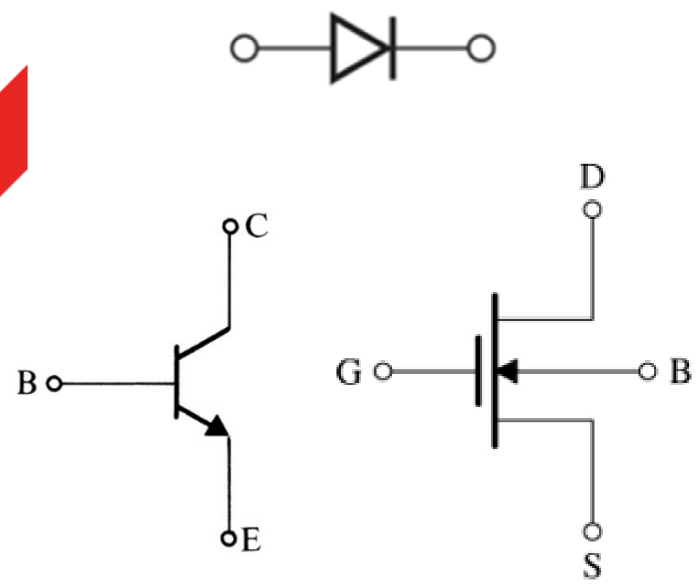
ELEC2005
Electrical and Electronic Systems

POWER SEMICONDUCTORS

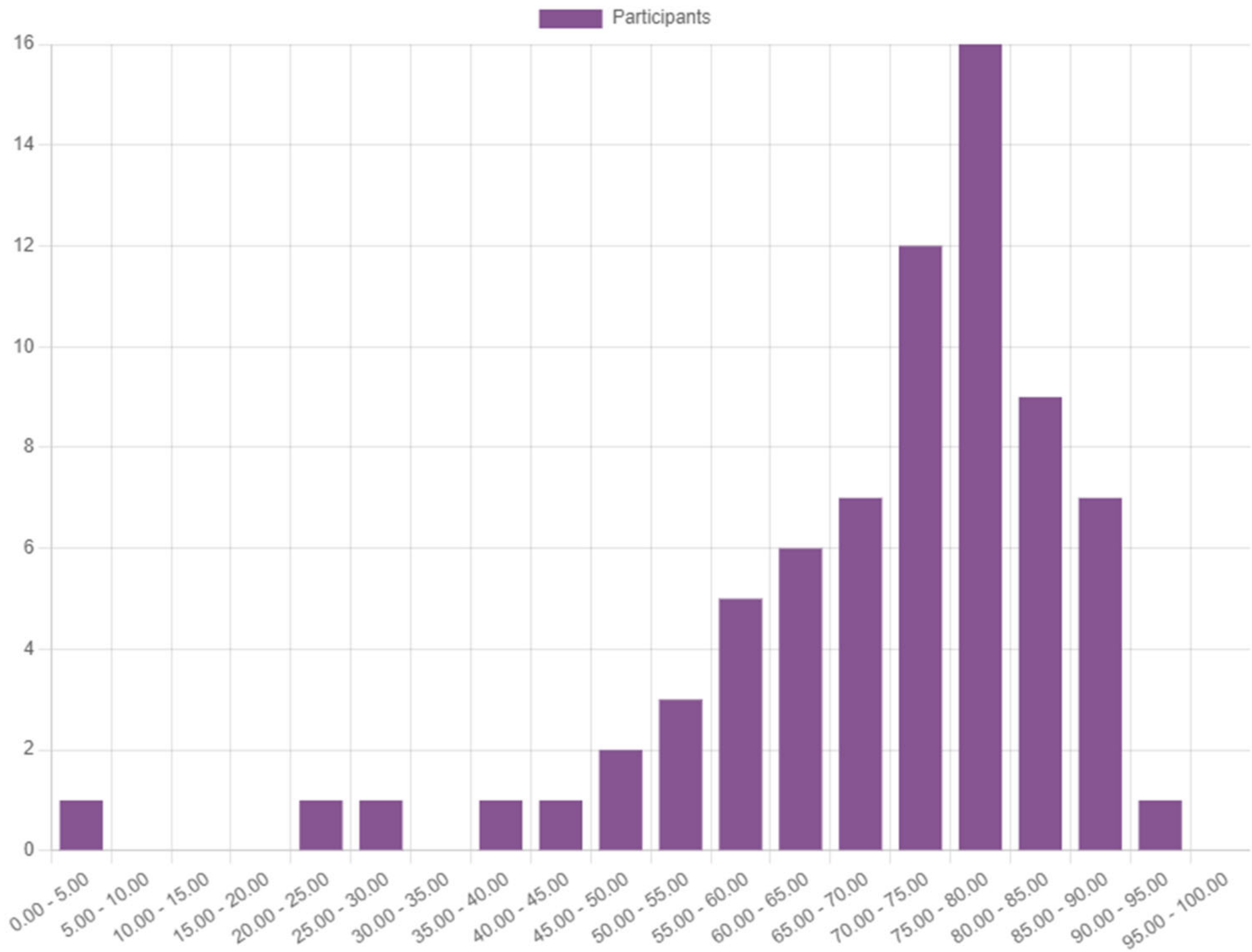
DAVID PAYNE



Assignment-1

Average Mark: 68

Marks distribution:

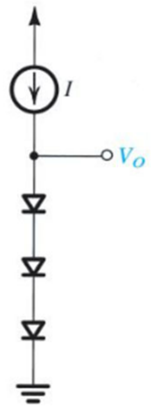


Most people did well in the assignment, if you need more assistance then please use consultation hours and email to bring raise questions, doubts and concerns!

Assignment-1

Q6 & Q7

The circuit shown below consists of three identical diodes which have an ideality factor of 1 and saturation current of 1E-16. They are operating at a thermal voltage of 25mV. Find the value of the current (I) required to obtain an output voltage of 2.44V. Express your answer in mA to 1 decimal place.



