Atomic numbers, Mass numbers

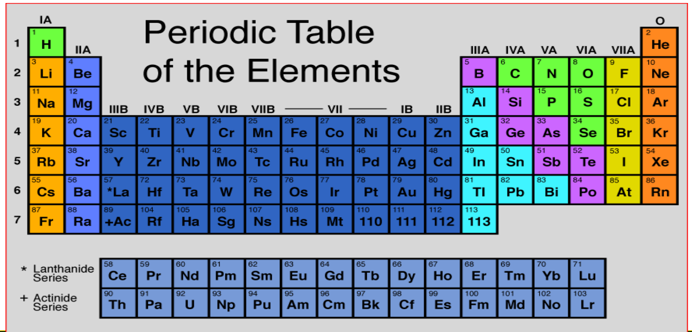
- There are 3 types of subatomic particles exist (1930s).
  - electrons (e^-)
  - protons (p^+).
  - neutrons (n^0) no charge, a mass similar to protons
- Elements are often symbolized with their mass number and atomic number

E.g. Oxygen: O^{16}_{8}

- These values are given on the periodic table

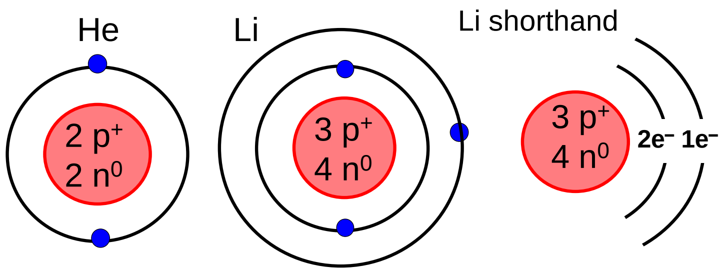
Periodic Table of Elements

- Elements in the periodic table are grouped by the number of electrons in their valence shell (most outer shell)



Bohr - Rutherford diagrams

- Putting all this together, we get B-R diagrams
- To draw them you must know the # of protons, neutrons, and electrons (2,8,8,2 filling order)
- Draw protons (p^+), (n^0) in circle (i.e. “nucleus”)
- Draw electrons around in shells

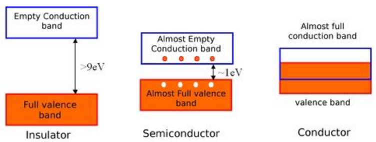


Electronic Semiconductor Devices

- Most electronic devices are made out of semiconductors, insulators, and conductors.
- Semiconductors
  - Old Days – Germanium (Ge)
  - Now – Silicon (Si)
  - Now – Gallium Arsenide (GaAs) used for high speed and optical devices.
  - New – Silicon Carbide (SiC) – High voltage Schottky diodes.

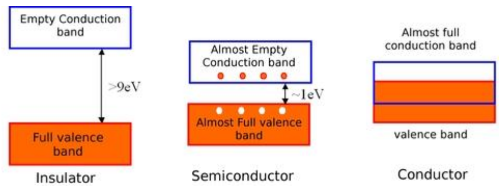
Conductors - Insulators - Semiconductors

- Solid-state materials can be classified into three groups: insulators, semiconductors and conductors.
  - **Insulators** are materials having an electrical conductivity $\sigma < 10^{-8}$ S/cm (e.g. diamond: 10^{-14} S/cm);
  - **Semiconductors** have a conductivity 10^{-8} S/cm $< \sigma < 10^{3}$ S/cm (for silicon it can range from 10^{-5} S/cm to 10^{3} S/cm);
  - **Conductors** are materials with high conductivities : $\sigma > 10^{3}$ S/cm (e.g. silver: 10^{6} S/cm.)
- The electrical properties of a given material depend on the electronic populations of conduction band



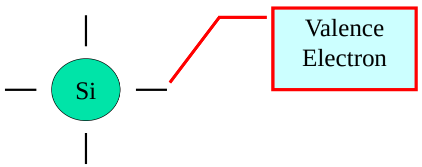
Conductors - Insulators - Semiconductors

- Elements in the periodic table are grouped by the number of electrons in their valence shell (most outer shell).
  - Conductors – Valence shell is mostly empty (1-3 electrons)
  - Insulators – Valence shell is mostly full
  - Semiconductors – Valence shell is half full (Or is it half empty?)



