EN 313 - Power Electronics

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Electrical energy

- Easy to transport
- Can be converted to mechanical energy and vice versa, with high efficiency
- Storage is the challenge[1]

0.6kg

2200 uF
500 V

Electrolytic capacitor
2.75"dia x 4.15" height

275 joules

10kg

12V
35Ah
Car
battery

7.75" x 5.1"x 9"
2 litres of electrolyte

1.5×10^6 joules

0.75kg

1 litre of petrol

33.5×10^6 joules

Electrical energy needs to exist at different levels depending on the type of application

[1] Images from manufacturers' datasheets and openclipart

Various levels of electrical energy

Domestic and industrial applications

- Cell phone battery: 5V DC
- Other batteries: AA and AAA (1.5V DC); 9V Rectangular
- Computer motherboard: $+5$V, $+3.3$V, ± 12V DC
- Analog/digital electronics: ± 15V, $\pm$ 12V or ± 5V DC
- Motors in domestic appliances: 1-Ph, 230V, 50Hz or 0-50Hz AC
- Industrial motors: 3-Ph, 415V-6600V, 0-50Hz AC
- Telecom power supply: 48V DC
- Automotive power system: 12V, 24V, 48V DC
- Railways: 3-Ph 2.2kV, 3-Ph 415V, 1-Ph 110V, 50Hz or 0-50Hz AC
  Input is 1-Ph 25kV 50Hz AC
- Aircraft: 115V/230V 400Hz AC, 28V DC

Various levels of electrical energy

Sources

- Power plants: 13.8kV, 11kV and 6.6kV AC
- AC transmission: 400kV, 33kV
- AC distribution: 11kV
- HVDC transmission: 765kV, 500kV DC
- Wind turbine generators: 690V to 3.3kV AC
- Photovoltaic array: 30V-50V DC
- Fuel cell stacks: 200V-300V DC
- Industrial power supply: 3-Ph, 415V/440V, 50Hz AC
- Domestic power supply: 1-Ph, 230V, 50Hz AC

Course structure

- Module 1.1: Introduction & Uncontrolled switches
- Module 1.2: Uncontrolled rectifiers (AC-DC)
- Module 2.1: Semi-controlled switches
- Module 2.2: Phase controlled rectifiers (AC-DC)
- Module 3: Fully controlled switches
- Module 4: DC-DC converters
- Module 5: DC-AC inverters
- Module 6: AC-AC converters

Power conversion: Basic ideas

Bridge circuit with 4 ideal switches

- AC-DC Rectifier
- DC-AC Inverter
- DC-DC Converter
- AC-AC Converter

Basic elements of a power converter

- Switch
- Inductor
- Capacitor

Performance metrics of a power converter

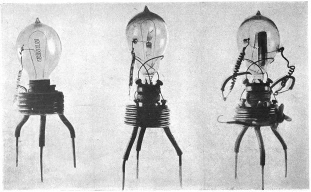
- Efficiency: Minimum power loss
- Output regulation: How close to the reference?
- How fast does the output reach the reference?
- How close are the output waveforms to the ideal case?

Bidirectional power flow: Application specific

Characteristics of an ideal switch

1. OFF State - $I_{OFF} = 0$, $-\infty < V_{OFF} < +\infty \Rightarrow$ Zero blocking loss
2. ON State - $V_{ON} = 0$, $-\infty < I_{ON} < +\infty \Rightarrow$ Zero conduction loss
3. $t_{ON \to OFF} = 0$, $t_{OFF \to ON} = 0 \Rightarrow$ Zero switching loss
4. Zero control effort
5. Stable in all ambient conditions $\Rightarrow$ Indestructible

