EN2110 - Electronics III
Lecture 5 - Semiconductor Devices

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Power Semiconductor Devices

Challenges

- Challenges in power semiconductor device design are,
  1. Obtaining a high breakdown voltage
  2. Low forward voltage drop
  3. Low on-resistance
- Challenge is longer switching times of high-voltage, low-on-resistance devices
- The breakdown voltage of a reverse-biased p-n junction is a function of doping level
  1. High breakdown voltage is obtained by low doping concentration and lengthy drift region
  2. Hence, higher on-resistance
- In majority carrier devices (MOSFET and Schottky diode) - first-order relationship between ON-resistance and rated voltage
- In minority carrier devices (p-n diode, BJT, IGBT, and thyristor family) - conductivity modulation

Conductivity Modulation

- When a minority-carrier device is at ON-state
  1. Minority carriers are injected into the lightly doped drift region by the forward-biased p-n junction
  2. High minority carrier concentration effectively reduces apparent resistivity of the region
- Minority-carrier devices exhibit lower ON-resistances than comparable majority-carrier devices
- But carrier injection gives rise reduced switching speed
  1. Conducting state of semiconductor device is controlled by the presence or absence of key charge quantities within the device
  2. Turn-ON and turn-OFF switching times are equal to the times required to insert or remove this controlling charge
  3. Minority-carrier devices exhibit significantly longer switching times
- Majority-carrier devices - low voltage + high switching frequency applications
- Minority-carrier devices - high voltage + low switching frequency applications

Power Diode - Introduction

- Power diode consists of three layers instead of two layers in low power diodes
  1. Heavily doped n-type substrate - Cathode
  2. Lightly doped n^- epitaxial layer - Drift region (cannot be found in low power diodes)
  3. Heavily doped p-type layer - Anode
- Drift region thickness - depends on breakdown voltage
- Cross-sectional area - depends on the total device current

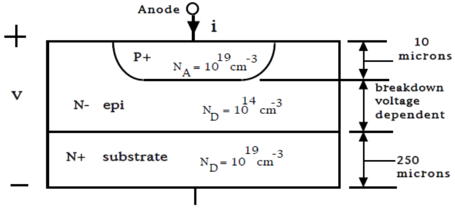

Figure: Cross section of a power diode

Power Diode - Basic Operation

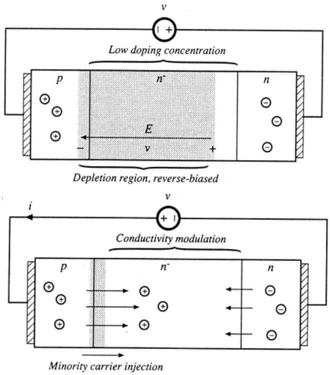

Figure: Power diode under reverse and forward biased states

- Applied voltage appears across the depletion region inside the n^- region under reverse-biased conditions
- Holes are injected across the forward-biased junction, and become minority carriers in the n^- region
- Effectively reduce the apparent resistivity of the n^- region via conductivity modulation
- Forward current $i(t)$ is comprised of,
  1. Holes that diffuse across the $p-n$ region and then recombine with electrons from the n region

Power Diode Symbol, Characteristics and Packages

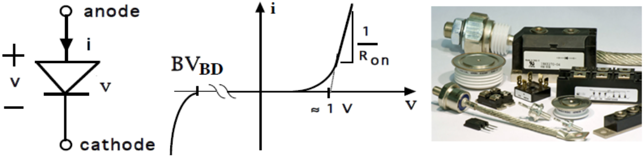

Figure: Power diode symbol, characteristics and packages

- Current grows linearly rather than exponentially
- Large current create ohmic drop that mask diode exponential characteristics
- This voltage drop across lightly doped drift region
- There is small leakage current until reverse biased voltage reach breakdown voltage (BV_{BD})
- After BV_{BD}, current increase dramatically and it is limited by external circuit
- Excessive power dissipation may quickly destroy diode