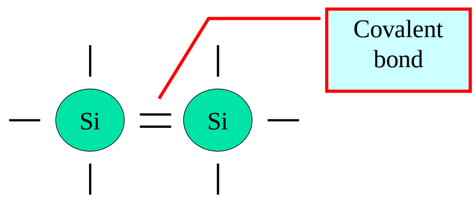
Semiconductors

- Silicon and Germanium are group 4 elements – they have 4 electrons in their valence shell.

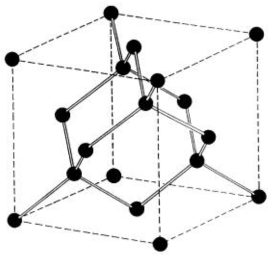


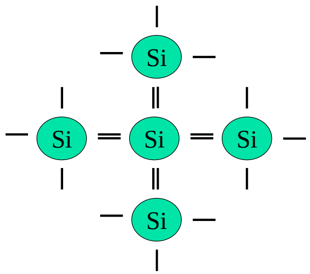
Silicon

- When two silicon atoms are placed close to one another, the valence electrons are shared between the two atoms, forming a covalent bond.



Semiconductor Crystal Lattice

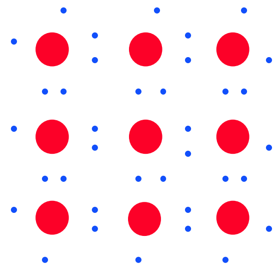


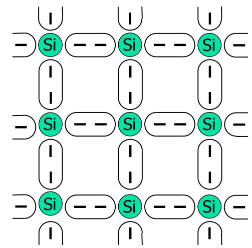


•An important property of the 5-atom silicon lattice structure is that valence electrons are available on the outer edge of the silicon crystal so that other silicon atoms can be added to form a large single silicon crystal.

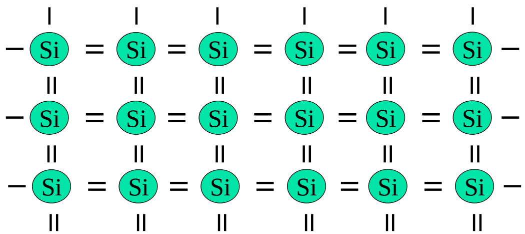
Valence electrons sharing

- Silicon atoms have 4 electrons in outer shell
- These electrons are shared with neighbor atoms on both sides to “fill” the shell





Intrinsic Semiconductor

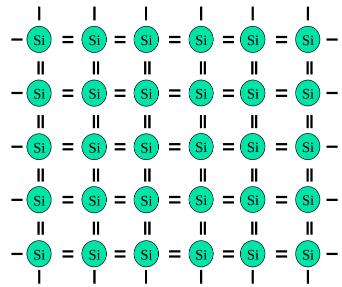


An **intrinsic semiconductor** is a single crystal semiconductor with no other types of atoms in the crystal.

Pure silicon
Pure germanium
Pure gallium arsenide.

Intrinsic semiconductor at 0^{o}K

- At 0 ^{o}K, each electron is in its lowest energy state so each covalent bond position is filled.
- If a small electric field is applied to the material, no electrons will move because they are bound to their individual atoms.
- => At 0 ^{o}K, silicon is an insulator.



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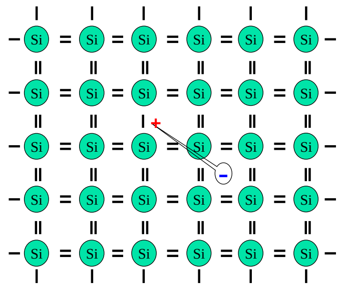
Intrinsic semiconductor at > 0ºK

- As temperature increases, the valence electrons gain thermal energy.
- If a valence electron gains enough energy, it may break its covalent bond and move away from its original position.
- This electron is free to move within the crystal.



