EE 330
Lecture 26

Thyristors

- SCR
- TRIAC

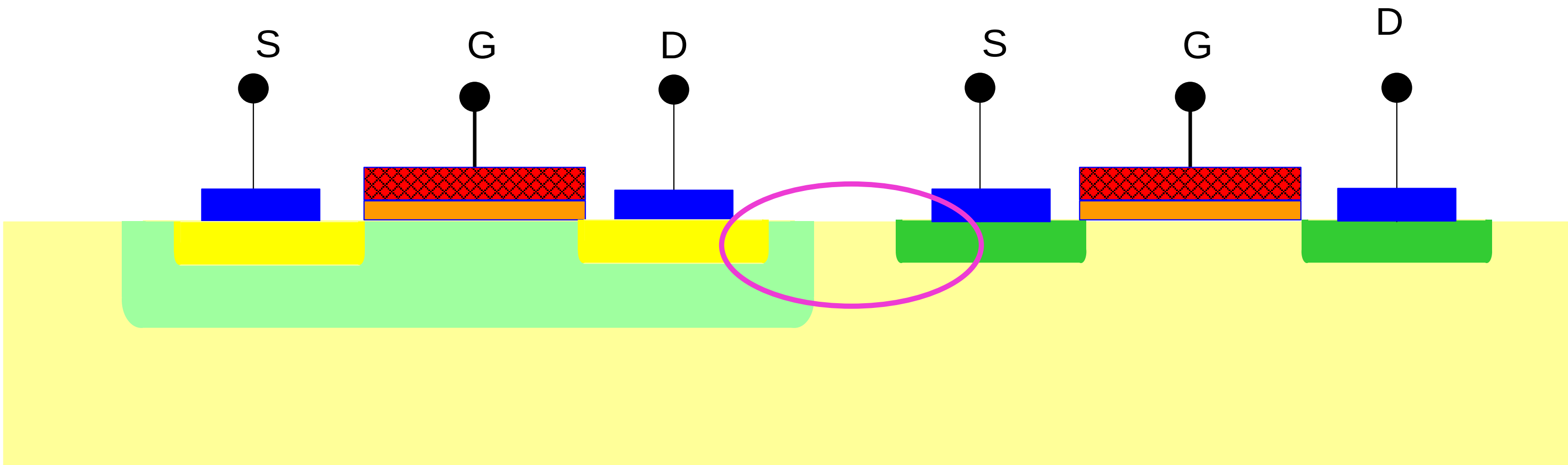
Area Comparison between BJT and MOSFET

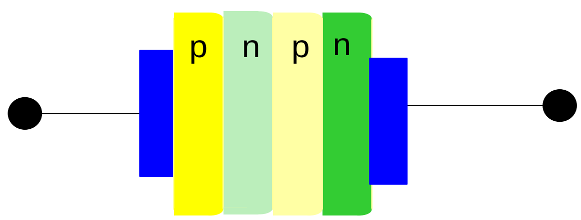
- BJT Area = 3600 λ^2
- n-channel MOSFET Area = 168 λ^2
- Area Ratio = 21:1

The Thyristor

A bipolar device in CMOS Processes

Consider a Bulk-CMOS Process





Have formed a lateral pnpn device !

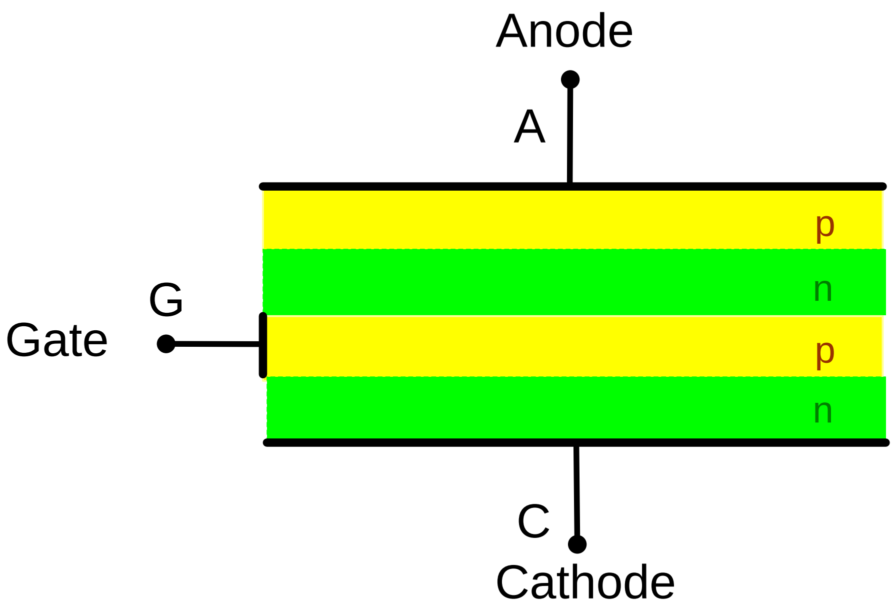
Will spend some time studying pnpn devices

Review from Last Lecture

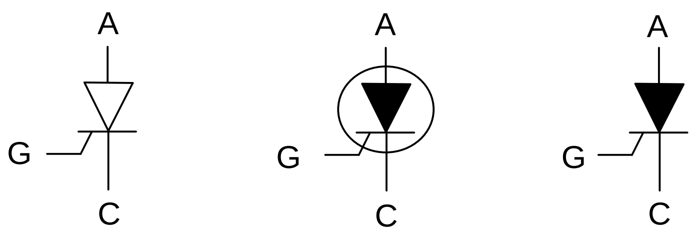
The SCR

Silicon Controlled Rectifier

- Widely used to switch large resistive or inductive loads
- Widely used in the power electronics field
- Widely used in consumer electronic to interface between logic and power



Usually made by diffusions in silicon



Symbols

Consider first how this 4-layer 3-junction device operates

Variation of Current Gain (β) with Bias for BJT

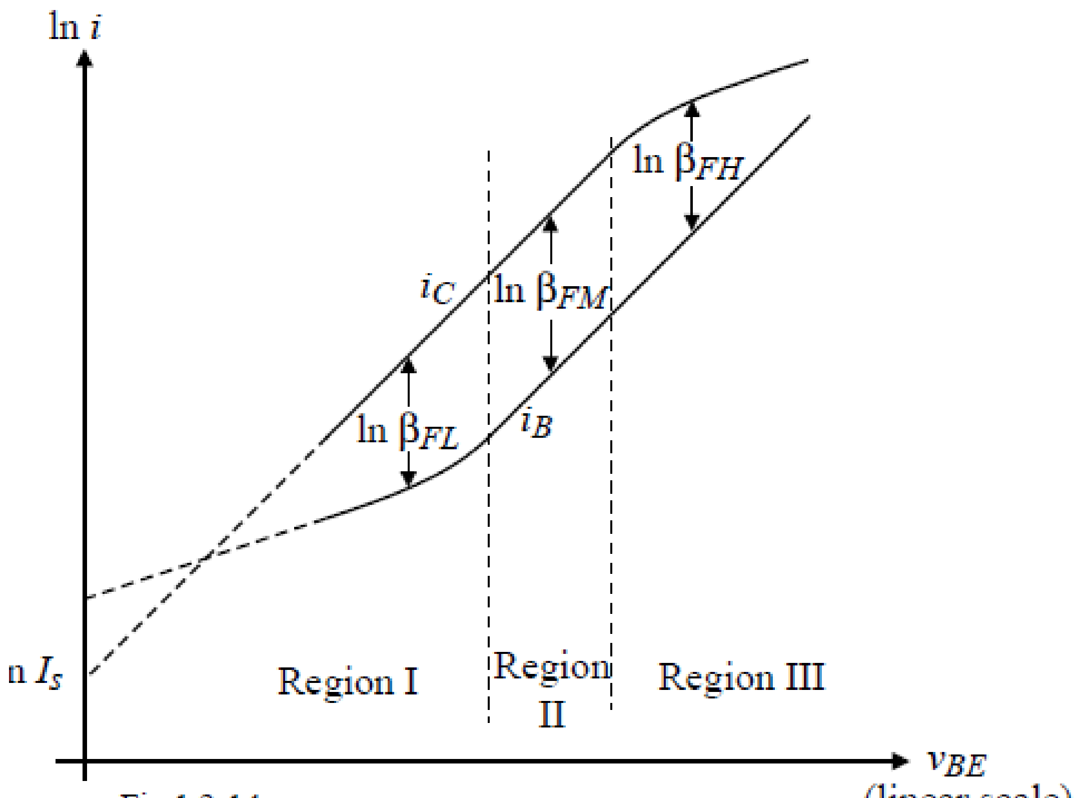


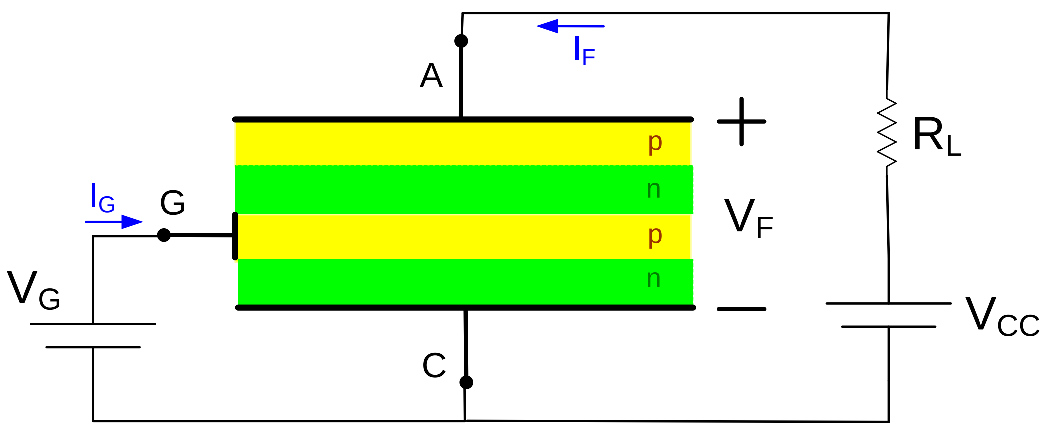
Fig.1.3-14

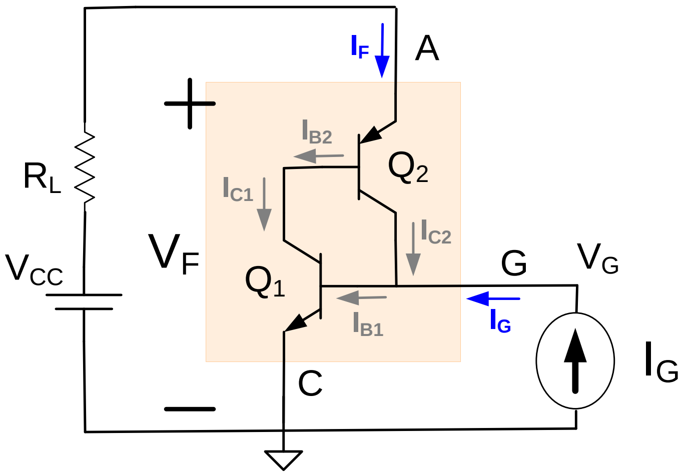
Note that current gain gets very small at low base current levels

Review from Last Lecture

Operation of the SCR

Consider a modified application by adding a load (depicted as R_L)





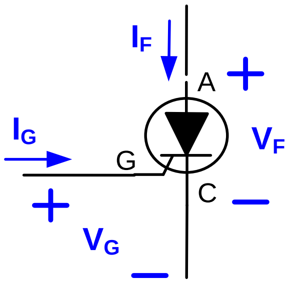
All operation is as before, but now, after the triggering occurs, the voltage V_F will drop to approximately 0.8 V and the voltage V_{CC}-.8 will appear across R_L

If V_{CC} is very large, the SCR has effectively served as a switch putting V_{CC} across the load and after triggering occurs, I_G can be removed!

But, how can we turn it off? Will discuss that later

Review from Last Lecture

Operation of the SCR



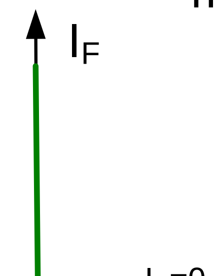
The Ideal SCR $\quad I_F = f(V_F, V_G)$

I_H is very small

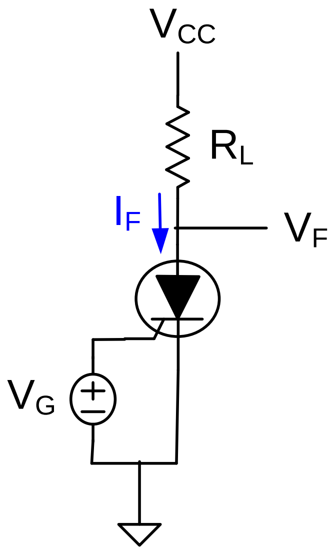
I_{G1} is small (but not too small)

$I_F = f(V_F, V_G)$ called the SCR model

As for MOSFET, Diode, and BJT, several models for SCR can be developed



Operation of the SCR



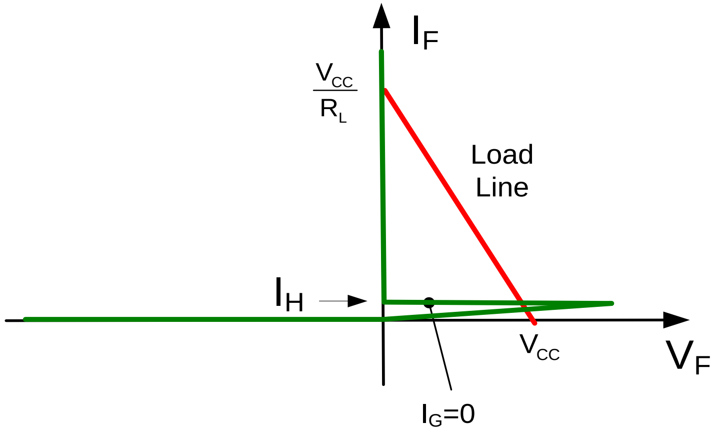
Operation with the Ideal SCR

Load Line: $V_{CC} = I_F R_L + V_F$

Analysis:

$$\left.\begin{aligned} V_{CC} &= I_F R_L + V_F \\ I_{FI} &= f(V_F, V_G) \end{aligned}\right\}$$

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



when I_G=0

Note three intersection points
Two (upper and lower) are stable equilibrium points, one is not

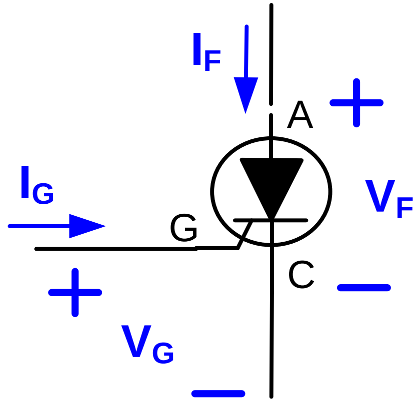
When operating at upper point, V_F=0 so V_{CC} appears across R_L We say SCR is ON

When operating at lower point, I_F approx 0 so no signal across R_L We say SCR is OFF

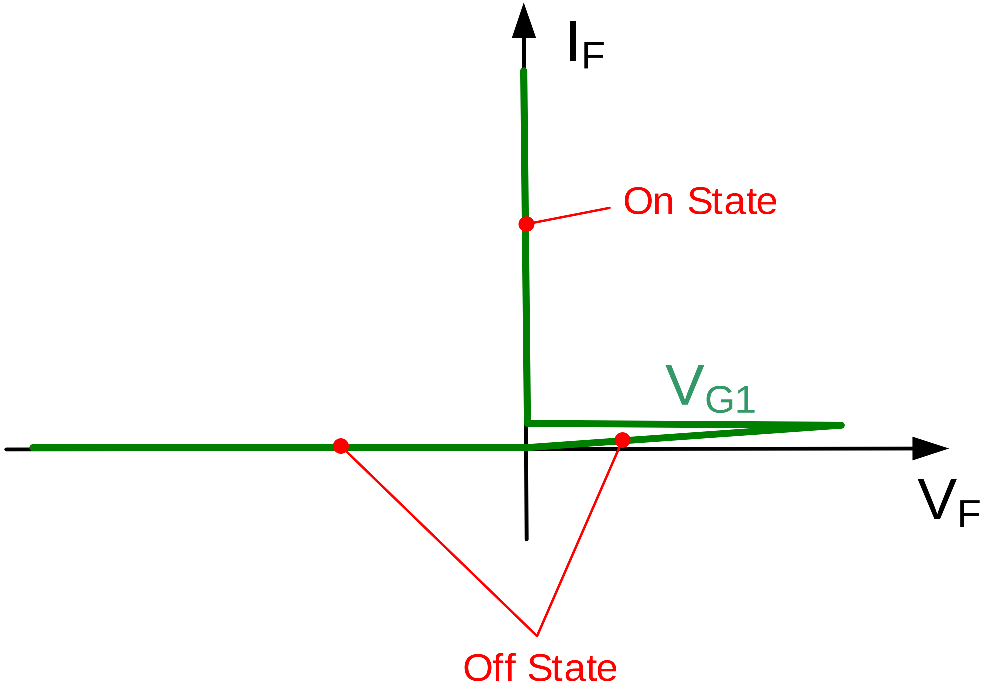
When I_G=0, will stay in whatever state it was in

