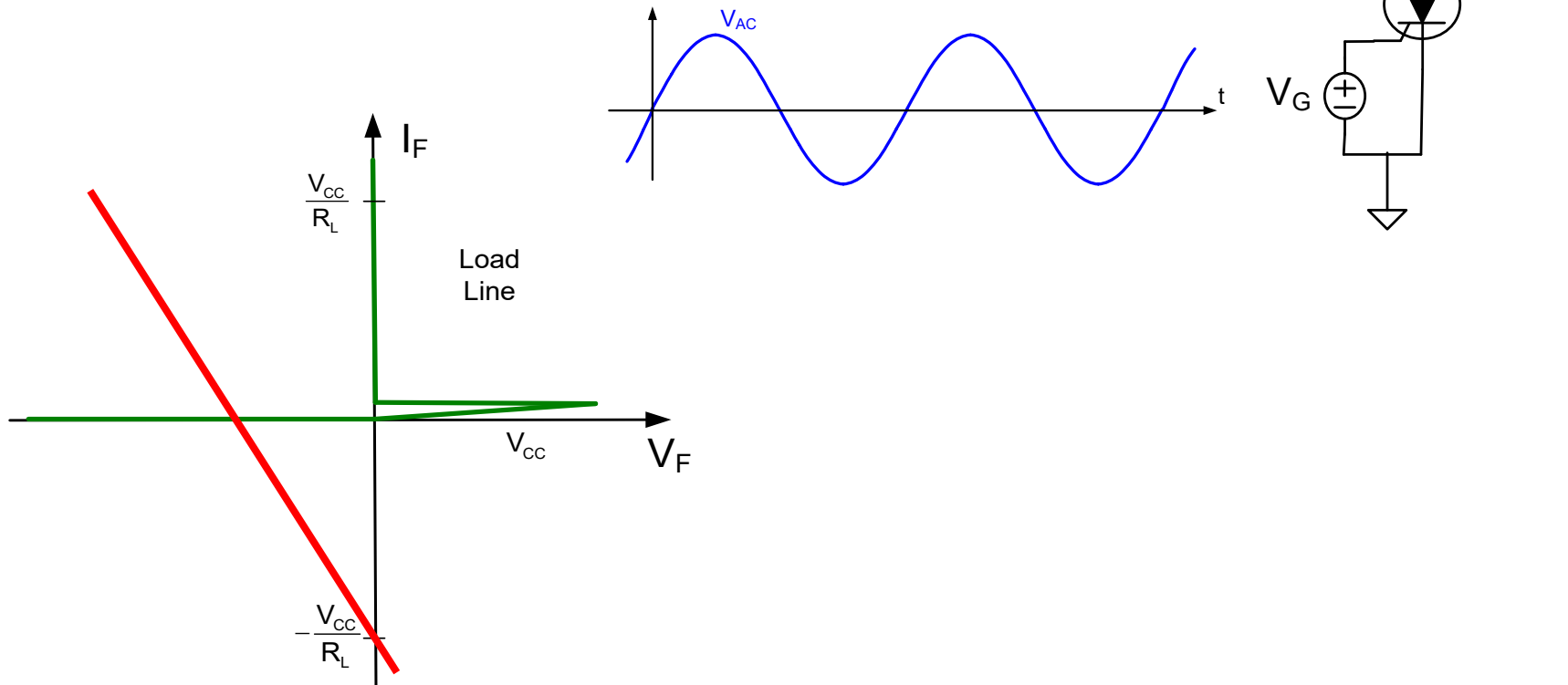
# Performance Limitations with the SCR



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

# Performance Limitations with the SCR

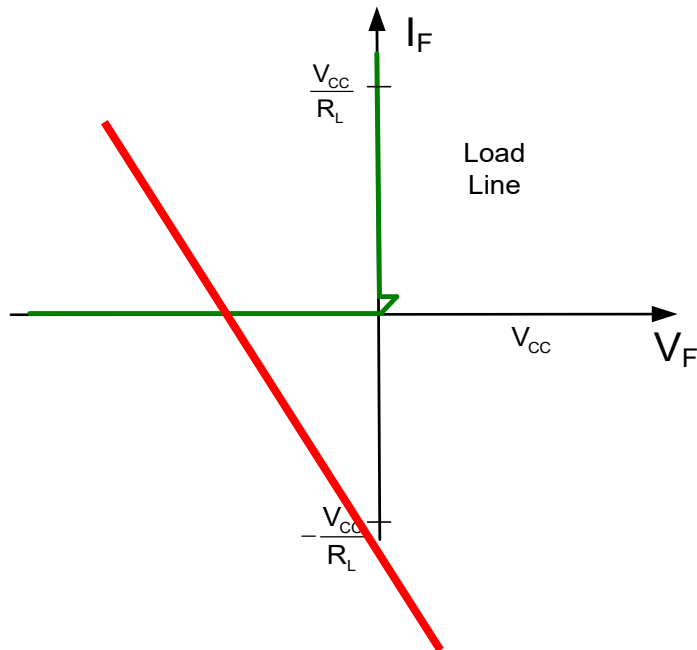
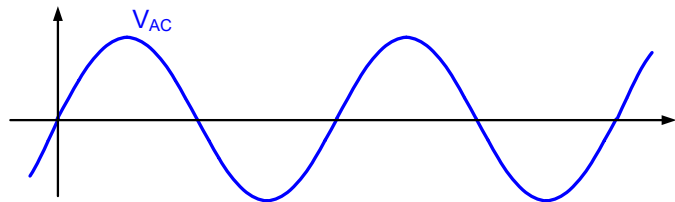
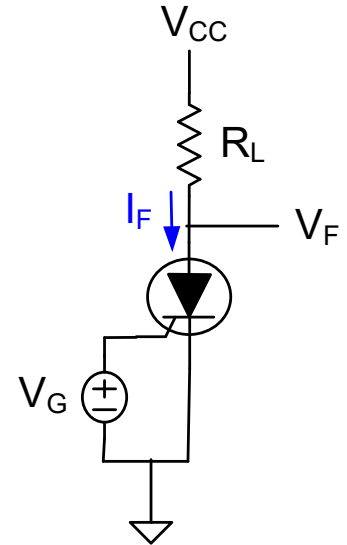
Assume  $V_{CC}$  is an AC signal (often 110V) and  $V_G$  is static