Power Diode - Switching Characteristics

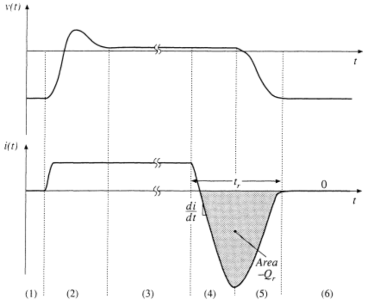

Figure: Voltage and current waveforms of a power diode

- During transients, significant deviations from the exponential characteristic are observed
- These deviations are associated with changes in the stored minority charge
- $Interval - 1$
  1. Zero current and negative voltage (Maximum will be diode PIV)

Switching Characteristics

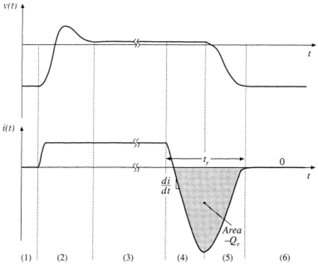

Figure: Voltage and current waveforms of a power diode

- $Interval - 2$
  1. Increasing current charges the effective capacitance of the reverse-biased diode
  2. Supplying charge to the depletion region and increasing the voltage $v(t)$
  3. The voltage becomes positive, and the diode junction becomes forward-biased
  4. Voltage may rise to a peak value of several volts reflecting the somewhat large resistance of the lightly doped n^- region

Switching Characteristics - Turn-OFF transient

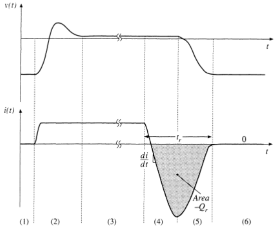

Figure: Voltage and current waveforms of a power diode

- $Interval - 2$
  1. Forward-biased pn^- junction continues to inject minority charge into the n^- region
  2. Conductivity modulation of the n^- region causes its effective resistance to decrease, and hence the forward voltage drop $v(t)$ also decreases

- Diode become equilibrium - minority carrier injection rate and recombination rate are equal
- $Interval - 3$
  1. Diode operates in the ON state and forward voltage drop is given by the diode static $I - V$ characteristics

Switching Characteristics

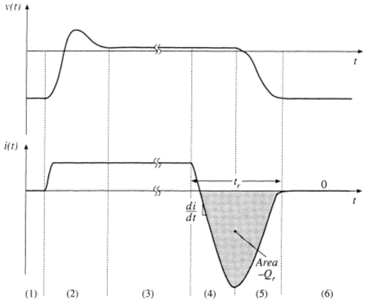

Figure: Voltage and current waveforms of a power diode

- $Interval - 4$
  1. Diode remains forward-biased while minority charge is present in the vicinity of the diode pn^{-} junction
  2. Stored minority charge is reduced by negative terminal current and by recombination
  3. At the end, stored minority charge has been removed and diode junction becomes reverse-biased

Switching Characteristics

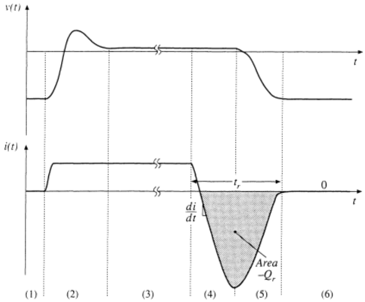

Figure: Voltage and current waveforms of a power diode

- $Interval - 5$
  1. Depletion region effective capacitance is then charged
  2. At the end of this period diode is able to block the entire applied reverse voltage
- $Interval - 6$
  1. Diode operates in the off state

Switching Characteristics - Reverse Recovery

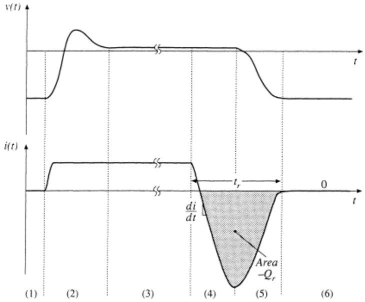

Figure: Voltage and current waveforms of a power diode

- Charge Q_r is called the recovered charge
- Portion of Q_r occurring during $interval - 4$ is actively removed minority charge
- Portion of Q_r occurring during $interval - 5$ is charge supplied to the depletion region
- Length of intervals 4 and 5 is called the *reverse recovery time* (t_{rr})