Operation of the SCR

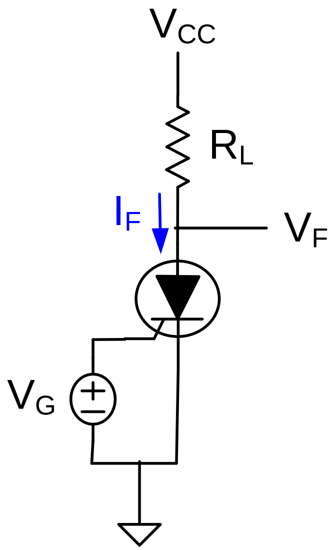
Operation with the Ideal SCR



$$I_{FI} = f\left(V_F, V_G\right)$$

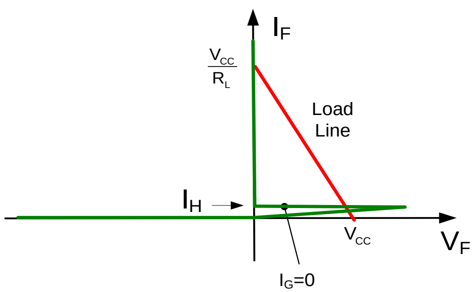


Operation of the SCR

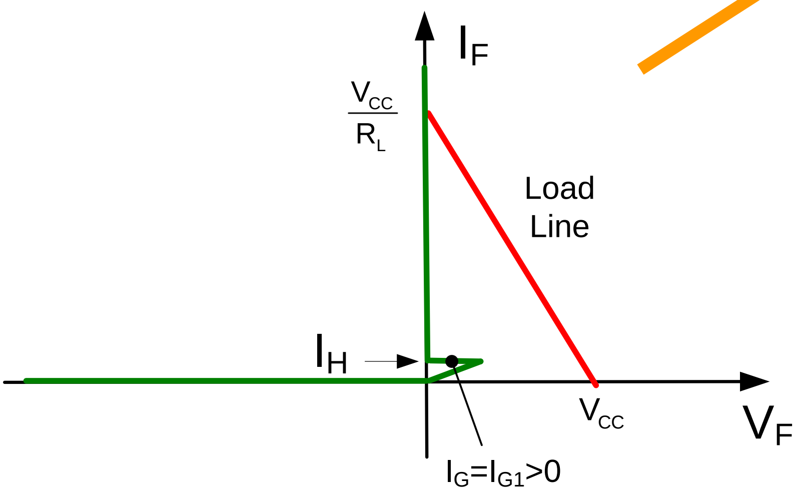


Operation with the Ideal SCR

Now assume it was initially in the OFF state and then a gate current was applied



$$\left.\begin{aligned} V_{CC} &= I_F R_L + V_F \\ I_{FI} &= f\left(V_F, V_G\right) \end{aligned}\right\}$$



Now there is a single intersection point so a unique solution

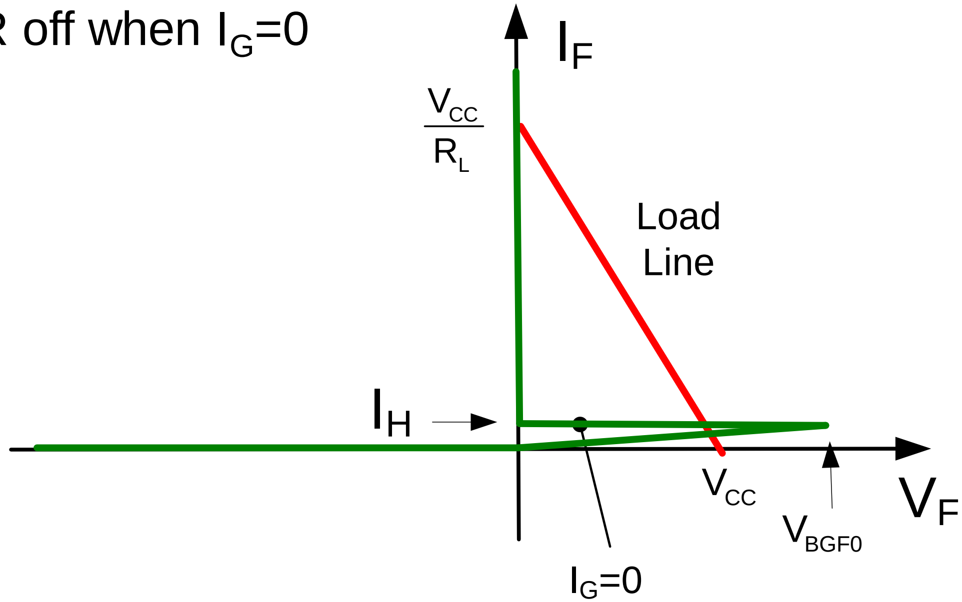
The SCR is now ON

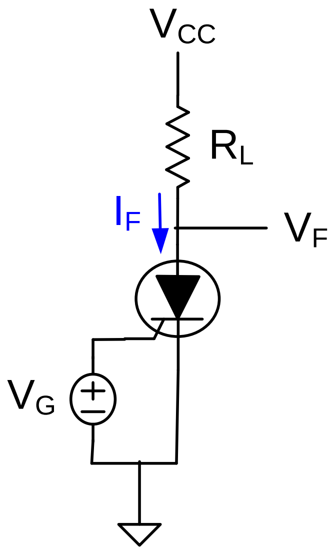
Removing the gate current will return to the previous solution (which has 3 intersection points) but it will remain in the ON state

Operation of the SCR

Operation with the Ideal SCR

Turning SCR off when $I_G=0$





Reduce V_{CC} so that V_{CC}/R_L goes below I_H

This will provide a single intersection point

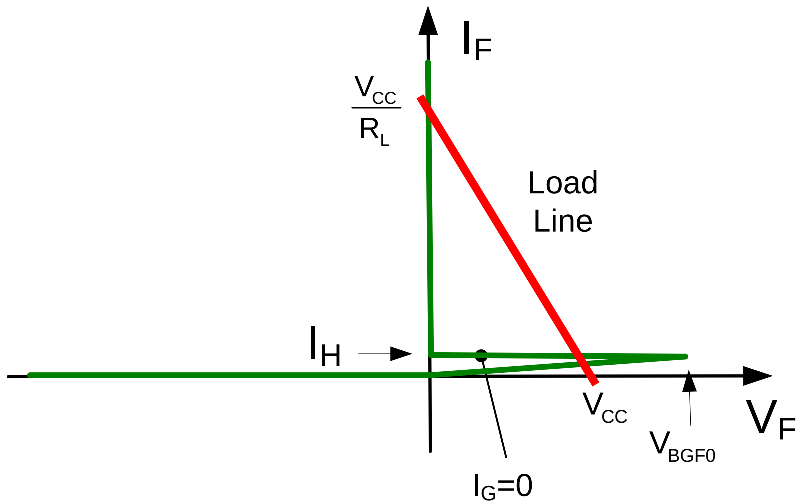
V_{CC} can then be increased again and SCR will stay off

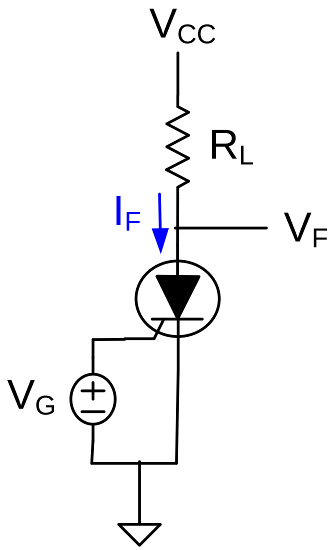
Must not increase V_{CC} much above V_{BGF0} else will turn on

Operation of the SCR

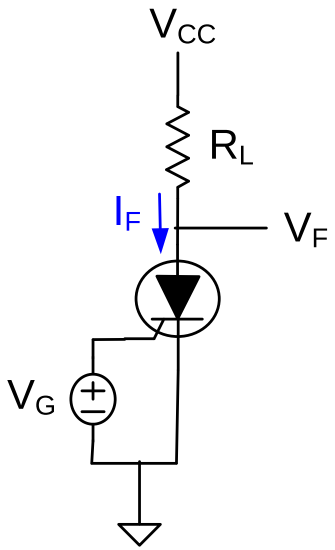
Operation with the Ideal SCR

Turning SCR off when I_G=0





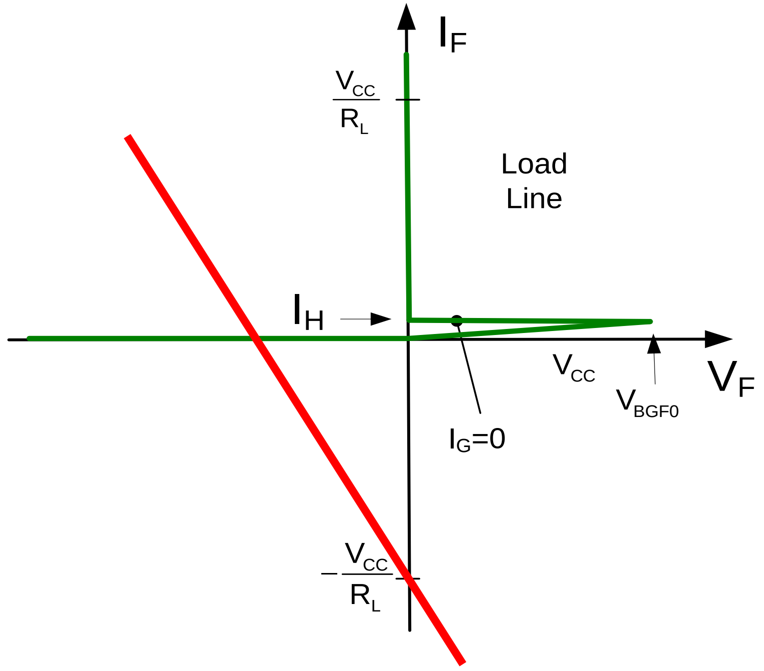
Operation of the SCR



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

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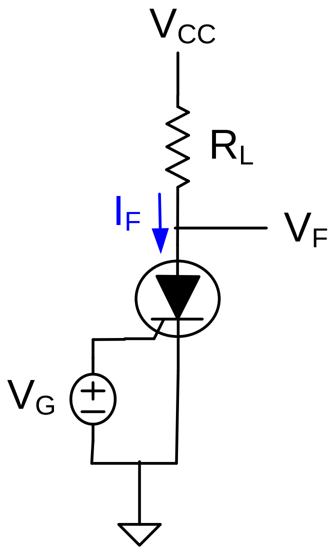
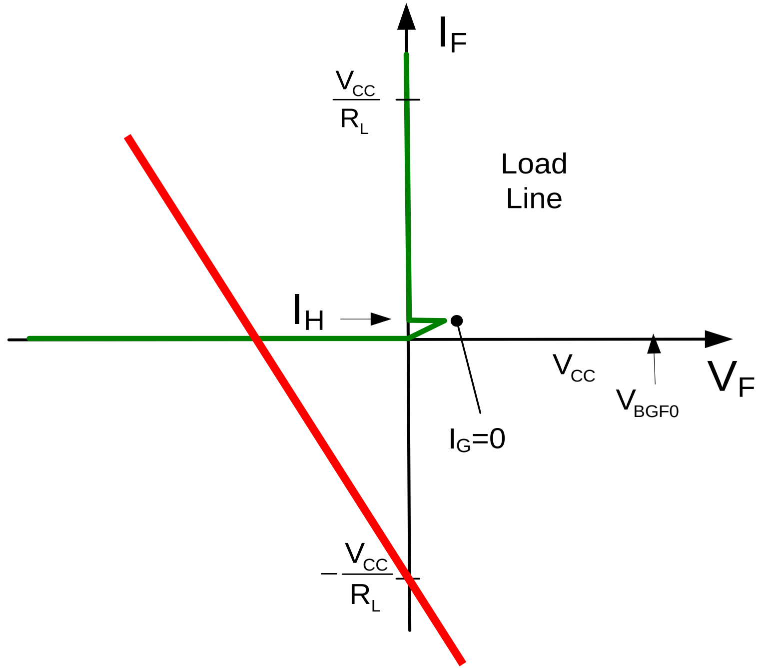
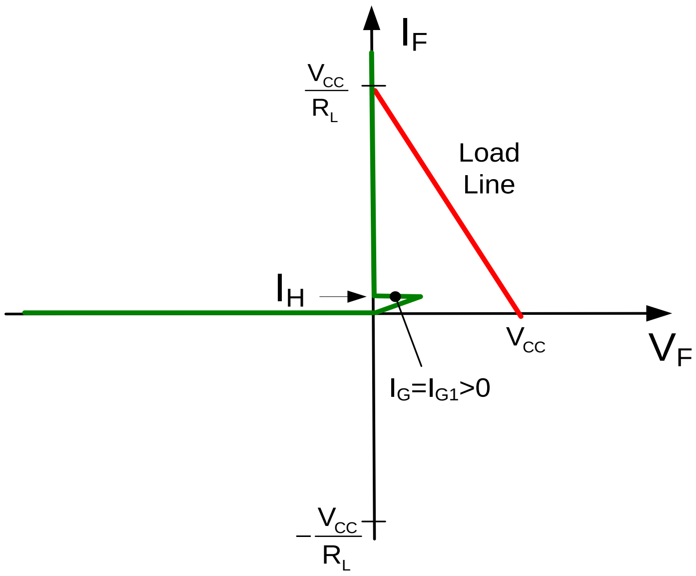


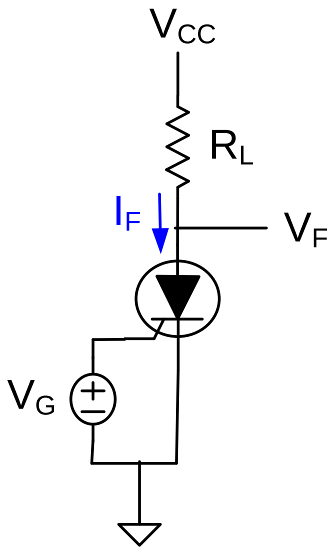


Operation of the SCR

Operation with the Ideal SCR

Turning SCR off when $I_G>0$





Reduce V_{CC} so that V_{CC}/R_L goes below I_H

This will provide a single intersection point

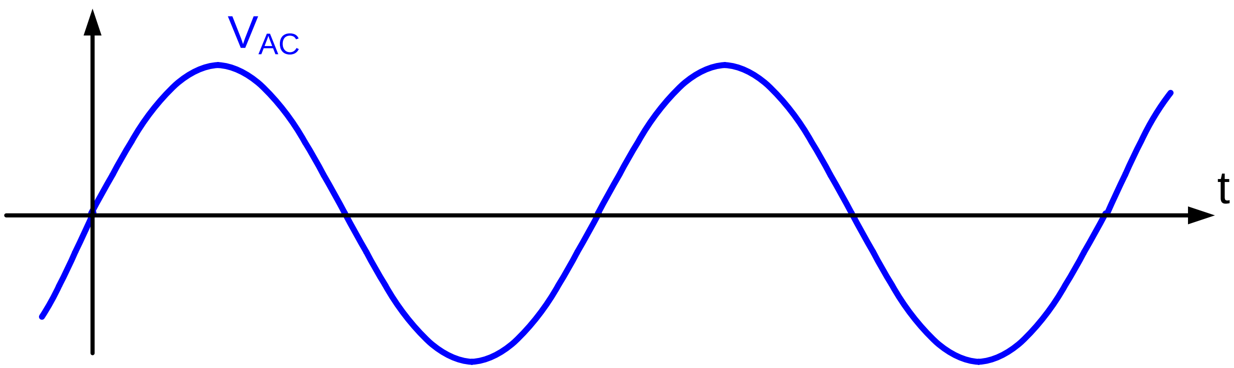
But when V_{CC} is then increased SCR will again turn on

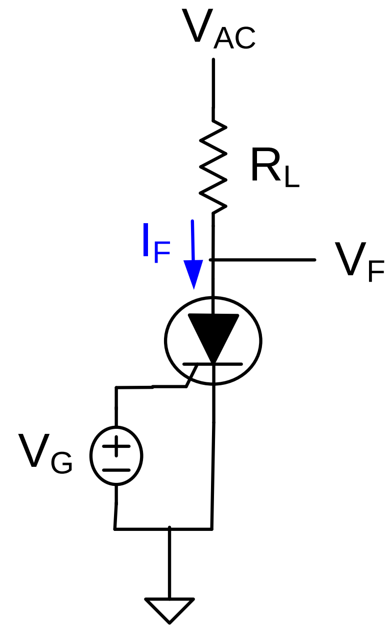
Not practical to turn it off if I_G is very large