Diode equation: $I_D = I_S \exp\left(\frac{V_D}{nV_T}\right)$ $V_D = \frac{2.44}{3} = 0.81333$

$\therefore I_D = 1\times10^{-16} \exp\left(\frac{0.813}{25\times10^{-3}}\right) = \underline{\underline{13.46\,mA}} = 13.5\,mA$

If a current of 1mA is drawn away by a load at the output terminal, what is the change in output voltage?
Give your answer in mV to one decimal places. we now have 12.5mA

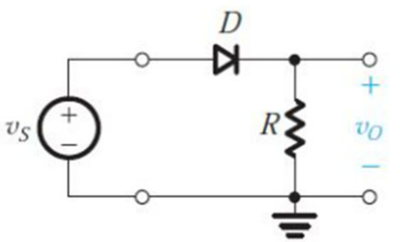
$V_D = V_T \ln\left(\frac{I_D}{I_S}\right) = 0.8115V$ $V_o = 3\times V_D = 2.435V$

Difference = $-5\,mV$

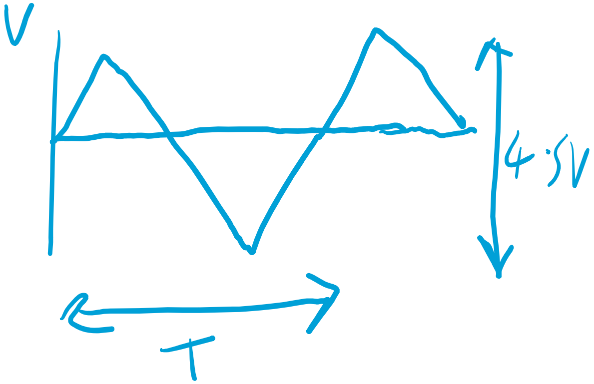
Assignment-1

Q8

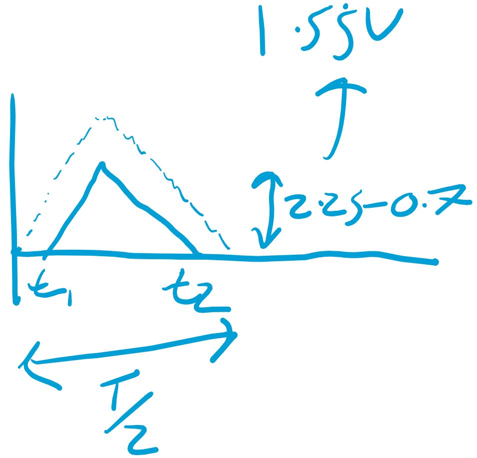
Consider the half-wave rectifier circuit shown below, which has a triangular-wave input V_s of 4.5V peak-to-peak amplitude and zero average, and a resistor value of R = 1 kΩ. Assume that the diode can be represented by the constant-voltage-drop model with V_D =0.7 V. Find the average value of V_o.
Give your answer in mV, to no decimal places.

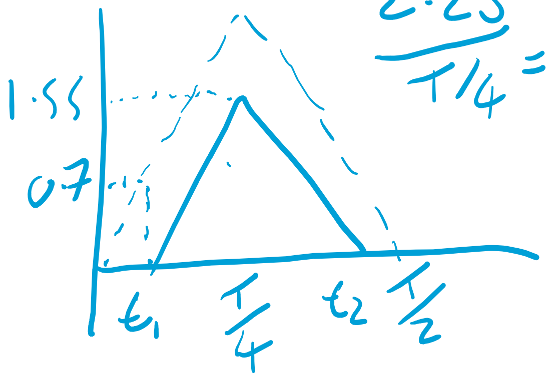


input :



V_o :





$\frac{2.25}{T/4} = \frac{0.7}{t_1}$ $\therefore t_1 = 0.0777T$

$t_2 = \frac{T}{2} - t_1 = 0.422T$

area of triangle:

$\frac{1}{2}\times b\times h = 0.5\times 0.344T\times 1.55$

$= 0.267T$

for average, divide by period

$V_{ave} = 267\,mV$

In Today's Lecture

- Introduction to Power semiconductors
- Diodes
- BJTs
- MOSFETS
- Insulated-Gat Bipolar Transistors (IGBTs)
- Thyristors:
  SCR GTO MCT
- Summary

