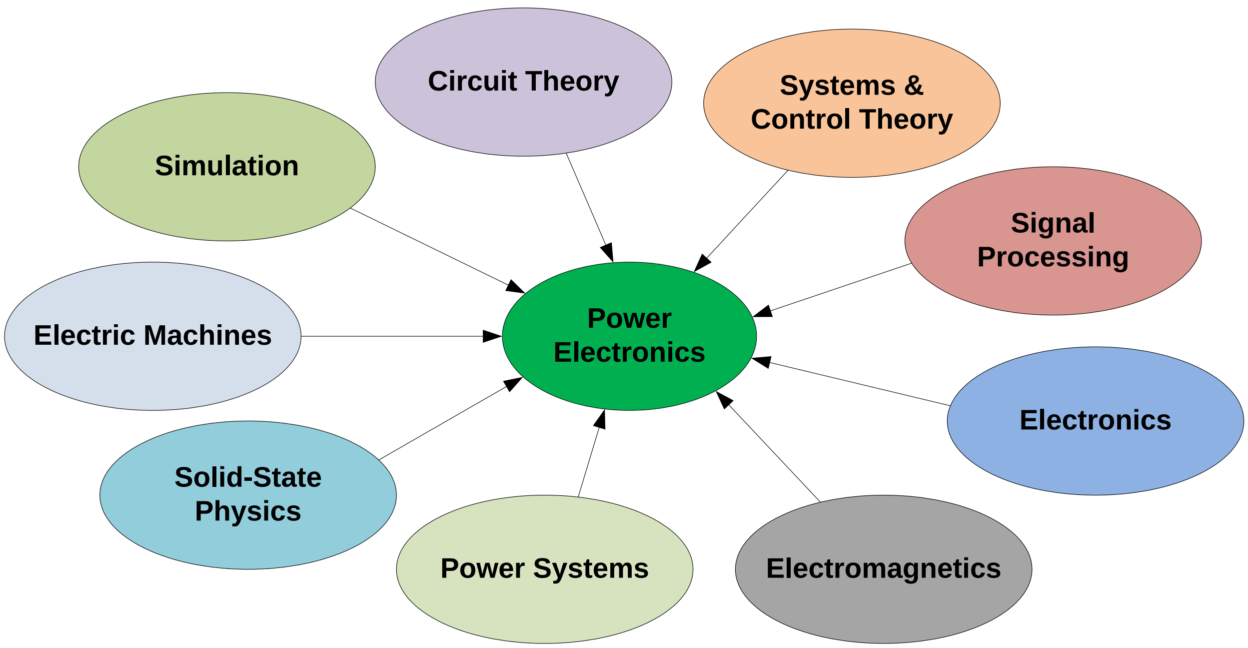
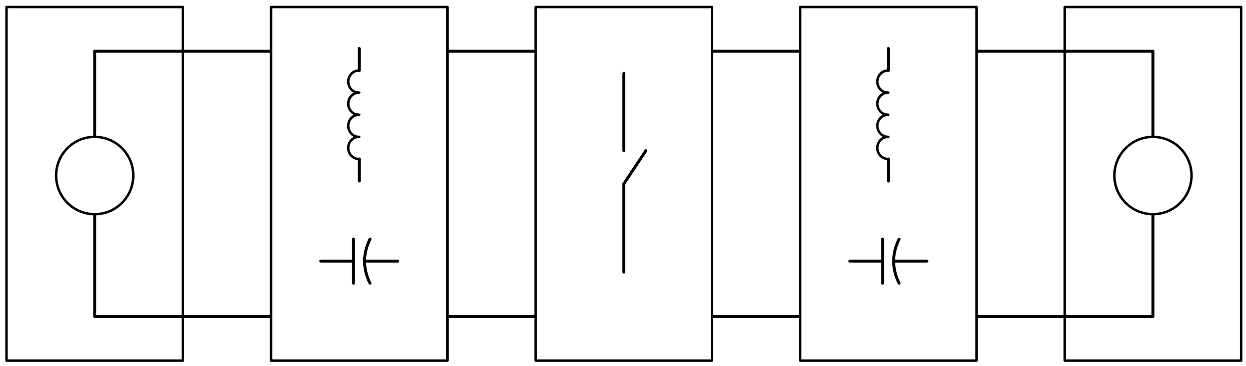


Interdisciplinary Nature of Power Electronics (from Course Textbook)

Power Electronics Applications

- Light Rapid Transit $\rightarrow$ 150 kW – 500 kW
- Electric Car $\rightarrow$ 20 kW Constant, 120 – 150 kW Peak
- Wind Energy $\rightarrow$ 1 MW – 5 MW
- Solar Energy $\rightarrow$ 10 kW (string inverters) distributed – 1 MW (centralized inverters)
- Locomotives $\rightarrow$ 2 – 4 MW
- Rolling Mills/Process Control $\rightarrow$ 10 kW – 10 MW
- Computers, PC $\rightarrow$ 600 W
- Workstations $\rightarrow$ 5 – 15 kW
- Robotics, Welding, HVAC, Etc.



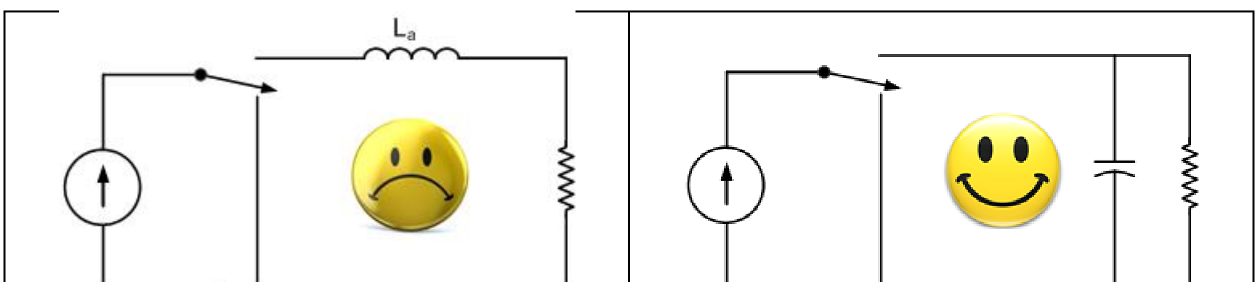
Typical Power Electronics Configuration

Power Electronics Review

Basic Rules of Power Electronics

- Inductor current cannot change instantaneously
- Capacitor voltage cannot change instantaneously
- Average voltage across an inductor = 0
- Average current through a capacitor = 0
- Energy is always conserved