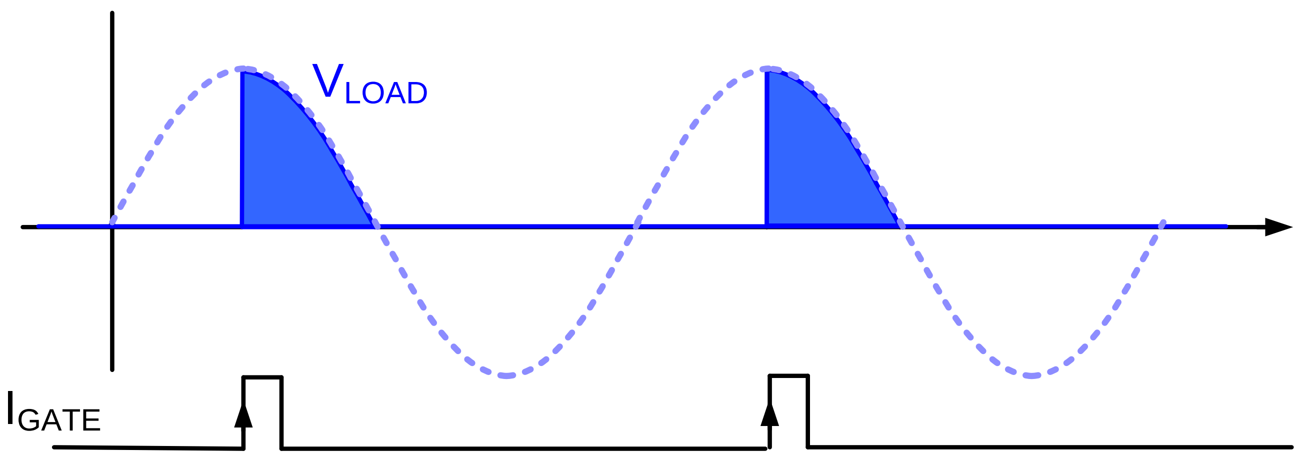
Operation of the SCR

Operation with the Ideal SCR

Duty cycle control of R_L



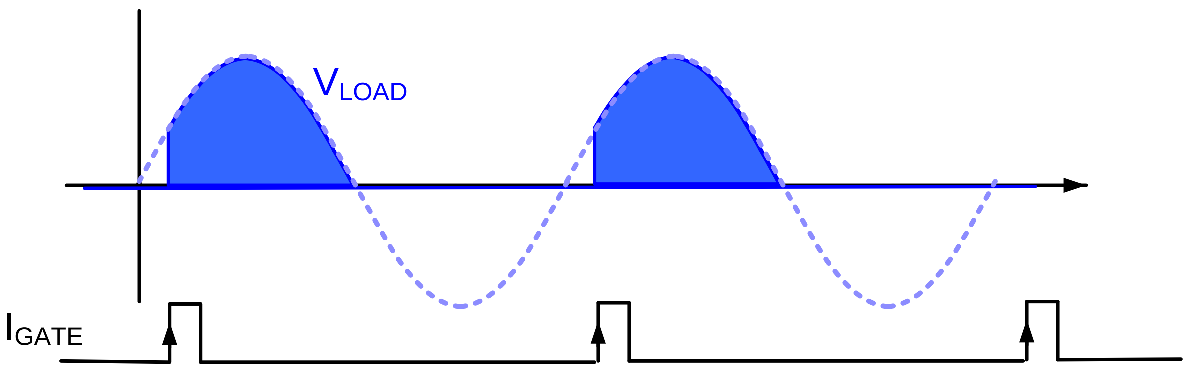


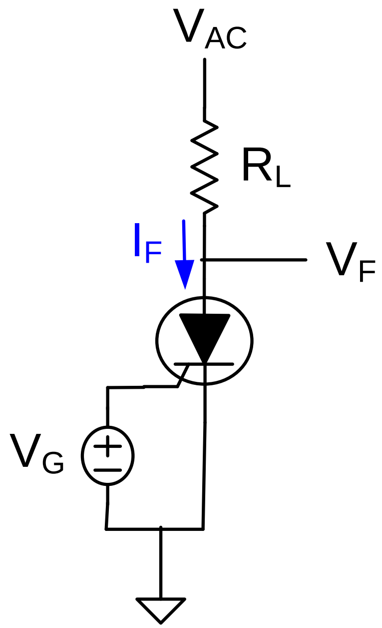


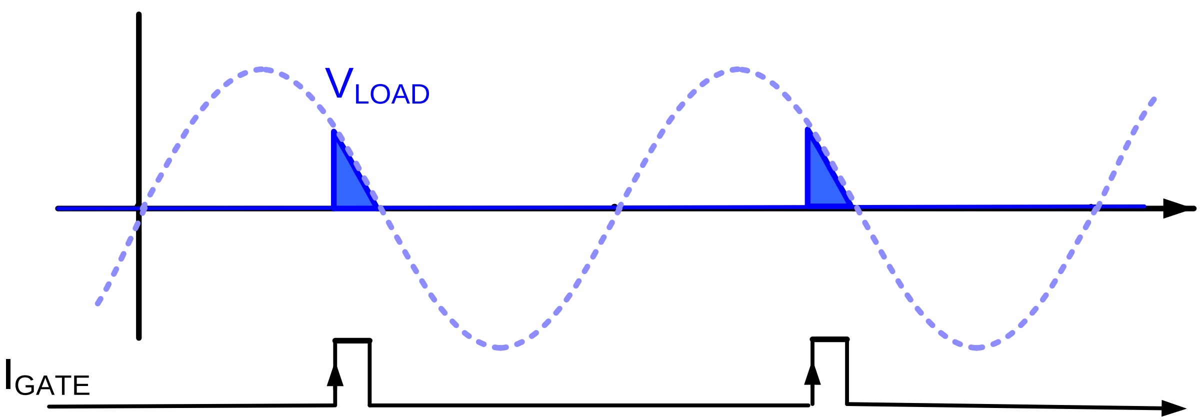
Operation of the SCR

Operation with the Ideal SCR

Duty cycle control of R_L



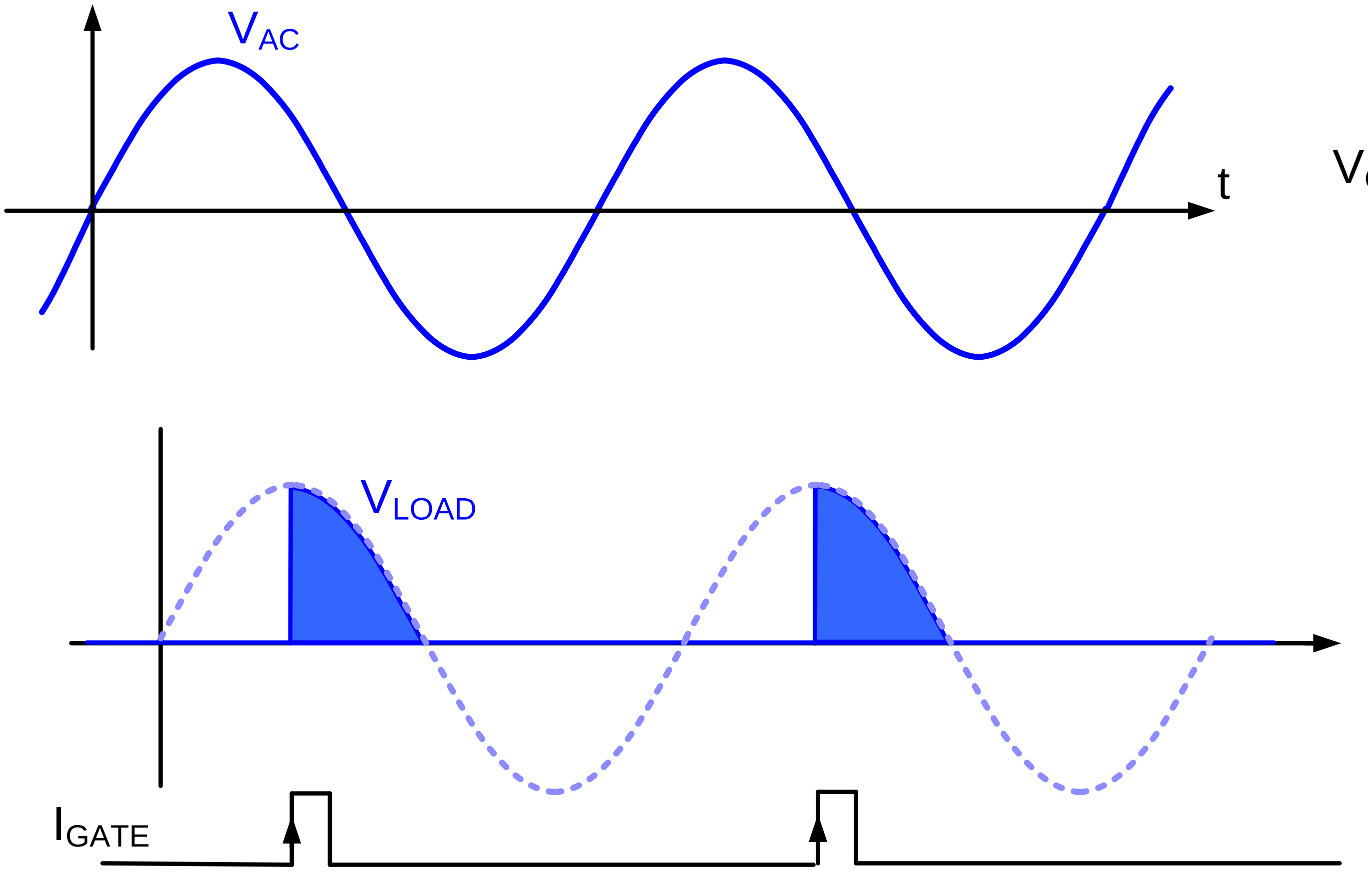


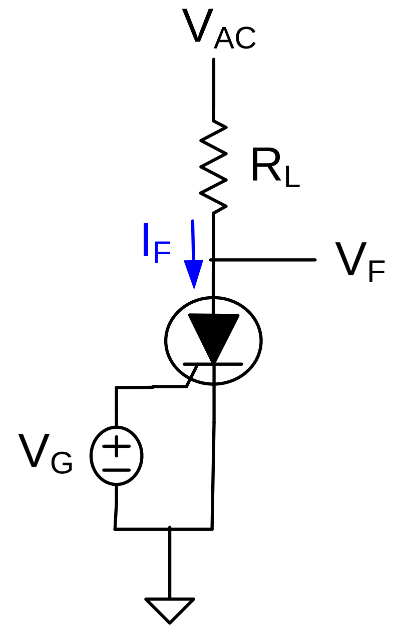


Operation of the SCR

Operation with the Ideal SCR

Duty cycle control of R_L

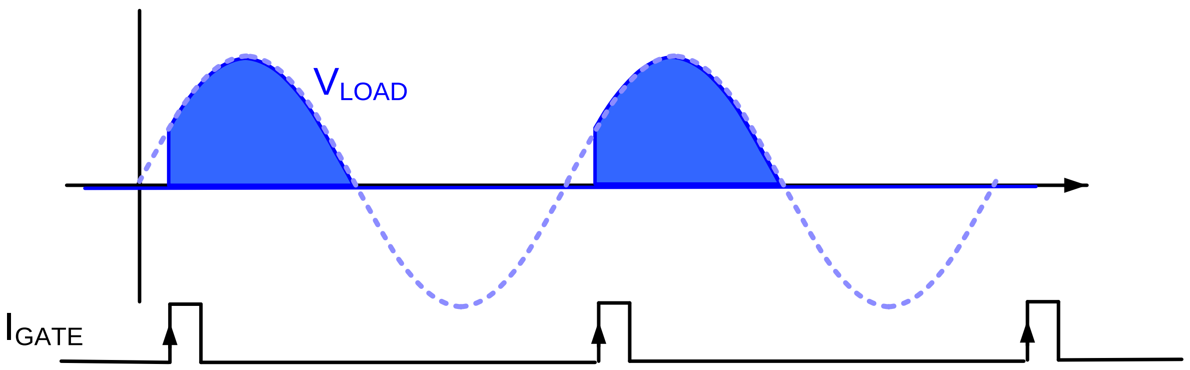


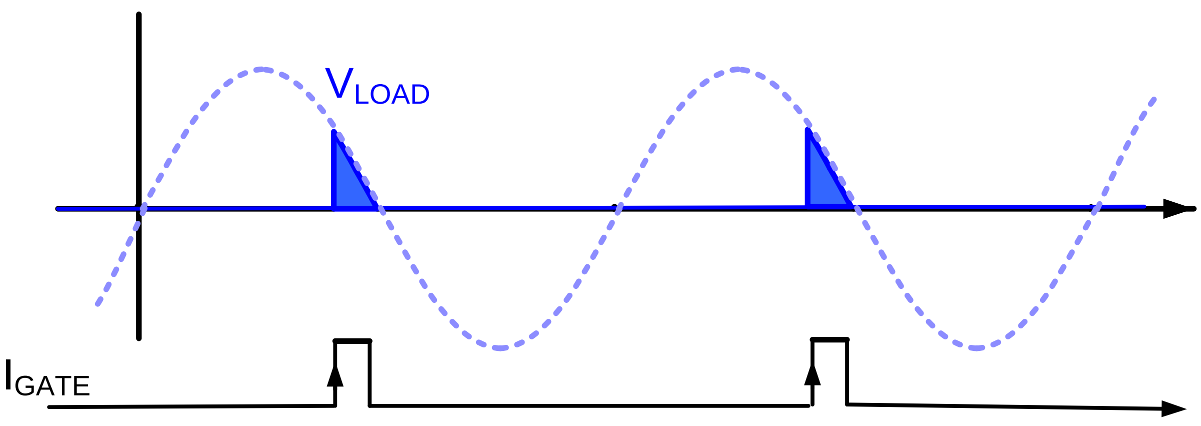


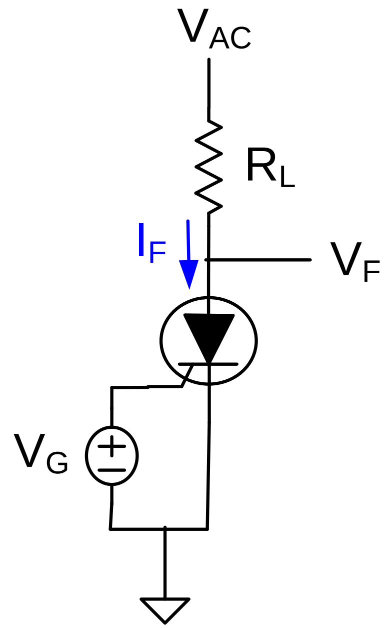
Operation of the SCR

Operation with the Ideal SCR

Duty cycle control of R_L

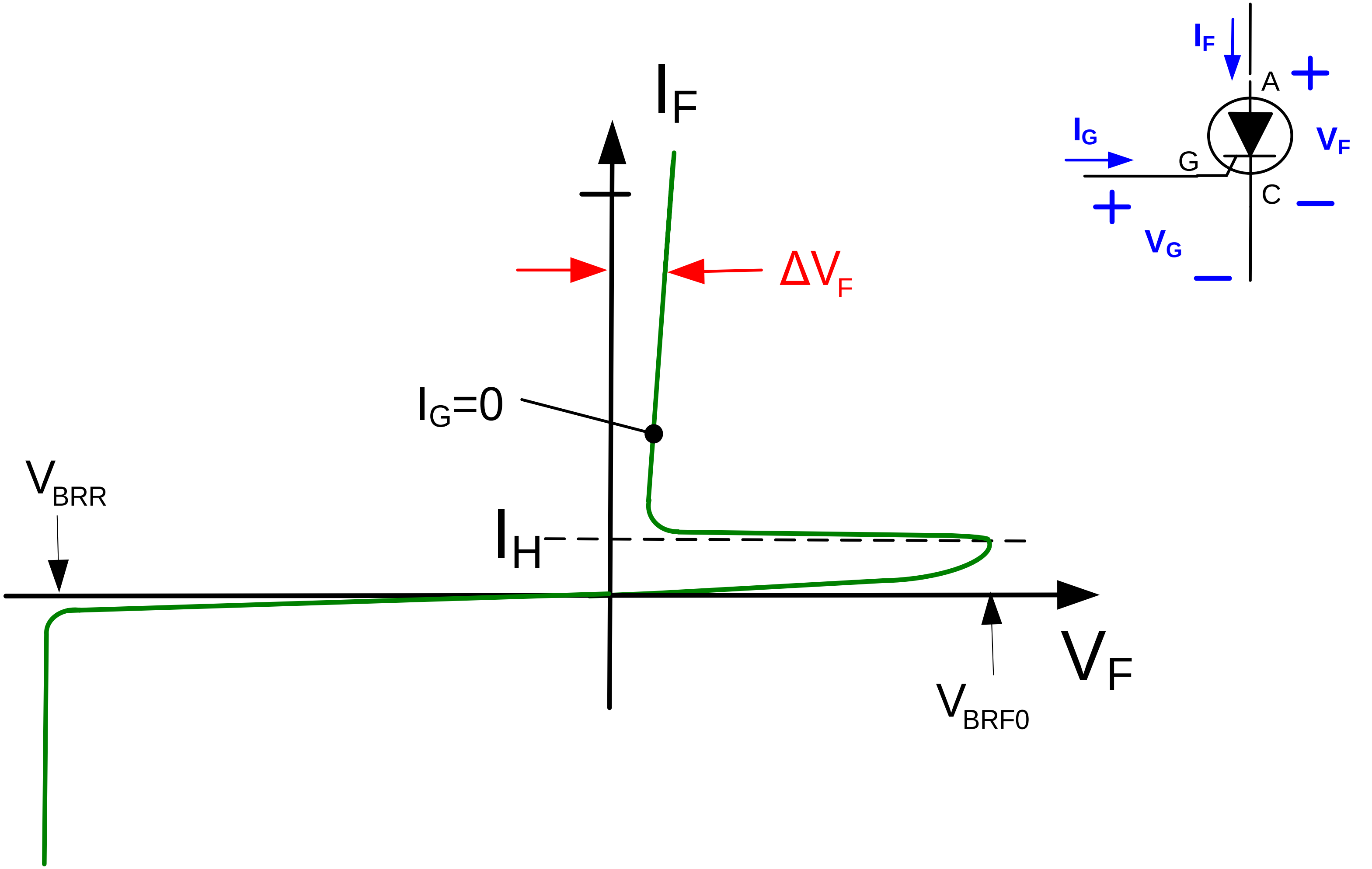






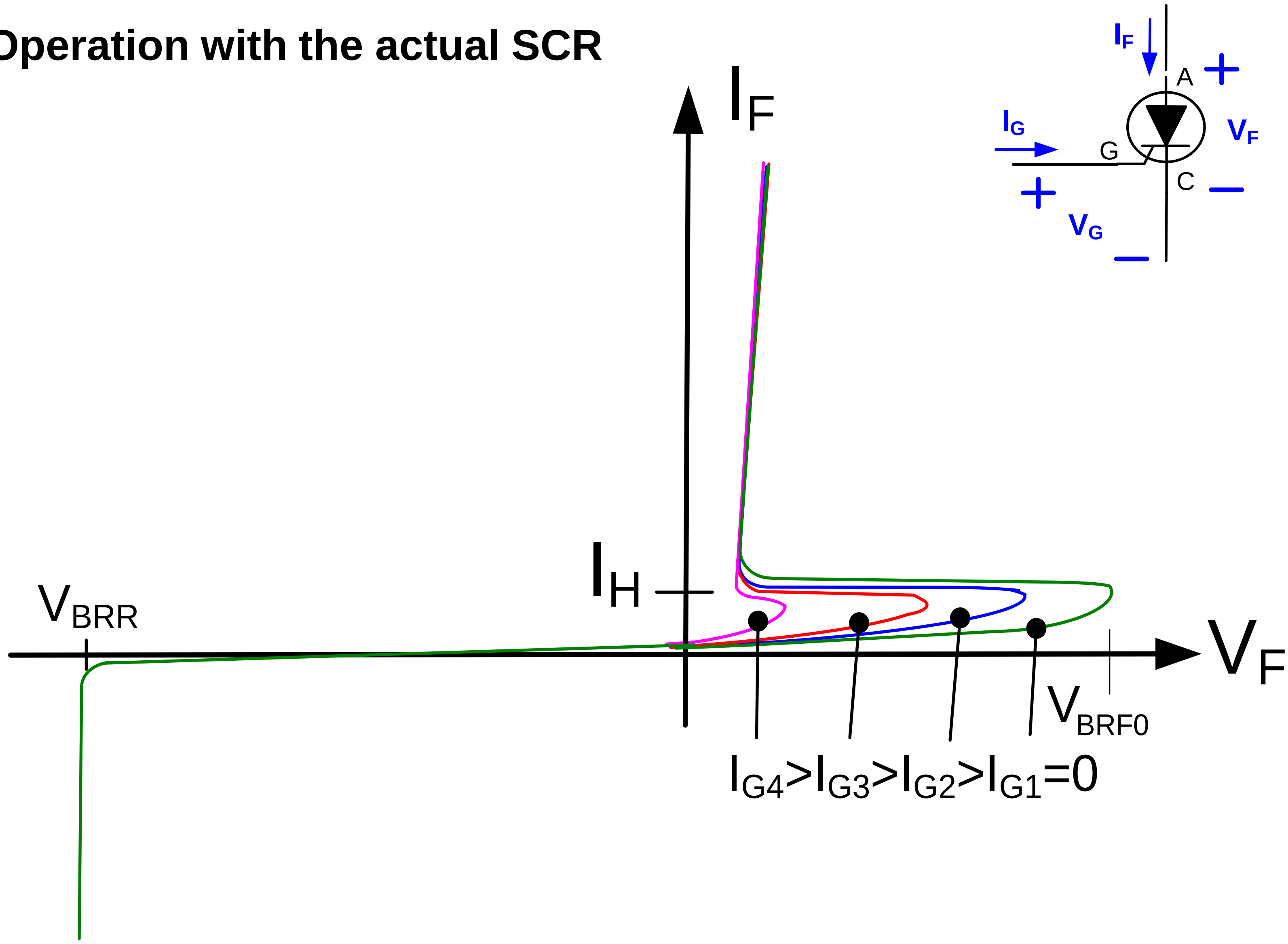
Operation of the SCR

Operation with the actual SCR



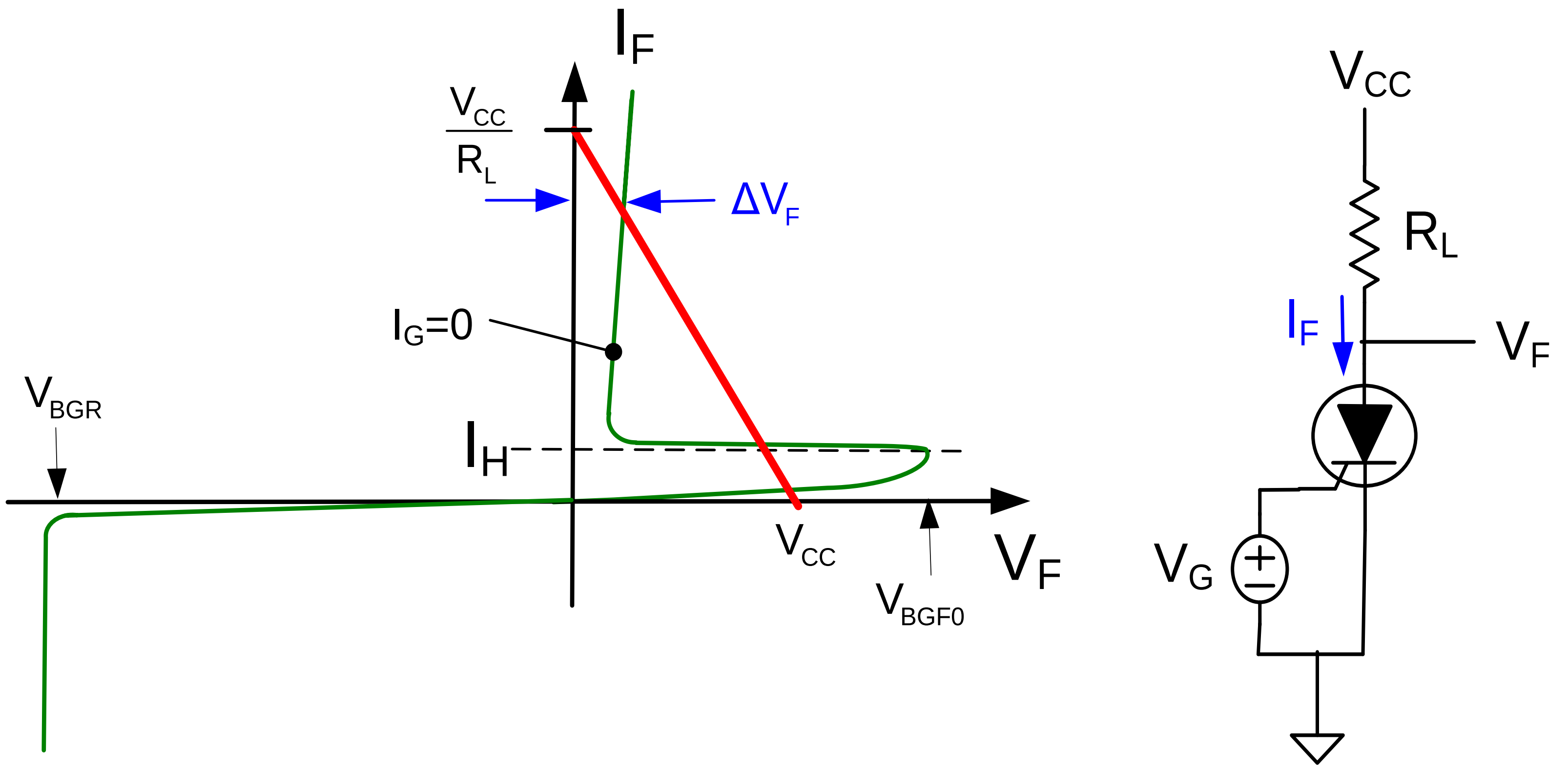
Operation of the SCR

Operation with the actual SCR



Operation of the SCR

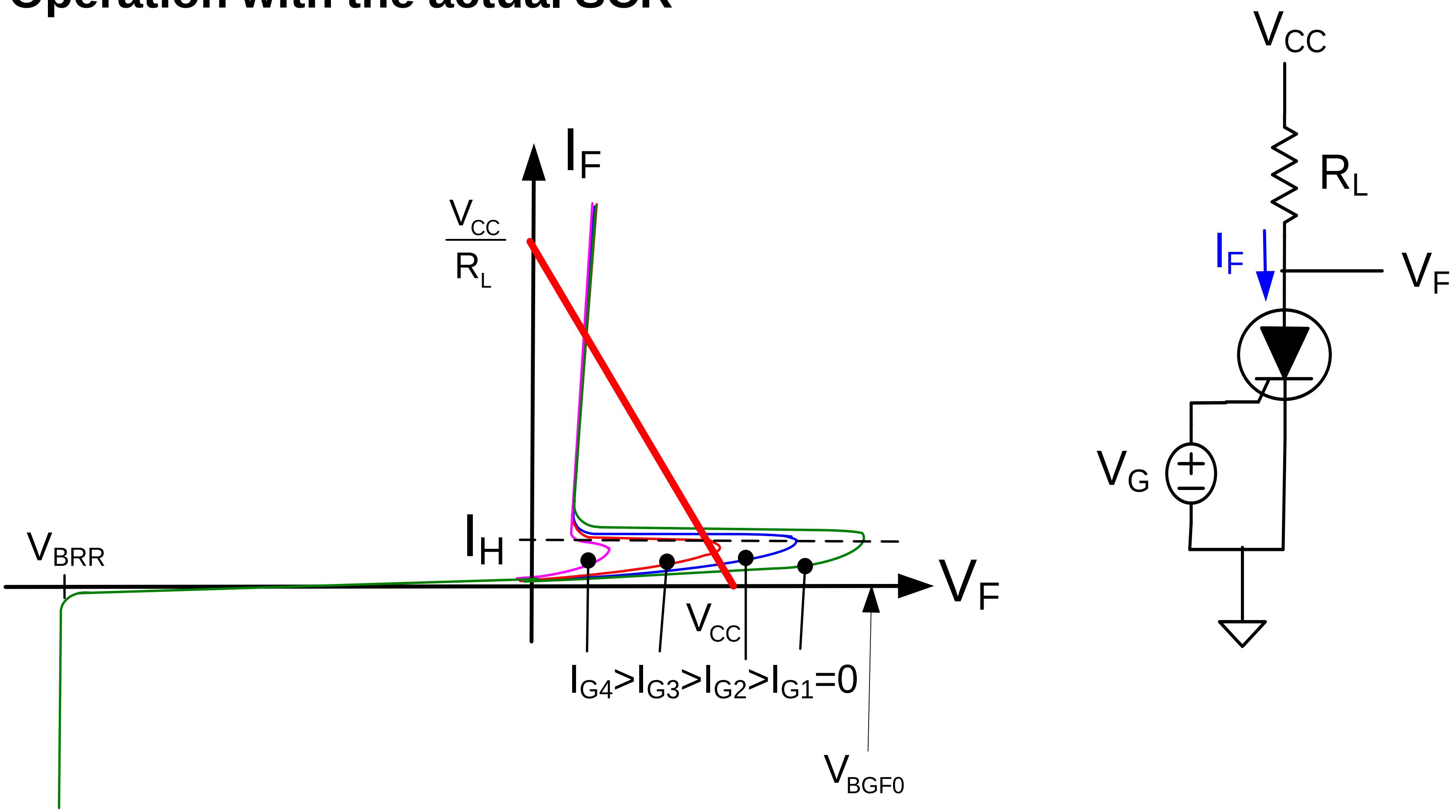
Operation with the actual SCR