- Carrier concentration is given as the number of particles per unit volume =

$$n_i = BT^{3/2} \exp\left(\frac{-Eg}{2KT}\right) \quad [\#/cm^3]$$

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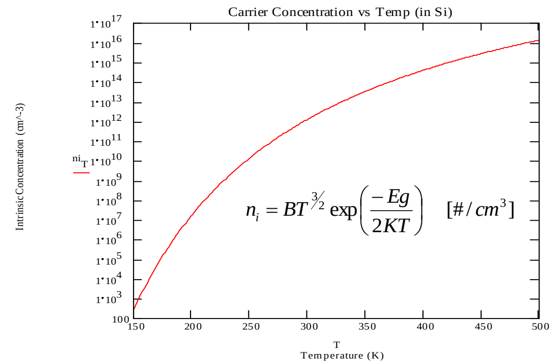
Increasing conductivity by temperature

As temperature increases, the number of free electrons and holes created increases exponentially, therefore the conductivity of a semiconductor is influenced by temperature



$$n_i = BT^{3/2} \exp\left(\frac{-Eg}{2KT}\right) \quad [\#/cm^3]$$

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Empty States - Holes

- An electron that has sufficient energy and is adjacent to an empty state may move into the empty state, leaving an empty state behind.
- Moving empty states can give the appearance that positive charges move through the material.
- This moving empty state is modeled as a positively charged particle called a hole.
- In semiconductors, two types of "particles" contribute to the current: positively charged holes and negatively charged electrons.

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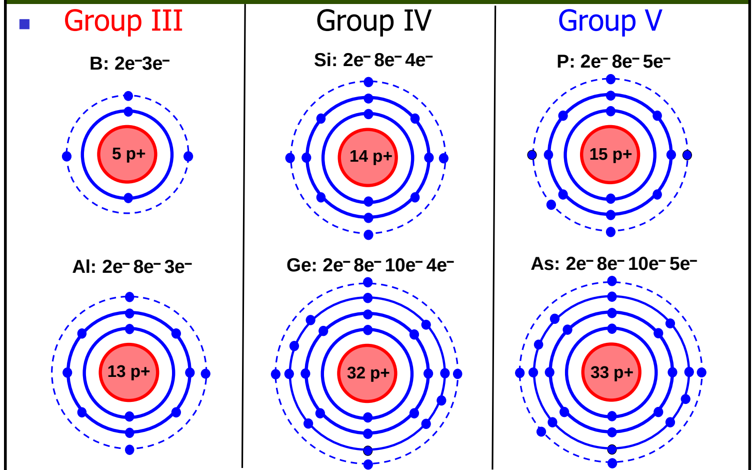
Extrinsic Semiconductors

- Since the concentrations of free electrons and holes is small in an intrinsic semiconductor, only small currents are possible.
- Impurities can be added to the semiconductor to increase the concentration of free electrons and holes.
- Adding impurities is called doping.
- An impurity would have one less or one more electron in the valance shell than silicon.
- Impurities for group 4 type atoms (silicon) would come from group 3 or group 5 elements.

Two Types of Dopants

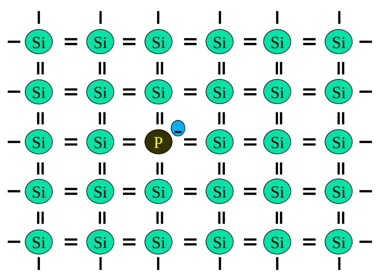
- N-type (Negative) – Free flowing electrons are added to the silicon crystal structure.
  - Examples include Group V elements including Phosphorous, Arsenic, and Antimony.
- P-type (Positive) - Lack electrons and serve as potential slots for migrating electrons.
  - Examples include Group III elements such as Boron, Aluminum, and Gallium

Group III, IV, V Elements



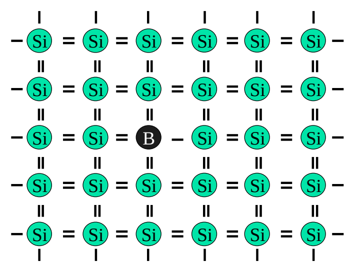
Extrinsic Semiconductors - n-type

- The most common group 5 elements are phosphorous and arsenic have 5 electrons in the valence shell.
- Four of the electrons fill the covalent bonds in the silicon.
- The 5th electron of impurity atom and is a free electron.
- A semiconductor doped with donor impurities has excess free electron and is called an n-type semiconductor



Extrinsic Semiconductors - p-type

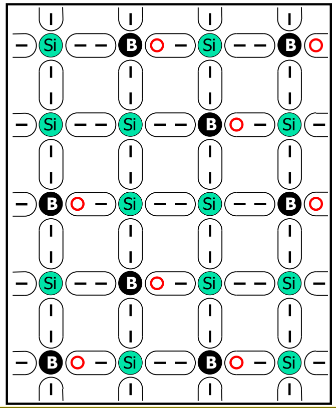
- The most common group 3 impurity is boron which has 3 valence electrons.
- Since boron has only 3 valence electrons, the boron atom can only bond with three of its neighbors leaving one open bond position, i.e. the hole.