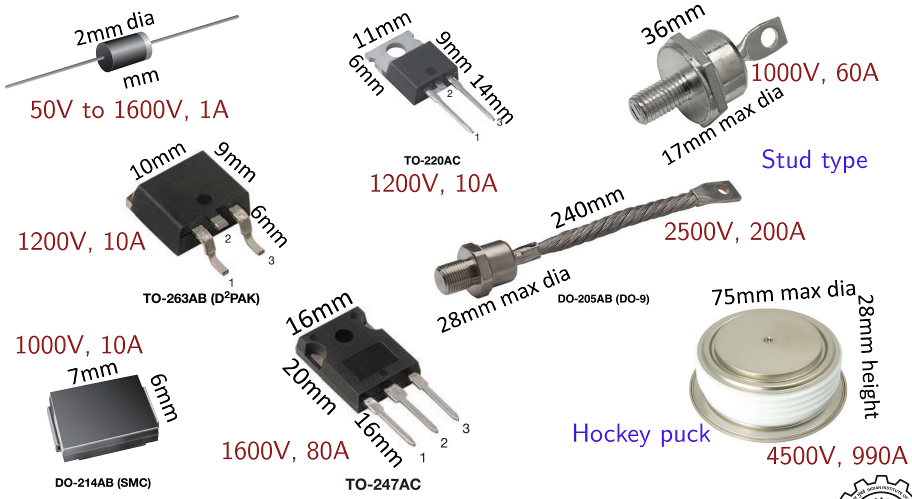
Vacuum tubes: Diodes, triodes, tetrodes and pentodes



Fleming Valves
John Fleming - 1904

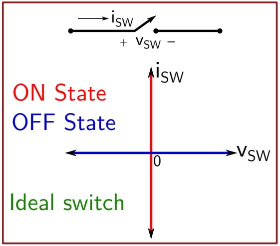
Images from internet

Semiconductor diodes (Power diodes)

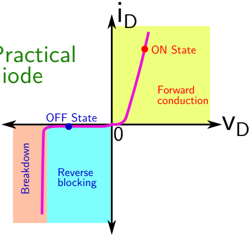


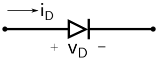
http://www.vishay.com/diodes

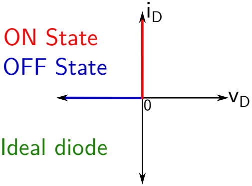
V-I characteristics of a diode



Practical diode

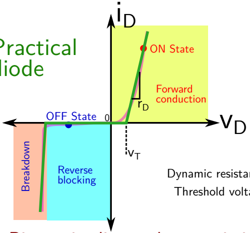






Ideal diode

Practical diode

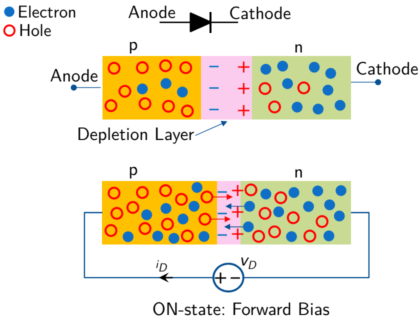


Dynamic resistance : r_D
Threshold voltage : v_T

Piece-wise linear characteristic

Practical diode:
Finite ON-state loss (conduction loss)
Negligible OFF-state loss (blocking loss)
OFF to ON: 'almost' instantaneous
ON to OFF: takes finite time
(reverse recovery time)

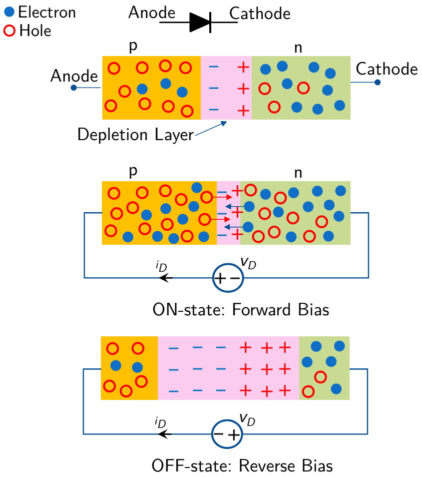
Semiconductor p-n junction diode



Conduction is due to
both electroncs and holes
diffusing across junction
Recombination on either side

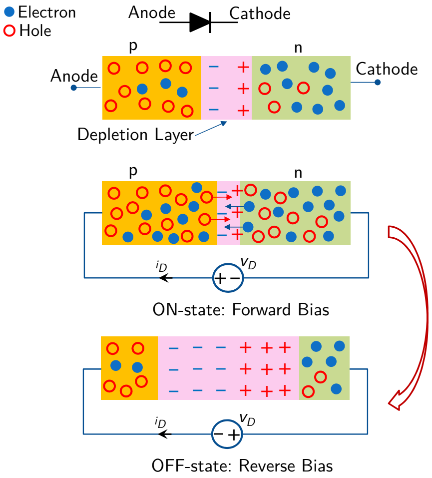
Voltage during ON-state
Forward voltage drop