Diode Types - Based on t_{rr}

- Standard recovery
  1. Reverse recovery time usually not specified
  2. Use in $50Hz$ and $60Hz$ applications
- Fast recovery and ultra fast recovery
  1. Reverse recovery time t_{rr} and recovered charge Q_r are specified by manufacturers
  2. Fast recovery - nS to μS
  3. Ultra fast recovery - Few nS

Power Diode - Parallel Operation

- Temperature coefficient of on-resistance and forward voltage drop of power semiconductor device play key role
- Diodes cannot be easily connected in parallel, because of their negative temperature coefficients
- Imbalance in device characteristics may cause one diode to conduct more current than the others
- Then that diode becomes hotter, which causes it to conduct even more of the total current
- Current does not divide evenly between the paralleled devices
- Current rating of one of the devices may be exceeded

MOSFET

Power Semiconductor Devices - MOSFET

- The power MOSFET is comprised of many small parallel-connected enhancement-mode MOSFET cells
- A cross-section of one cell is illustrated in figure

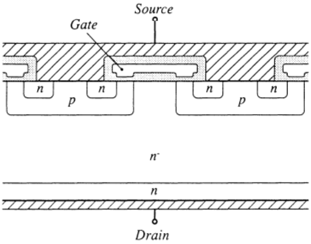

Figure: Cross section of power MOSFET

- Current flows vertically through the silicon wafer:
- The metallized drain connection is made on the bottom of the chip
- The metallized source connection and polysilicon gate are on the top surface

MOSFET - OFF state Operation

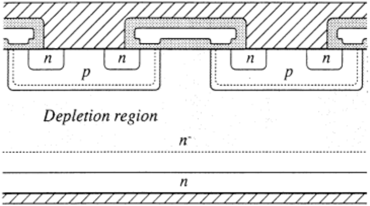

Figure: MOSFET operation when $V_{DS} \geq 0$

- Both the pn and pn^- junctions are reverse-biased
- The applied drain-to-source voltage then appears across the depletion region of the pn^- junction
- The n^- region is lightly doped, such that the desired breakdown voltage rating is attained
- As the breakdown voltage is increased, the on-resistance becomes dominated by the resistance of the n^- region
- ON-resistance increases rapidly as there are no minority carriers to cause conductivity modulation

MOSFET - ON state Operation

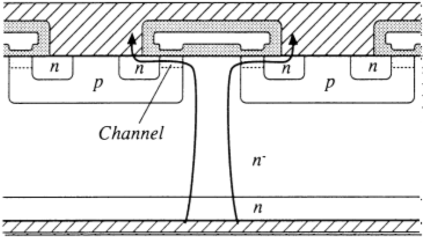

Figure: MOSFET operation when at ON state

- Sufficiently large positive gate-to-source voltage need to be applied
- A channel then forms at the surface of the p region, underneath the gate
- The drain current flows through the n^- region, channel, n region, and out through the source contact
- The on-resistance of the device is the sum of the resistances of the n region, the channel, the source and drain contacts

MOSFET - Body Diode

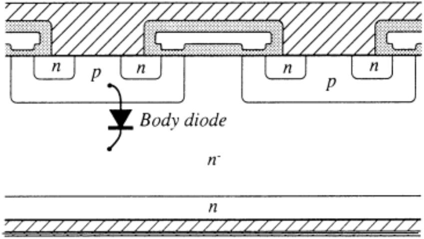

Figure: Formation of body diode

- The pn^- forms an effective diode in parallel with the MOSFET channel
- The body diode can become forward-biased when the drain-to-source voltage $v_{DS}(t)$ is negative
- MOSFETs are not optimized with respect to the speed of their body diodes although they are capable to conduct total MOSFET current
- The large peak currents that flow during the reverse recovery transition of the body diode can cause device failure