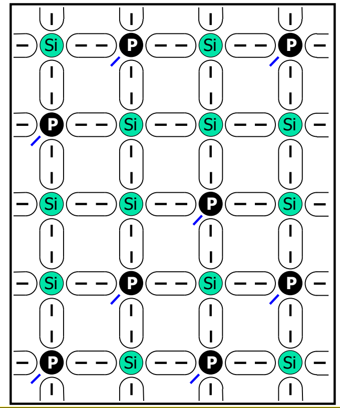


P-N Junction Diode

Extrinsic Semiconductors: p-type & n-type

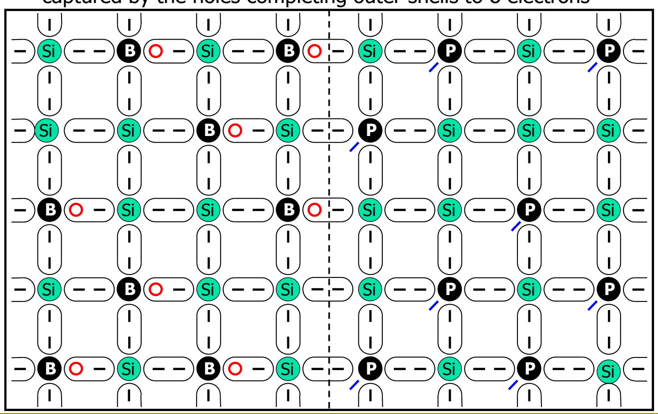
In the doped semiconductors the conductivity is due to the presence of free electrons (n-type) or holes (p-type)





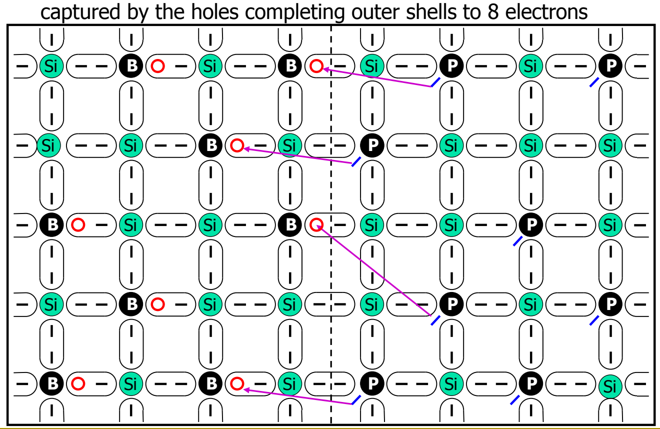
p-n junction (diffusion)

free electrons (from n-type) migrating toward p-type until they captured by the holes completing outer shells to 8 electrons



p-n junction (diffusion)

free electrons (from n-type) migrating toward p-type until they are captured by the holes completing outer shells to 8 electrons



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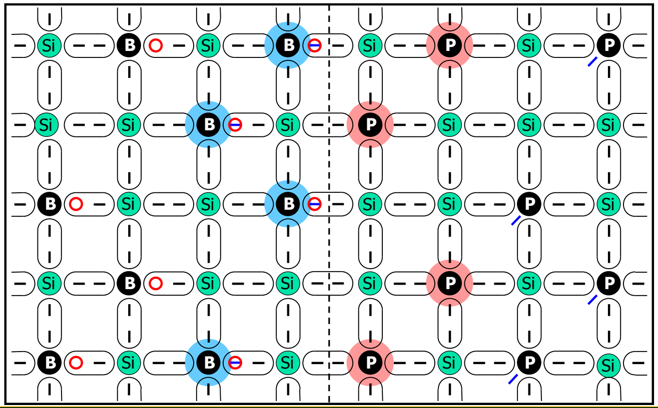
p-n junction (after diffusion)