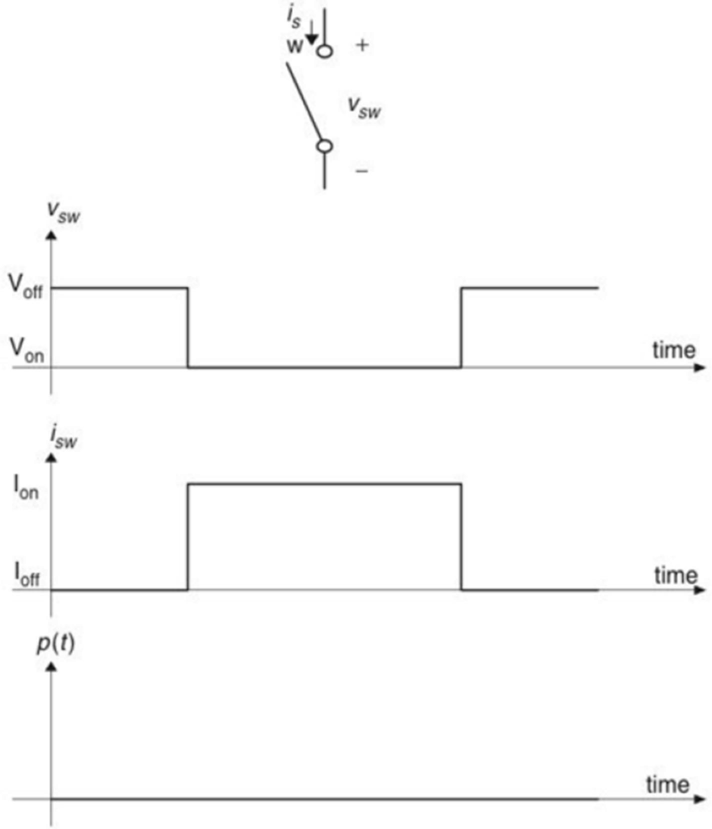
Intro to power semiconductors

INTRO

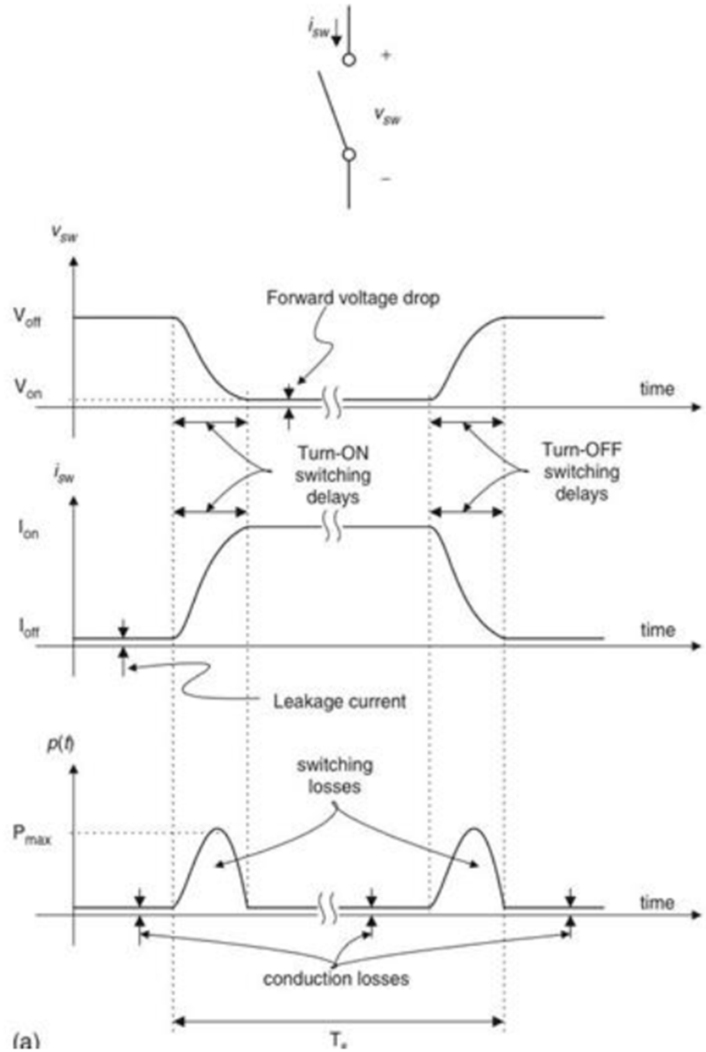
- Power devices (usually switches) with either 2 (diodes) or 3 (transistors) terminals.
- Designed to be able to handle large currents/voltages for power applications – designed to be in the on or off state, with rapid switching between
- A vast range of devices exist, their operation and power/speed handling capabilities vary significantly.
- In the ideal case we would want these to work like a perfect and instantaneous switch
  - No switching delay, no voltage drop across the switch
  - No voltage or current limit.

Intro to power semiconductors

SWITCHING



Ideal switch



Practical switch

Lecture 7

1. **Diodes**
2. BJTs
3. MOSFETS
4. Insulated-Gate Bipolar Transistors (IGBTs)
5. Thyristors:
   SCR GTO MCT
6. Summary

Power Diodes

INTRO AND STRUCTURE

- We have already covered ideal diodes, simple diode models and worked with signal diodes in the lab.
- We have discussed and tested some diode circuit applications.
- Power diodes differ from signal diodes in their construction, instead of a simple PN junction, there are extra layers with different doping.

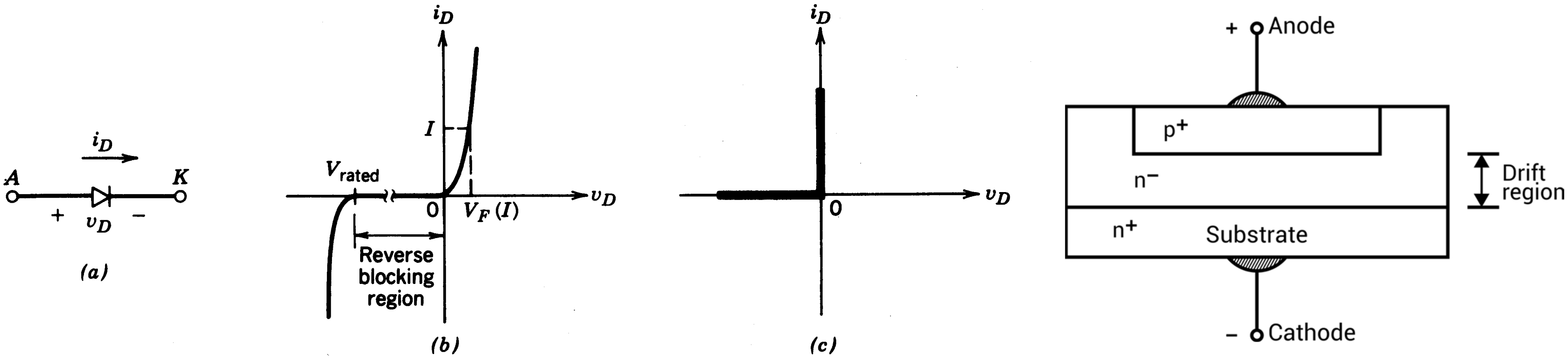


Figure 2-1 Diode: (*a*) symbol, (*b*) *i–v* characteristic, (*c*) idealized characteristic.