MOSFET - Static Characteristics

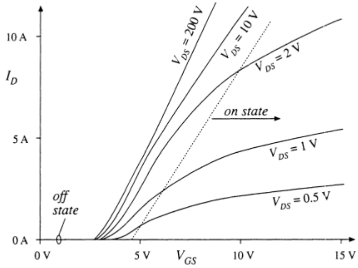

Figure: Static output characteristics of MOSFET

- The device operates in the OFF state when the gate-to-source voltage is less than the threshold voltage V_{th} (around $3V$)
- When the gate-to-source voltage greater than 6 or 7 V, the device operates in the ON state
- The gate is driven to 12 or 15 V to ensure minimization of the forward voltage drop
- In the on state, V_{DS} roughly proportional to the I_D

MOSFET - Capacitances

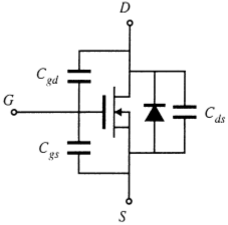

Figure: Equivalent MOSFET with body diode and capacitances

- The major capacitances of the MOSFET are illustrated
- Switching times of the MOSFET are determined by the times required for the gate driver to charge and discharge these capacitances

- The rate at which the drain current changes is dependent on the rate at which the gate-to-source capacitance is charged by the gate drive circuit
- The rate at which the drain voltage changes is a function of the rate at which the gate-to-drain capacitance is charged
- The drain-to-source capacitance leads directly to switching loss in PWM converters
- energy stored in this capacitance is lost during the transistor turn-on transition

MOSFET - Characteristics of Capacitances

- The gate-to-source capacitance is essentially linear
- The drain-to-source and gate-to-drain capacitances are strongly nonlinear
- The incremental drain-to-source capacitance can be written as

$$C_{DS}(V_{DS}) = \frac{C_o}{\sqrt{1 + \frac{V_{DS}}{V_o}}}$$

- Where C_o and V_o are constants that depend on the construction of the device
- These capacitances can easily vary by several orders of magnitude as V_{DS} varies over its normal operating range
- For $V_{DS} >> V_O$

$$C_{DS}(V_{DS}) \approx C_o \sqrt{\frac{V_o}{V_{DS}}} = \frac{C_o'}{\sqrt{v_{DS}}}$$

MOSFET - Selection

- The gate charge (Q_g)
  1. The gate charge (Q_g) is the charge that the gate drive circuit must supply to the MOSFET to raise the gate voltage from zero to some specified value
  2. At a specified value of off state drain-to-source voltage - typically 80% of the rated V_{DS}
  3. The total gate charge is the sum of the charges on the gate-to-drain and the gate-to-source capacitances
  4. The total gate charge is a measure of switching speed of the MOSFET
- ON-resistance
  1. Conduction loss are the limiting factors
  2. MOSFETs may be operated at average currents somewhat less than the rated value
- MOSFETs are usually the device of choice at voltages less than or equal to approximately 400 to 500 V
- Used for high switching speed applications
- But with high ON-state losses compared to minority carrier devices

Bipolar Junction Transistor (BJT)

BJT - Internal Structure

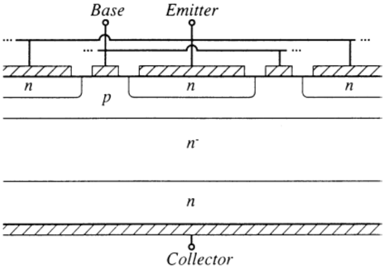

Figure: Cross section of NPN power BJT

- Current flows vertically through the silicon wafer
- A lightly doped n^- region - to obtain the desired voltage breakdown rating
- OFF-state operation
  1. Both pn BE junction and the pn^- BC junctions are reverse-biased
  2. The applied collector-emitter voltage then appears essentially across the depletion region of the pn^- junction

BJT - Operation

- ON-state operation
  1. Both junctions are forward-biased
  2. substantial minority charge is then present in the p and n^- regions
  3. This minority charge causes the n^- region to exhibit a low on-resistance via the conductivity modulation effect
- Active region
  1. pn BE junction is forward-biased and the pn^- BC junction is reverse-biased
  2. The I_C is proportional to the base region minority charge, which in turn is proportional (in equilibrium) to the I_B
- Quasi-saturation
  1. Quasi-saturation occurs when the I_B is insufficient to fully saturate the device
  2. The minority charge present in the n^- region is insufficient to fully reduce the on-resistance