"Golden Rules" of Power Electronics



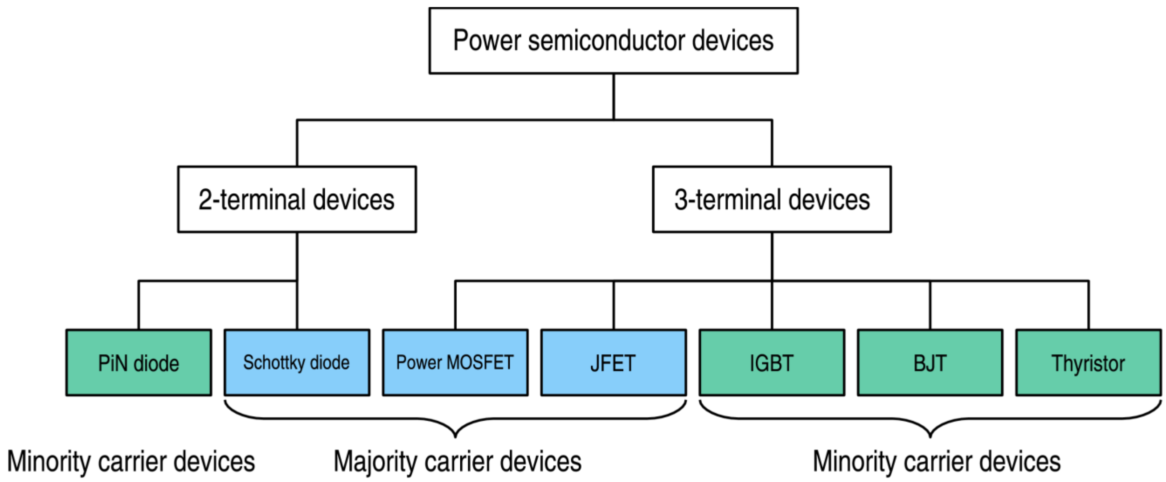
Not good, cannot change current instantaneously through an inductor	No problem, capacitor current can change instaneously, voltage cannot

An Example of the Basic Rules of Power Electronics

Voltage source → equivalent to a capacitor
must be interfaced with L or I_s

Current source → equivalent to an inductor
must be interfaced with C or V_L

Power Electronic Devices



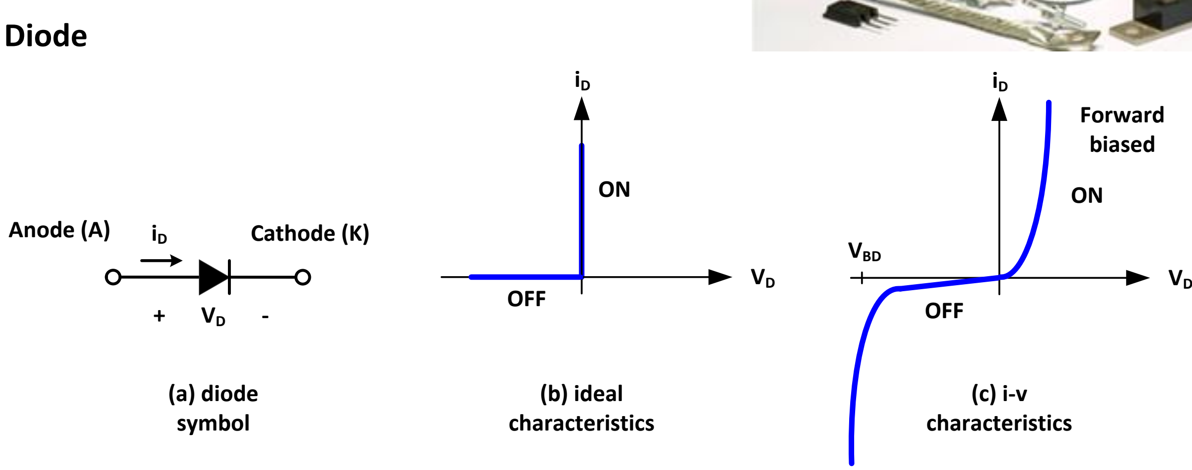
Power Electronic Devices (copied from https://commons.wikimedia.org/wiki/File:Power_devices_family.png)

Power Electronic devices are usually (and always in the context of this course) used as a commutation mode, i.e. either on or off.

from Greek
di – two
ode - path

Power Diode

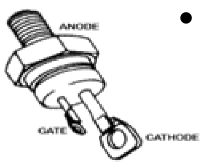
- First power diode developed in 1952
- Replaced mercury-arc converters

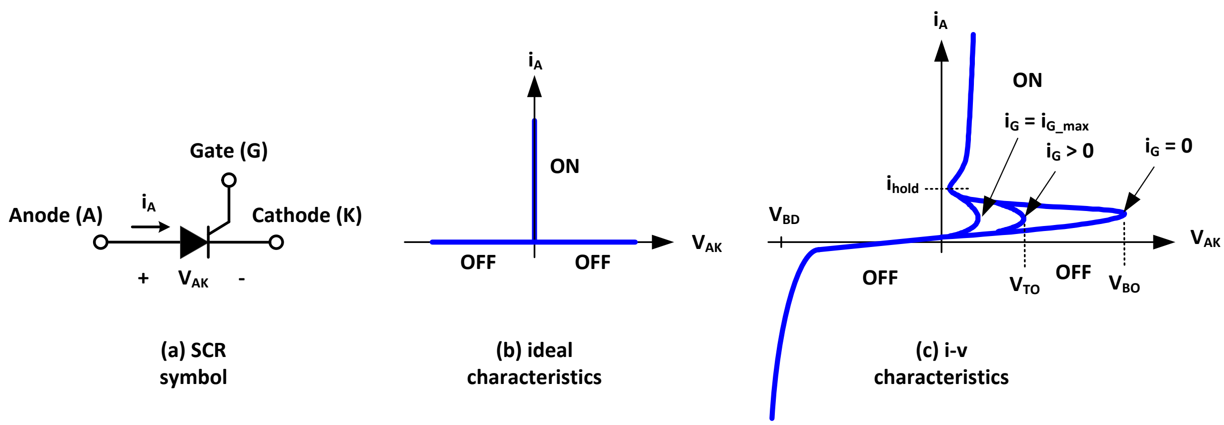


Diode Characteristics

Thysristor – Silicon Controlled Rectifier (SCR)

- First commercially available power electronic device (GE – 1957)
- Was essentially the only viable power electronics device for the next 25 years
- Converts AC grid power to DC
  - DC machines (process industry, traction drives, etc.)
  - DC power supplies (welding, metal plating, battery chargers, etc.)
- Load Commutated Device (turns off when current goes to zero)
- Later developments in SCRs → GTO, MCT, IGCT (Turn-off devices)