Semiconductor p-n junction diode



Increased width of depletion layer to support reverse voltage

Semiconductor p-n junction diode

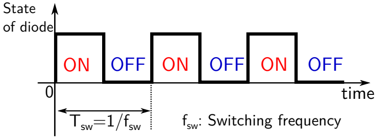


Turn-OFF process
Concentrations of
electrons and holes to be restored
Recovery of injected minority carriers
on either side - Reverse recovery

Important specifications of a diode

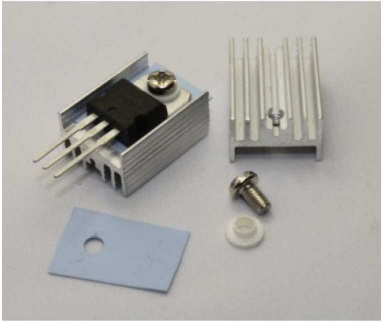
- V_{RRM}: Reverse breakdown voltage
- I_{FAV}: Average forward current
- I_{FRMS}: RMS forward current
- V_F: Forward voltage drop
- r_D: Dynamic resistance
- t_{rr}: Reverse recovery time
- $R_{\theta,jc}$: Thermal resistance (Junction-to-case)
- I^2t rating: Short-term surge energy

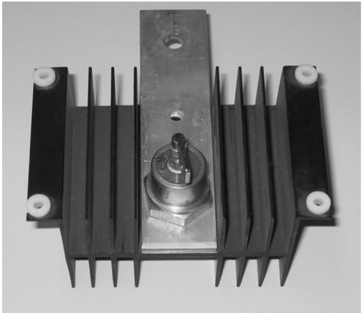
Power loss in a diode



- Total power loss $P_{tot} = P_{cond} + P_{sw}$
- $P_{cond} = P_{ON} = (v_T I_{FAV}) + (r_D I_{FRMS}^2)$
  I_{FAV} and I_{FRMS} are the average and RMS values of diode current, respectively, over a duration of T_{sw}
- $P_{sw} = \cancelto{0}{P_{turnON}} + P_{turnOFF} = V_R Q_{rr} f_{sw}$
  V_R is the reverse blocking voltage and Q_{rr} is the reverse recovery charge
- $Q_{rr} = \dfrac{1}{2} I_{rr} t_{rr}$
  I_{rr} is the peak reverse current and reverse recovery current waveform is approximated as a triangle

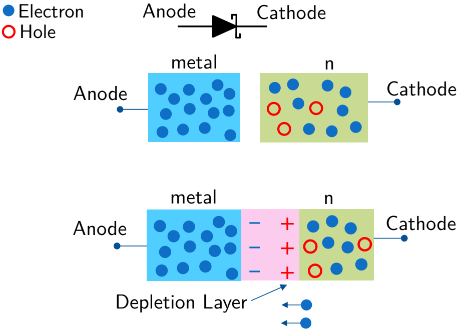
Handling temperature rise: Use of heat sinks





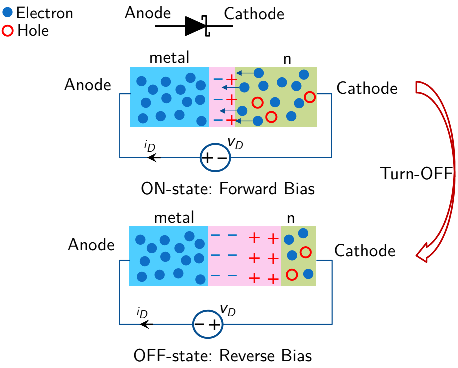
Images from internet

Metal-semiconductor junction (Schottky diode)



- Different absolute potential energies of electrons (e_{PE})
- Choice of a metal with lower e_{PE} than a semiconductor
- More electron flow from n-side when the junction is formed
- Metal is negatively charged - Electric field in depletion region

Metal-semiconductor junction (Schottky diode)



- Forward bias: More energy for electrons on n-side to move towards metal
- No minority carriers injected
- Reverse bias: Energy of electrons on n-side is below the thermal equilibrium value
- Turn-OFF process: No charge to recover

Schottky diodes made with Silicon (Si) are available only upto a blocking voltage of 200V, beyond which the ON-state voltage drop increases prohibitively. Wide band-gap semiconductor materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) are used to make Schottky diodes of higher voltage rating, upto 1200V at present, with low ON-state voltage drop.