BJT - Switching Waveforms

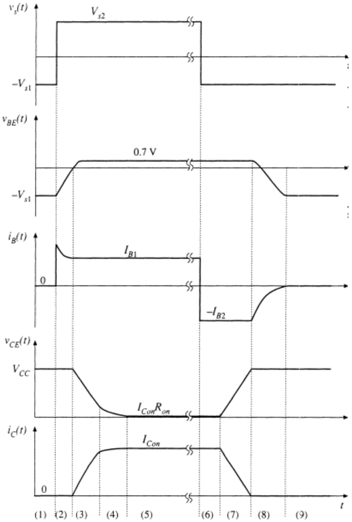

Figure: Switching waveforms

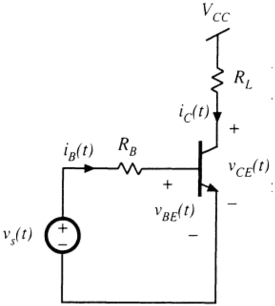

Figure: Power BJT in circuit

- Turn-ON and OFF waveforms of power BJT are shown in figure

BJT - Switching Waveforms

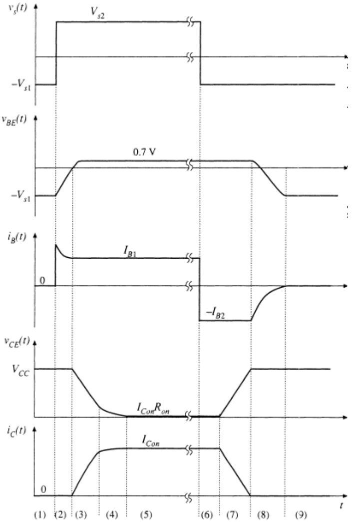

Figure: Switching waveforms

- Interval 1
  1. The transistor operates in the off state
  2. The BE junction is reverse biased by the $v_s(t) = -V_{s1}$
- Interval 2
  1. Turn-ON transition is initiated at the beginning of this interval
  2. Positive current is supplied by source v_s
  3. This current charges the capacitances of the depletion regions of the reverse biased BE and BC junctions
  4. BE voltage exceeds zero sufficiently for the BE junction to become forward biased

BJT - Switching Waveforms

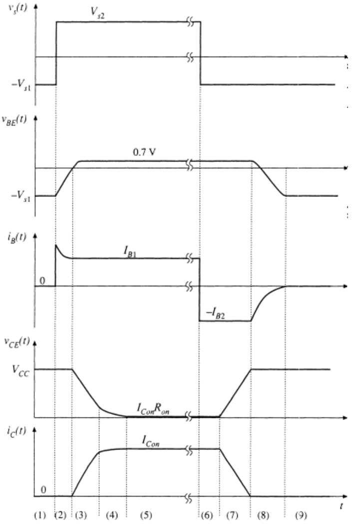

Figure: Switching waveforms

- Interval 3
  1. Minority charge is injected across the base-emitter junction from the emitter into the base region
  2. Collector current is proportional to this minority base charge
  3. Decrease in collector voltage, reduce voltage across the reverse-biased BC depletion region (Miller) capacitance
  4. Turn-ON time can be reduced by reducing R_B or increasing $v_s(t)$ due to increase of I_B
- Interval 4
  1. BC pn^- junction becomes forward biased and minority carriers are then injected into the n^- region
  2. Apparent resistance of the n^- region decreases via conductivity modulation

BJT - Switching Waveforms

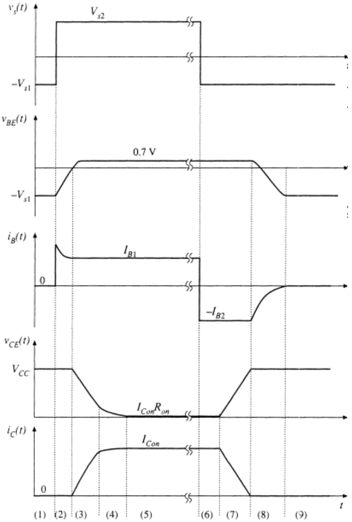

Figure: Switching waveforms

- Interval 5
  1. Reaches on state equilibrium at the beginning of this interval
- Interval 6
  1. Turn-OFF process is initiated when the source voltage changes to $v_s(t) = -V_{s1}$
  2. The BE junction remains forward biased as long as minority carriers are present in its vicinity
  3. I_C continues to be $i_c(t) = I_{C,on}$ as long as the minority charge exceeds the amount necessary to support the active region conduction of $I_{C,on}$
  4. Negative base current actively removes the total stored minority charge
  5. Recombination further reduces the stored minority charge
  6. Length of this period is called as *storage time*