Power Diodes

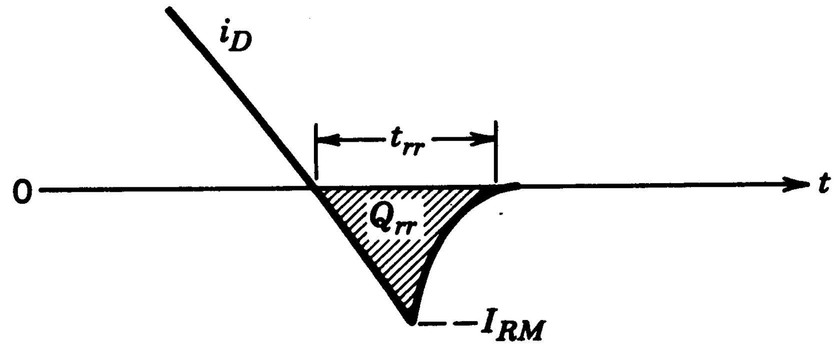
IMPORTANT PARAMETERS

- Diodes have several key parameters, some of which are constant and some which vary with condition.
- Voltage rating – max instantaneous voltage the device can block in the off state
- Current rating – max instantaneous, average or RMS current that it can conduct in the on state
- Switching speed – transition speed from on to off (or vice versa)
- On State voltage – Voltage dropped across the device when it is conducting.

Power Diodes

SWITCHING STATES

- Their On and off states controlled by the power circuit
- Diode Turn-off is not instant, a sudden change in polarity will not immediately stop current flow
- There is an additional charge Qrr that needs to be supplied to complete turn-off – The diode conducts a negative current for duration t_{rr}
- This is known as Reverse Recovery
- Power diodes are classified based on their reverse Recovery Characteristics General/Fast-recovery/Shottky



Power Diodes

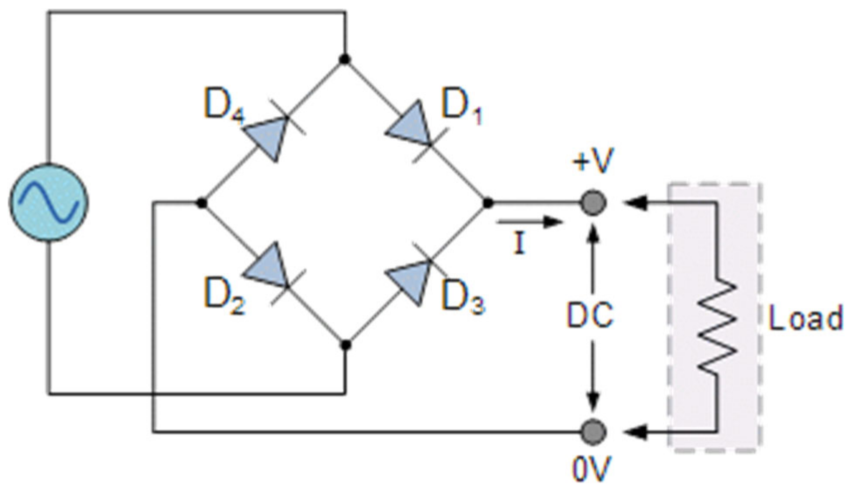
CLASSIFICATIONS

- General Purpose Diodes
  - Relatively high trr (~25 microseconds)
  - Good for low-frequency applications up to ~1khz
  - Typical current ratings 1-1000A, voltage ratings 50V-5KV
- Fast Recovery Diodes
  - Relatively low trr (<5 microseconds)
  - Good for power conversion systems
  - Typical current ratings1-1000A, voltage ratings 50V-3KV
- Schottky Diodes
  - These have a metal/semiconductor junction, rather than PN
  - Very fast switching (low trr in the nanoseconds).
  - Typical current ratings 1-300A, voltage ratings ~100V

Power Diodes

APPLICATIONS

- Power diodes are broadly used in power electronics, example applications include:
- Freewheeling diodes/clamp diodes/snubber diodes
  -protect circuits from damage caused by abrupt reduction in current flow
- AC/DC conversion/ Rectification
  -Changing between alternating and direct current
- Battery charging



Lecture 7

1. Diodes
2. **BJTs**
3. MOSFETS
4. Insulated-Gate Bipolar Transistors (IGBTs)
5. Thyristors:
   SCR GTO MCT
6. Summary

BJTs for Power Applications

INTRO AND STRUCTURE

- We have covered BJT fundamentals and how they can be used as switches and amplifiers.
- For power switching applications the cut-off and saturation regions are used
- Similarly to power diodes, high power rated BJTs have an additional n-region

