REVIEW OF ELECTRICAL CONCEPTS

Electric Current

Symbol: I or i | Unit: Ampere (A) | Sign: Direction

Definition: One Ampere (A) of current equals one Coulomb (C) of charge passing through a defined surface in one second (s).

Related Variable (macroscopic point) –
Current Density (current at a point)

Symbol: J | Unit: Ampere per area (A/m^2 or A/cm^2)

Voltage (Electric Potential)

Symbol: V or v | Unit: Volt (V) | Sign: Polarity

Definition: One Volt (V) of voltage equals work per charge of one Joule per Coulomb (J/C) for moving a positive charge between the defined two points.

Related Variable (macroscopic point) –
Electric Field (voltage per unit length at a point)

Symbol: E | Unit: Volt per length (V/m or V/cm)

Ohm's Law

Proportionality between current and voltage defined as: $V_{12} = R\ I_{12}$

Resistance R

Symbol: R | Unit: Ohm (Ω) | Sign (Passive): Power Absorbed

ELECTRICAL RESISTIVITY/CONDUCTIVITY

Resistivity

Symbol: ρ Unit: (Ohm–meter) (Ω-m) or
(Ohm–centimeter) (Ω-cm)

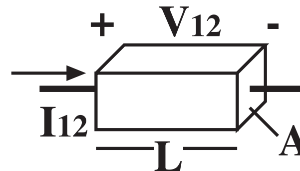
Conductivity

Symbol: σ Unit: $(\text{Ohm–meter})^{-1}$ $(\Omega\text{-m})^{-1}$ or
$(\text{Ohm–centimeter})^{-1}$ $(\Omega\text{-cm})^{-1}$

Relation: $\rho = 1/\sigma$ and $\sigma = 1/\rho$

Ohm's Law

Assuming a uniform material of constant resistivity or conductivity with a cross-sectional area A and a length L.



Resistance $R = (L/A)\rho = (L/A\sigma)$

Ohm's Law: $E = \rho J$ or $J = \sigma E$

Note for the assumptions: $E = V_{12}/L$ and $J = I_{12}/A$,
hence $V_{12}/L = \rho I_{12}/A$ or $V_{12} = [(L/A)\rho] I_{12} = R I_{12}$

Electrical Classification of Solids

Electrical resistivity or conductivity is a measure of how well an electrical carrier can move through a material.

While materials are comprised of many electrons, only the mobile carriers affect the electrical characteristics.

Types:

Insulator – a material with high resistivity or low conductivity
Conductor – a material with low resistivity or high conductivity

RESISTIVITY/CONDUCTIVITY EXAMPLES

Insulators

Porcelain: $\rho \sim 10^{12}$ to 10^{14} (Ω-cm) at typical operating temperatures

Conductors*

Silver: $\rho = 1.629 \times 10^{-6}$ (Ω-cm) at temperature T = 300 K
Copper: $\rho = 1.725 \times 10^{-6}$ (Ω-cm) at temperature T = 300 K
Gold: $\rho = 2.271 \times 10^{-6}$ (Ω-cm) at temperature T = 300 K
Aluminum: $\rho = 2.733 \times 10^{-6}$ (Ω-cm) at temperature T = 300 K

Copper as an Example

Approximate Temperature Dependence (Temperature T in degrees C)
where the temperature coefficient of resistivity $\alpha_{20} = 3.9 \times 10^{-3}$ (C)$^{-1}$

$$\rho(T) = \rho_{20} [1 + \alpha_{20} (T - 20)]$$

T= 350 K (77 C*): $\rho \sim 2.1 \times 10^{-6}$ (Ω-cm) & $\sigma \sim 4.8 \times 10^{5}$ (Ω-cm)$^{-1}$
Reference T= 20 C*: $\rho_{20} \sim 1.7 \times 10^{-6}$ (Ω-cm) & $\sigma_{20} \sim 6.0 \times 10^{5}$ (Ω-cm)$^{-1}$
T= 273 K (0 C*): $\rho \sim 1.5 \times 10^{-6}$ (Ω-cm) & $\sigma \sim 6.5 \times 10^{5}$ (Ω-cm)$^{-1}$