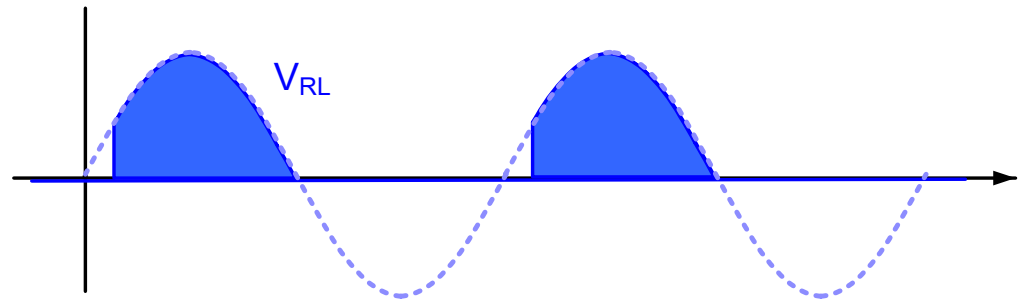
SCR is always off

# Performance Limitations with the SCR

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

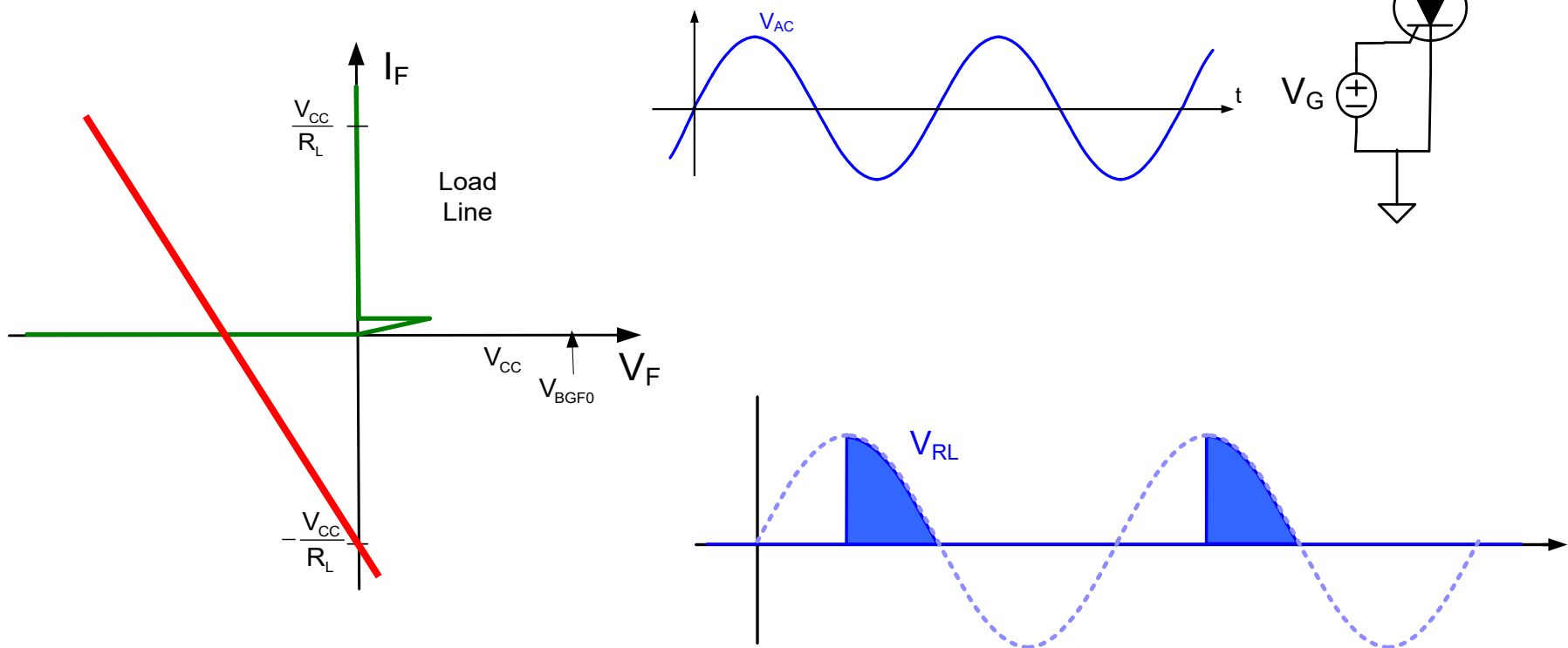


SCR is ON about 50% of the time



# 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  $V_G$

# Outline

## Two-Port Amplifier Models

## Bipolar Processes

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

## Special Bipolar Processes

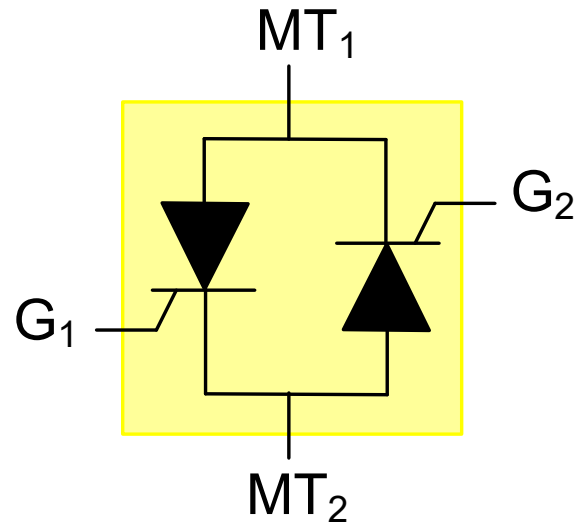
- Thyristors

SCR



TRIAC

# Bi-directional switching



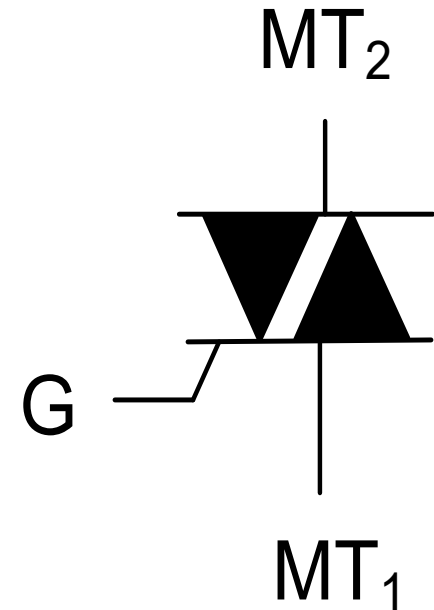
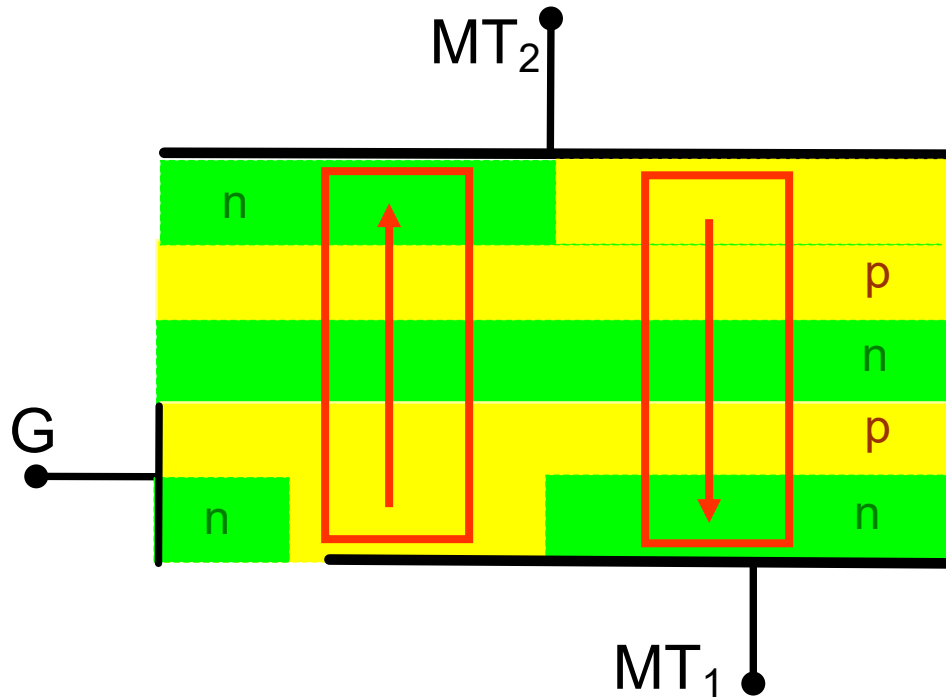
Use two cross-coupled SCRs

## Limitations

Size and cost overhead with this solution

Inconvenient triggering since  $G_1$  and  $G_2$  WRT different terminals

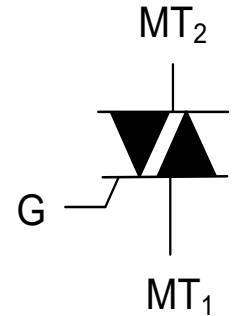
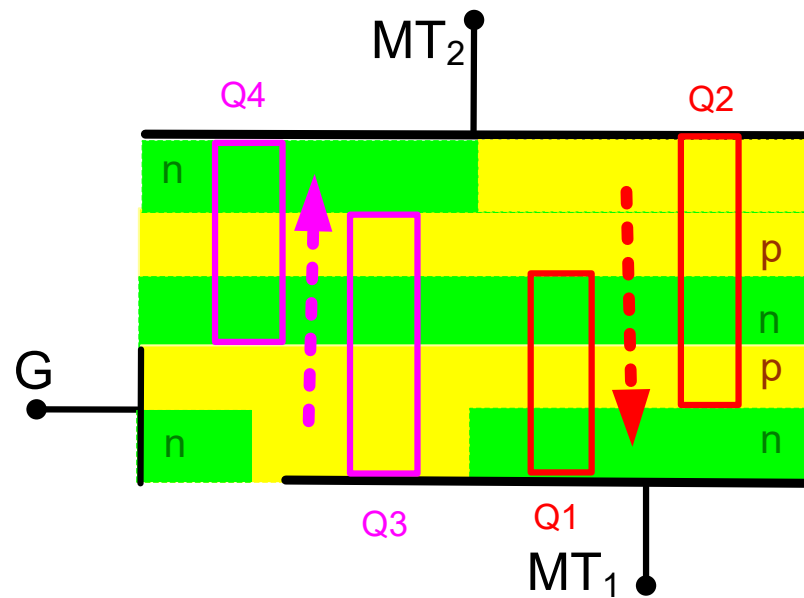
# Bi-directional switching with the Triac



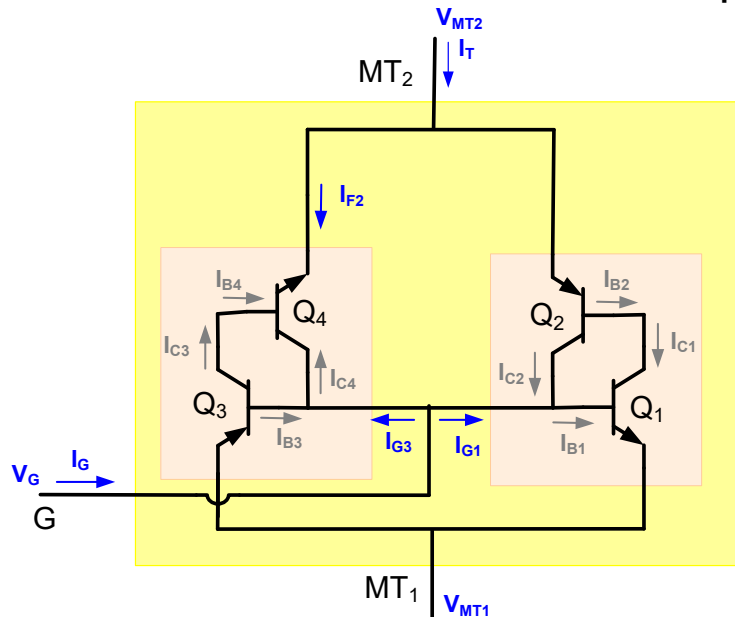
- Has two cross-coupled SCRs !
- Manufactured by diffusions
- Single Gate Control



# 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  $V_{MT2}-V_{G-MT1}$  plane) for operation

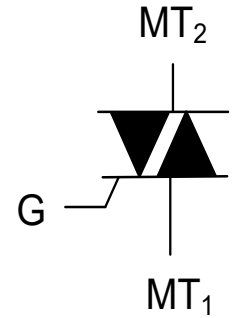
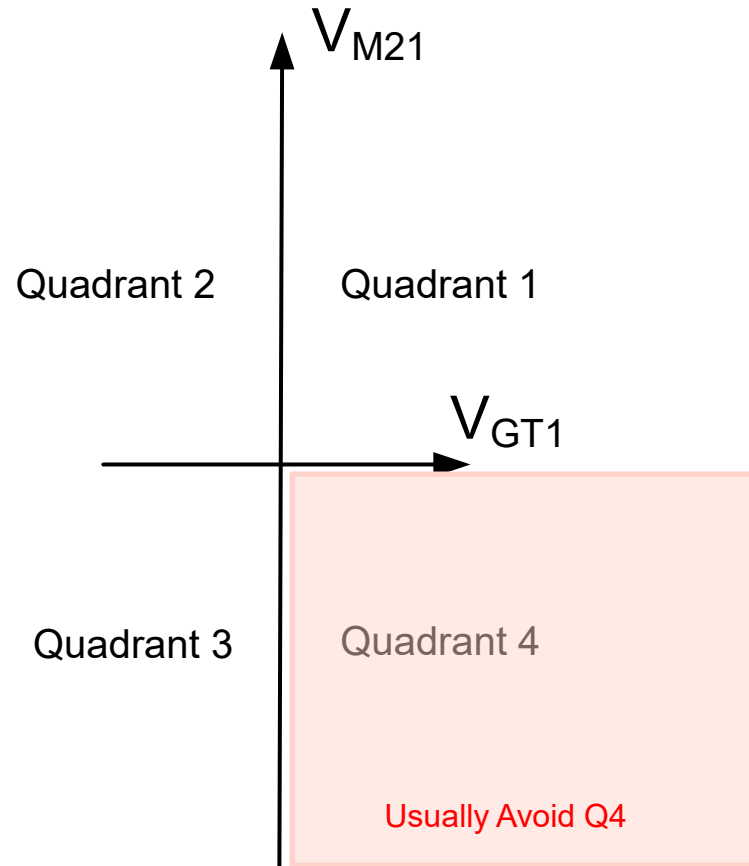
$V_{MT2} > V_{MT1}$	$V_{G-MT1} > 0$	Quadrant 1
$V_{MT2} > V_{MT1}$	$V_{G-MT1} < 0$	Quadrant 2
$V_{MT2} < V_{MT1}$	$V_{G-MT1} < 0$	Quadrant 3
$V_{MT2} < V_{MT1}$	$V_{G-MT1} > 0$	Quadrant 4

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

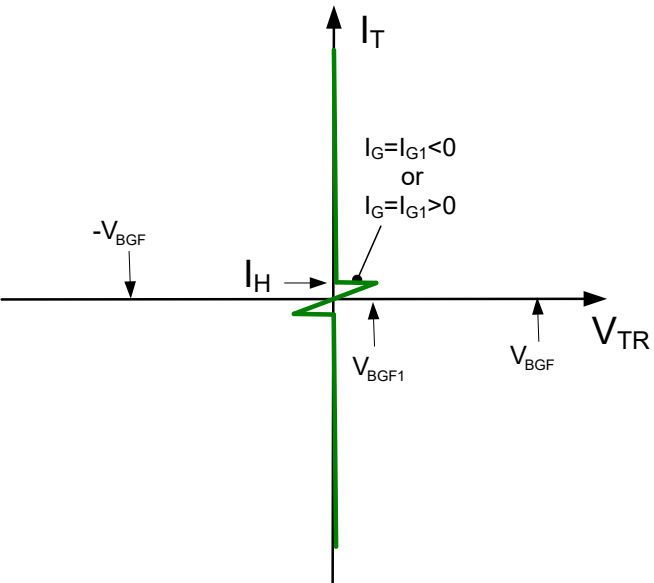
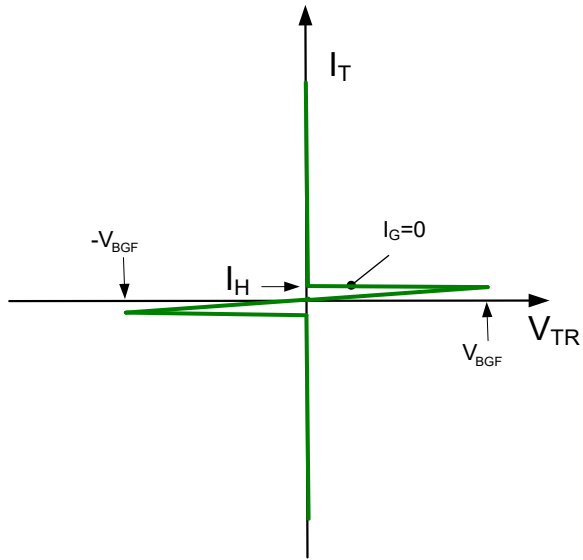
# The Triac