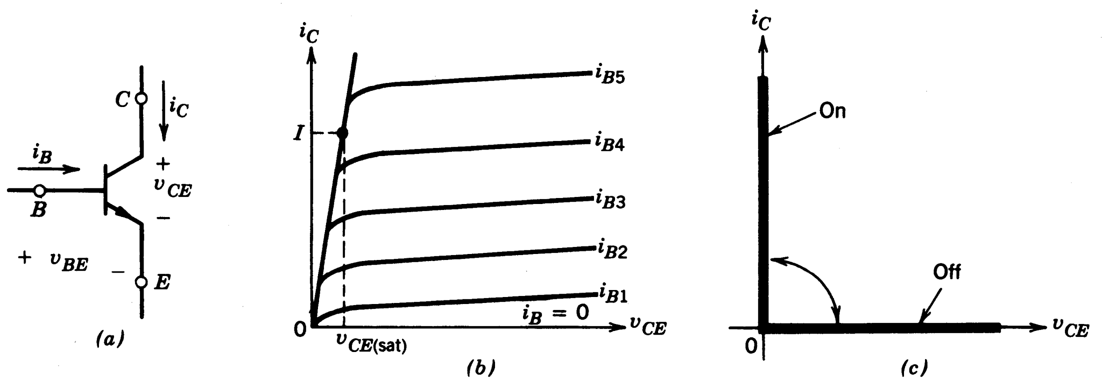
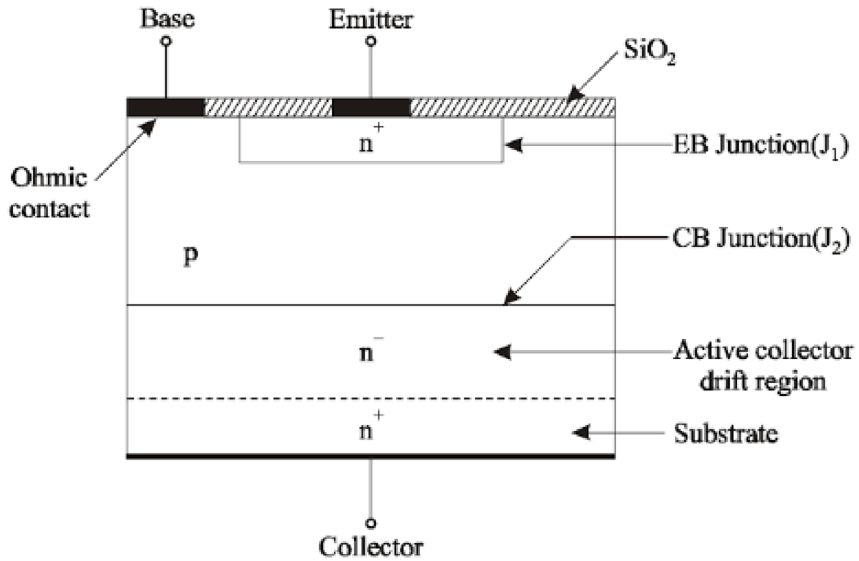


Figure 2-7 A BJT: (*a*) symbol, (*b*) *i*–*v* characteristics, (*c*) idealized characteristics.



BJTs for Power Applications

CIRCUIT CONFIGURATIONS

- Usually used in the common emitter configuration.
- To handle higher switching currents a Darlingon pair/triple Darlington configuration can be used.
- This configuration can generally be treated just like a single transistor but with: $\beta_{\text{Darlington}} = \beta_1 \cdot \beta_2 + \beta_1 + \beta_2$
- Downside is that the voltage drop also increases:

$$V_{BE} = V_{BE1} + V_{BE2}$$

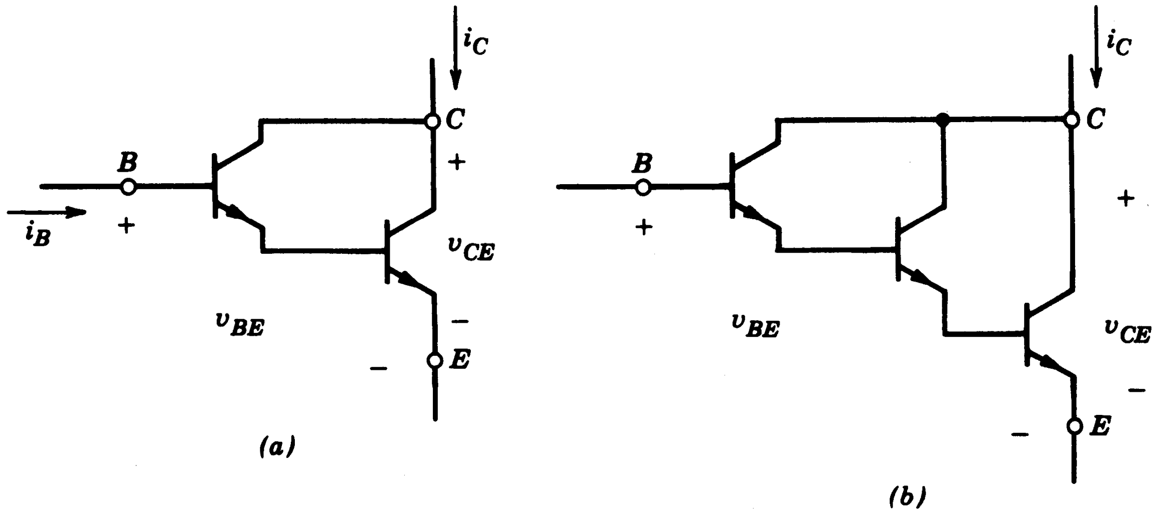


Figure 2-8 Darlington configurations: (*a*) Darlington, (*b*) triple Darlington.

BJTs for Power Applications

RATINGS AND APPLICATIONS

- Generally superseded by other technologies, but still used in some cases, can be cheaper than MOSFETs etc.
- Used in output stages of audio amplifiers, touch sensitive switches, computer controlled relays, low power AC/DC supplies.
- Switching speeds in the tens of kHz, some devices can handle 10-100s of amps and up to 1KV.

Examples of BJT rating:

Parameter	Small-signal BJT (2N2222A)	Power BJT (2N3055)	Power BJT (2N6078)
V_{CE} (max) (V)	40	60	250
I_C (max) (A)	0.8	15	7
P_D (max) (W)	1.2	115	45
β	35 – 100	5 – 20	12 – 70
f_T (MHz)	300	0.8	1