B - negative charge P - positive charge



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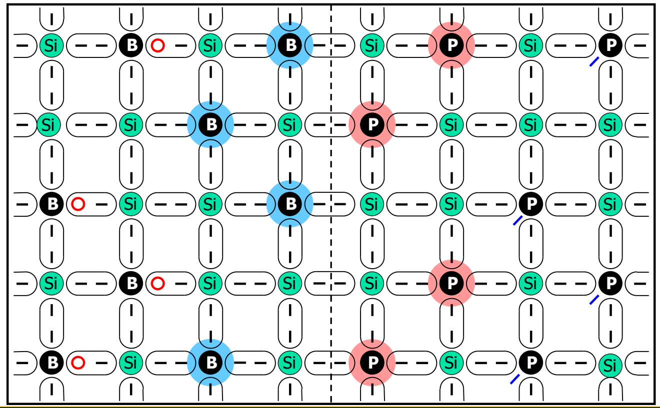
p-n junction (after diffusion)

B - negative charge P - positive charge



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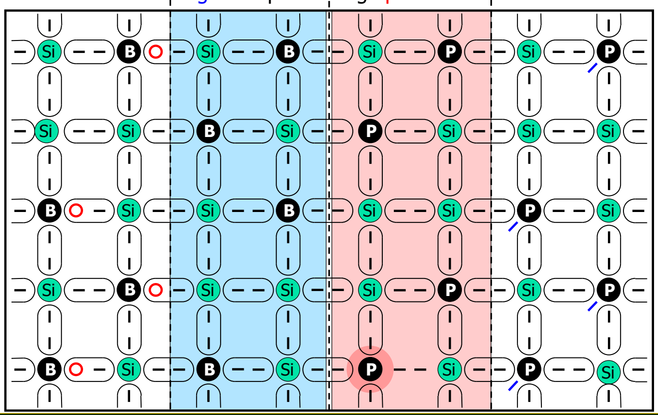
Depletion Area – no carries

free holes | depletion (no carriers) | free electrons

neutral | negative space charge positive | neutral



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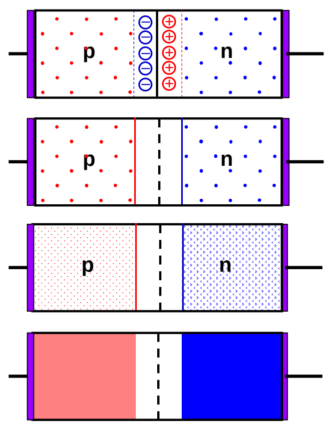
Different presentations of pn – junction



Legend:

Blue - negative, red – positive

⊖ ⊕ - Space charge

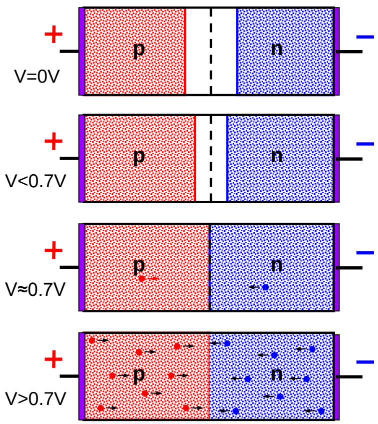
· · - Carriers: electrons, holes

Space charge is not shown, i.e.
Depletion area is blank – no carriers

Carriers dots represented as coloured pattern

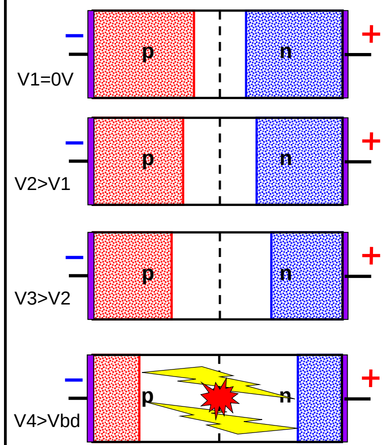
Conducting area is coloured

Effect of Applied Voltage - Forward Bias



- Forward bias attracts carriers to the depletion area, therefore narrows it.
- At V<0.7V depletion narrows but still exists – no current
- At V ≈ 0.7V the depletion almost gone – small current
- At V > 0.7V – no depletion, diode in conducting regime

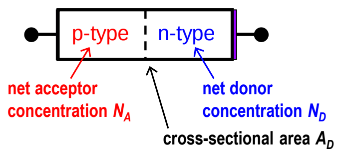
Effect of Applied Voltage - Reverse Bias