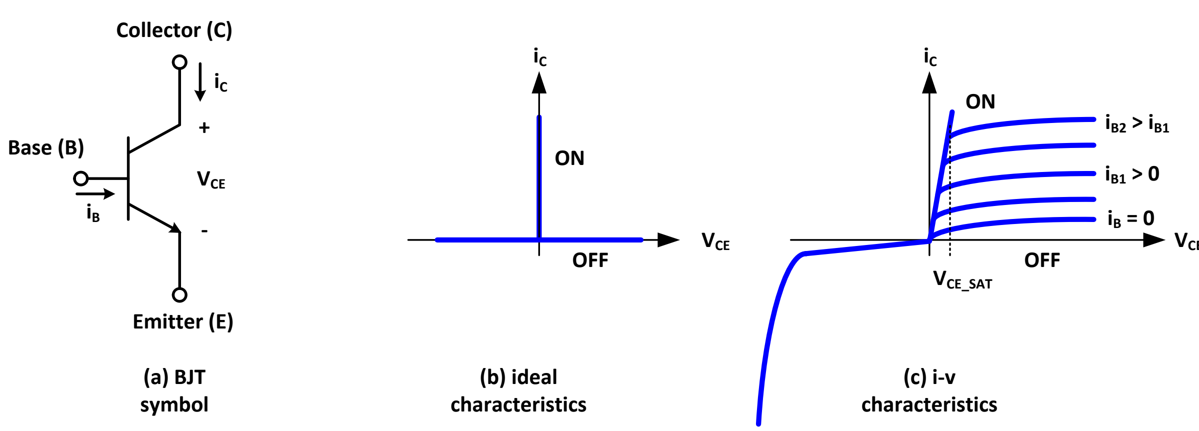




Thyristor Characteristics

Bipolar Junction Transistor

- Developed in 1970
- Low to medium power and frequency
- Difficult base drive requirements (current controlled)
- Essentially obsolete due to voltage controlled (FET) devices

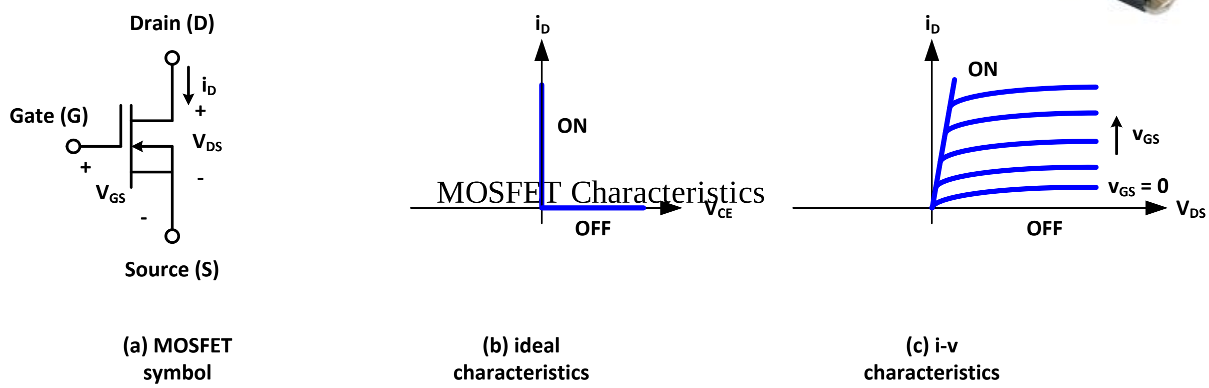


BJT Characteristics

game changer for low power application

MOSFET

- Developed in 1978
- Voltage controlled gate → low gate drive power required
- Used pervasively in low to medium power
- Capable of very high frequency

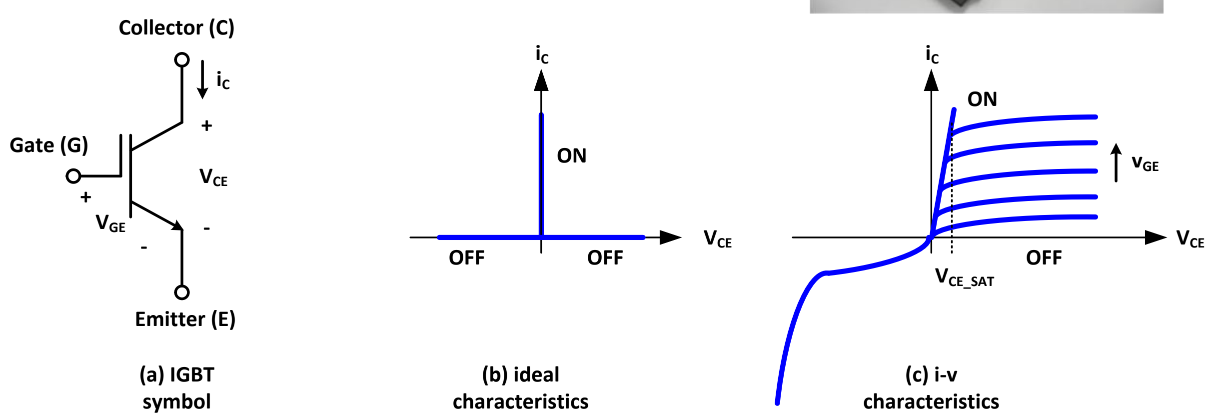


MOSFET Characteristics

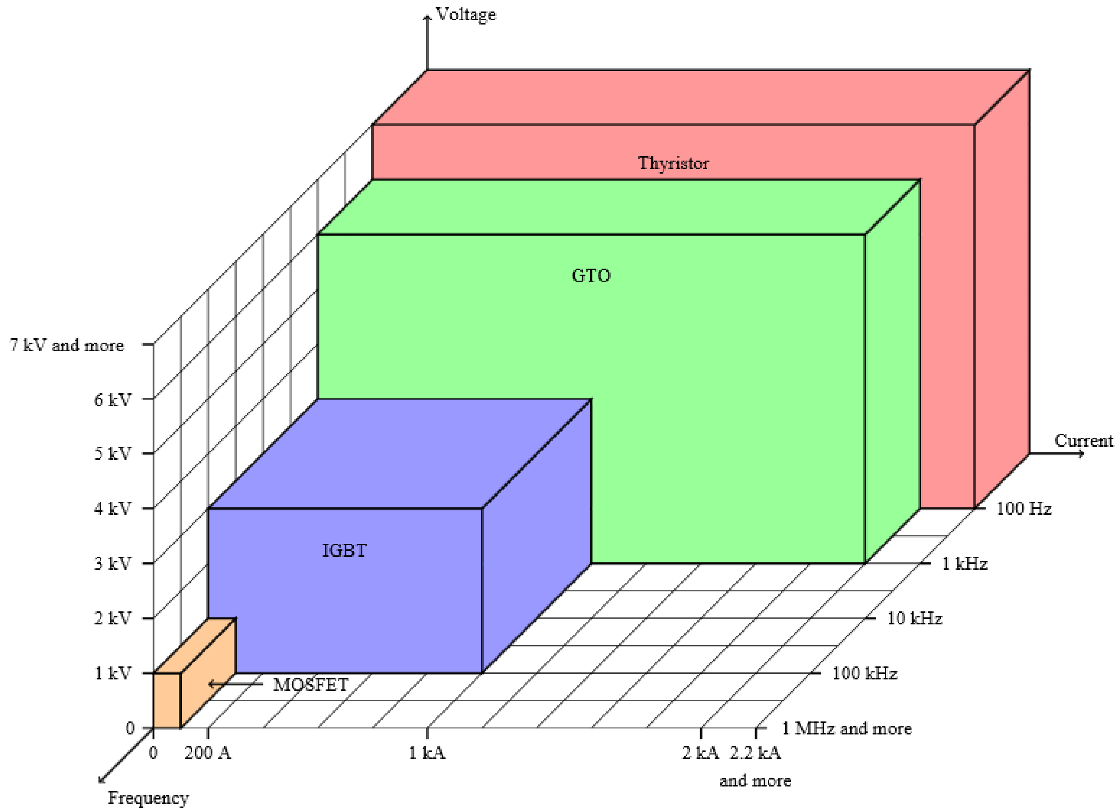
game changer for medium power application