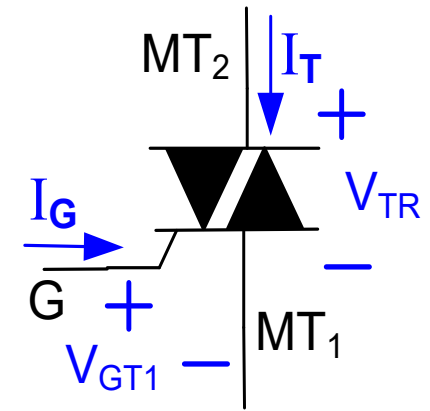
Defines 4 quadrants (in  $V_{MT21}$ - $V_{G-MT1}$  plane) for operation

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

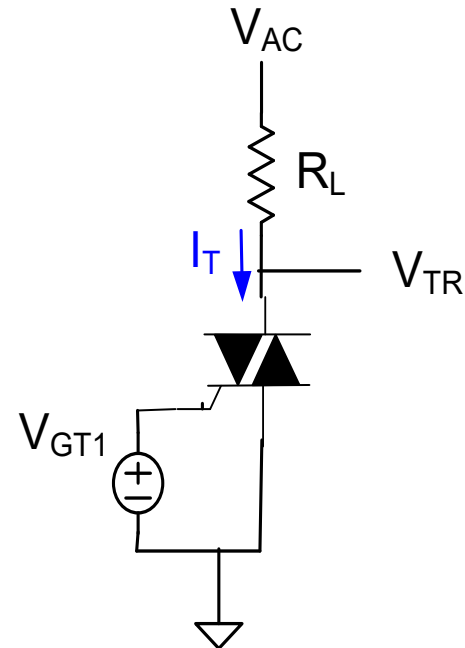
## The ideal Triac



## The Triac



Consider the basic Triac circuit

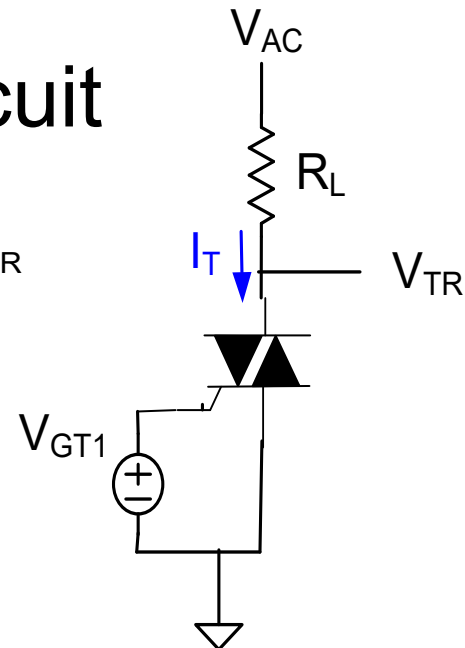


Assume ideal Triac

# The Basic Triac Circuit

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

Analysis:  $V_{AC} = I_T R_L + V_{TR}$   
 $I_T = f_A(V_{TR}, V_{GT1})$

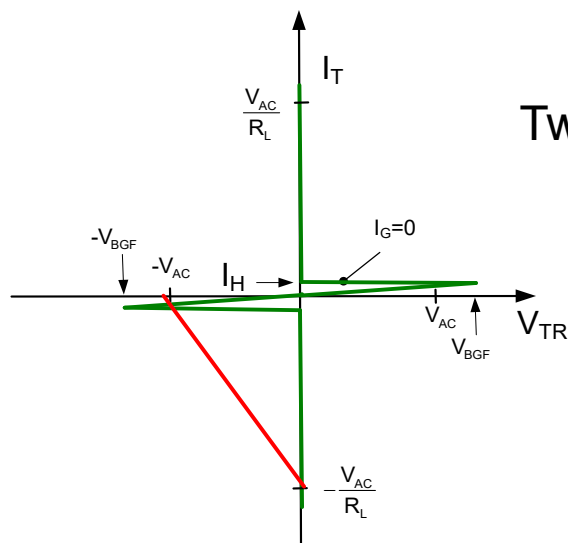
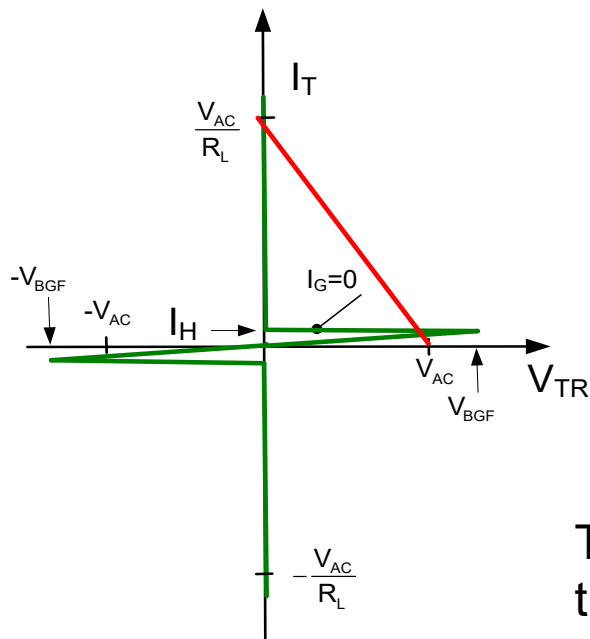


The solution of these two equations is at the intersection of the load line and the device characteristics

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

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

Why?

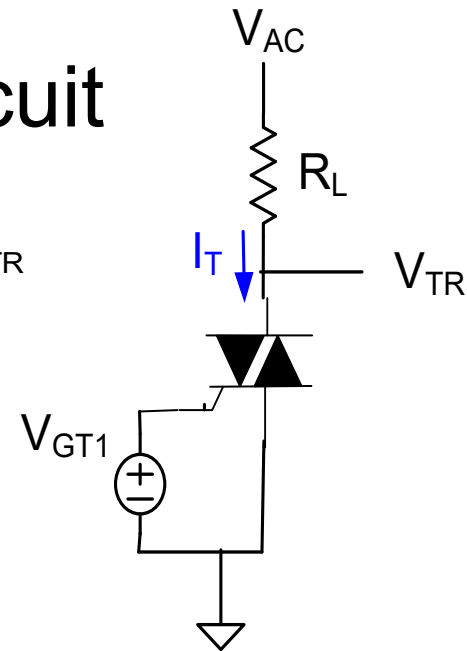


Assume ideal Triac

# The Basic Triac Circuit

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

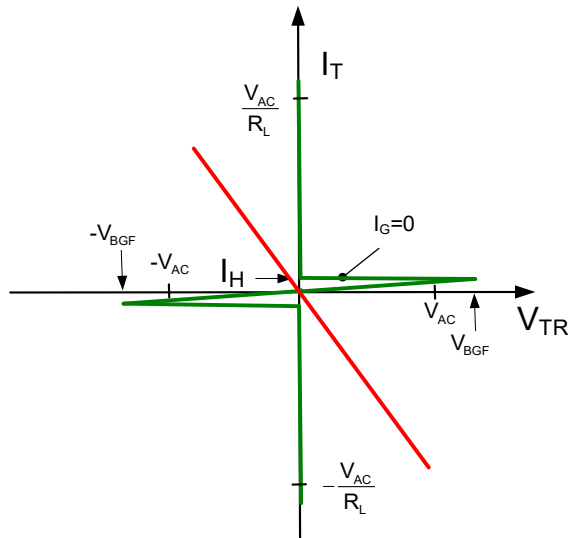
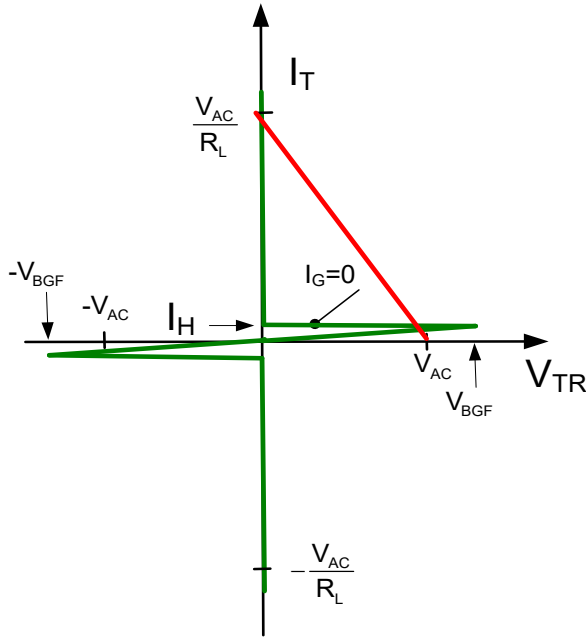
Analysis:  $V_{AC} = I_T R_L + V_{TR}$   
 $I_T = f_A(V_{TR}, V_{GT1})$



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

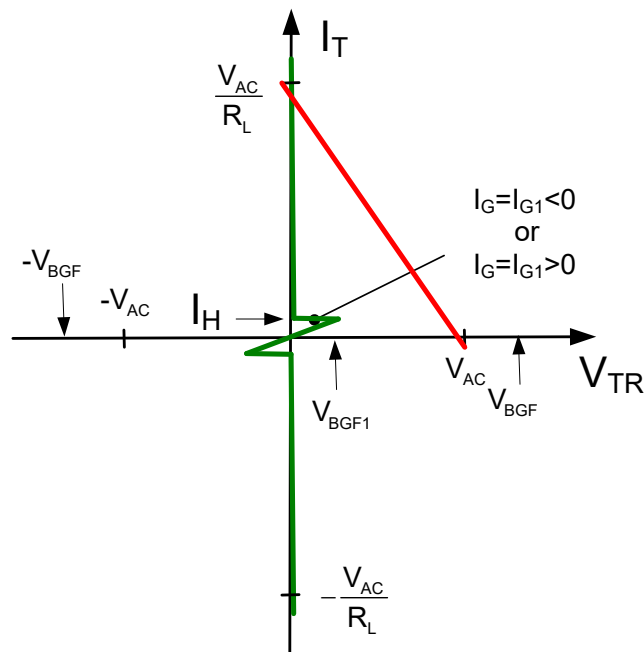
Why?