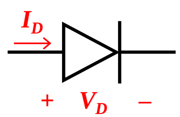
- As voltage increases, the potential barrier to carrier diffusion across the junction increases
- The depletion area widens
- No current
- When the electric field exceeds a critical value ($E_{crit} \cong 2\text{x}10^5$ V/cm), the reverse current shows a dramatic increase – reversable <u>breakdown</u> occurs

The *pn* Junction Diode

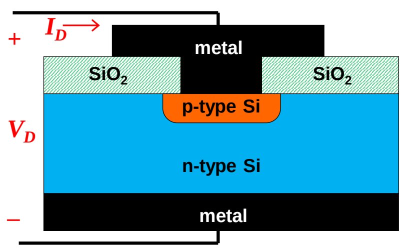
<u>Schematic diagram</u>



<u>Circuit symbol</u>



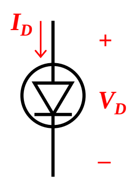
<u>Physical structure</u>:
(an example)



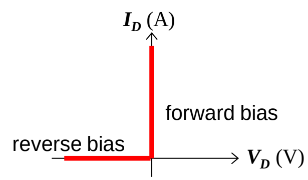
For simplicity, assume that the doping profile changes abruptly at the junction.

Ideal Diode Model of pn Diode

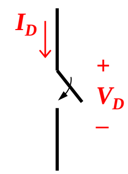
<u>Circuit symbol</u>



***<u>I-V</u>* <u>characteristic</u>**



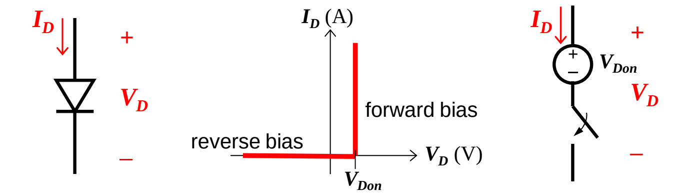
<u>Switch model</u>



- An ideal diode passes current only in one direction.
- An ***ideal diode*** has the following properties:
  - when $I_D > 0$, $V_D = 0$
  - when $V_D < 0$, $I_D = 0$

Diode behaves like a switch:
- closed in forward bias mode
- open in reverse bias mode

Large-Signal Diode Model



For a Si diode, $V_{Don} \cong 0.7$ V

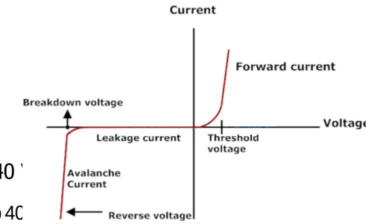
RULE 1: When $I_D > 0$, $V_D = V_{Don}$

RULE 2: When $V_D < V_{Don}$, $I_D = 0$

Diode behaves like a voltage source in series with a switch:
- closed in forward bias mode
- open in reverse bias mode

Diode *V-I* Characteristics

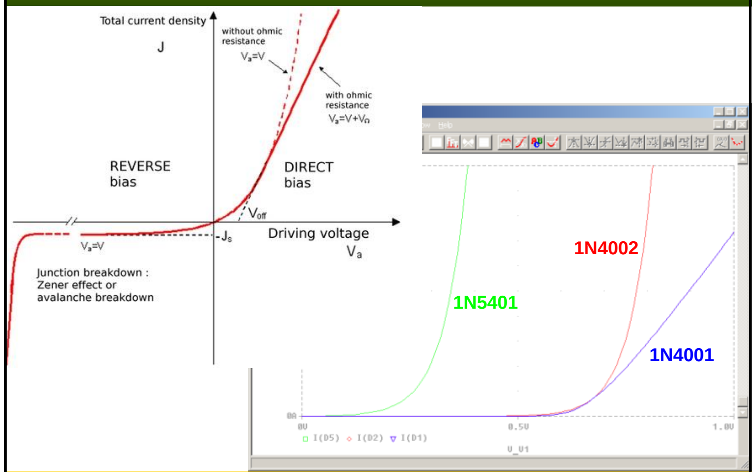
- The current through the pn junction is expressed by Schockley equation :
- $$I \approx I_s\left(\exp\frac{eV}{kT}-1\right)=I_s\left(\exp\frac{V}{V_T}-1\right)$$
- where VT= e/kT is Thermal Voltage
- I_S is the reverse saturation current
- at room temperature $1/V_T = e/kT \sim 40$
- If V > +0.1 V $\quad I \approx I_s\left(\exp\frac{eV}{kT}\right)=I_s(\exp 40$
- If V < - 0.1 V $\quad I \approx I_s(0-1) = -I_s$