BJT - Switching Waveforms

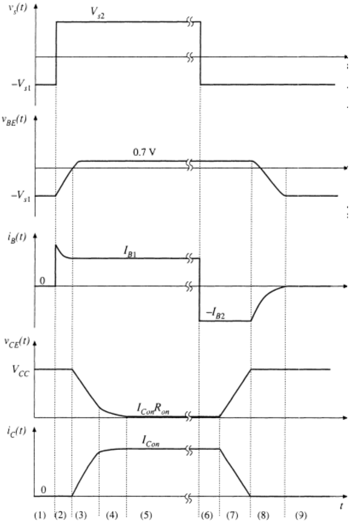

Figure: Switching waveforms

- Interval 7
  1. The collector current $i_c(t)$ is now proportional to the stored minority charge
  2. The collector current decreases due to recombination and the negative base current
  3. I_B must charge the Miller capacitance and increase collector voltage
- Interval 8
  1. Reverse-biased base-emitter junction capacitance is discharged to voltage $-V_{s1}$,

Base Drive Current

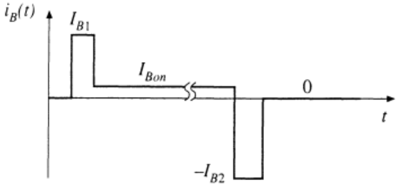

Figure: Base drive current

- It is possible to turn-OFF the transistor using $I_{B2} = 0$
- This leads to very long storage and turn-off switching times (stored minority charge must be removed passively, via recombination)
- Initial I_{B1} is large in magnitude - charge is inserted quickly into the base, and the turn-ON switching times are short
- ON state current I_{Bon} is chosen, to yield a reasonably low CE forward voltage drop
- Turn-OFF switching times are minimized by large $-I_{B2}$ that charge is removed quickly from the base

Second Break Down

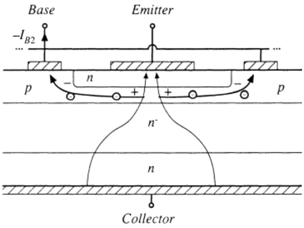

Figure: Second break down

- The lateral base current through the p region leads to a voltage drop in p material
- Turn-OFF instance
  1. Base-emitter junction voltage to be greater in the center of the base region
  2. Collector current to focus near the center of the base region

- Turn-ON instance
  1. Collector current to crowd near the edges of the base region
- Hot spots are induced at the center or edge of the base region due to
  1. CE voltage and I_C are simultaneously large during the switching transitions

IGBT

Introduction

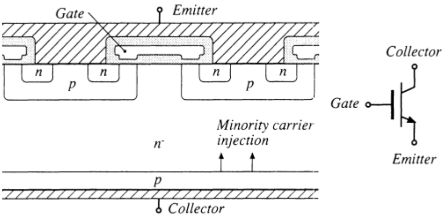

Figure: IGBT cross section

- Crosshatched regions are metallized contact and shaded regions are insulating silicon dioxide layers
- IGBT is a four-layer power semiconductor device having a MOS gate
- The function of the added p region is to inject minority charges into the n^- region while the device operates in the ON state
- The pn^- junction is forward-biased, and the minority charges injected into the n^- region cause conductivity modulation when IGBT conducts
- The forward voltage drops of these devices are typically 2 to 4V