Still two stable equilibrium points and one unstable point

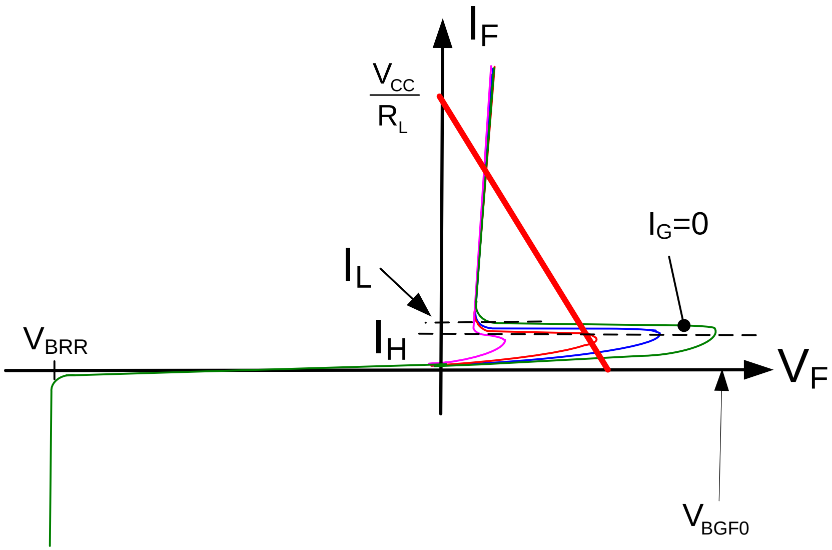
Operation of the SCR

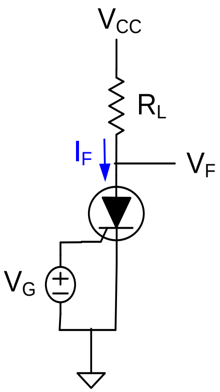
Operation with the actual SCR



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

SCR Terminology

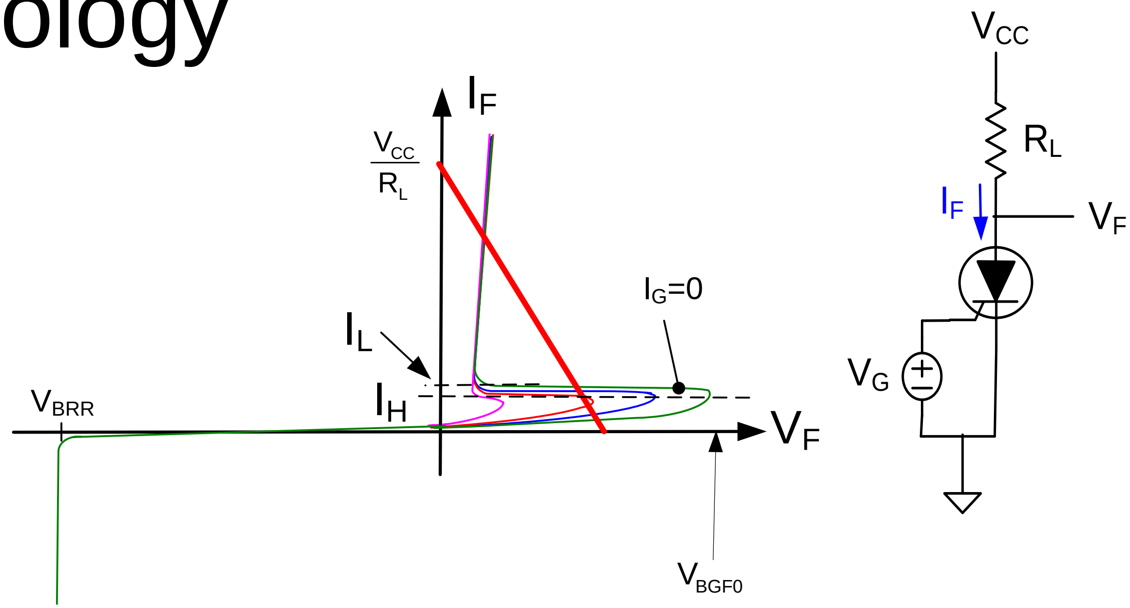




I_H is the holding current
I_L is the latching current (current immediately after turn-on)
V_{BGF0} is the forward break-over voltage
V_{BRR} is the reverse break-down voltage
I_{GT} is the gate trigger current
V_{GT} is the gate trigger voltage

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

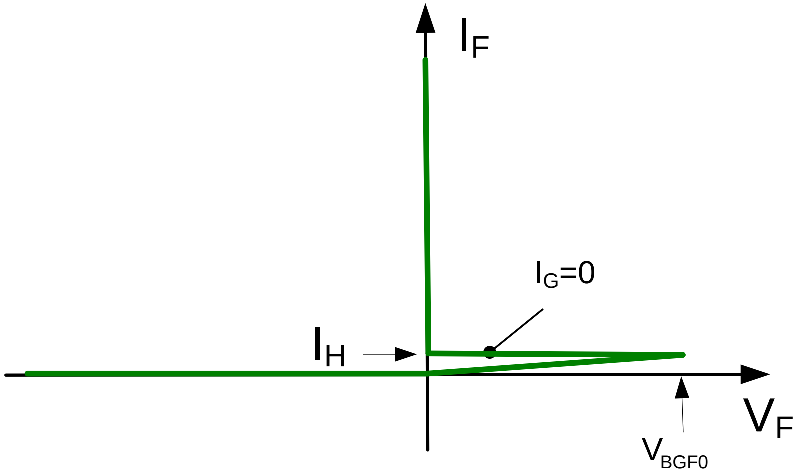
SCRs

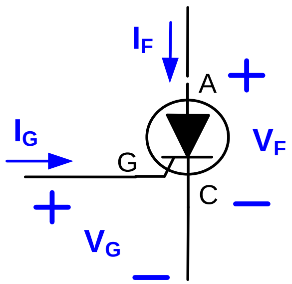
→ Triacs

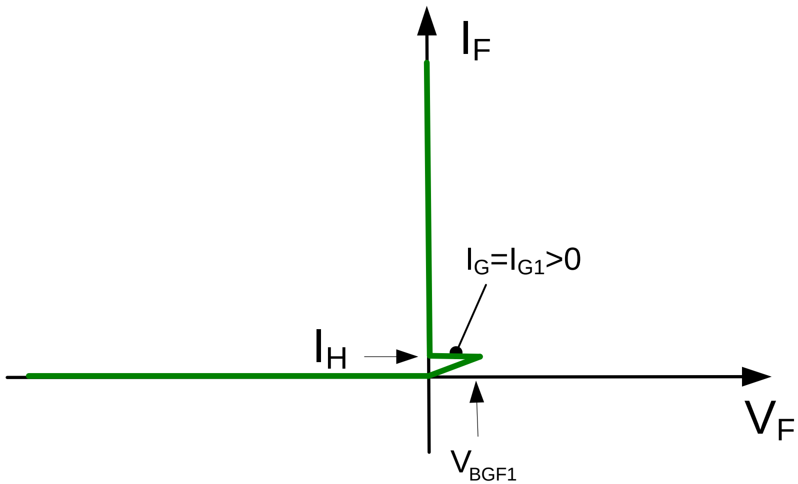
The bad

Parasitic Device that can destroy integrated circuits

Limitations of the SCR





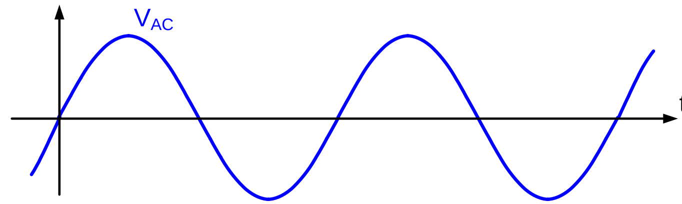


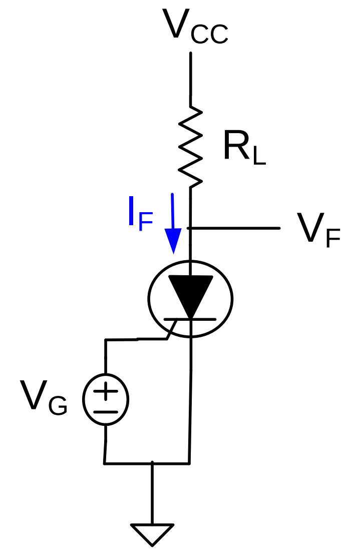
1. Only conducts in one direction
2. Can’t easily turn off (though not major problem in AC switching)