Lecture 7

1. Diodes
2. BJTs
3. **MOSFETS**
4. Insulated-Gate Bipolar Transistors (IGBTs)
5. Thyristors:
   SCR GTO MCT
6. Summary

Power MOSFETs

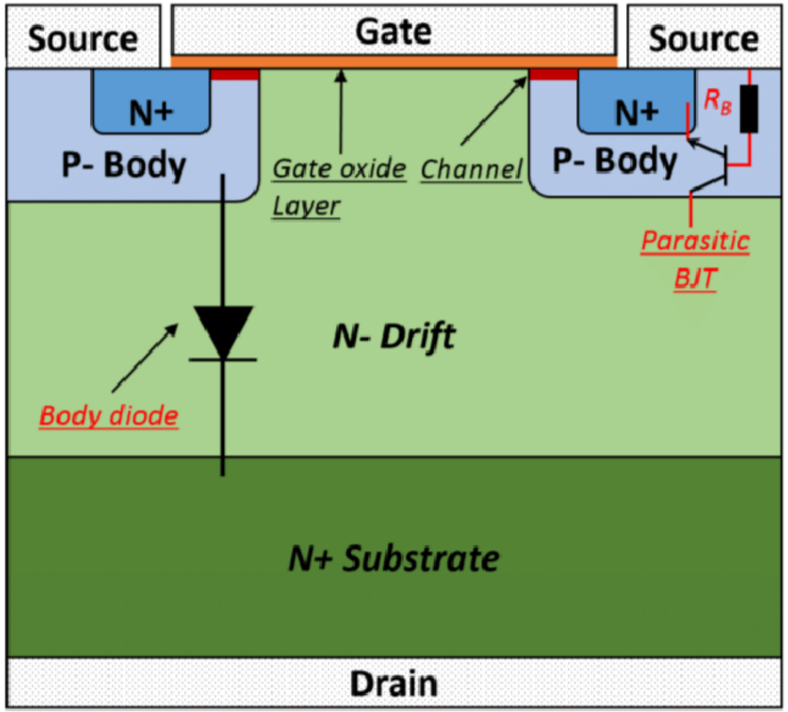
INTRO

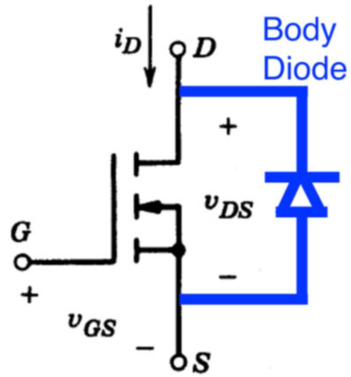
- Power MOSFETs are the most common power semiconductor device
- We have studied general MOSFET devices in some detail during this unit
- Power MOSFETs are a specific type of this technology designed to handle high power levels.
- They have the advantage of high switching speed, and good low voltage efficiency.
- Often they are low gain devices
- Very commonly used for relatively ‘low voltage’ switching (<200V)

Power MOSFETs

STRUCTURE

- Typically made using silicon and fabricated as a vertical diffused MOS structure
- Source terminal is above the drain, so current flow is primarily vertical
- The vertical structure means that the voltage rating depends on the doping and thickness of the N+ layers, whilst the current depends on the channel width.
- This design allows for higher currents and power ratings than the traditional lateral mosfet.



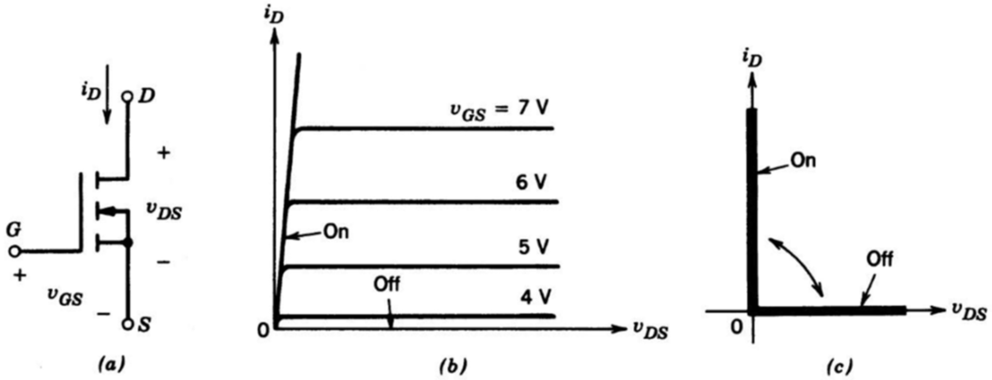


Power MOSFETs

RATINGS & APPLICATIONS

- Voltages typically up to ~ 200V
- Current up to ~100A
- Frequencies in excess of 100khz
- Account for >50% of power transistor market.
- Used for high power and rapid switching
- Applications include:

  - Power supplies, DC-DC Convertors, Low-Voltage Motor Controllers, Vehicle electronics



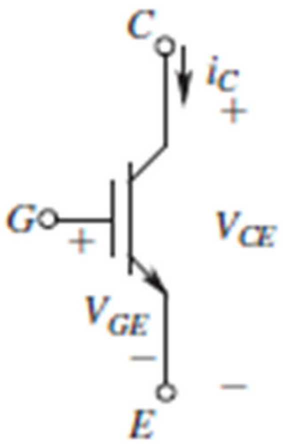
Lecture 7

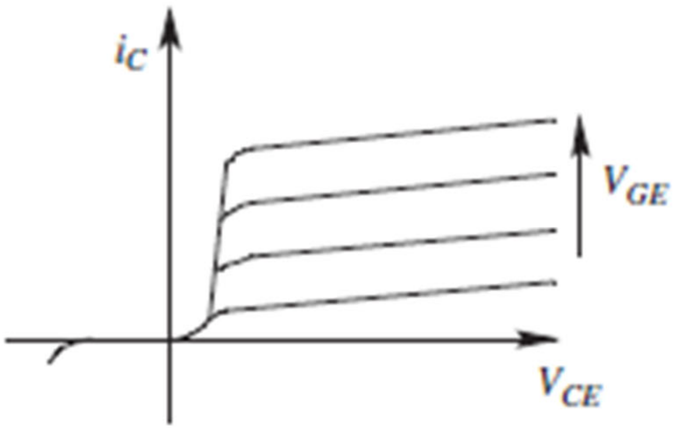
1. Diodes
2. BJTs
3. MOSFETS
4. **Insulated-Gate Bipolar Transistors (IGBTs)**
5. Thyristors:
   SCR GTO MCT
6. Summary

