Thyristors
- SCR
- TRIAC
Area Comparison between BJT and MOSFET

- BJT Area = \(3600 \lambda^2\)
- n-channel MOSFET Area = \(168 \lambda^2\)
- Area Ratio = 21:1
The Thyristor

A bipolar device in CMOS Processes

Consider a Bulk-CMOS Process

Have formed a lateral pnnpn device!

Will spend some time studying pnnpn devices
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

Consider first how this 4-layer 3-junction device operates
Variation of Current Gain ($\beta$) with Bias for BJT

Review from Last Lecture

Note that current gain gets very small at low base current levels
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.
The Ideal SCR

\[ I_F = f(V_F, V_G) \]

\[ I_H \] 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:

\[ V_{CC} = I_F R_L + V_F \]
\[ I_{FI} = f (V_F, V_G) \]

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

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 when \( I_G = 0 \).
Operation of the SCR

Operation with the Ideal SCR

\[ I_{Fi} = f(V_F, V_G) \]
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.

\[ V_{CC} = I_F R_L + V_F \]
\[ I_{FI} = f(V_F, V_G) \]

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

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

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

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 $R_L$

![Diagram of SCR operation with voltage and current waveforms. The diagram shows $V_{AC}$, $V_{LOAD}$, $I_{GATE}$, and the circuit with $V_{AC}$, $R_L$, and $V_F$.]
Operation of the SCR

Operation with the Ideal SCR

Duty cycle control of $R_L$

$V_{LOAD}$

$I_{GATE}$

$I_F$

$V_{LOAD}$

$I_{GATE}$

$V_{AC}$

$V_{F}$

$V_{G}$
Operation of the SCR

Operation with the Ideal SCR

Duty cycle control of $R_L$

- $V_{AC}$
- $V_{LOAD}$
- $I_{GATE}$
- $I_F$
- $V_G$
- $V_{AC}$
- $V_{LOAD}$
- $I_{GATE}$
- $R_L$
Operation of the SCR

Operation with the Ideal SCR

Duty cycle control of $R_L$

\[ V_{LOAD} \]

$V_{LOAD}$

$I_{GATE}$

$V_{AC}$

$R_L$

$I_F$

$V_F$

$V_G$

$V_{LOAD}$

$I_{GATE}$
Operation of the SCR

Operation with the actual SCR

\[ I_F = 0 \]

\[ \Delta V_F \]

\[ V_{BRF0} \]

\[ V_{BRR} \]

\[ I_F \]

\[ I_G \]

\[ V_F \]

\[ V_G \]
Operation of the SCR

Operation with the actual SCR

\[ V_{BRR} \]

\[ I_H \]

\[ I_F \]

\[ I_G > I_{G3} > I_{G2} > I_{G1} = 0 \]

\[ V_{BRF0} \]

\[ V_F \]
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
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

6V

S1

Reset Switch (NC)

DUT

V1

Buzzer

R

S2

NC Foil/Widow Switch

V2
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

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:

- 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: $V_{MT2} < V_{MT1}$, $V_{G-MT1} > 0$

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 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: \( V_{AC} = I_T R_L + V_{TR} \)
\( I_{FI} = f(V_{TR}, V_{GT1}) \)

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 \( V_{AC} \)
The Basic Triac Circuit

Assume ideal Triac

Load Line: \( V_{cc} = I_T R_L + V_{TR} \)

Analysis: \( V_{AC} = I_T R_L + V_{TR} \)

\( I_{FI} = f(V_{TR}, V_{GT2}) \)

Single solution for both positive and negative \( V_{AC} \)

Thus this state turns on the Triac for any input
The Basic Triac Circuit

Assume ideal Triac
The Actual Triac

\[ I_T > I_{G4} > I_{G3} > I_{G2} > I_{G1} = 0 \]
The Actual Triac in Basic Circuit

\[ I_G = 0 \]

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

- Quadrant 1: $I_G > I_G^3 > I_G^2 > I_G^1 = 0$
- Quadrant 2: $I_G^4 < I_G^3 < I_G^2 < I_G^1 < 0$
- Quadrant 3: $I_G^4 < I_G^3 < I_G^2 < I_G^1 < 0$
- Quadrant 4: $I_G^4 > I_G^3 > I_G^2 > I_G^1 = 0$
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 $Q_2$-$Q_3$ quadrants or $Q_1$-$Q_3$ 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)

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

Quadrant 1

$V_{M21}$

Quadrant 4

$V_{M21}$

Quadrant 3

$V_{M21}$

Quadrant 2

$V_{M21}$

$I_T$

$I_T$

$V_{GT1}$

$V_{GT1}$
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

Quad 1 : Quad 4

(not attractive because of Quad 4)

Quad 2 : Quad 3

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

(V_{GG} \text{ often from logic/control circuit})
Some Basic Triac Application Circuits

Limitations?

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

Direct digital control of trigger voltage/current with dedicated IC
Some Basic Triac Application Circuits

Quad 1 : Quad 3
Some Basic Triac Application Circuits

Quad 1/ Quad 2 : Quad 3/Quad 4

Not real popular
End of Lecture 26