IGBT

- Developed in 1983
- Combined power of BJT and gate control of MOSFET
- Currently on 6th generation design



IGBT Characteristics



Current/Voltage/Switching Frequency Domains of Main Power Electronic Switches
(Copied from https://en.wikipedia.org/wiki/Power_semiconductor_device)

Introduction to Power Semiconductor Devices

-Primary devices currently used in Power Electronics

- Power Diodes
- Power Metal Oxide Silicon Field Effect Transistors (MOSFETs)
- Bipolar Junction Transistors (BJTs)
- Insulated Gate Bipolar Transistors (IGBTs) ← Evolution of BJT and MOSFET
- Thyristors (SCR, GTO, MCT, IGCT)

-On resistance vs. breakdown voltage vs. switching times
-Minority and majority carrier devices
-Not a course in semiconductor physics, but we need to know the basics

<u>Power Electronics Semiconductor Physics Background Material</u>

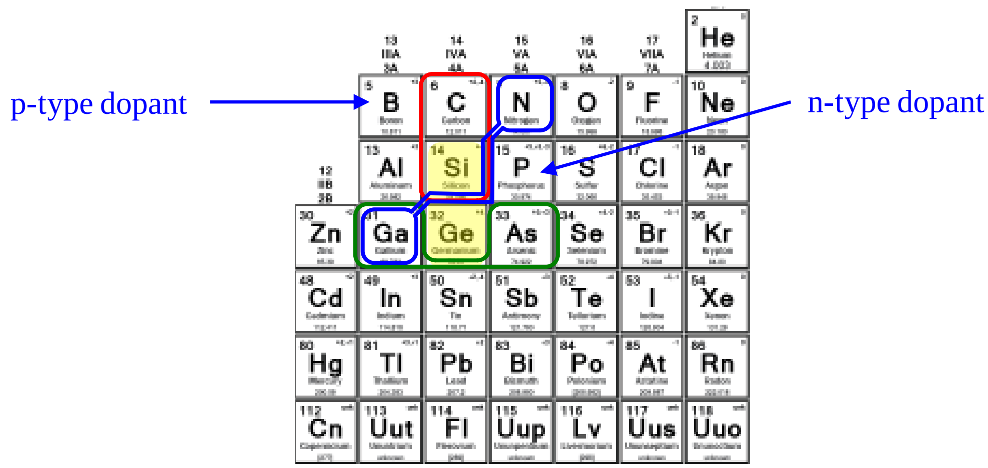
Not a course in semiconductor physics, but we'll explore the basics as they pertain to power electronics devices.

Common Semicoductors:

Material	Symbol	Group
Germanium	Ge	IV
Silicon	S	IV
Gallium Arsenide	GaAs	III-V
Silicon Carbide	SiC	IV
Gallium Nitride	GaN	III-V
Gallium Phosphide	GaP	III-V

Elemental Semiconductors (Germanium, Silicon)

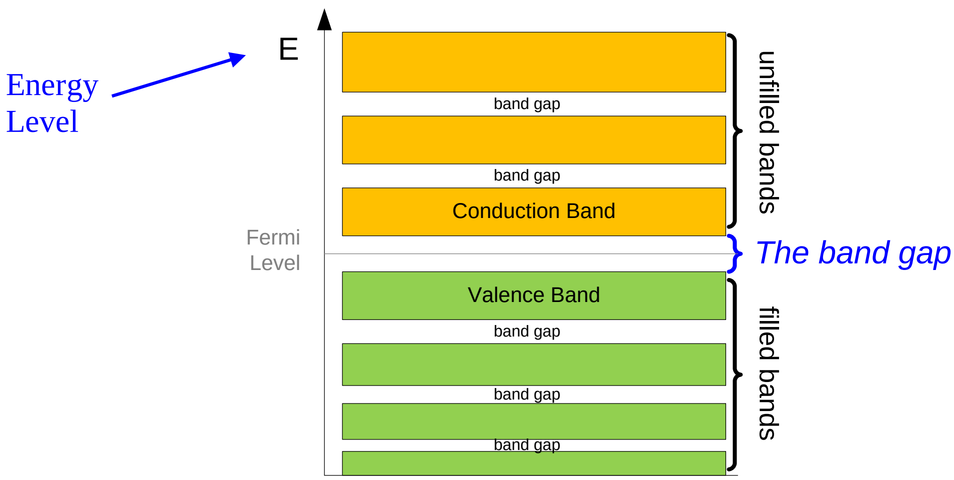
Compound Semiconductors (Gallium Arsenide, Silicon Carbide, Gallium Nitride, Gallium Phosphide)



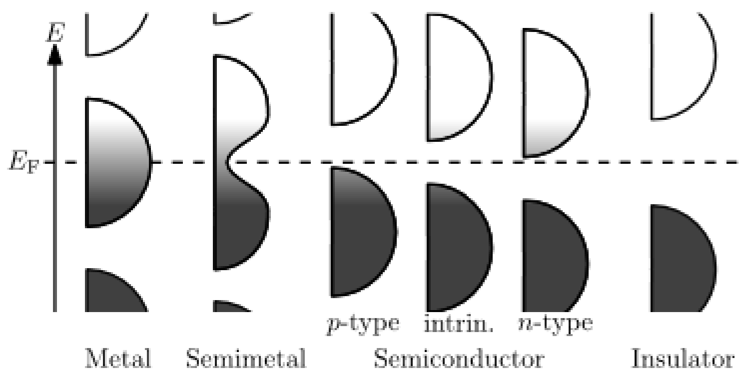
Semiconductors on Periodic Table

The Fermi-Dirac distribution function gives the probability that (at thermodynamic equilibrium) a state having energy ϵ is occupied by an electron:

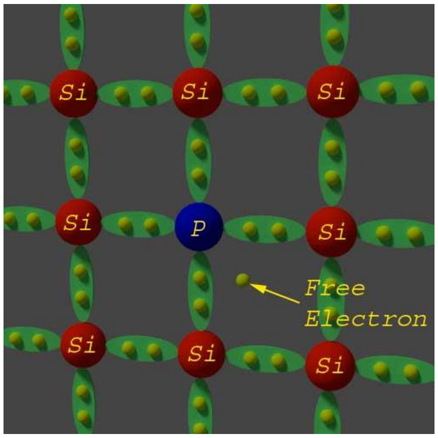
$$f(\epsilon) = \frac{1}{e^{(\epsilon-\mu)/KT}+1} \qquad \text{at Fermi Level } (\epsilon = \mu) \quad \rightarrow \quad f(\epsilon = \mu) = \frac{1}{2}$$