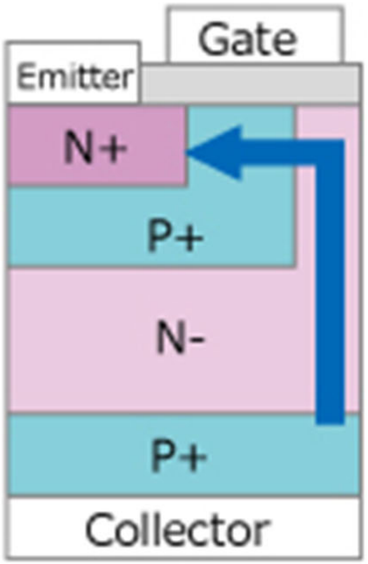
IGBTs

INTRO

- IGBT stands for Insulated Gate Bipolar Transistor
- Combine the ease of control of a MOSFET with low on-state losses, even at higher voltages (>200V)
- Circuit symbol is similar to BJT but with an extra line.



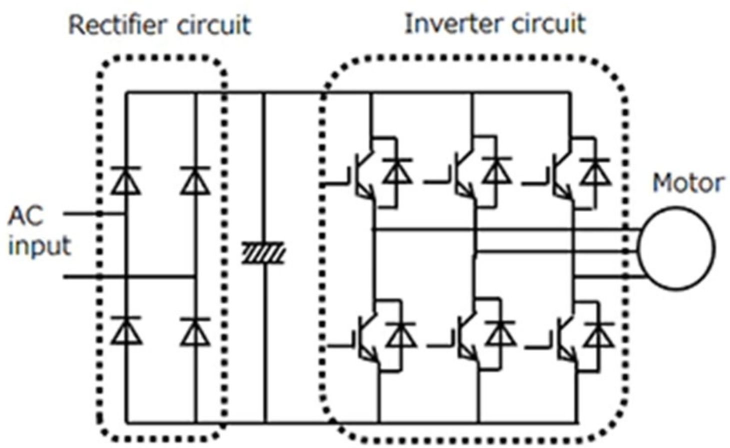




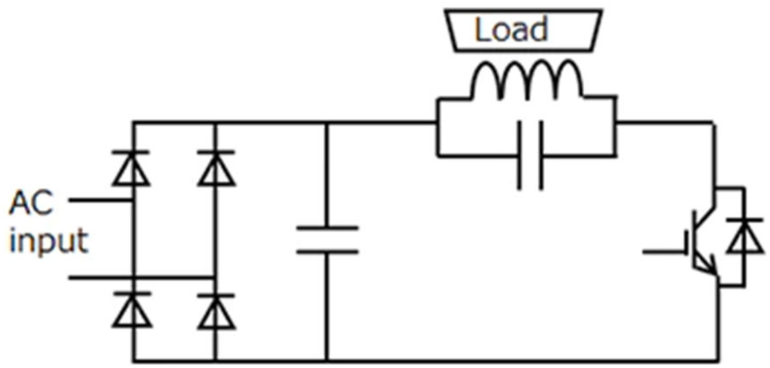
IGBTs

RATINGS & APPLICATIONS

- Voltage ratings up to ~5KV and current ratings up to ~2000A.
- Most commercial designs do not block reverse polarity voltages
- Typically used for convertors over a wide power range (1kW up to >1MW) at switching frequencies <100khz.
- Used in motor drive circuits, UPS, induction cooktops.



Motor Drive Circuit



Induction Cooktop Circuit

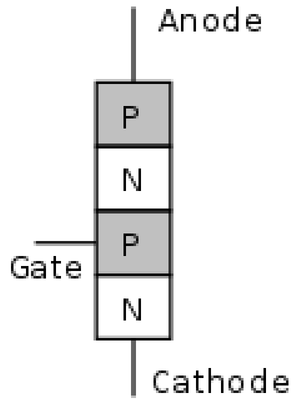
Lecture 7

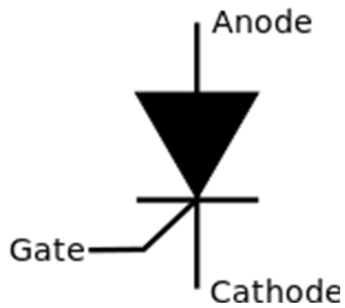
1. Diodes
2. BJTs
3. MOSFETS
4. Insulated-Gate Bipolar Transistors (IGBTs)
5. **Thyristors: SCR GTO MCT**
6. Summary

Thyristors

INTRO

- Thyristors are four-layer semiconductor devices with alternating doped regions, e.g. PNPN
- Essentially a semi-controllable diode
- Typically three electrodes, anode, cathode and gate.
- Various types of thyristor are available, most common is the Silicon Controlled Rectifier (SCR)
- They work as a bistable switch, conducting when there is a current trigger at the gate, they keep conducting until a reverse bias is applied.
- Only a short pulse is needed at the gate to turn the diode on.





Thyristors

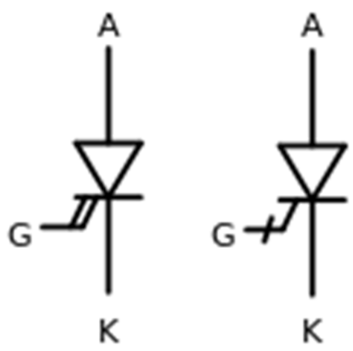
SILICON CONTROLLED RECTIFIER (SCR)

- SCR is the most common type of Thyristor, the terms are often used synonymously
- Like a modified diode, SCRs are unidirectional, they only conduct current on one direction
- 3 Modes of operation:
  Forward blocking mode – Anode has + voltage and cathode has -, gate held at zero potential, only a small leakage current flows from A to C.
  Forward conduction mode – as above but potential between anode and cathode is increased beyond breakdown, or a positive pulse is sent to the gate, now in the on state (conducting)
  Reverse blocking mode - Anode has - voltage and cathode has +, behaves like two diodes in series, only a small leakage current flows.
- SCRS are typically used in medium-high voltage control (power regulator, light dimmer etc.)