Because when it goes through 0 there is only one solution and that corresponds to the OFF state



Assume ideal Triac

# The Basic Triac Circuit



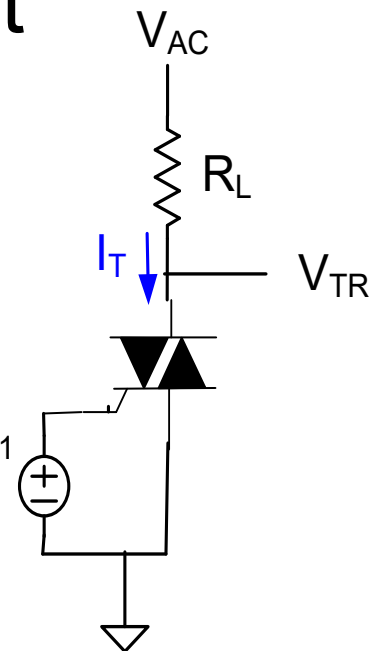
Load Line:  $V_{CC} = I_T R_L + V_{TR}$

Analysis:

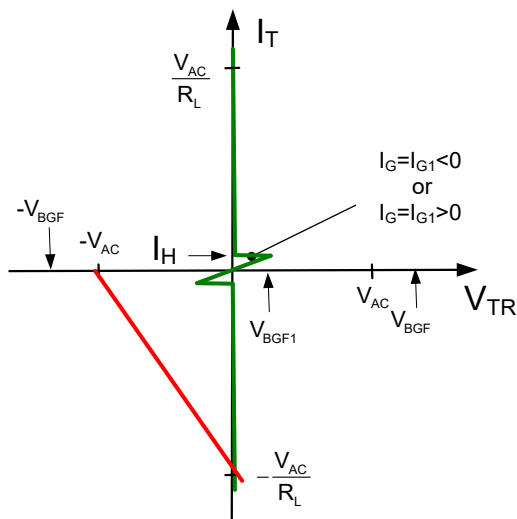
$$V_{AC} = I_T R_L + V_{TR}$$

$$I_T = f_A(V_{TR}, V_{GT1})$$

$V_{GT1}$



Single solution for both positive and negative  $V_{AC}$

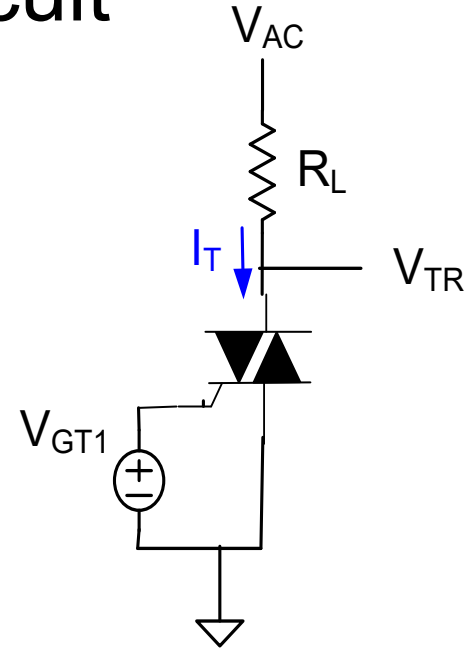
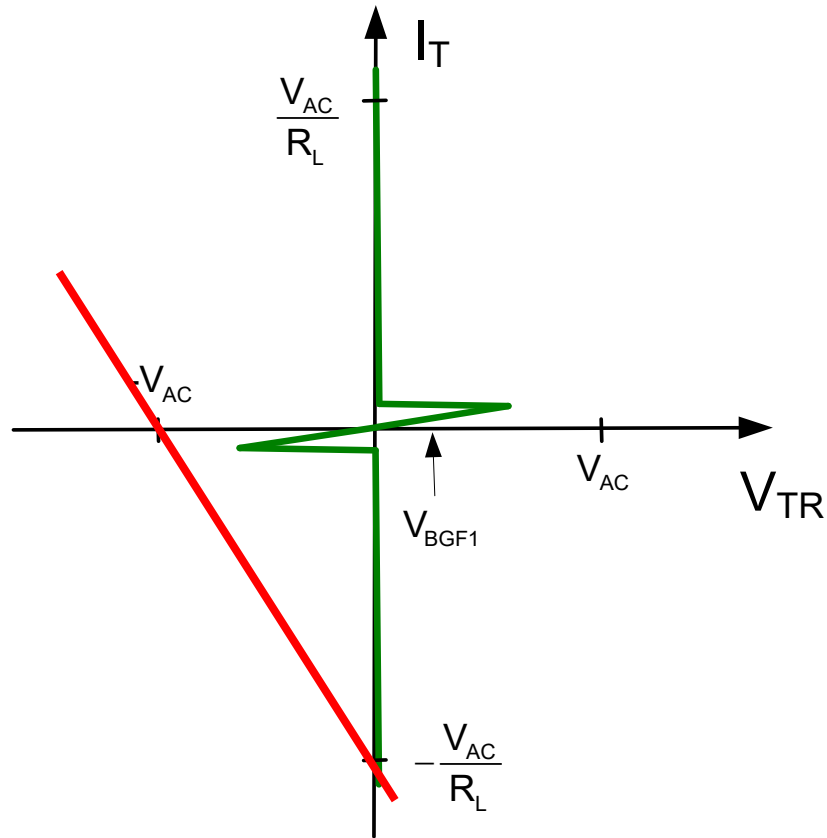


If  $V_{AC}$  is a sinusoidal signal will stay ON

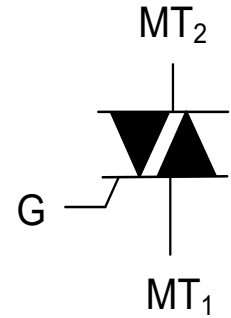
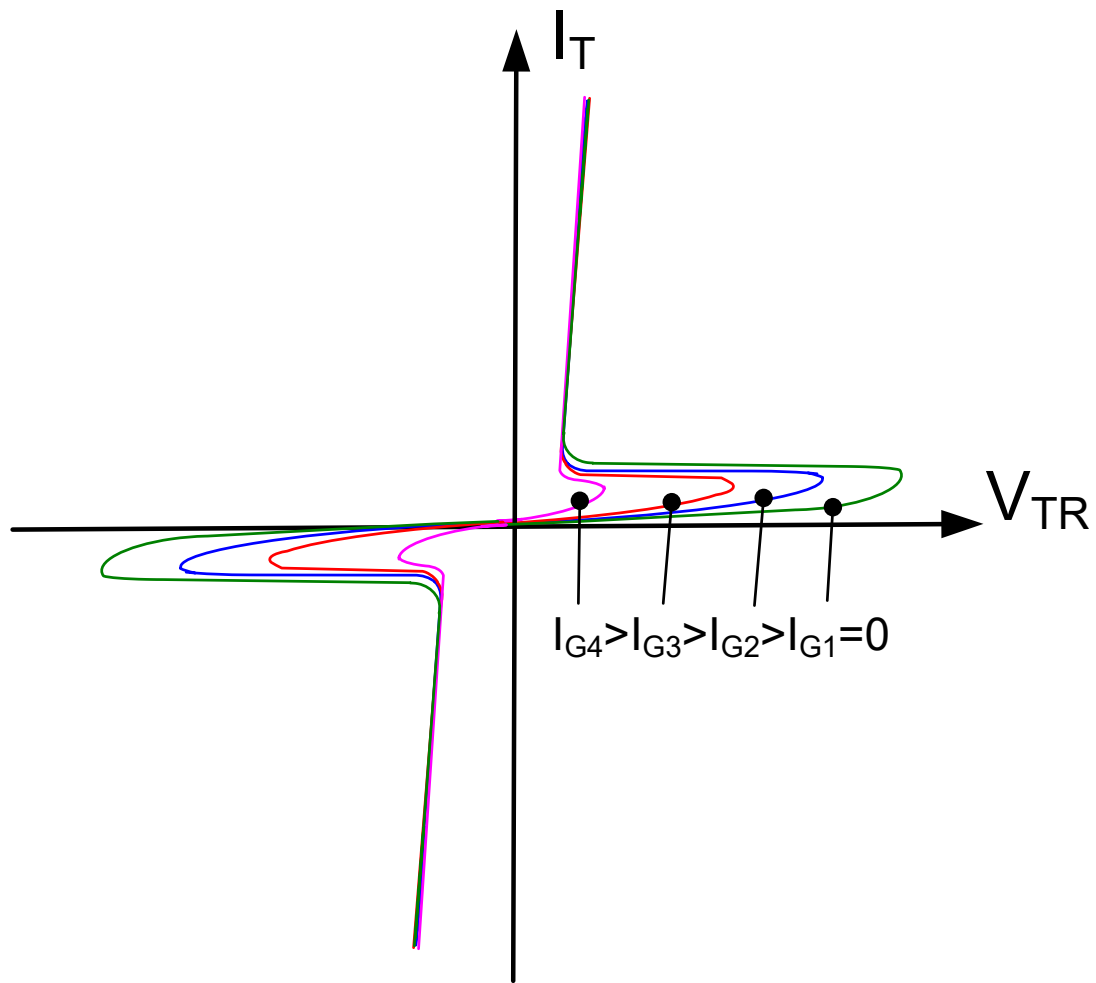
(except for small time when  $I_T = 0$  but then ON and OFF state of Triac do not alter current in circuit)