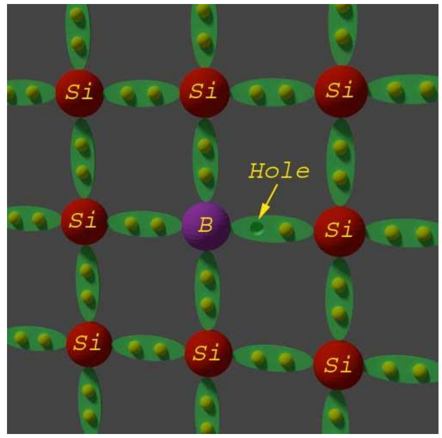


Semiconductor Material Band Structure

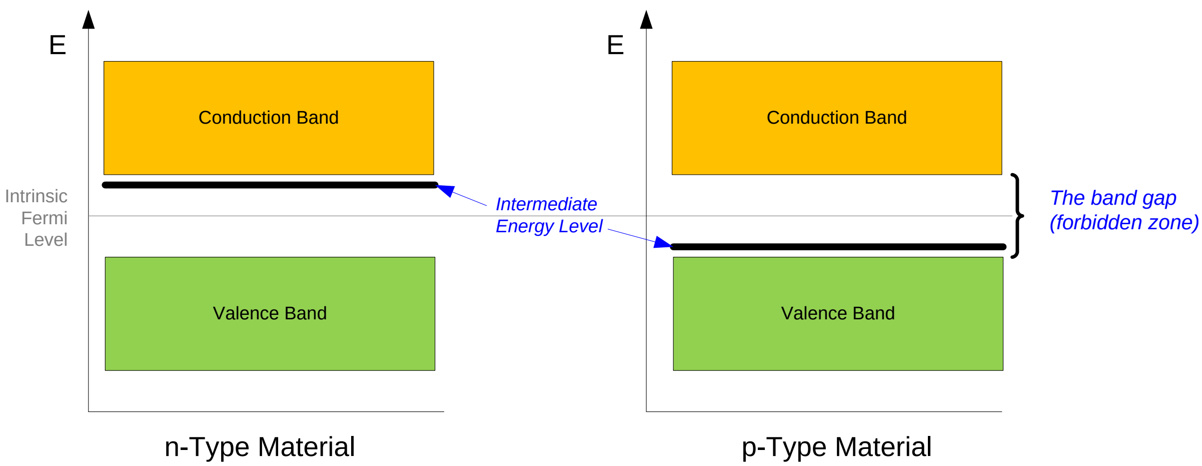


Filling of the electronic states in various types of materials at equilibrium. Here, height is energy while width is the density of available states for a certain energy in the material listed. The shade follows the Fermi–Dirac distribution (black = all states filled, white = no state filled). In metals and semimetals, the Fermi level EF lies inside at least one band. In insulators and semiconductors the Fermi level is inside a band gap; however, in semiconductors the bands are near enough to the Fermi level to be thermally populated with electrons or holes. (Copied from https://en.wikipedia.org/wiki/Fermi_level)





pictures from http://www.electrical4u.com/donor-and-acceptor-impurities-in-semiconductor/



Doped Silicon Showing Lattice Structure and Corresponding Energy Levels

Material Conduction in Semiconductors

Group IV – 4 valence electrons

At temperatures above absolute zero, some electrons break free from covalent bond (known as ***thermal ionization***) and become a ***free electron***. A ***hole*** is left behind. Electrons and holes are known as ***charge carriers***. Each electron-hole pair creates two charge carriers (a positive and a negative). There is an equal number of holes and electrons within intrinsic semiconductors. Electron-hole pairs take place randomly throughout lattice structure and increase with temperature (increased number of charge carriers with increased temperature). As electrons move, they fill a hole left by other electron. This is known as ***Recombination***.

Holes don't physically move, but appear to move as electrons fill other holes along the path.

Thermal ionization creates an equal number of electrons and holes. For a pure (intrinsic) semiconductor:

$n_i^2 \approx Ce^{\left(\frac{-qE_g}{kT}\right)}$ carrier density

where

n_i – density of electrons and holes at thermal equilibrium
C – constant of proportionality
q – magnitude of the electron charge
E_g – energy gap of the semiconductor (1.1 eV for silicon)
k – Boltzmann's contant
T – Temperature (in degrees Kelvin)

Doped Semiconductors

Thermal equilibrium density of electrons and holes can be modified by the addition of impurity atoms, called ***dopants***, in the lattice structure. For Silicon, dopants come from Group III (such as Boron) which make p-Type, or Group V (such as Phosphorous) which make n-Type.

Semiconductor density $\approx 10^{23}\,\frac{atoms}{cm^3}$

Typical dopant density $\approx 10^{19}\,\frac{atoms}{cm^3}$

Because dopant density is orders of magnitude lower than semiconductor material, the rate at which covalent bonds are broken by thermal ionization and refilled by free electron (electron-hole recombination) is relatively unchanged. Thus:

$n_0 p_0 = n_i^2$

where

n_0 – thermal equilibrium electron density
p_0 – thermal equilibrium hole density

For a p-Type material:

$n_0 \approx \frac{n_i^2}{N_a}$ and $p_0 \approx N_a$ (with $N_a \gg n_i$)

where

N_a – ionized acceptor density

For a n-Type material:

$p_0 \approx \frac{n_i^2}{N_d}$ and $n_0 \approx N_d$ (with $N_d \gg n_i$)

where
N_d – ionized donor density

Recombination Rate of Free Carriers
In thermal equilibrium, free electrons and holes must be captured (recombined) at the same rate they are generated by thermal energy. The recombination rate is a material dependent property.

$$\frac{d(\delta n)}{dt} = -\frac{\delta n}{\tau}$$

exponential decay for positive δn
$\delta n(t) = \delta n_o e^{-\frac{t}{\tau}}$

where
δn – excess carrier density (in excess of n_o)

- Excess carrier lifetime increases with temperature → longer switching times for minority carrier devices
- Large excess carrier densities shorten recombination lifetime due to Auger recombination which can lead to increased on-state losses at high current levels

$$\tau = \frac{\tau_o}{1 + \frac{\delta n^2}{n_b^2}}$$

where
τ_o – excess carrier lifetime with $\delta n \ll n_b$

Current Flow
Standard convention is current flow is in direction of hole migration and opposite the direction of electron migration. There are two mechanisms for current flow, ***drift*** and ***diffusion***.