Thyristors

GATE-TURN-OFF THYRISTORS (GTO)

- A type of thyristor that provides additional control
- As the name suggests, for a GTO the gate can be used to turn off the device (unlike with a regular SCR)
- Requires a negative signal at the gate to turn-off.
- Has the drawback of long switch-off times, so can only be used at slow switching speeds. (up to 1khz) – can use a snubber circuit to reduce turn off time
- Applications include high speed motor drives and high power invertors



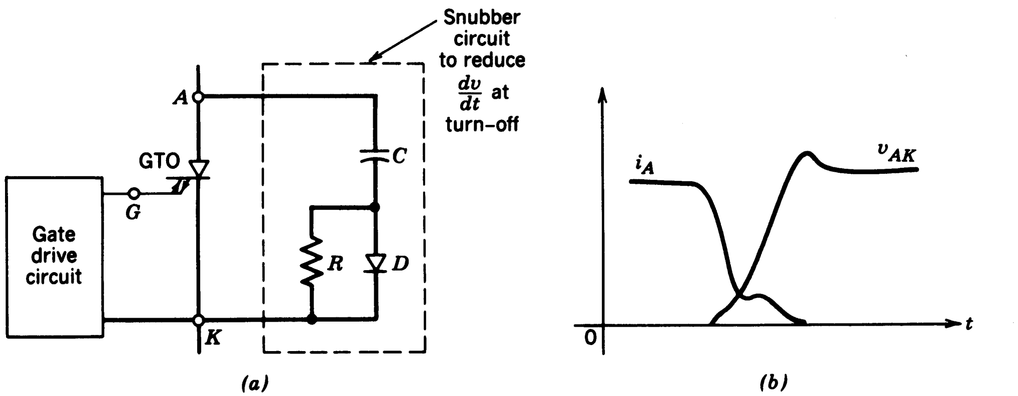
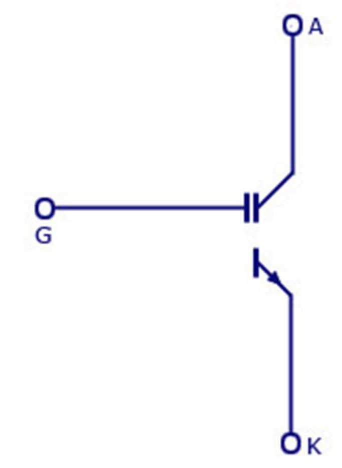


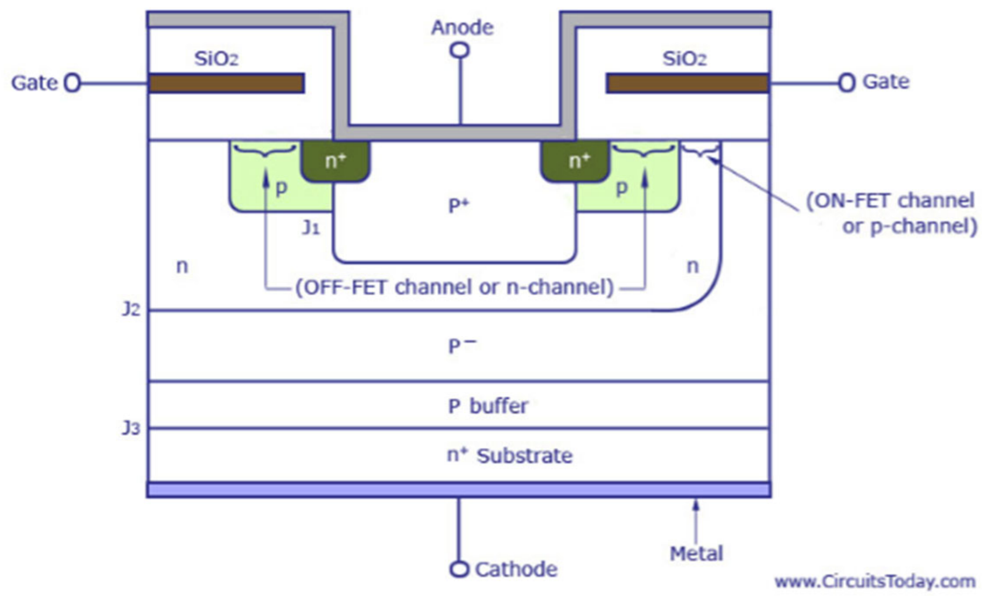
Figure 2-11 Gate turn-off transient characteristics: (*a*) snubber circuit, (*b*) GTO turn-off characteristic.

Thyristors

MOS CONTROLLED THYRISTORS (MCT)

- MCTs are a more modern device, essentially consisting of a thyristor with two MOSFETs built into the gate.
- These MOSFETS are used to turn the gate on and off.
- In this case a negative pulse (relative to the anode) turns the device on
- MCTs offer
  - low forward conduction loss
  - fast switching
  - High input impedance at gate





Lecture 7

1. Diodes
2. BJTs
3. MOSFETS
4. Insulated-Gate Bipolar Transistors (IGBTs)
5. Thyristors:
   SCR GTO MCT
6. **Summary**

Power Semiconductors

SUMMARY

- A wide range of devices exist (not all covered here)
- Device choice is a design matter, you must consider:
  Control requirements, Voltage Rating, Current Rating, Frequency, Efficiency, Cost etc.

Device	*Power Capability*	*Switching Speed*
BJT	Medium	Medium
MOSFET	Low	Fast
GTO	High	Slow
IGBT	Medium	Medium
MCT	Medium	Medium

Power Semiconductors

SUMMARY