Assume ideal Triac

# The Basic Triac Circuit

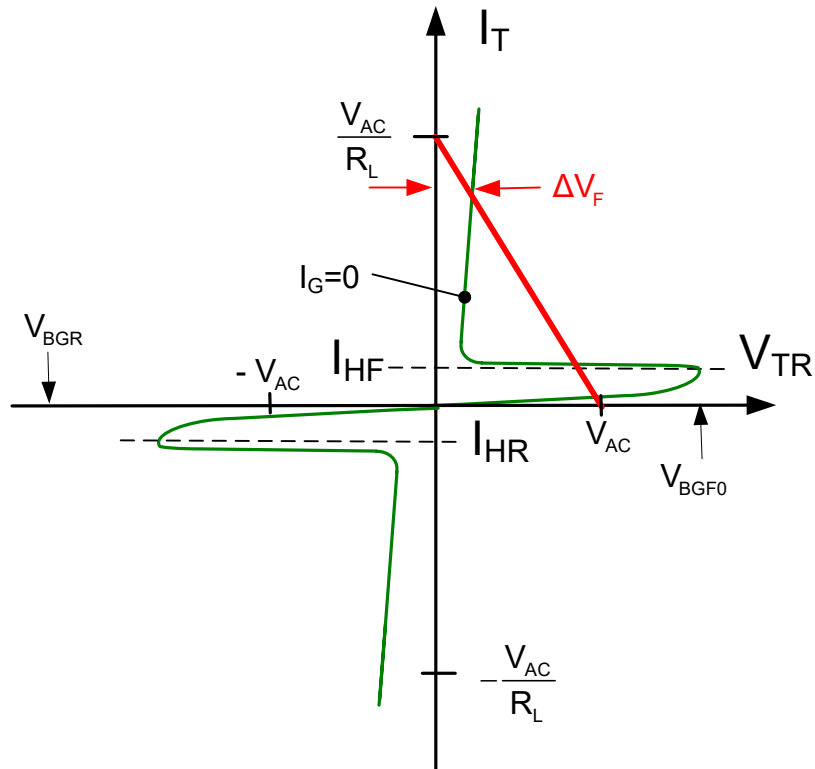


# The Actual Triac

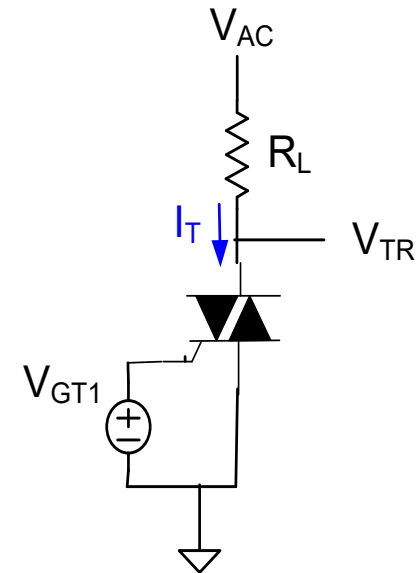




# The Actual Triac in Basic Circuit

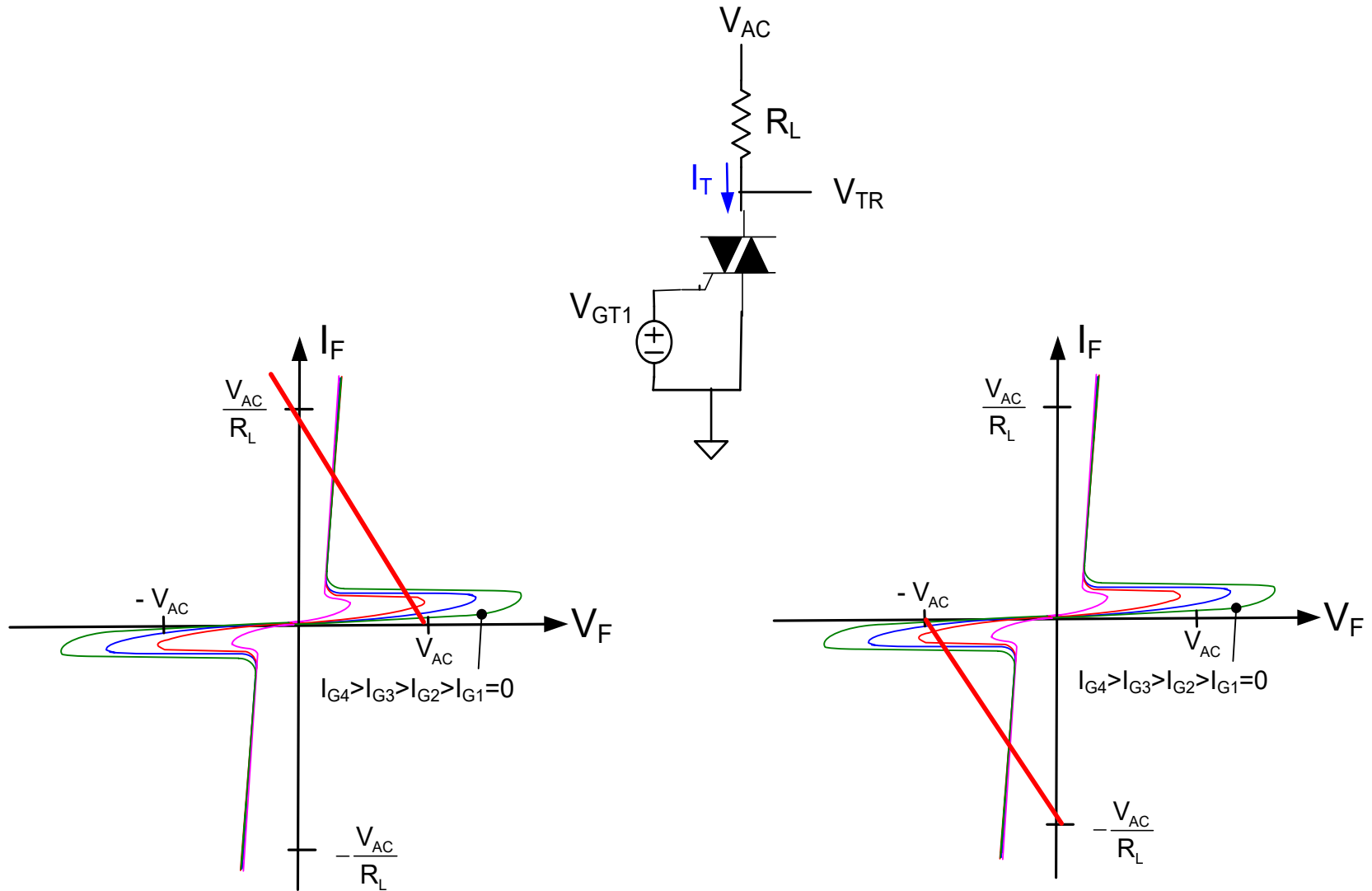


$I_G=0$  State



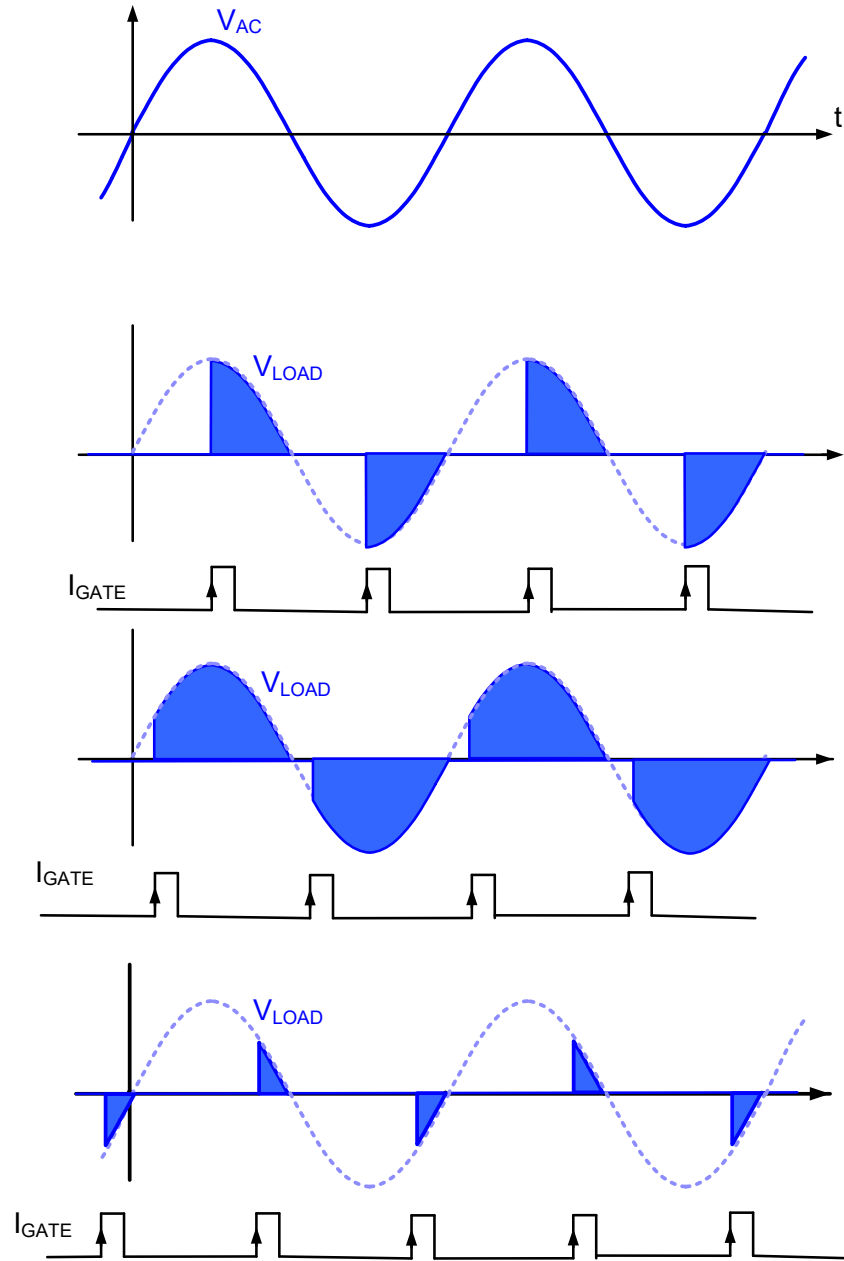
Two stable operating points  
(as long as  $V_{AC}$  not near 0)

# The Actual Triac in Basic Circuit



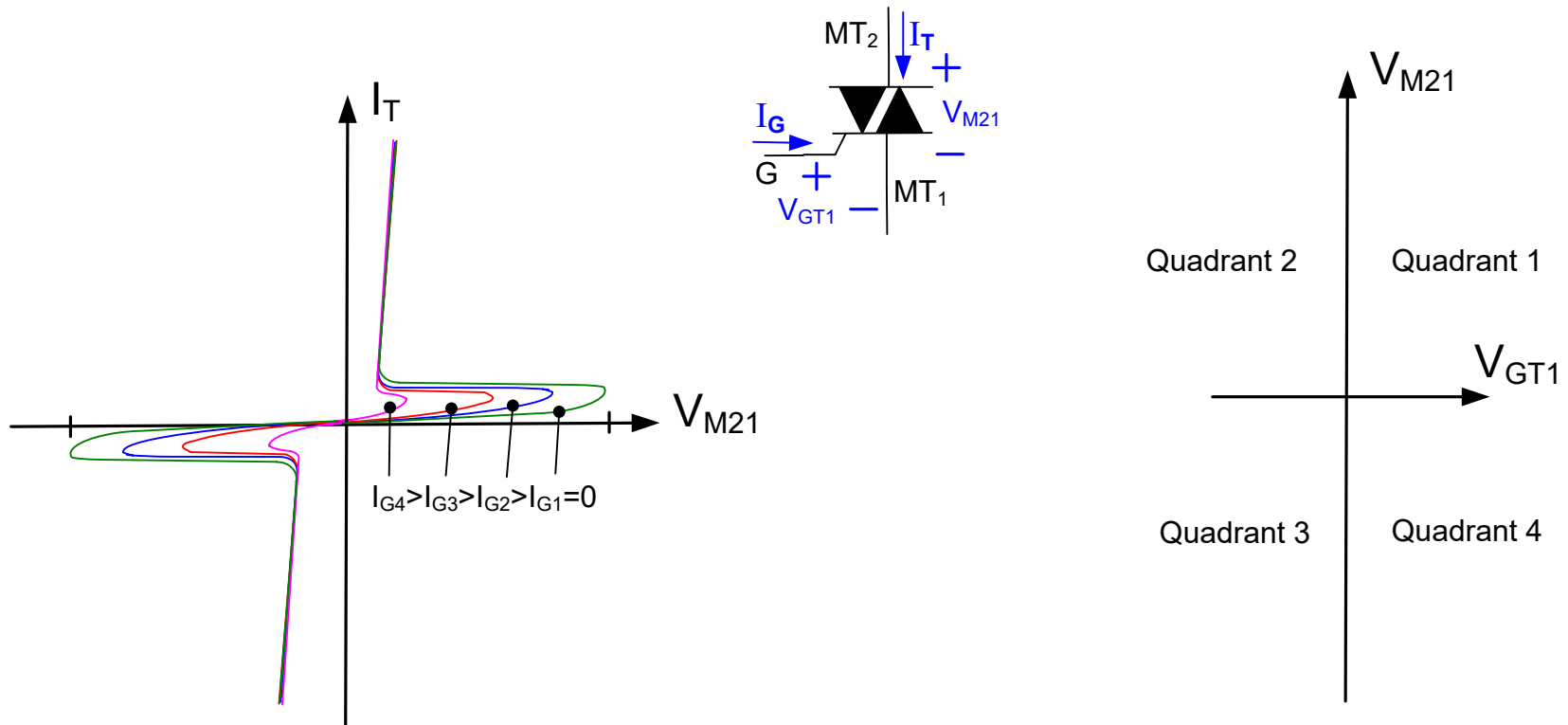
Can turn on for either positive or negative  $V_{AC}$  with single gate signal