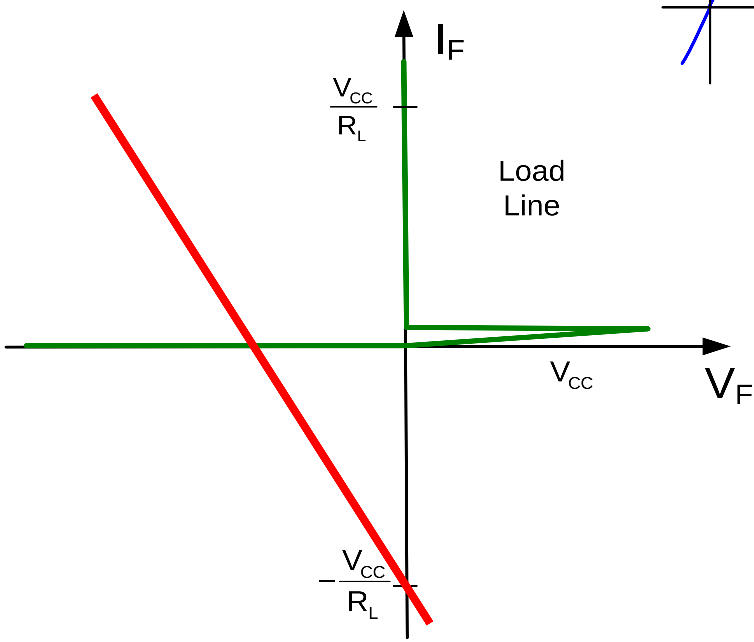
Operation of the SCR

Performance Limitations with the SCR

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

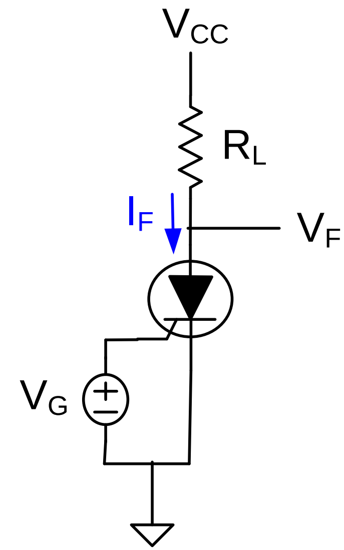






SCR is always off

Operation of the SCR



Performance Limitations with the SCR

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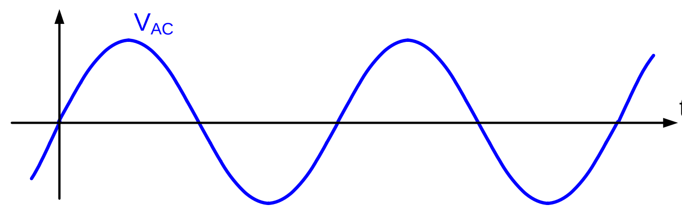
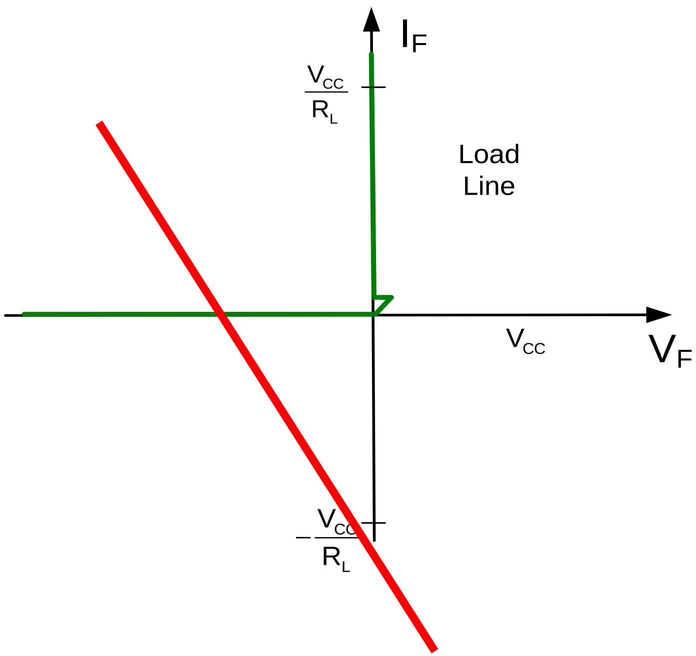
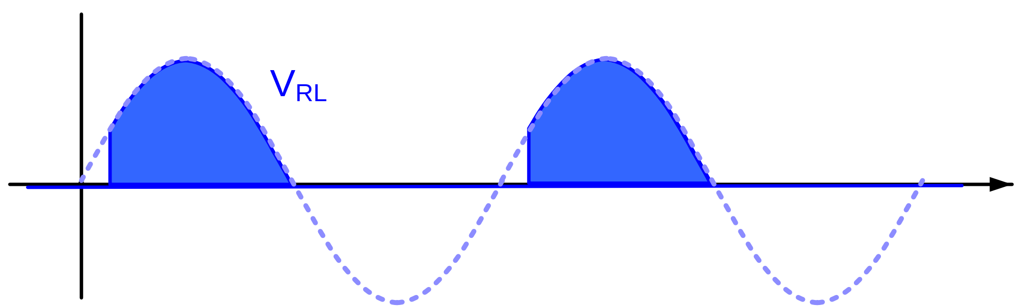




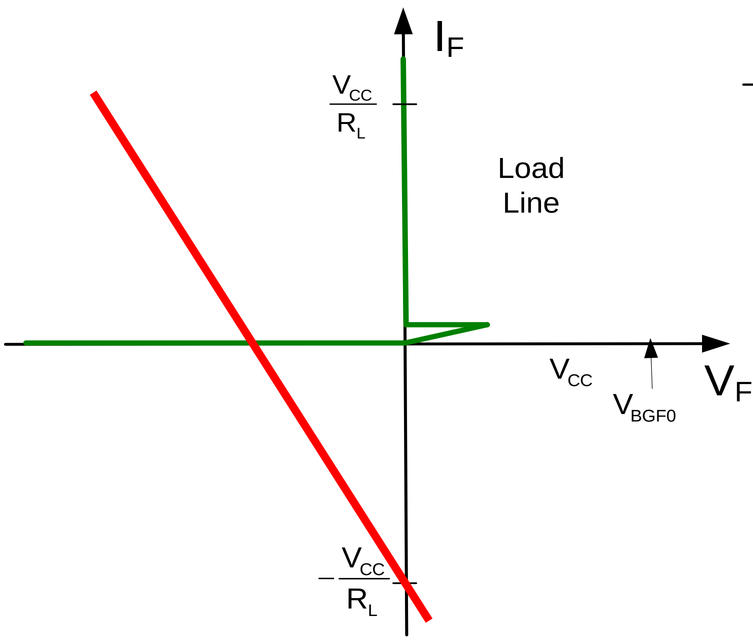


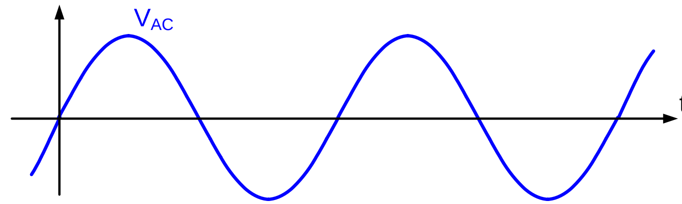
SCR is ON about 50% of the time

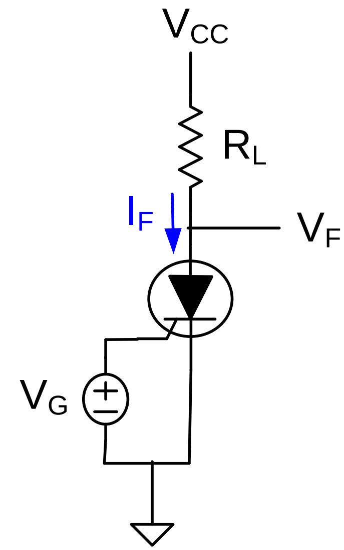
Operation of the SCR

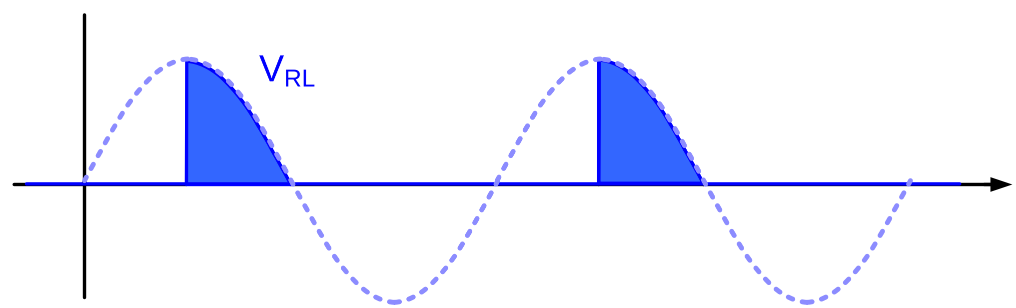
Performance Limitations with the SCR

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





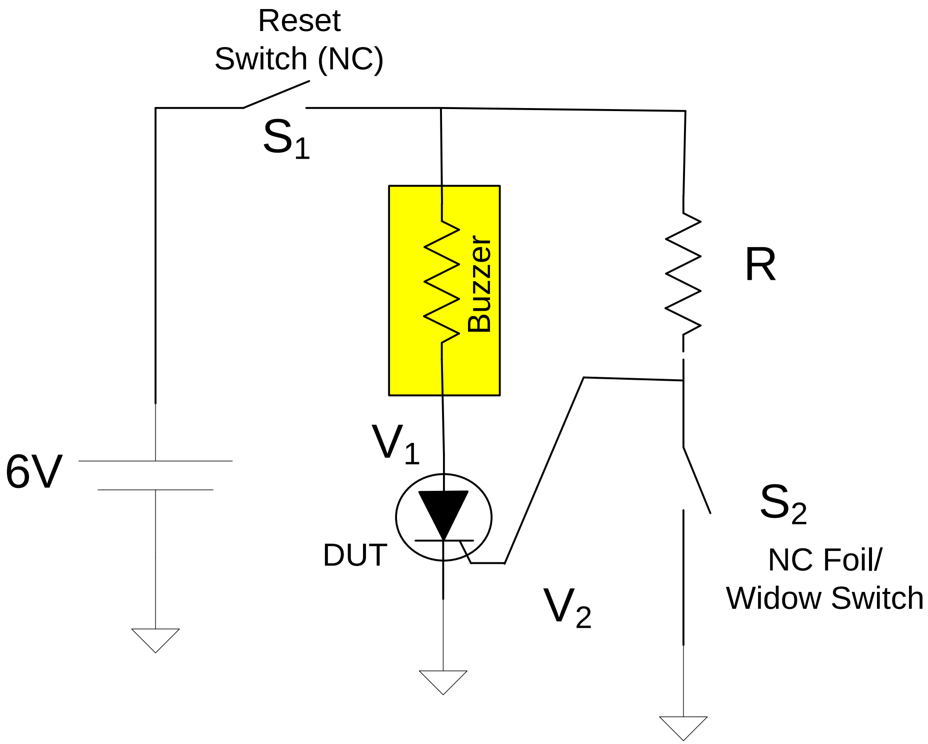




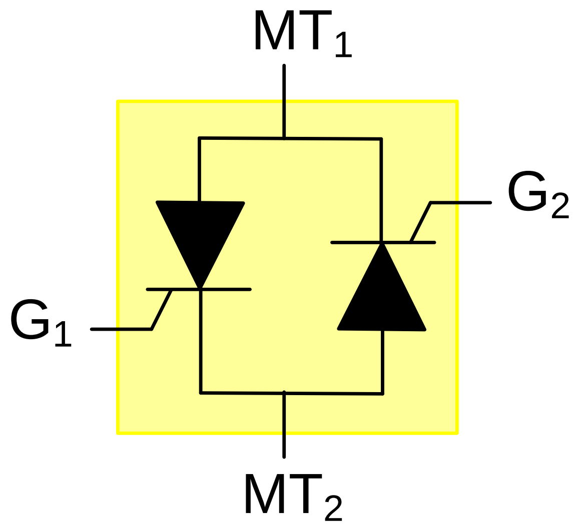
SCR is ON less than 50% of the time (duty cycle depends upon V_G)

Often use electronic circuit to generate V_G

Alarm Application



Bi-directional switching

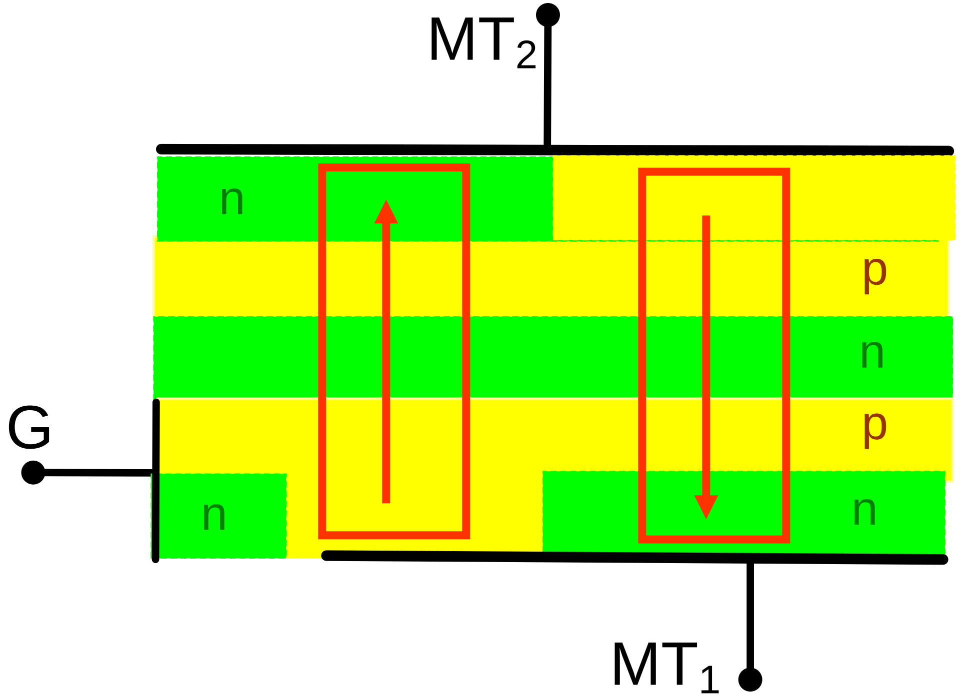


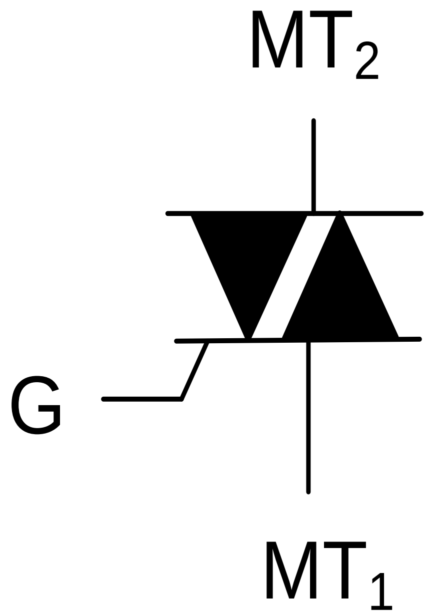
Use two cross-coupled SCRs

Limitations

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

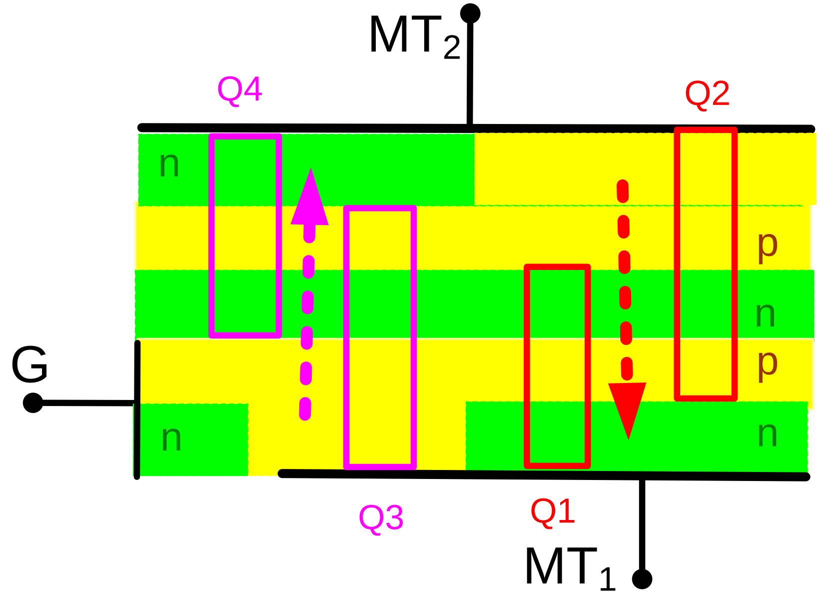
Bi-directional switching with the Triac

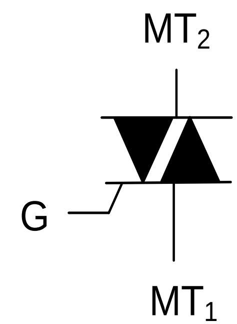




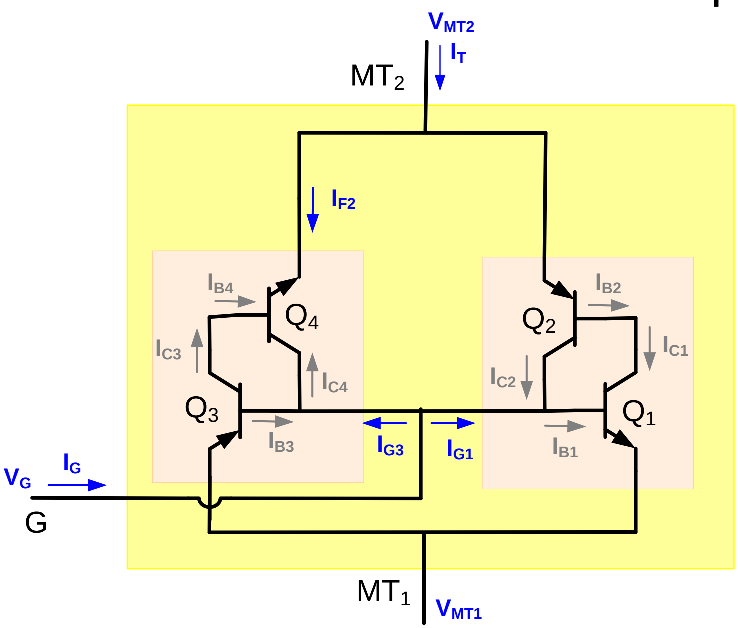
- Has two cross-coupled SCRs !
- Manufactured by diffusions
- Single Gate Control

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-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

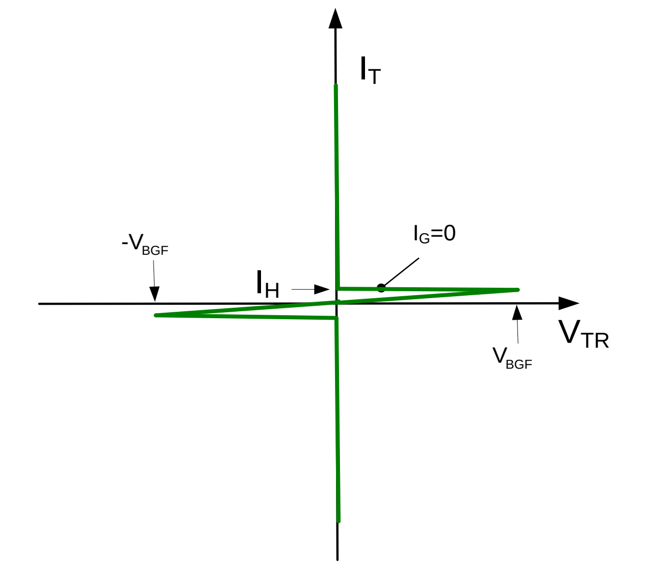
Usually use only one V_G:V_{MT} for control