- V-I characteristics of some diodes are more accurate with extended Schockley equation, where **η** is the emission coefficient

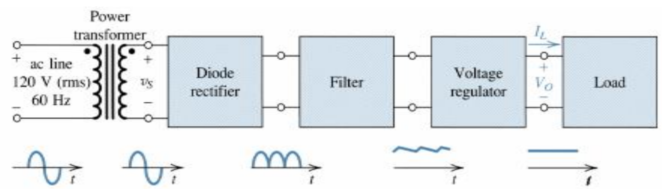
$$I \approx I_s\left(\exp\frac{eV}{\eta\cdot kT}-1\right)=I_s\left(\exp\frac{V}{\eta\cdot V_T}-1\right)$$

Practical Diode *V-I* Characteristics



Linear Power Supplies

- Linear Power Supplies consists of several functional blocks:
  1. Power (Step-Down) Transformer – lower ac voltage
  2. Rectification - create a non-zero average DC voltage
  3. Filtering - get rid of any residual AC voltage from the source.
  4. Regulation - eliminate the effects of changes in the load and the source voltage.



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Rectifiers

- A rectifier circuit converts an ac voltage to a pulsating dc voltage.
- A principle component of Rectifiers is a diode
- Three types of rectifier circuits are discussed here.
  - Half-wave rectifiers
  - Full-wave rectifiers
  - Full-wave bridge rectifiers

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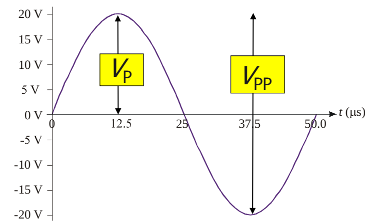
Sine wave voltage and current values

There are several ways to specify the voltage of a sinusoidal voltage waveform. The amplitude of a sine wave is also called the peak value, abbreviated as V_P for a voltage waveform.

Example

The peak voltage of this waveform is

20 V.



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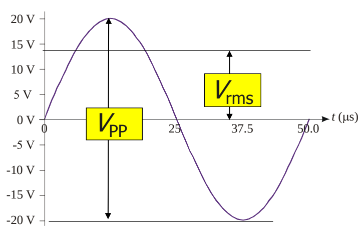
Sine wave voltage and current values

The voltage of a sine wave can also be specified as either the peak-to-peak or the rms value. The peak-to-peak is twice the peak value. The rms value is 0.707 times the peak value.

The peak-to-peak voltage is40 V.

The rms voltage is 14.1 V.



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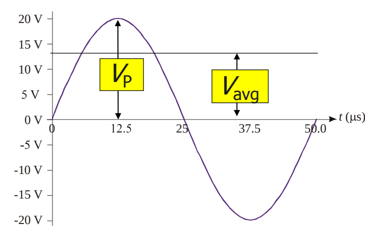
Sine wave voltage and current values

For some purposes, the average value (actually the half-wave average) is used to specify the voltage or current. By definition, the average value is as 0.637 times the peak value.

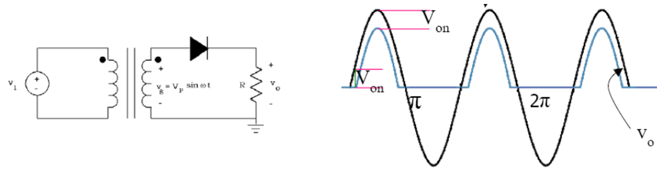
The average value for the sinusoidal voltage is

12.7 V.

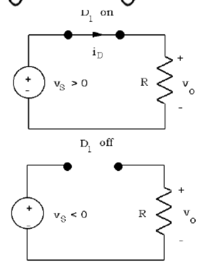


Half-wave rectifier

- A single diode is used to form the half-wave rectifier circuit.