# Phase controlled bidirectional switching with Triacs



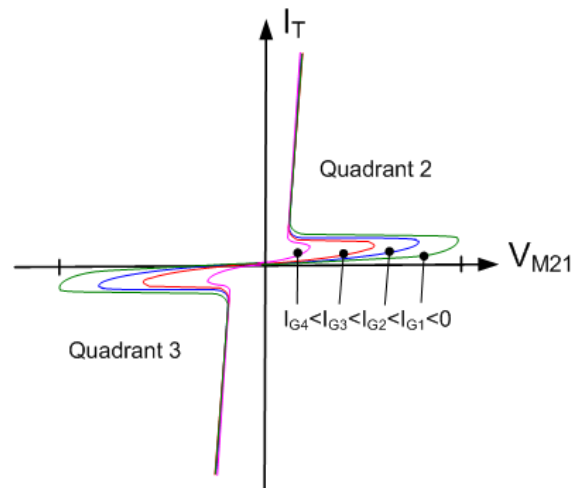
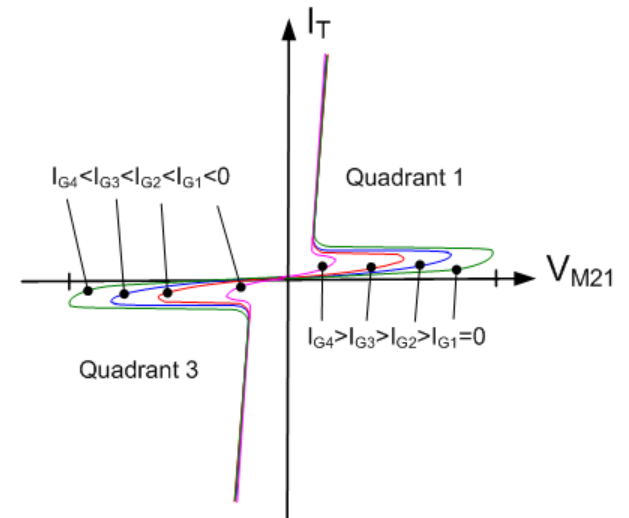
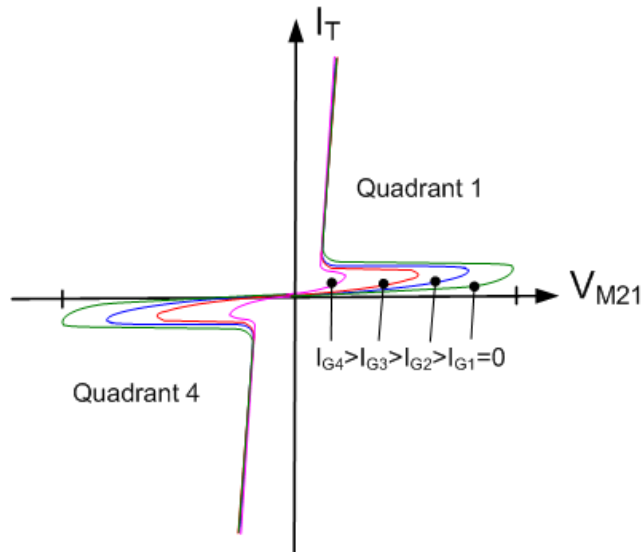
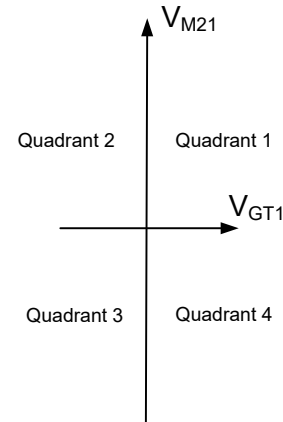
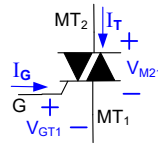
# Quadrants of Operation Defined in $V_{M21}$ - $V_{GT1}$ plane

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

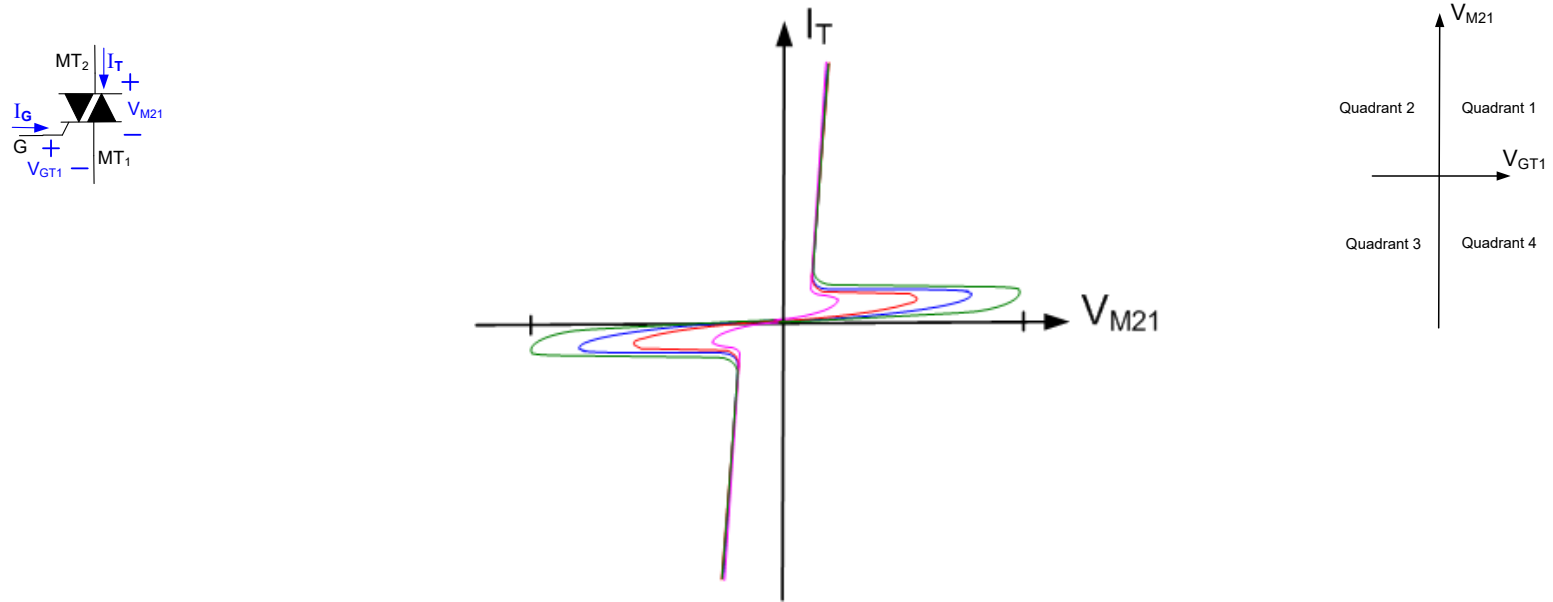


But for any specific circuit, can map quadrants from the  $V_{M21}$ - $V_{GT1}$  plane to  $I_T$ - $V_{M21}$  plane

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



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



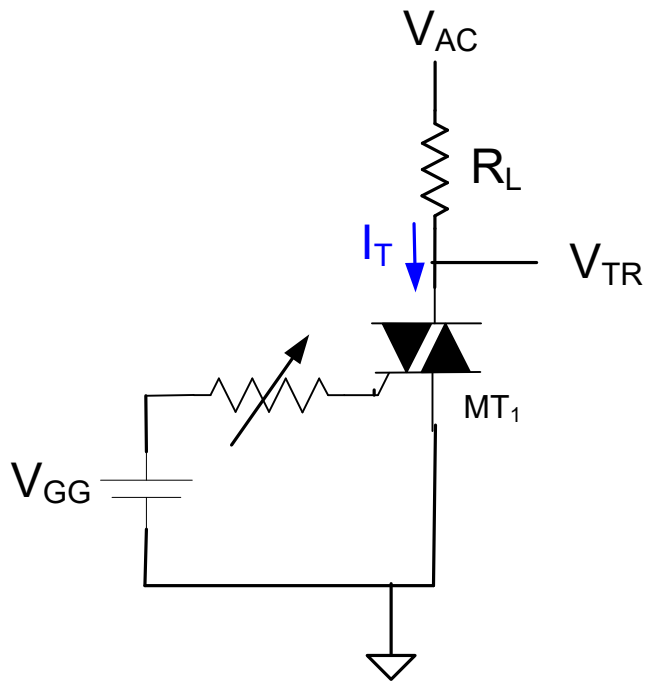
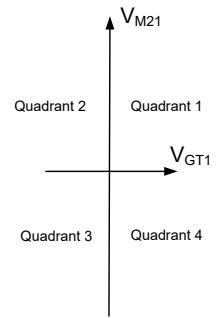
Curves may not be symmetric between  $Q_1$  and  $Q_3$  in the  $I_T$ - $V_{M21}$  plane

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

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)

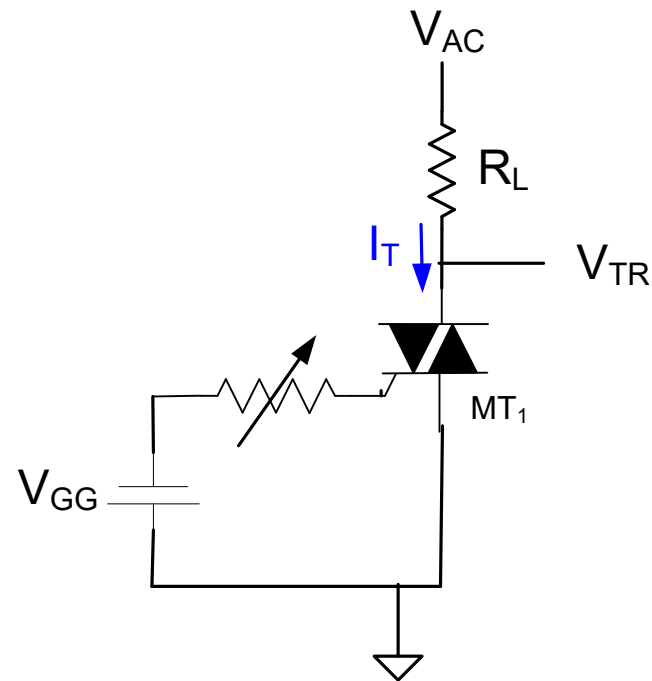
# Some Basic Triac Application Circuits



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

Quad 1 : Quad 4

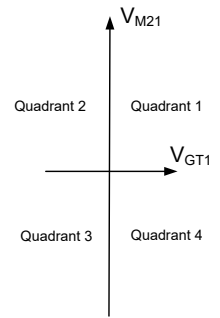
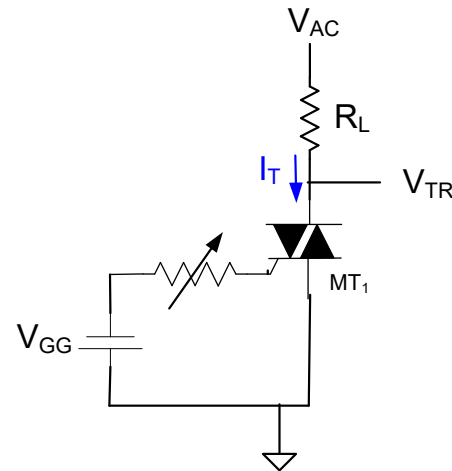
(not attractive because of Quad 4)



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

Quad 2 : Quad 3

# Some Basic Triac Application Circuits



Quad 2 : Quad 3

Limitations ?

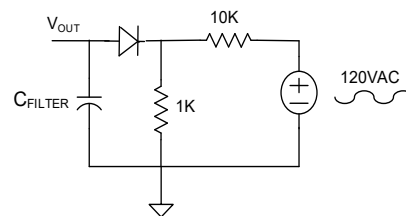
If  $V_{AC}$  is the standard 120VAC line voltage, where do we get the dc power supply?