$J_{drift} = q\mu_n nE + q\mu_p pE$ drift → current due to electric field

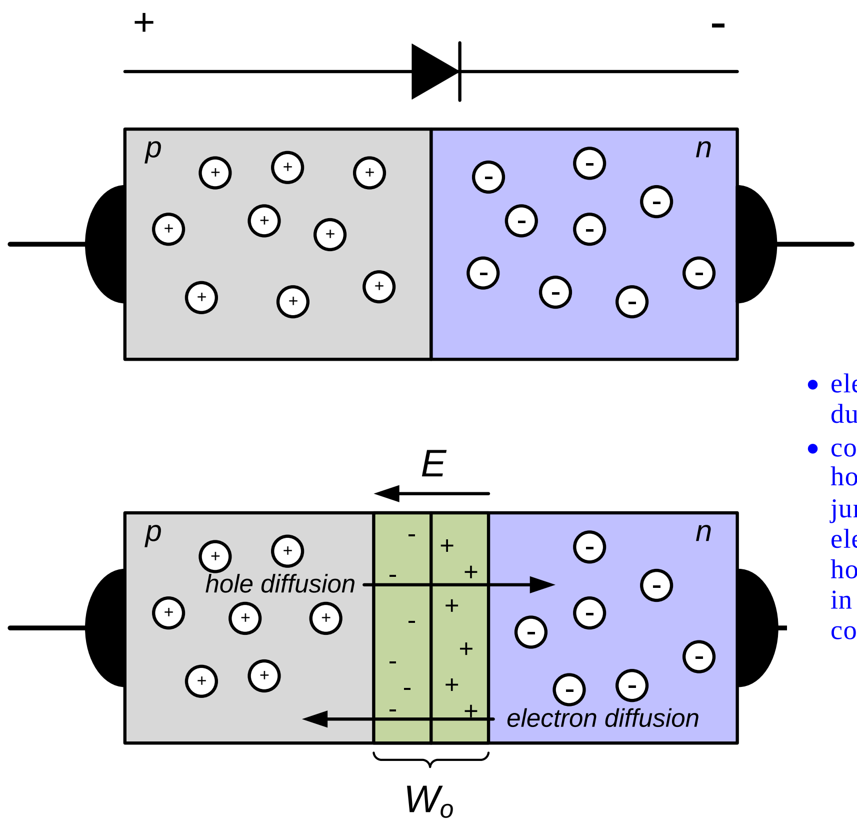
where
μ_n – electron mobility [cm^2/Vs]
μ_p – hole mobility [cm^2/Vs]
n – number of free electrons per unit volume [#/cm^3]
p – number of free hole per unit volume [#/cm^3]
E – Electric Field Intensity [V/cm]

$J_{diffusion} = qD_n\frac{dn}{dx} - qD_p\frac{dp}{dx}$ diffusion → current due to carrier density gradient

where

D_n – electron diffusion constant [cm^2/s]
D_p – hole diffusion constant [cm^2/s]

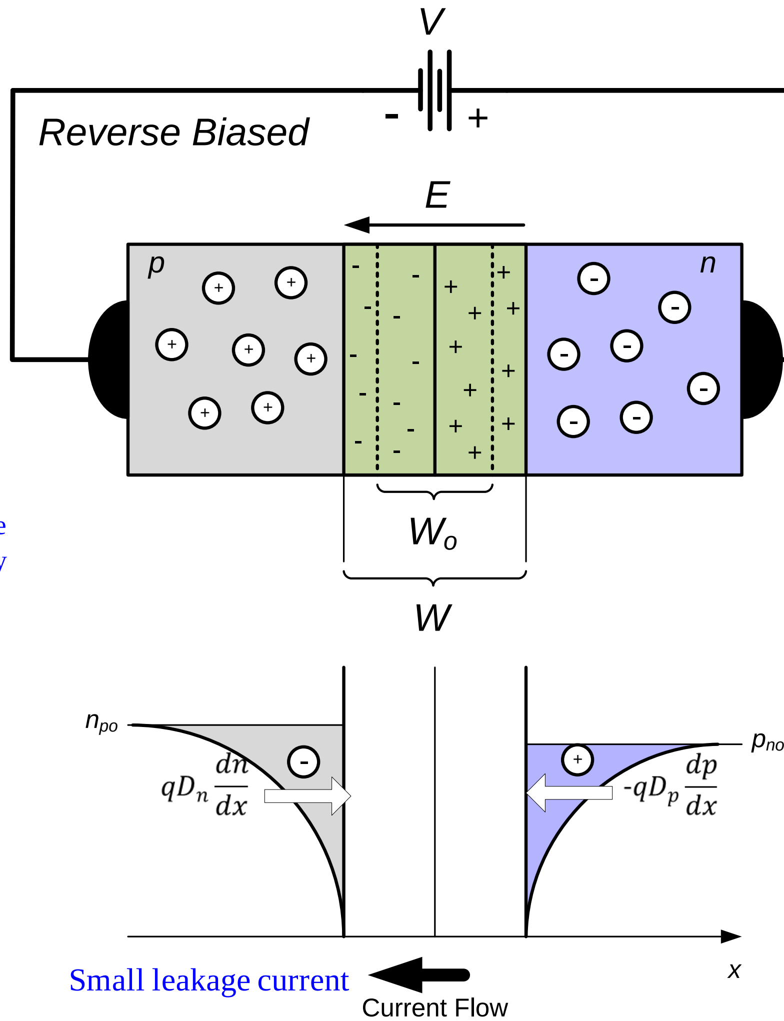
Diode Structure



- electrons bouncing around due to thermal energy
- concentration gradient of holes and electrons at junction causes diffusion of electrons into p region and holes into n region (diffuses in direction of decreasing concentration)

Diagram of a Diode Showing Depletion (Space Charge) Region

- Depletion region formed by charged atoms left behind by the holes and electrons that have diffused across the junction.
- This depletion region (also known as space charge region) creates an electric field which increases energy barrier and opposes diffusion current, promotes drift current
- An equilibrium is eventually reached where diffusion current is offset by drift current due to electric field in the depletion region



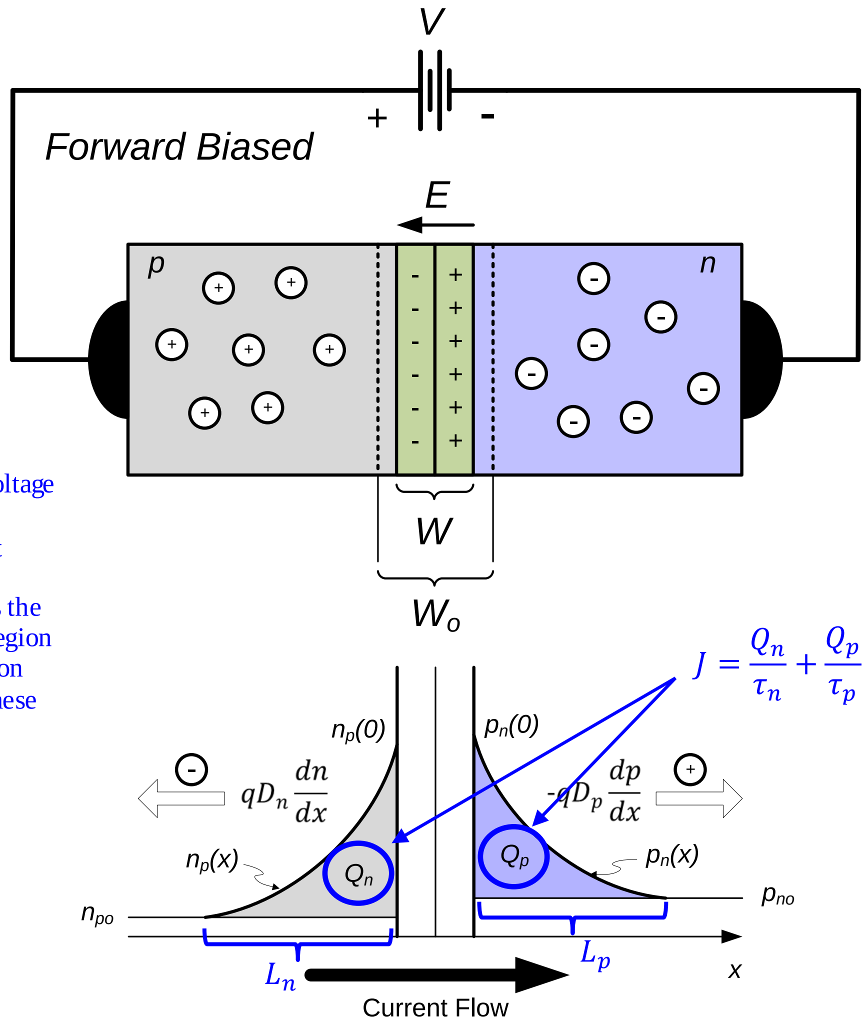
- Application of an external reverse voltage causes the depletion region to increase
- Reverse voltage blocked by the depletion region
- Stored charge of depletion region acts as capacitance