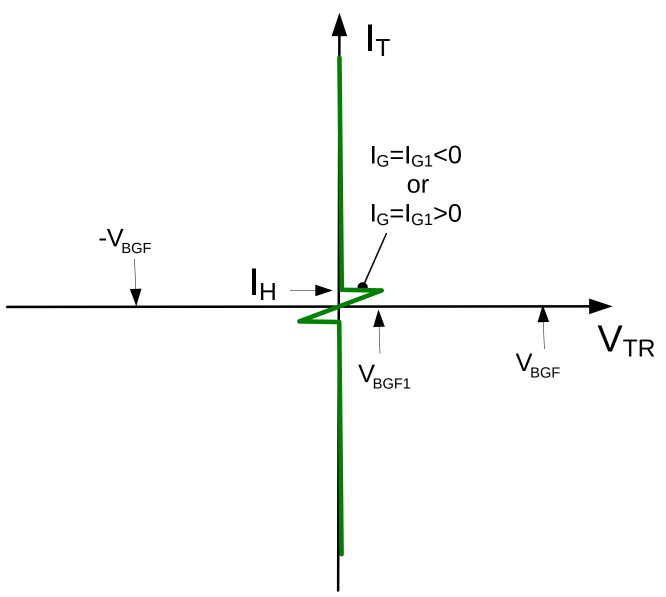
Different voltage, duration strategies exist for triggering

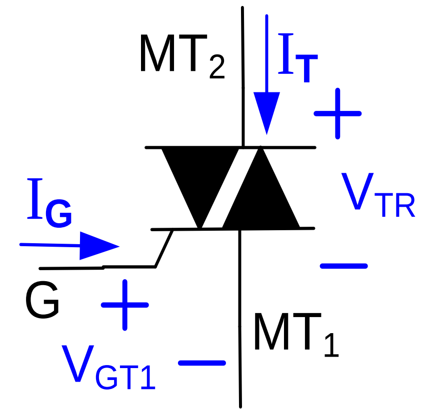
Can't have single V_G:V_{MT} control with two SCRs

The Triac

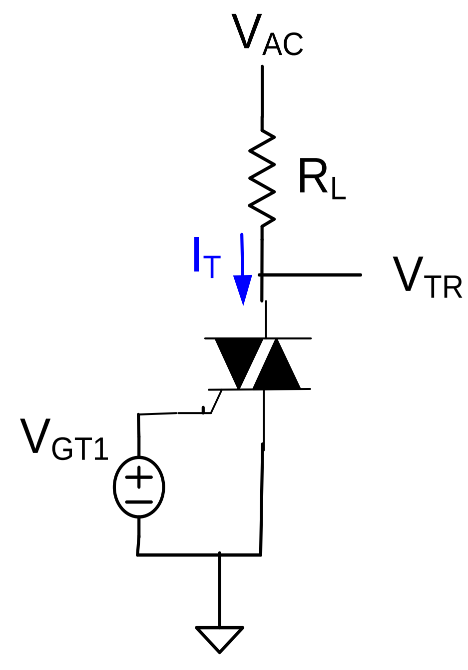
The ideal Triac





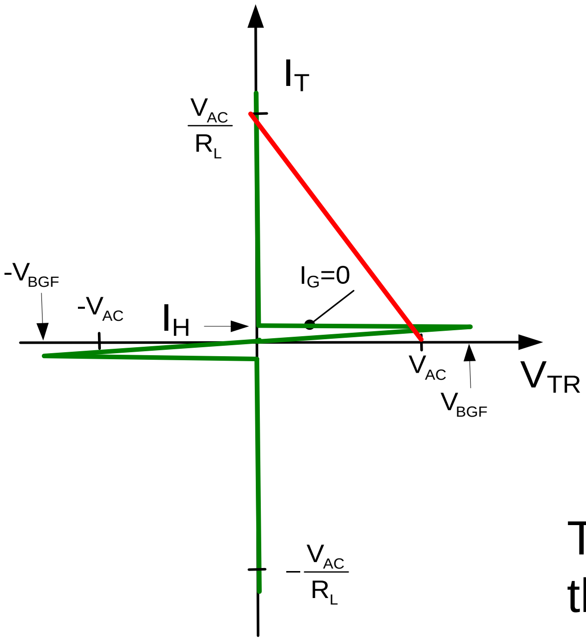


Consider the basic Triac circuit



The Basic Triac Circuit

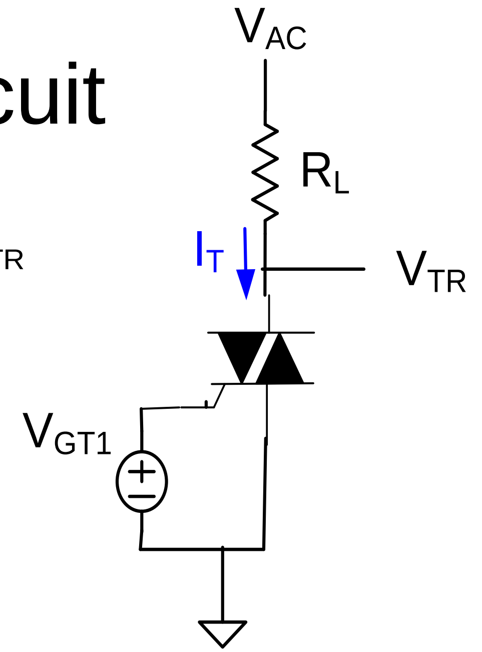
Assume ideal Triac



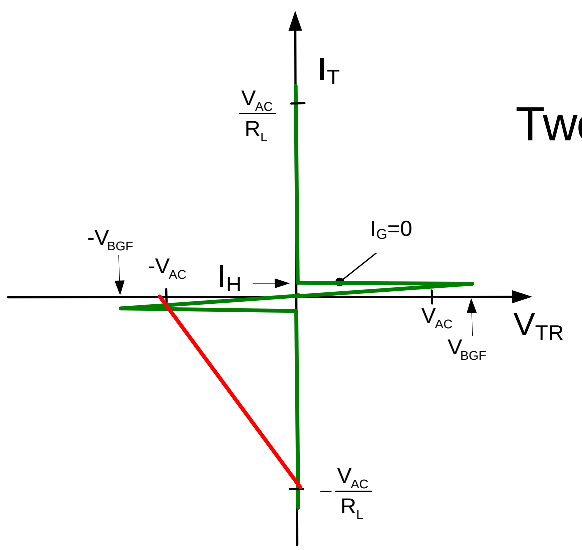
Load Line: $V_{CC} = I_T R_L + V_{TR}$

Analysis:

$$\left.\begin{array}{l} V_{AC} = I_T R_L + V_{TR} \\ I_{FI} = f\left(V_{TR}, V_{GT1}\right) \end{array}\right\}$$



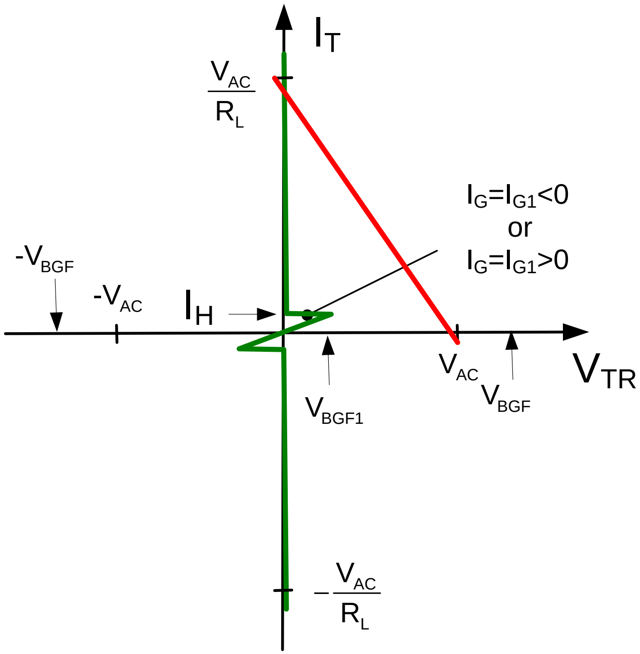
The solution of these two equations is at the intersection of the load line and the device characteristics

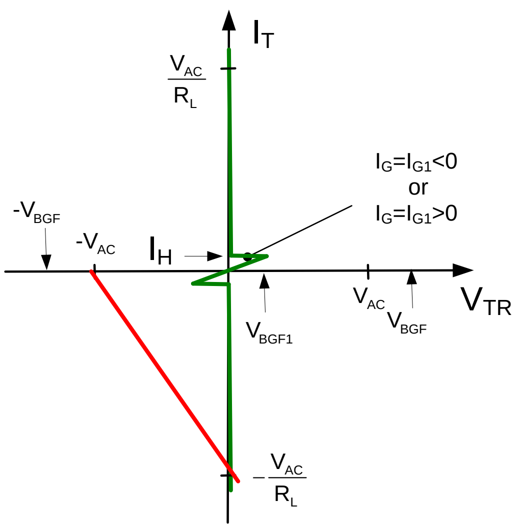


Two stable operating points for both positive and negative V_{AC}

The Basic Triac Circuit

Assume ideal Triac

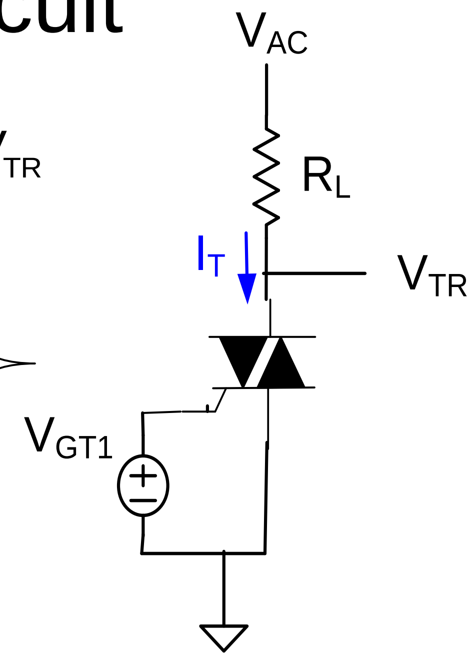




Load Line: $V_{CC} = I_T R_L + V_{TR}$

Analysis:

$$\left. \begin{aligned} V_{AC} &= I_T R_L + V_{TR} \\ I_{FI} &= f\left(V_{TR}, V_{GT2}\right) \end{aligned} \right\}$$

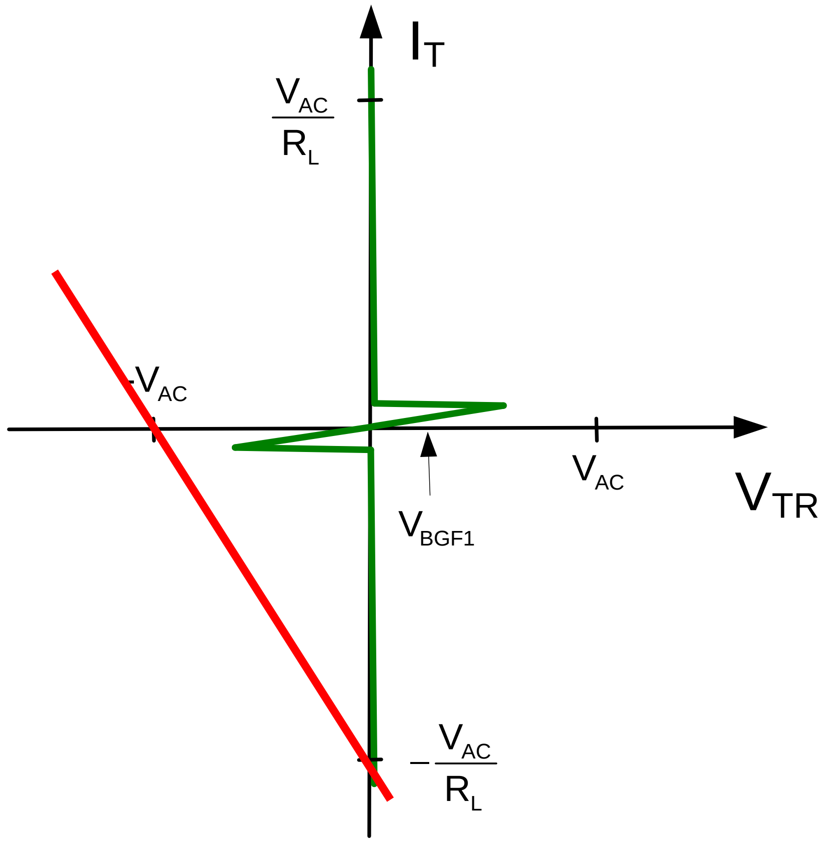


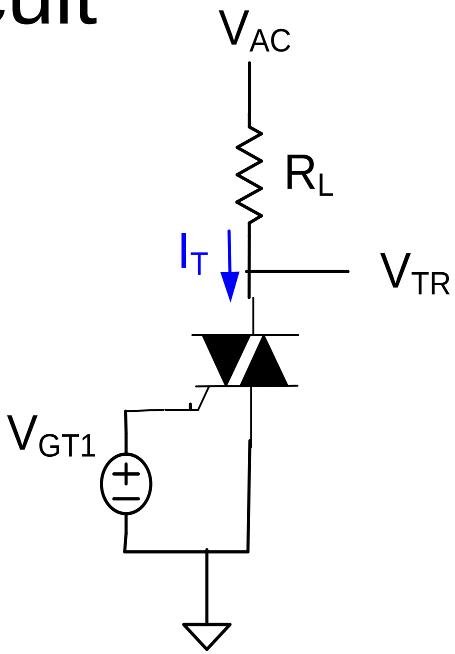
Single solution for both positive and negative V_{AC}