\$1,607.00

AGILENT TECHNOLOGIES

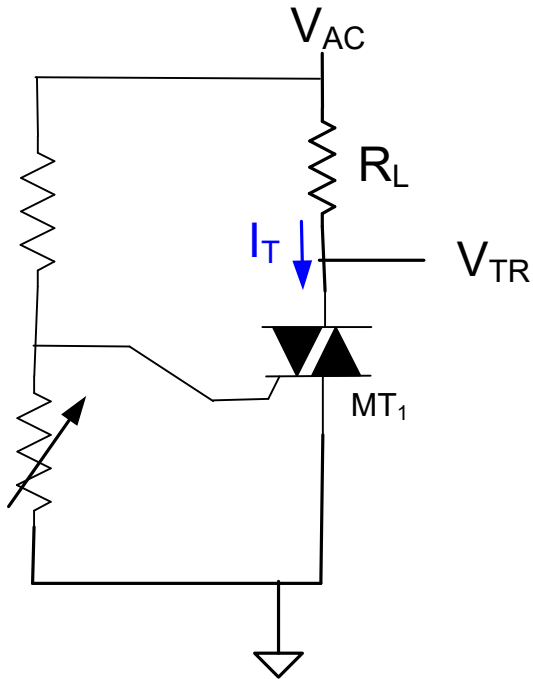
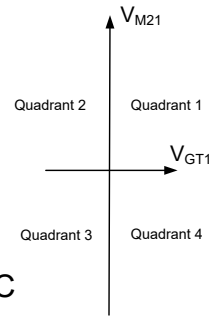
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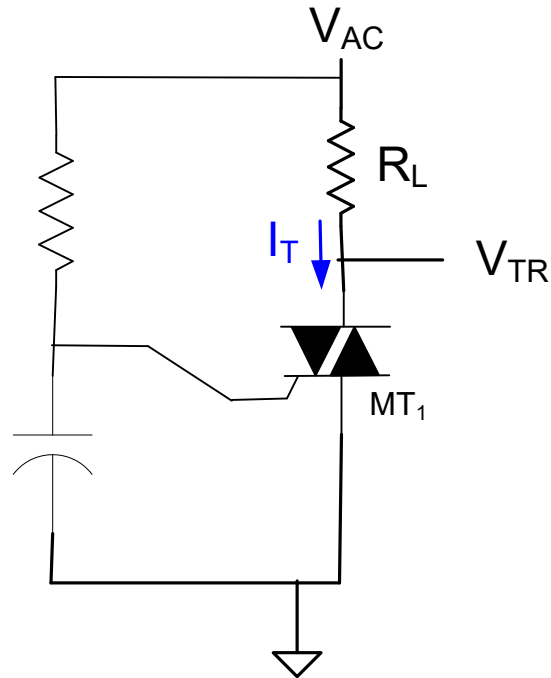
Direct digital control of trigger voltage/current with dedicated IC



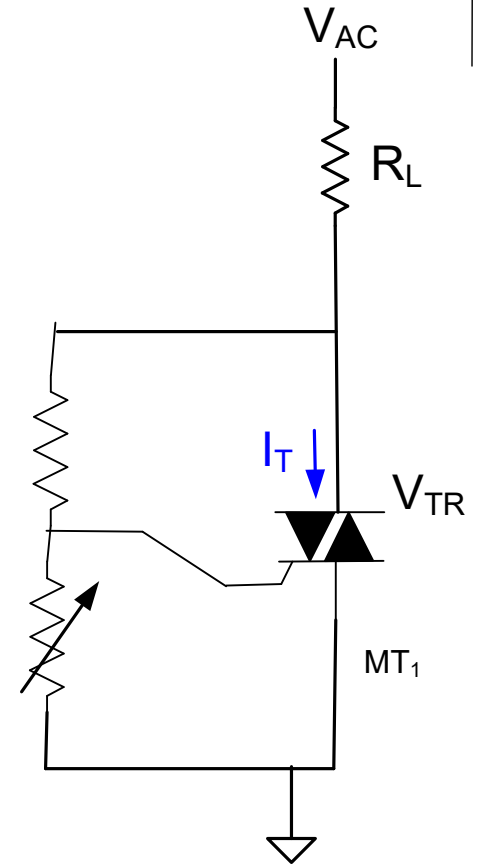
# Some Basic Triac Application Circuits



Quad 1 : Quad 3

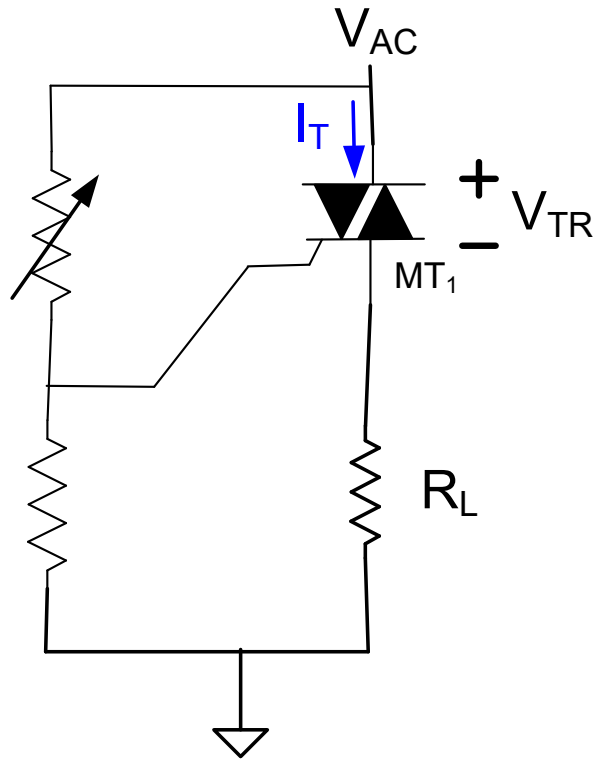
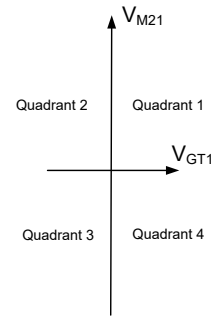


Quad 1 : Quad 3



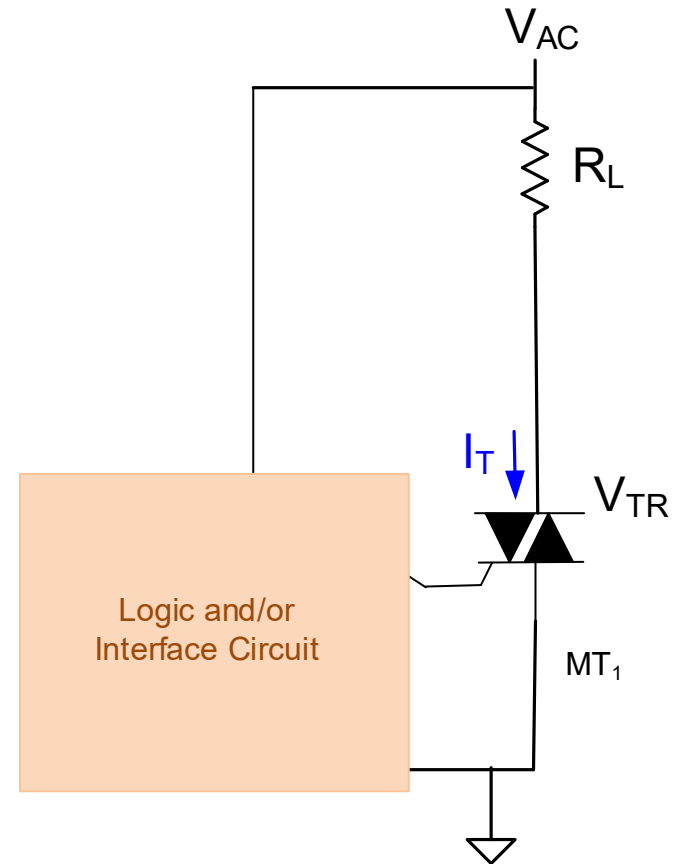
Quad 1 : Quad 3

# 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 as in incandescent light dimmers to very high current levels

$I_{\text{TRIAC}}$  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:



**PT40QP<sub>x</sub>45**

**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

$V_{\text{DRM}}$	<b>4500V</b>
$I_{\text{T(AV)}}$	<b>760A</b>
$I_{\text{TSM}}$	<b>13000A</b>
$di/dt$	<b>5000A/<math>\mu</math>s</b>

$I_{\text{TSM}}$  is the non-repetitive surge peak current

Important parameter to consider when switching inductive loads (motors)

From ABB Web Site

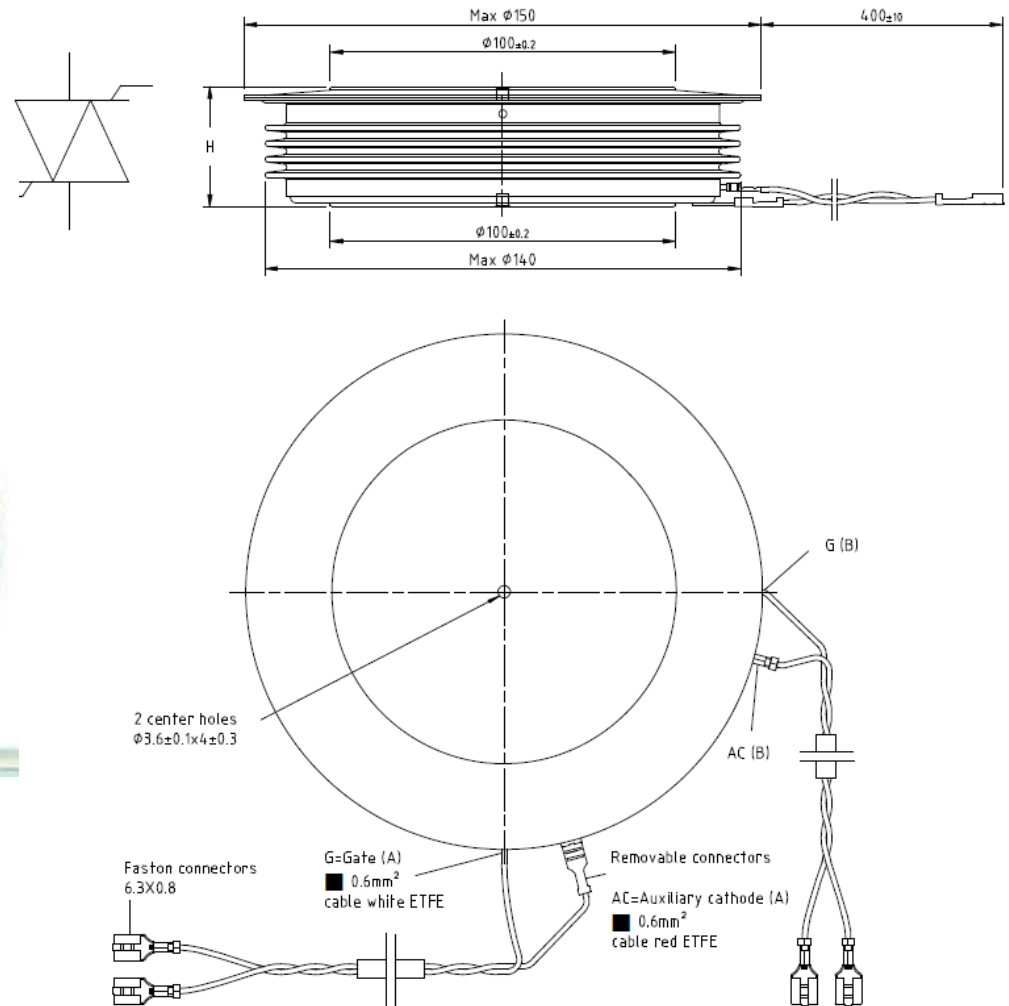
$V_{RM}$	=	6500 V
$I_{T(AV)M}$	=	1405 A
$I_{T(RMS)}$	=	2205 A
$I_{TSM}$	=	$22 \times 10^3$ A
$V_{T0}$	=	1.2 V
$r_T$	=	0.6 m $\Omega$

## Bi-Directional Control Thyristor

# 5STB 13N6500



Diameter = 140mm



Thanks to Prof. Ajjarapu for providing the following slides:

## THE BIDIRECTIONAL CONTROL THYRISTOR (BCT)

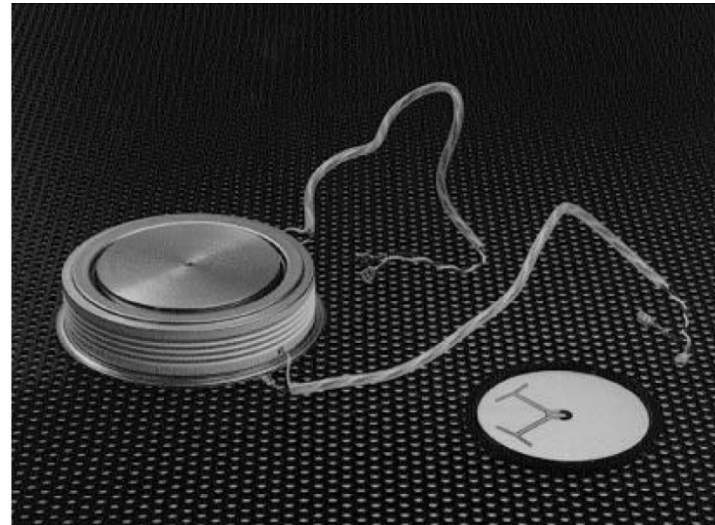
by

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.