Reversed Biased Diode Showing Depletion Region

$$W = W_o\sqrt{1 - \frac{V}{\varphi_c}} \qquad \text{where} \quad \varphi_c = \frac{kT}{q}\ln\left(\frac{N_a N_d}{N_i^2}\right)$$

Reversed bias voltage increases the potential barrier which inhibits carrier diffusion.

- Application of positive voltage reduces depletion region
- Depletion region field not large enough to prevent diffusion of charge across the junction – holes from p-region and electrons from n-region diffuse across junction (these are minority carriers)



Forward Biased Diode Showing Depletion Region

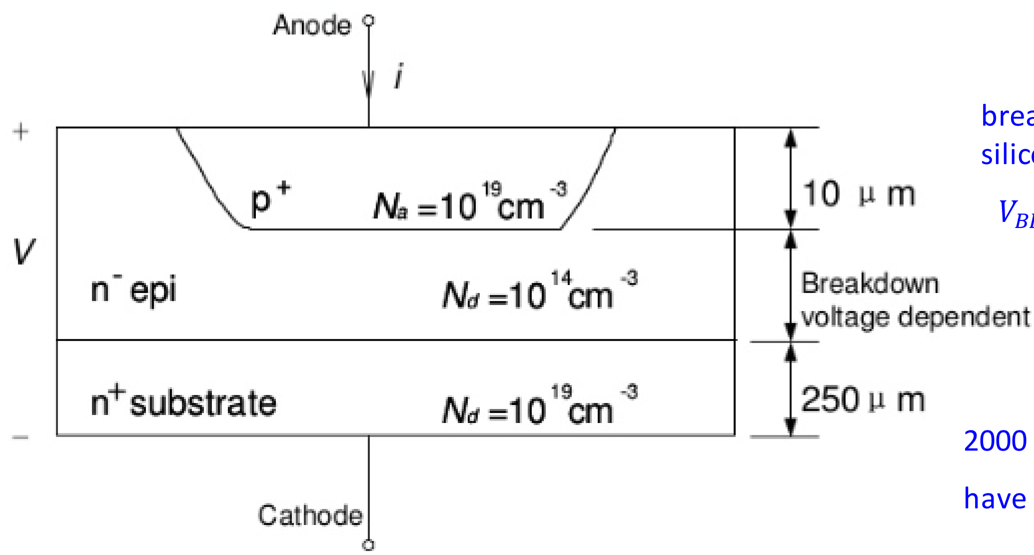
Forward biased voltage lowers potential barrier and upsets equilibrium between drift and diffusion currents (diffusion currents dominate). Injected minority carriers eventually recombine with majority carriers as they diffuse further into opposite region.

$L_n = \sqrt{D_n \tau_n}$ and $L_p = \sqrt{D_p \tau_p}$

where

D_n – electron diffusion constant
D_p – hole diffusion constant
τ_n – electron minority carrier lifetime
τ_p – hole minority carrier lifetime

Power Diodes

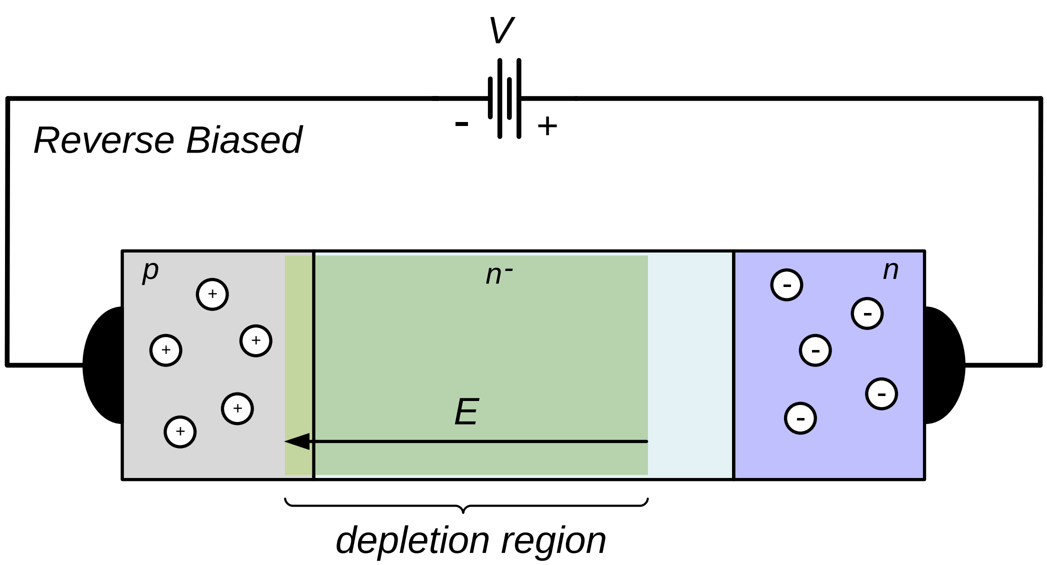


breakdown voltage of silicon:

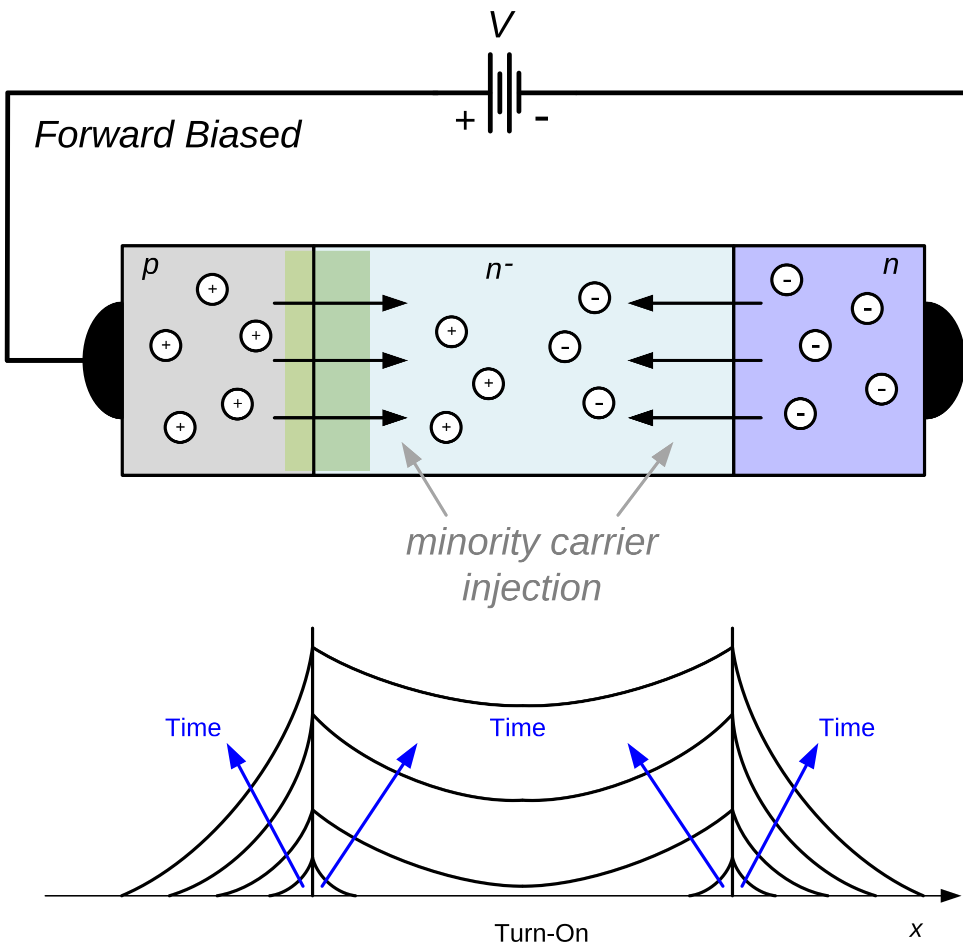
$$V_{BD} \approx 200{,}000 \frac{V}{cm} \approx 20 \frac{V}{\mu m}$$

2000 V diode must have n⁻ - region of $\approx 100\mu m$

Physical Structure of Power Diode

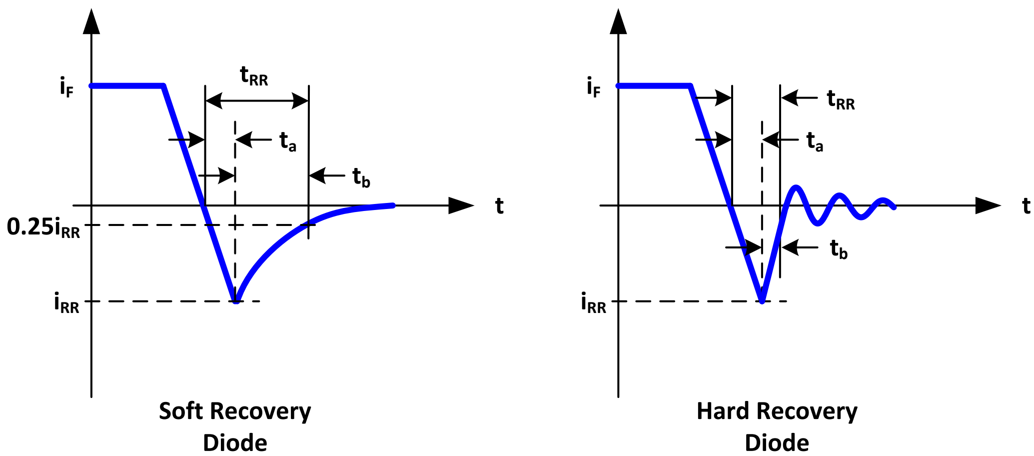


Reversed Biased Power Diode Showing Depletion Region

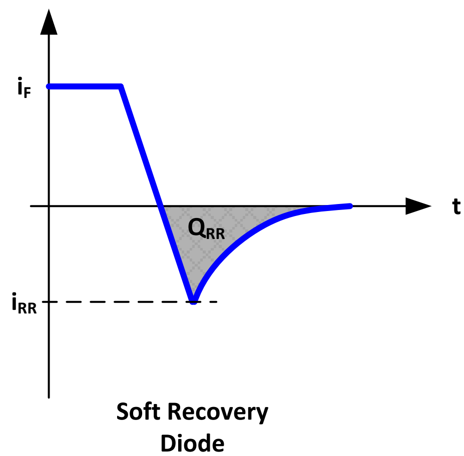


Forward Biased Power Diode Showing Depletion Region

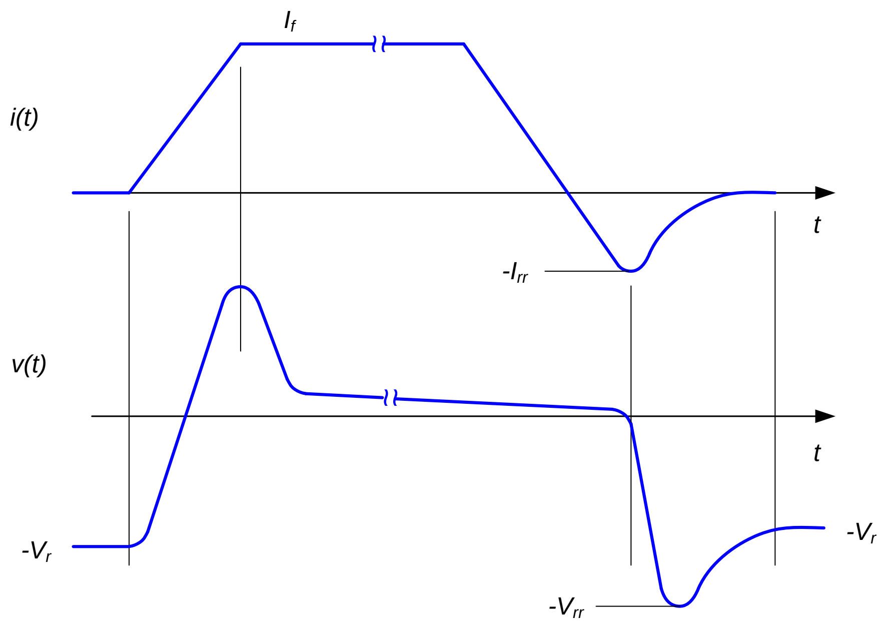
- diode turn-off in reverse (recombination of minority carriers)
- recombination affects turn-off time and stored charge



Diode Recovery Speeds: Left – Slow, Right – Fast



Stored Charge in Diode Recovery



Typical Switching Waveforms of Power Diode