Equivalent Circuit

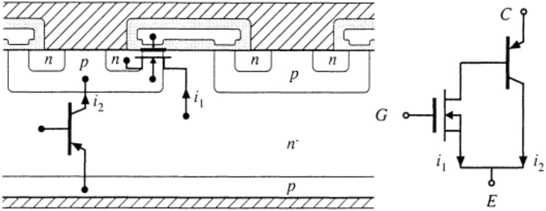

Figure: IGBT equivalent circuit

- The IGBT functions effectively as cascaded,
  1. n-channel power MOSFET
  2. PNP emitter-follower BJT
- Hence, there are two effective currents
- The price paid for the reduced voltage drop of the IGBT is its increased switching times

Current Tailing

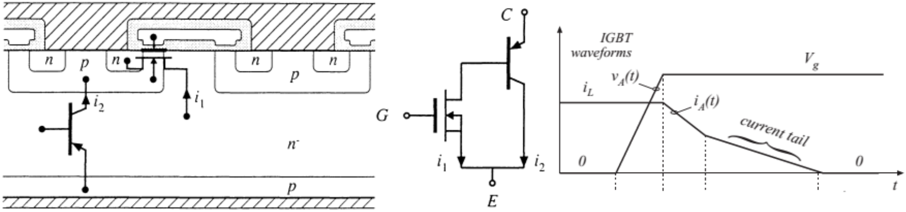

Figure: IGBT current tailing

- The effective MOSFET can be turned off quickly - by removing the gate charge
- This causes the channel current i_1 to quickly become zero
- The PNP collector current i_2 continues to flow as long as minority charge is present in the n^- region
- No way to actively remove the stored minority charge other than recombination
- The switching frequencies of PWM converters containing IGBTs are typically in the range 1 to $30kHz$.

IGBT - More Info

- pn^- junction of the IGBT is not normally designed to block significant voltage
- Hence, IGBT has negligible reverse voltage-blocking capability
- IGBT ON resistance has positive temperature coefficient
- IGBTs can be easily connected in parallel, with a modest current derating
- Large modules are commercially available, containing multiple parallel-connected chips

Silicon Controlled Rectifier (SCR)

Introduction

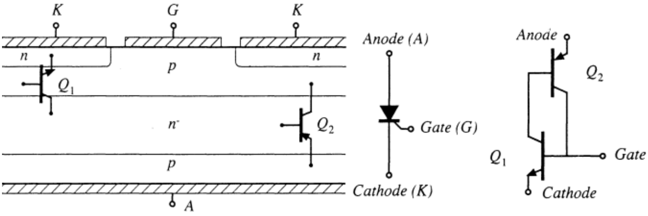

Figure: SCR cross section, symbol and equivalent circuit

- Silicon-controlled rectifier (SCR) is the oldest among conventional semiconductor power devices
- Devices having voltage ratings of 5000 to 7000 V and current ratings of several thousand amperes are available
- Four layer device
- Effective transistor Q_1 is composed of the n, p, and n^- regions, while effective transistor Q_2 is composed of the p, n^-, and p regions

SCR Operation

- SCR can enter the on state when the applied v_{AK} is positive
- Positive gate current i_G causes Q_1 to turn-ON
- This in turn supplies base current to Q_2, and causes it to turn-ON
- Effective connections of the base and collector regions of transistors Q_1 and Q_2 constitute a positive feedback loop
- Currents of the transistors will increase regeneratively
- Minority carriers are injected into all four regions, and the resulting conductivity modulation leads to very low forward voltage drop
- SCR cannot be turned off except by application of negative anode current or negative anode-to-cathode voltage
- During the turn-OFF transition, the rate at which forward anode to cathode voltage is reapplied must be limited, to avoid re triggering the SCR
- During turn-OFF time minority stored charge is
  1. Actively removed via negative anode current
  2. Recombination

SCR Characteristics

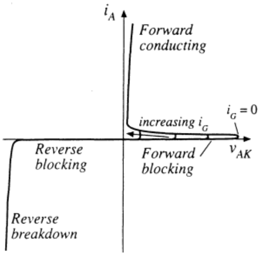

Figure: Characteristics curve

- SCR is a voltage-bidirectional two quadrant switch
- The turn-ON transition is controlled actively via the gate current
- The turn-OFF transition is passive

- The device is capable of blocking both positive and negative anode to cathode voltages
- One of the pn^- junctions is reverse-biased depending on applied voltage
- Depletion region extends into the lightly doped n^- region