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:

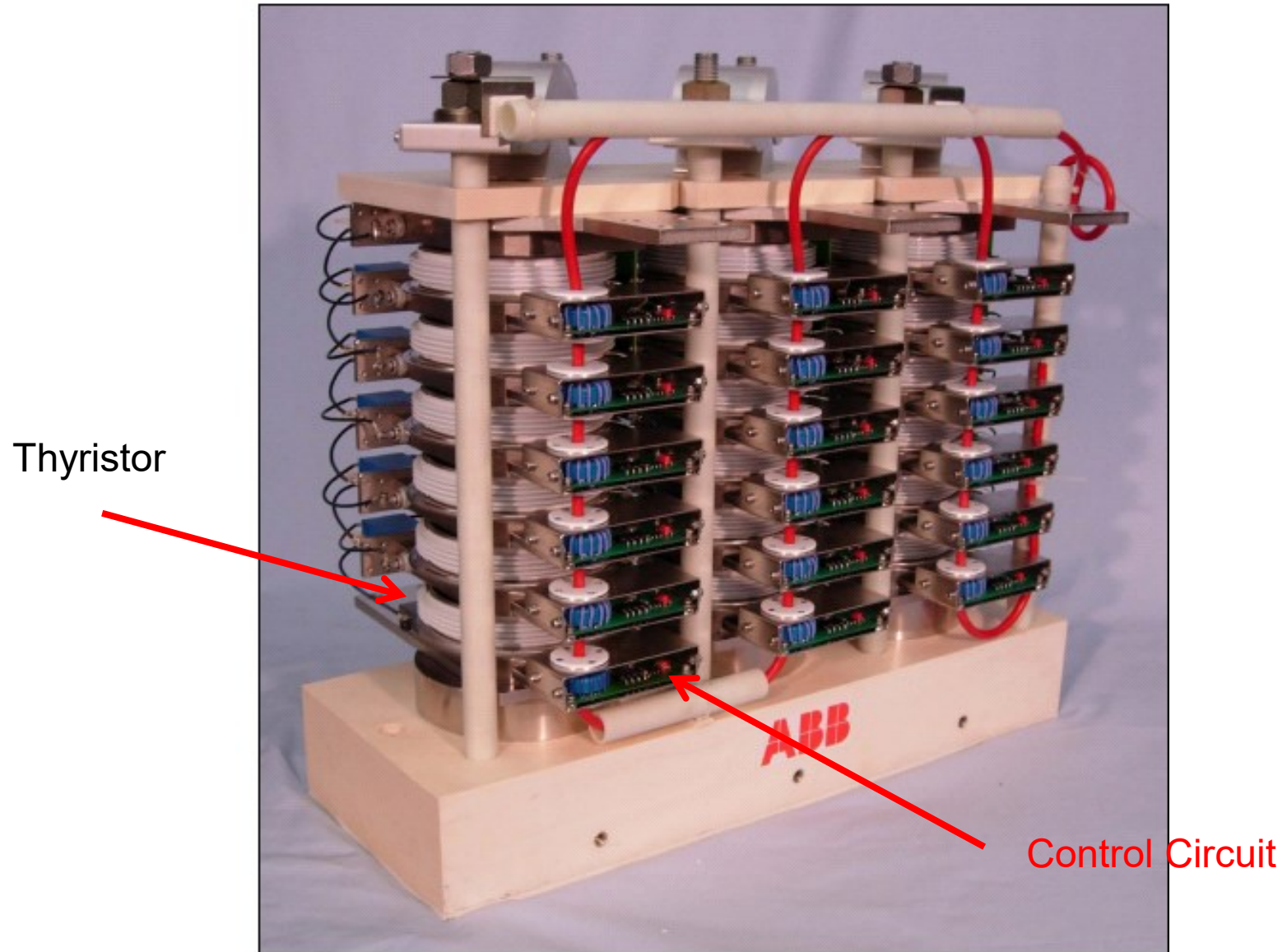


Fig.3: Thyristor Switch Assembly A-STP 5742U-18-CC

Thanks to Prof. Ajjarapu for providing the following slides:

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

Gate Lead  
(White)

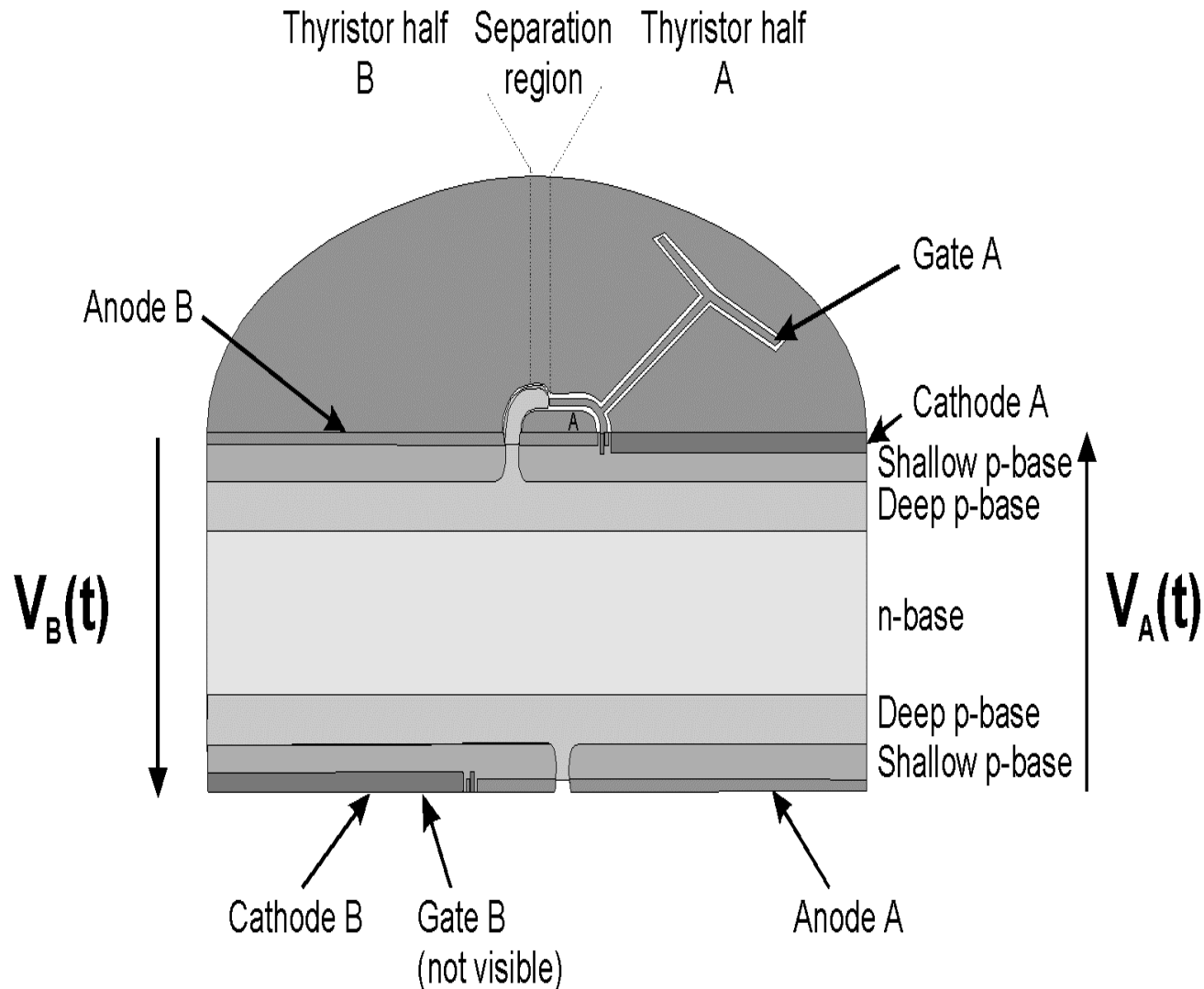
Cathode Lead



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

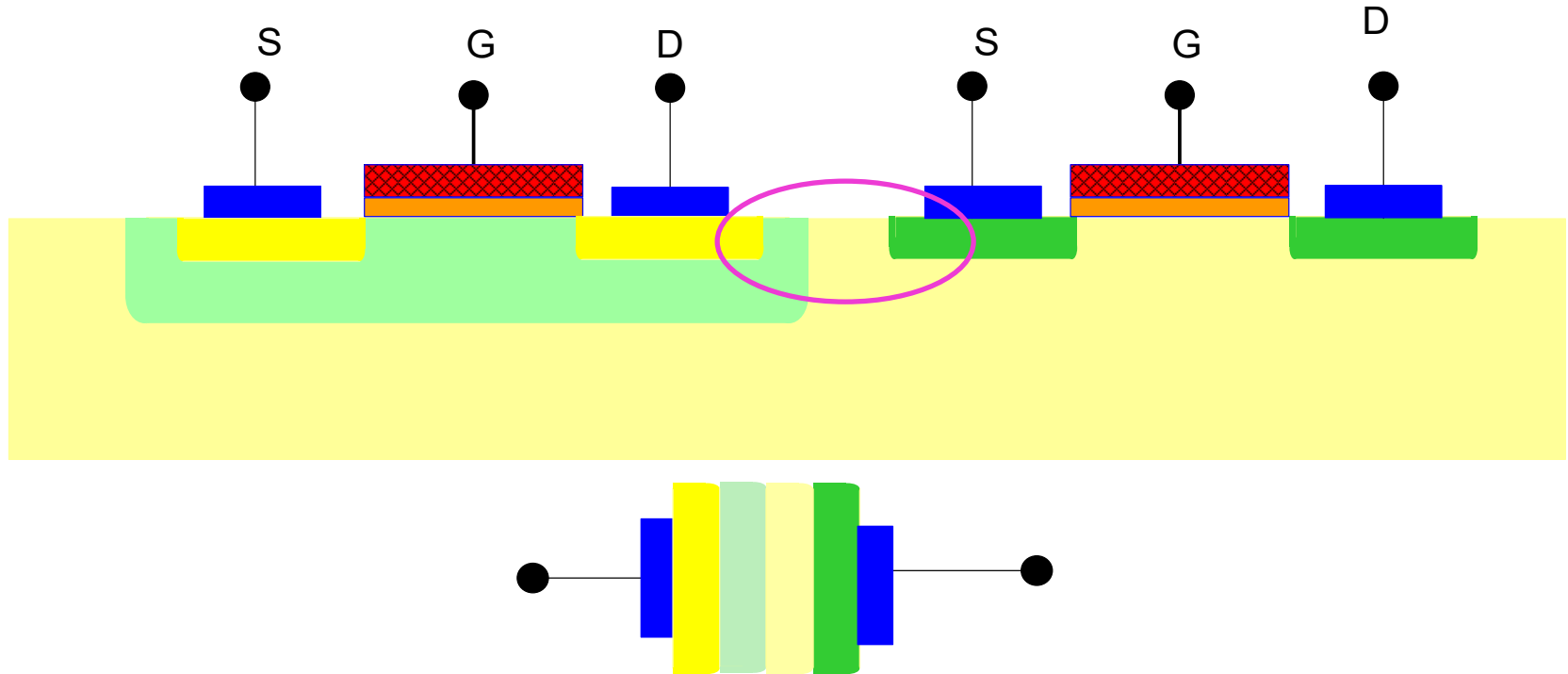
 The bad

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**





Stay Safe and Stay Healthy !

End of Lecture 30