Thus this state turns on the Triac for any input

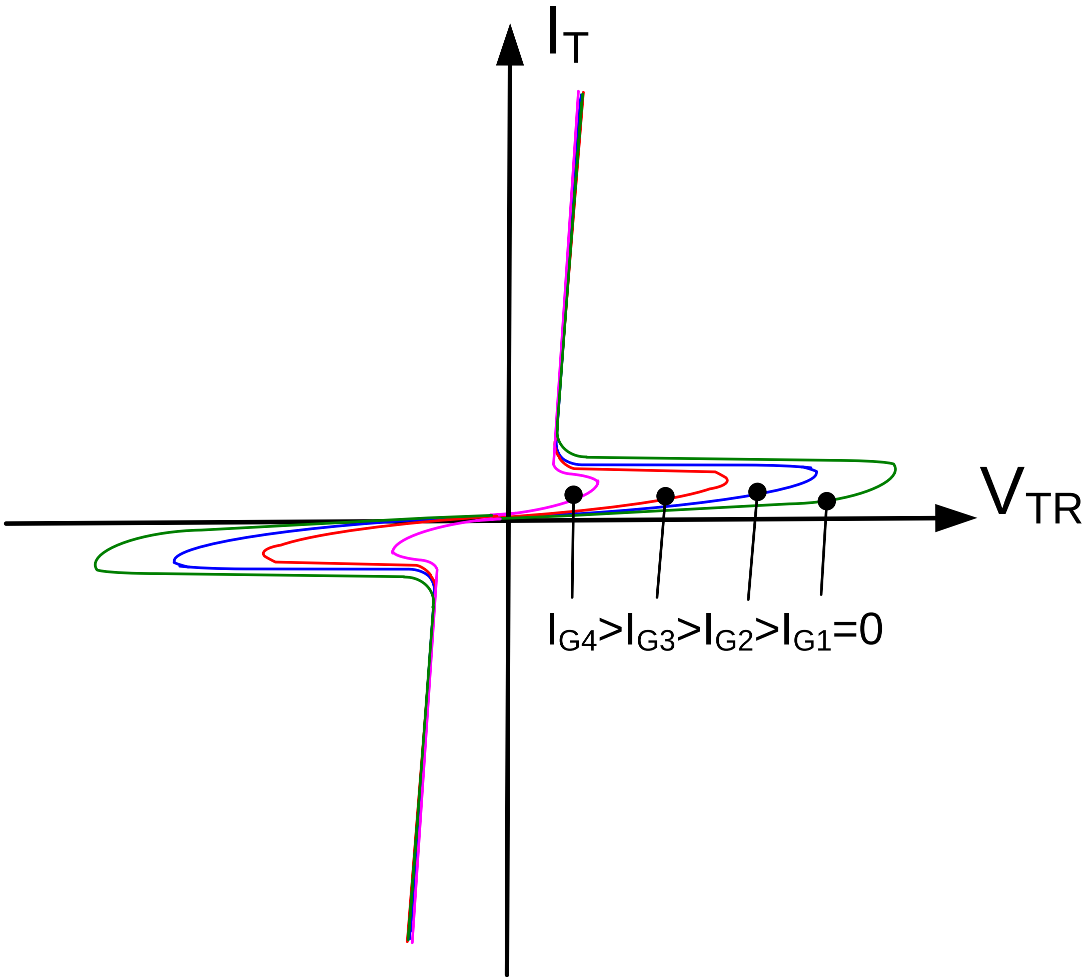
Assume ideal Triac

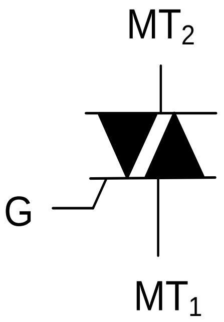
The Basic Triac Circuit



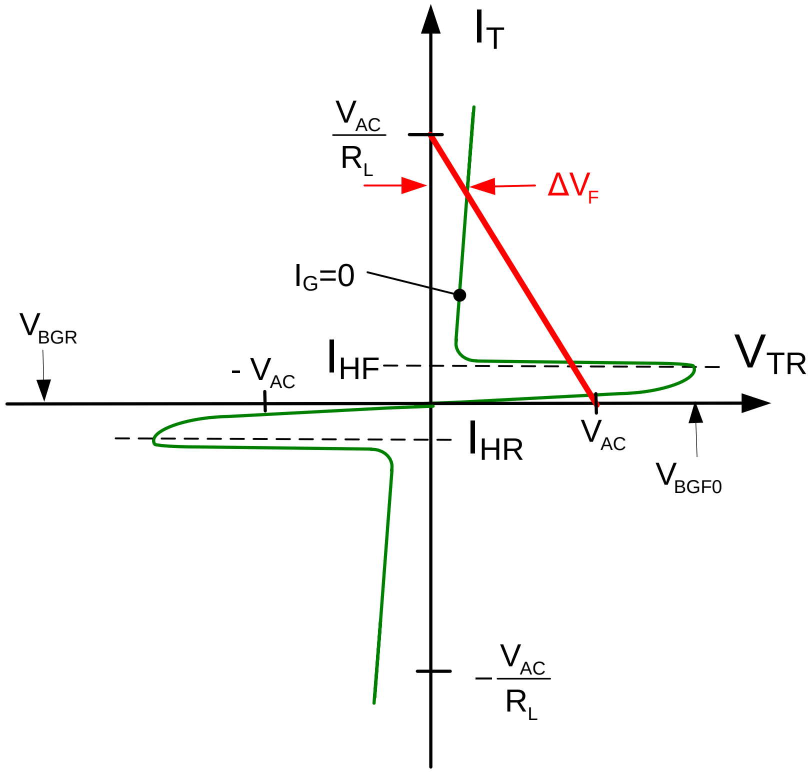


The Actual Triac

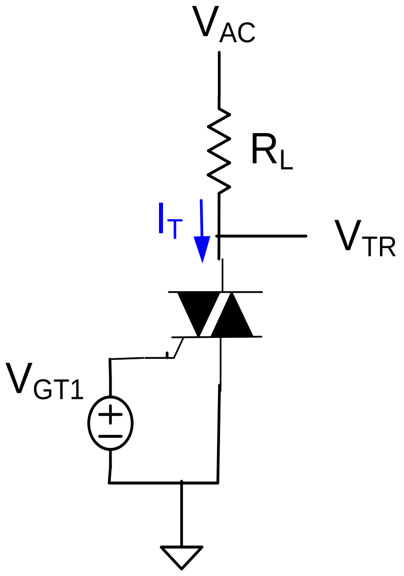




The Actual Triac in Basic Circuit

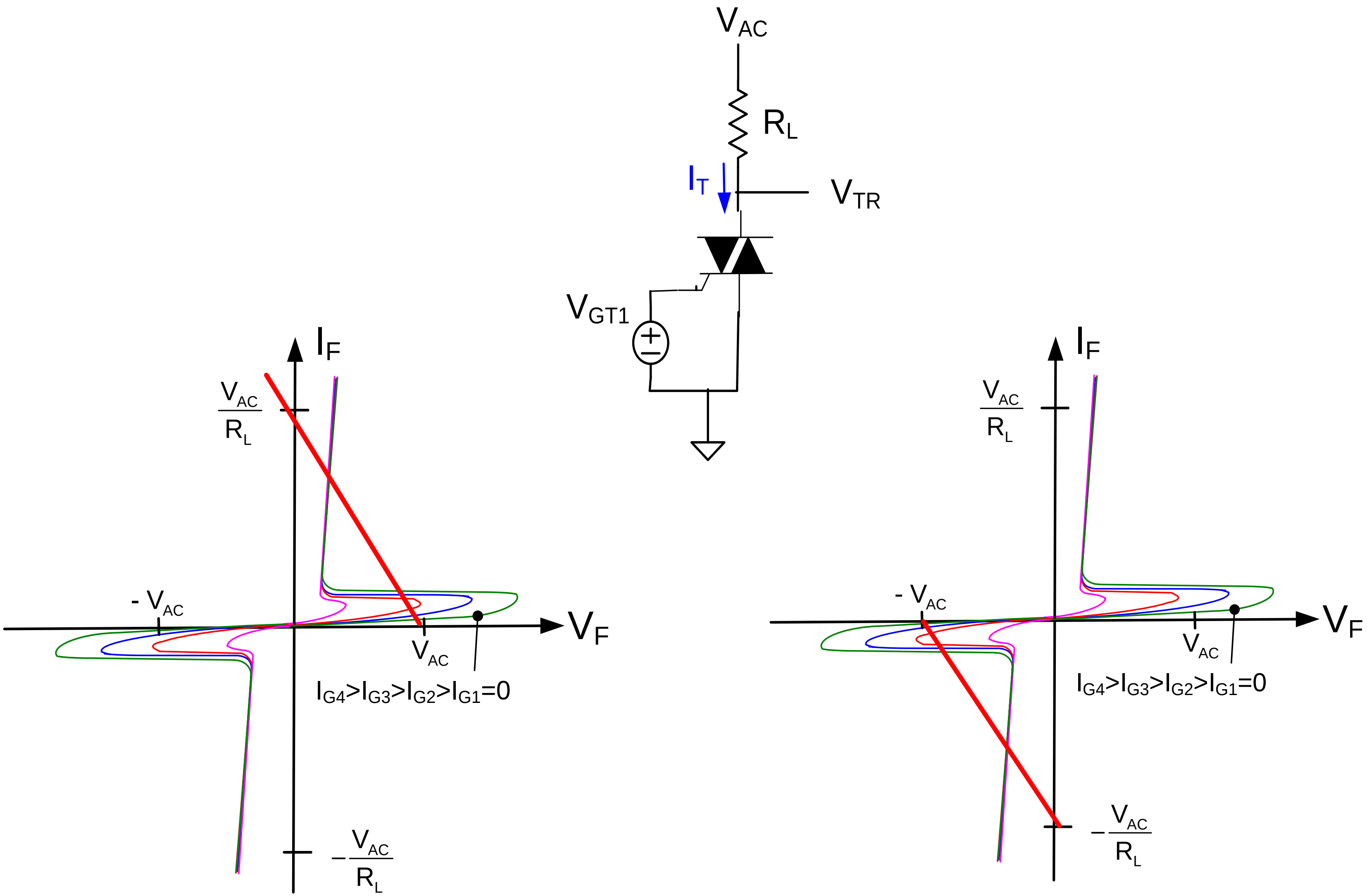


I_G=0 State



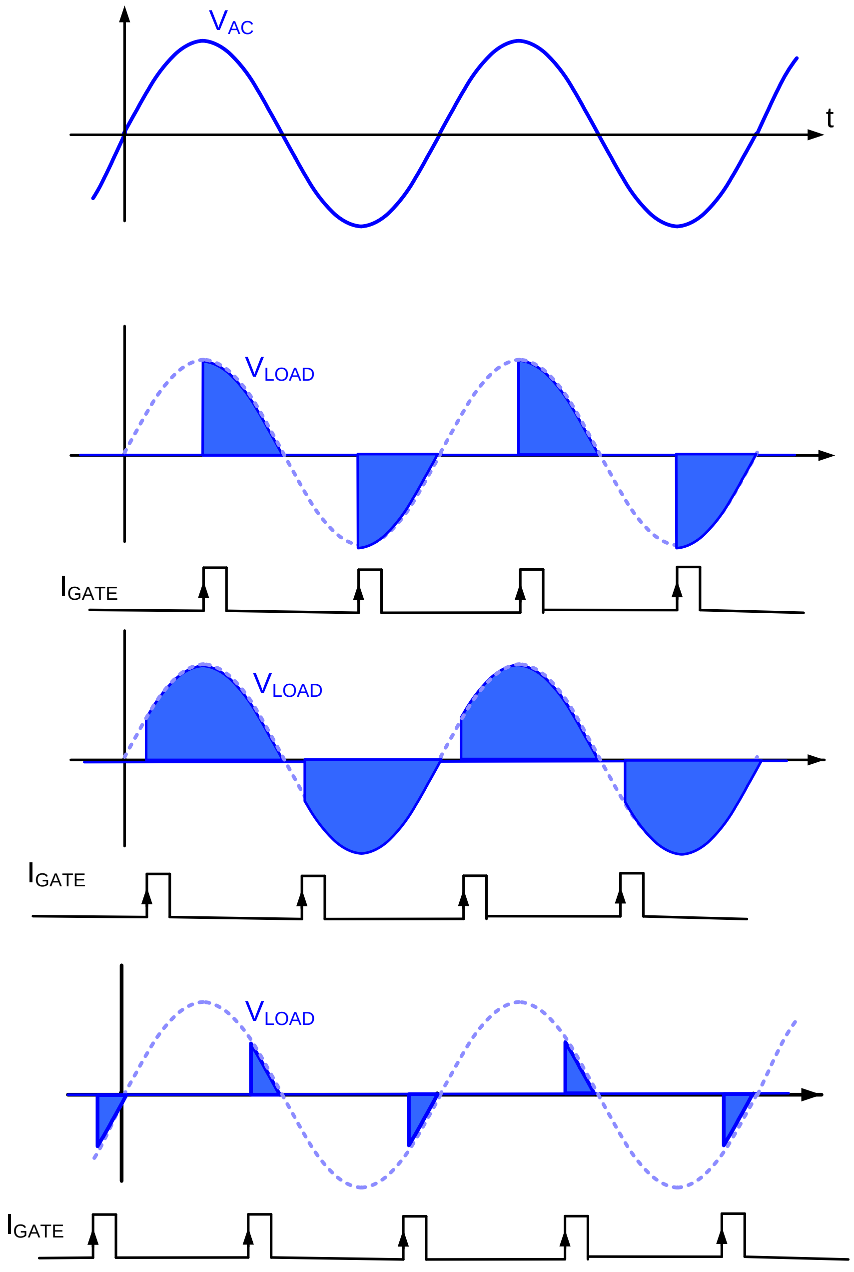
Two stable operating points

The Actual Triac in Basic Circuit



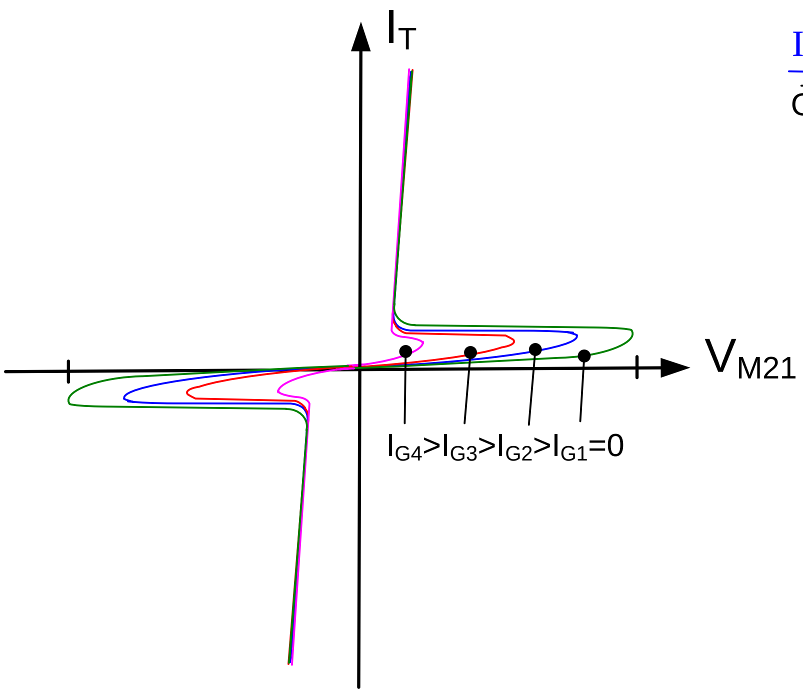
Can turn on for either positive or negative V_{AC} with single gate signal

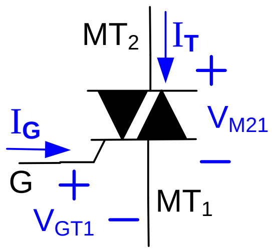
Phase controlled bidirectional switching with Triacs

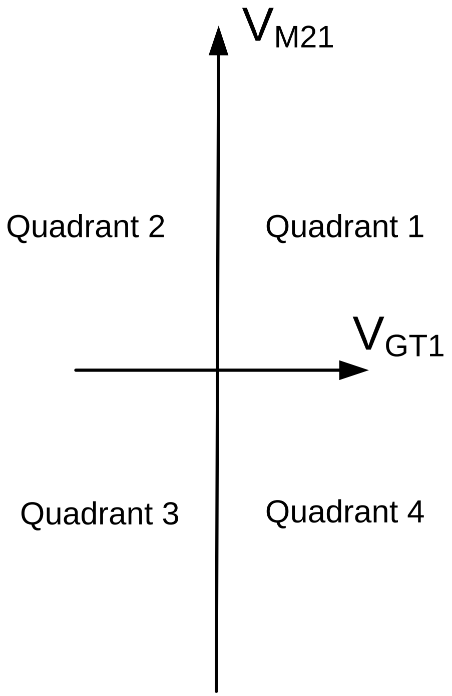


Quadrants of Operation Defined in V_{M21}-V_{GT1} plane

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

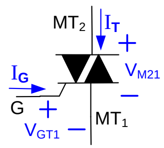


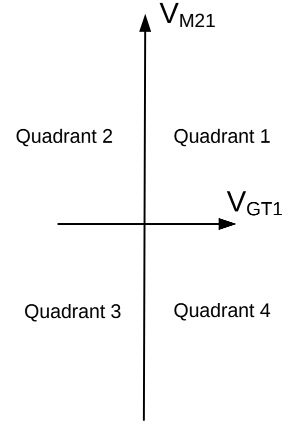


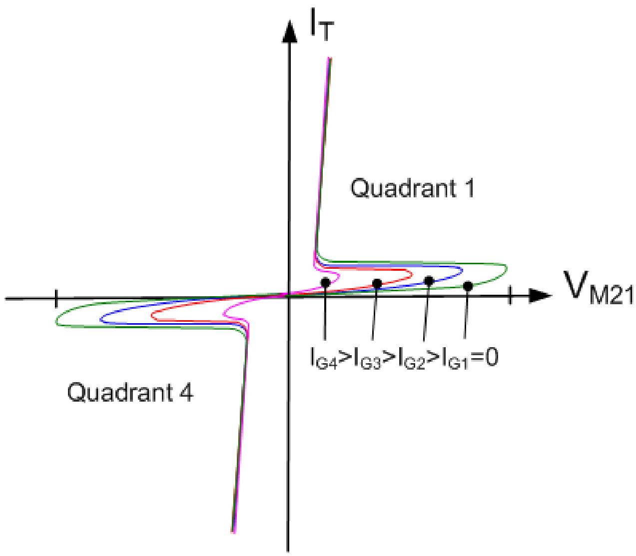


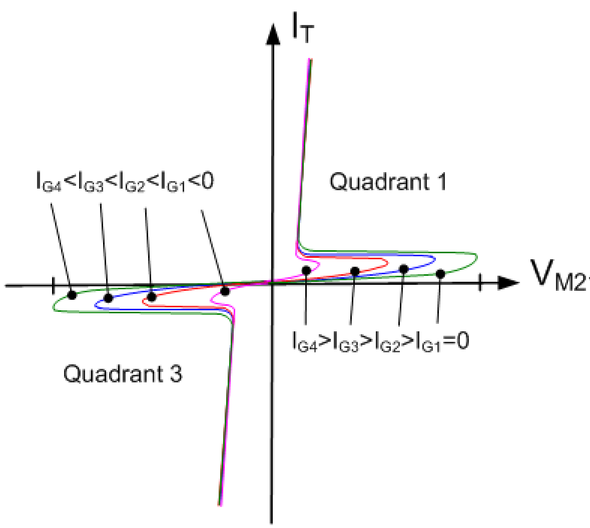
But for any specific circuit, can map quadrants from the V_{M21}-V_{GT1} plane to I_T-V_{M21} plane

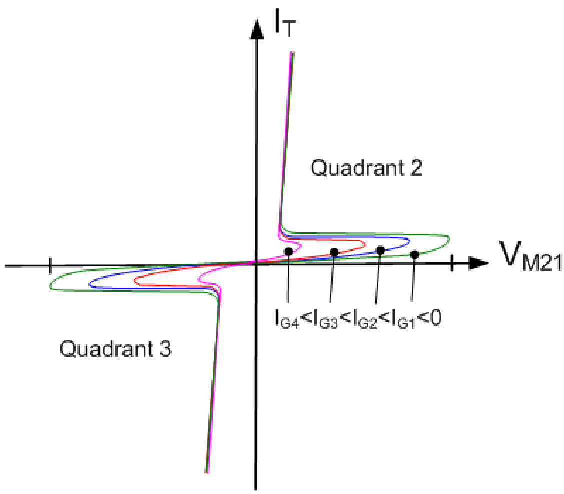
Identification of Quadrants of Operation in I_T -V_{M21} plane



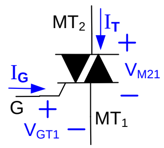


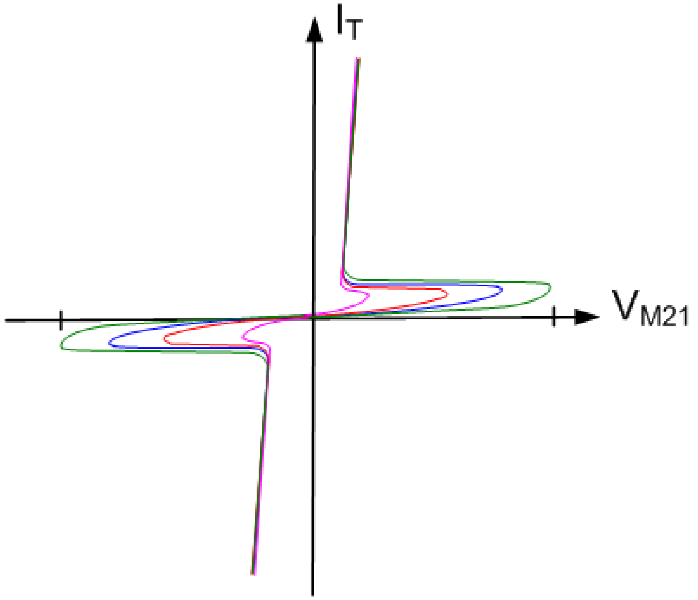


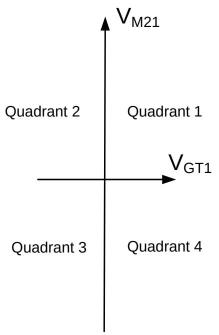




Identification of Quadrants of Operation in I_T-V_{M21} plane







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

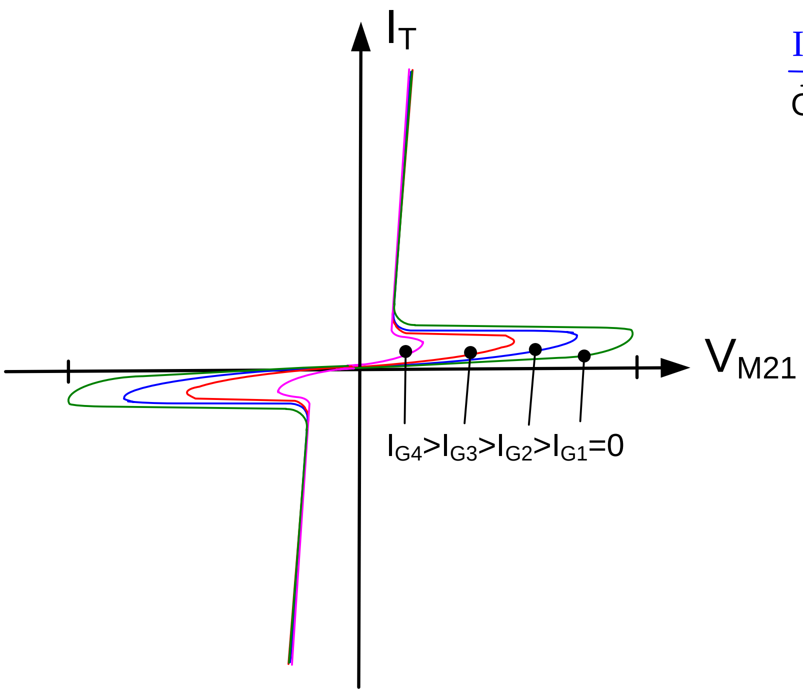
Turn on current may be large and variable in Q_4 (of the V_{M21}-V_{GT1})