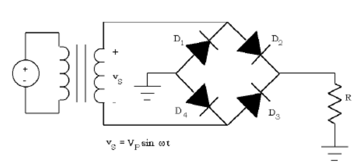


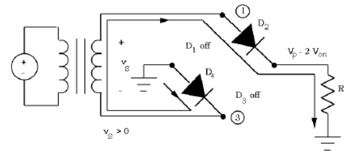
- During the first half of the cycle, which Vs> 0, the diode is forward biased or conducting current.
- During the second half, Vs< 0, the diode turns off.



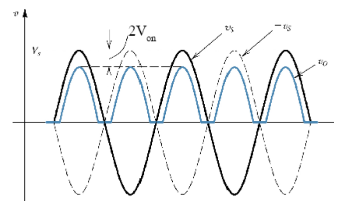
Full-Wave Bridge Rectifier

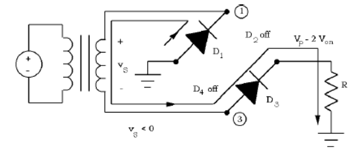
- The bridge rectifier requires four diodes, but it does not require a centre-tapped transformer.





Equivalent circuit for $v_S > 0$

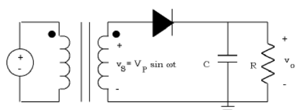




Equivalent circuit for $v_S < 0$

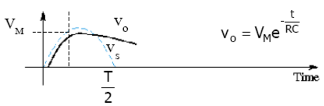
Capacitive Filters

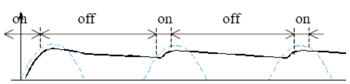
- Consider a half-wave rectifier with a capacitive filter below.
- Before the signal reaches its first peak during the positive half of the sine wave, the diode is on and, Vo= Vs-Von



When Vs begins to decrease, the diode is off and the capacitor voltage also starts to decrease. In other words the capacitor is being discharged through R.

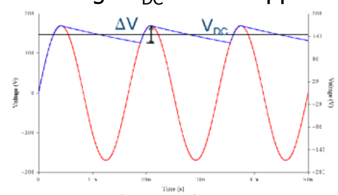
When Vs is greater than the capacitor voltage, the diode turns back on and the capacitor is charged until Vs begins to decrease again.





Ripples

- The output rectifier voltage can be represented as a sum of average dc voltage V_{DC} and ac ripple voltage ΔV



- For half-wave rectifier with a capacitive filter

$$V_{DC} = V_{MAX} - \Delta V / 2 \qquad \Delta V = V_{MAX} / fRC$$

- To lower the ripple voltage
  - Increase C or
  - use full-wave rectifier

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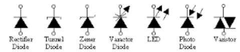
Types of Diodes

- The types of diode are as follow:
  - P-N junction diode
  - Zener diode
  - Schottky diode
  - Light emitting diode
  - Laser diode
  - Photo diode
  - Varactor diode
  - Tunnel diode
  - PIN diode
  - Avalanche diode



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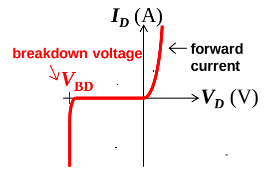
Zener Diode

- A Zener diode is a diode which works in the forward direction as an ideal diode,
- but also permits it to flow in the reverse direction when the voltage is above a certain value known as the breakdown voltage, "Zener voltage", "Avalanche point", or "peak inverse voltage".
- The device consists highly doped, p-n junction operating in the breakdown region.
- Conventional diodes never operate in the breakdown region,
- but the Zener diode can safely be operated at this point.



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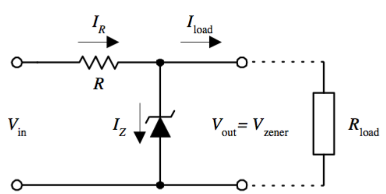
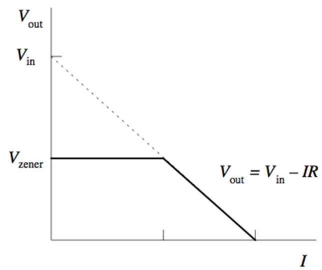
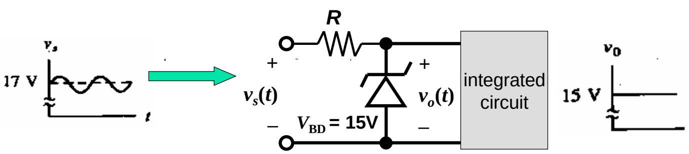
Zener Diode

A ***Zener diode*** is designed to operate in the breakdown mode.







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