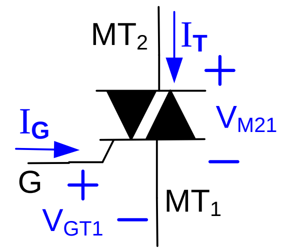
Generally avoid operation in Q_4 (of the V_{M21}-V_{GT1} plane)

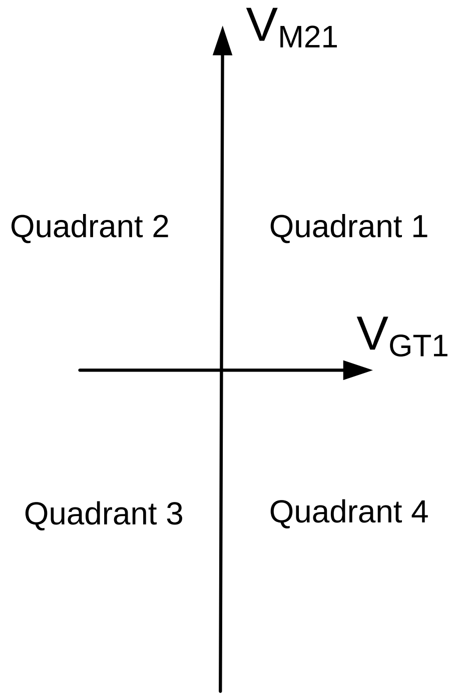
Most common to operate in Q2-Q3 quadrants or Q1-Q3 quadrants (of the V_{M21}-V_{GT1} plane)

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

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







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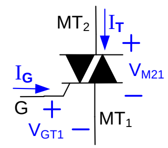
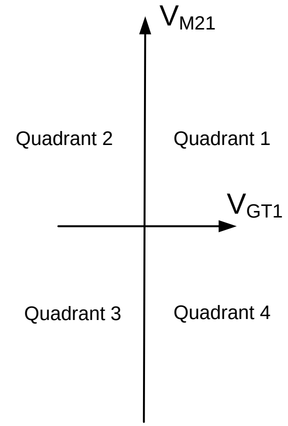
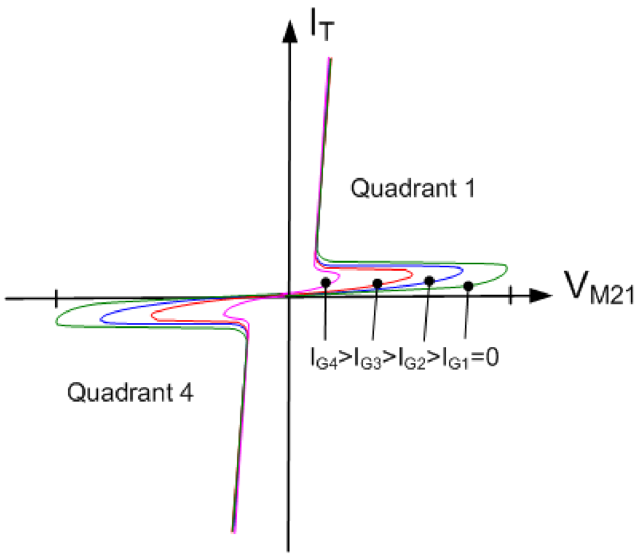
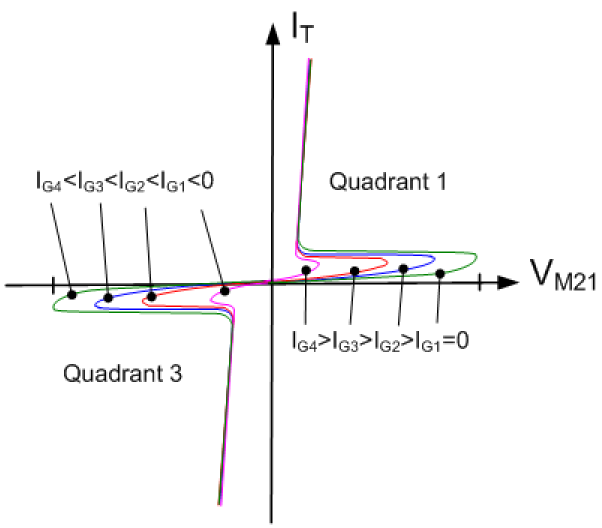
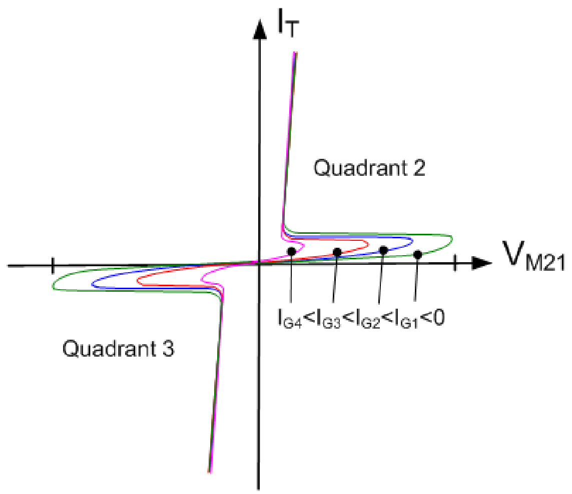


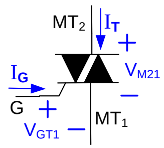


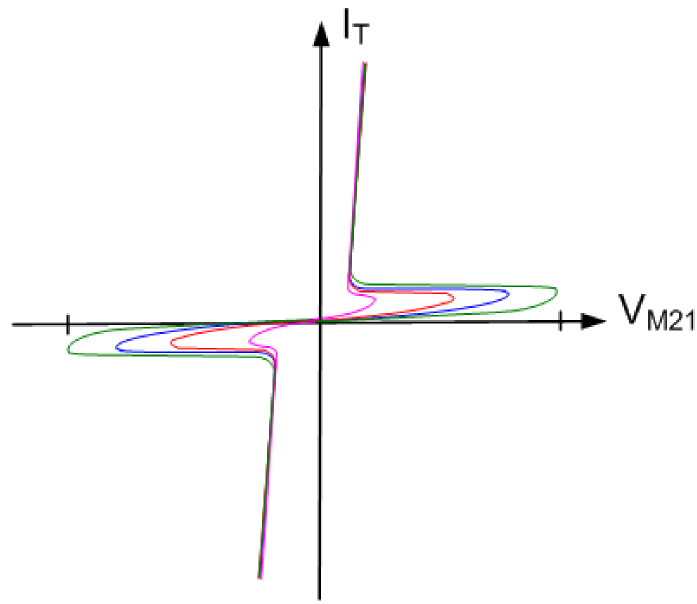


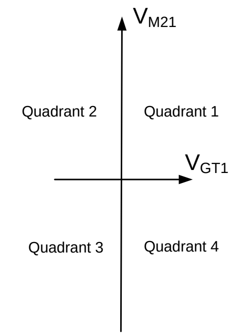




Identification of Quadrants of Operation in I_T-V_{M21} plane







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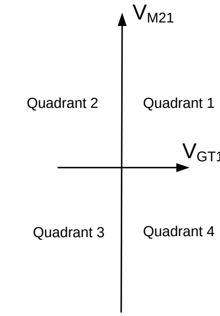
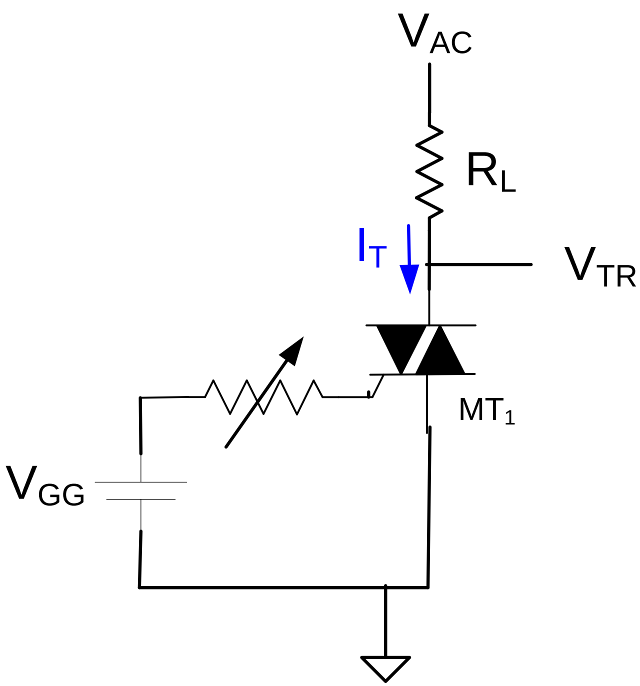
Turn on current may be large and variable in Q_4 (of the V_{M21}-V_{GT1})

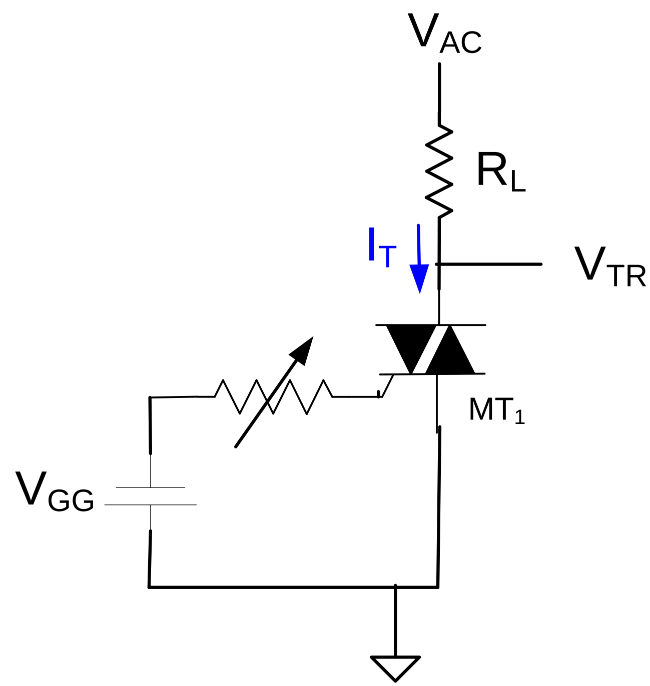
Generally avoid operation in Q_4 (of the V_{M21}-V_{GT1} plane)

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)

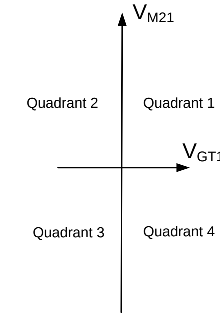
Quad 1 : Quad 4

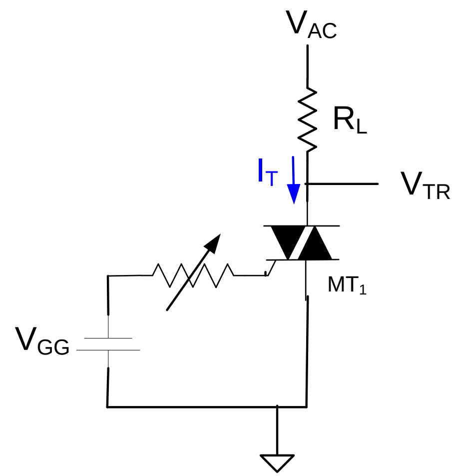
(not attractive because of Quad 4)

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

Quad 2 : Quad 3

Some Basic Triac Application Circuits



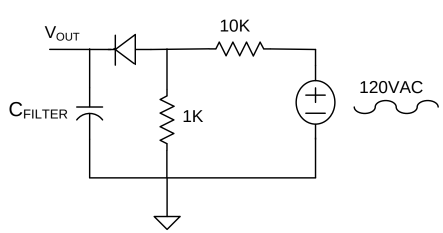


Quad 2 : Quad 3

Limitations ?

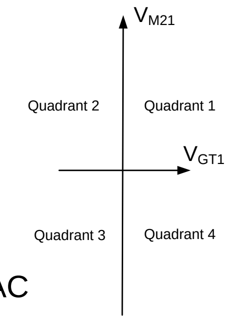
If V_{AC} is the standard 120VAC line voltage, where do we get the dc power supply?

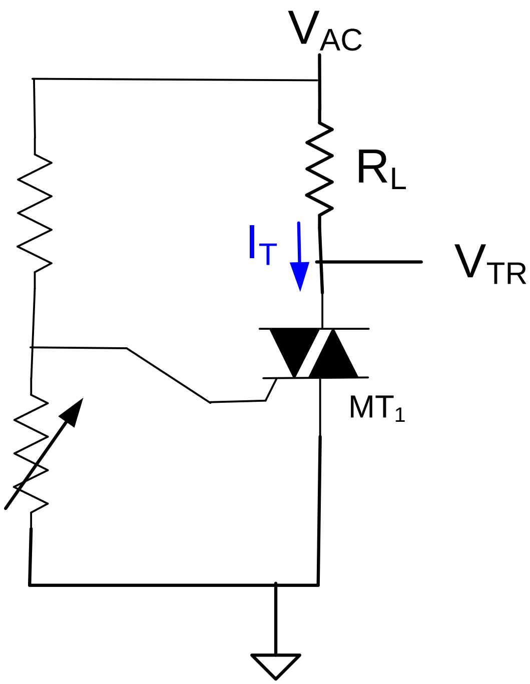
$1,607.00
AGILENT TECHNOLOGIES
E3631A



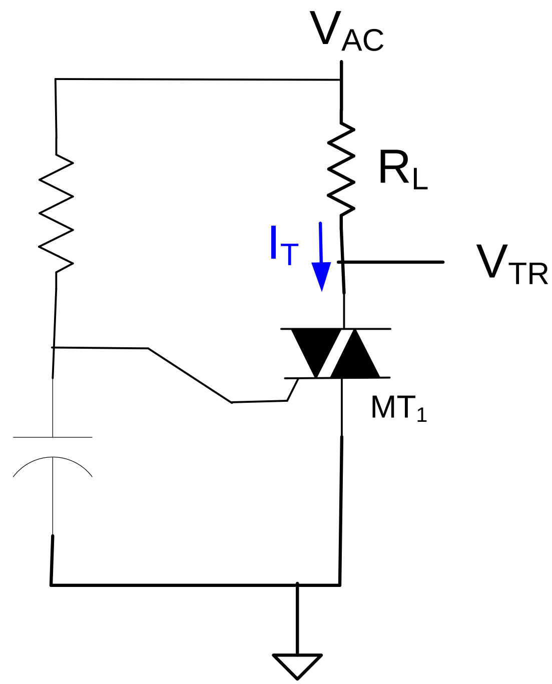
Direct digital control of trigger voltage/current with dedicated IC

Some Basic Triac Application Circuits

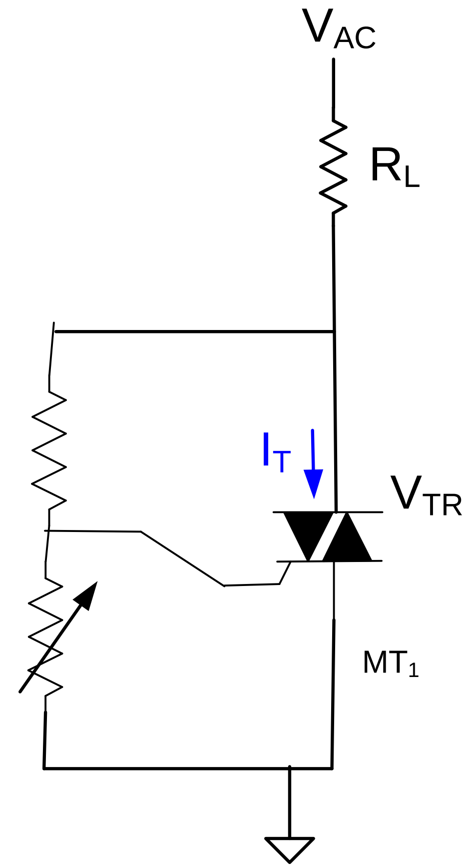




Quad 1 : Quad 3

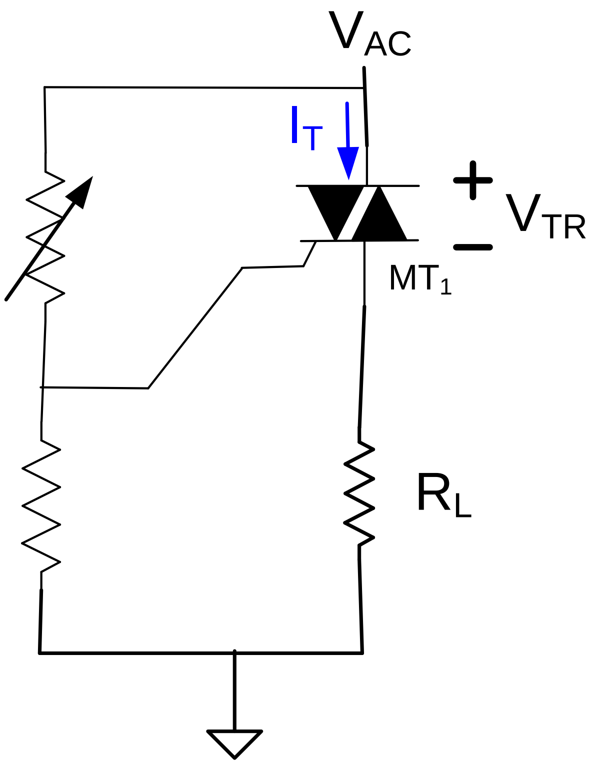


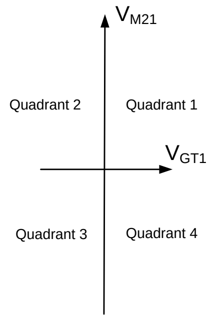
Quad 1 : Quad 3



Quad 1 : Quad 3

Some Basic Triac Application Circuits





Quad 1/ Quad 2 : Quad 3/Quad 4

Not real popular

End of Lecture 26