Resistance Calculations at 300 K (1 mil = 0.001 inch)
For 10.0 cm of American Wire Gauge (AWG) size #12 copper
(cross-sectional area = (π/4) (80.81 mils)^2 = (π/4) (0.205257 cm)^2

$R = (L/A)\rho = [(10.0 \text{ cm})/(\pi/4)(0.205257 \text{ cm})^2](1.725 \times 10^{-6}\ \Omega\text{-cm})$
$R = 5.21 \times 10^{-4}\ \Omega$

For 10.0 cm of American Wire Gauge (AWG) size #24 copper at 20 C
(cross-sectional area = (π/4) (20.10 mils)^2 = (π/4) (0.051054 cm)^2

$R = (L/A)\rho = [(10.0 \text{ cm})/(\pi/4)(0.051054 \text{ cm})^2](1.725 \times 10^{-6}\ \Omega\text{-cm})$
$R = 8.426 \times 10^{-3}\ \Omega$

*Reference: David R. Lide (editor), *CRC Handbook of Chemistry and Physics*, 71st Edition, (CRC Press, Boston, 1990).

ELECTRONIC PROPERTIES OF MATERIALS

Electronic Configuration of Atoms

Electron e – an elementary negatively-charged particle in a

Quantum-mechanical physical laws as part of an (isolated) atom

- e's can only have discrete energies
- e's cannot have the same quantum state (related to energy level)

Ground-state configuration identified by atomic quantum nomenclature
Energy states (starting with the lowest energy)

- 1s states with two possible e's: $1s^1$ or $1s^2$
- 2s states with two possible e's: $2s^1$ or $2s^2$
- 2p states with six possible e's: $2p^1$, $2p^2$, $2p^3$, $2p^4$, $2p^5$, or $2p^6$
- 3s states with two possible e's: $3s^1$ or $3s^2$
- 3p states with six possible e's: $3p^1$, $3p^2$, $3p^3$, $3p^4$, $3p^5$, or $3p^6$
- 4s states with two possible e's: $4s^1$ or $4s^2$
- 3d states with ten possible e's: $3d^1$, $3d^2$, $3d^3$, … , or $3d^{10}$
- 4p states with six possible e's: $4p^1$, $4p^2$, $4p^3$, $4p^4$, $4p^5$, or $4p^6$
- …

Examples by row of periodic table (elements with e's in lowest energy state)

First Row: H – $1s^1$, and He – $1s^2$

Second Row: Li – $1s^22s^1$, Be – $1s^22s^2$, B – $1s^22s^2\ p^1$,
C – $1s^22s^2\ p^2$, N – $1s^22s^2\ p^3$, O – $1s^22s^2\ p^4$,
F – $1s^22s^2\ p^5$, and Ne – $1s^22s^2\ p^6$

Third Row: Na – $1s^22s^2\ p^63s^1$, Mg – $1s^22s^2\ p^63s^2$,
Al – $1s^22s^2\ p^63s^2\ p^1$, Si – $1s^22s^2\ p^63s^2\ p^2$,
P – $1s^22s^2\ p^63s^2\ p^3$, S – $1s^22s^2\ p^63s^2\ p^4$,
Cl – $1s^22s^2\ p^63s^2\ p^5$, and Ar – $1s^22s^2\ p^63s^2\ p^6$

Periodic Table

Elements in columns have similar properties

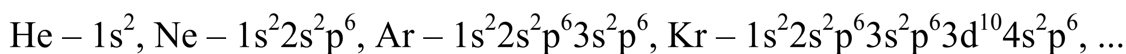
Column IV Examples: C – $1s^22s^2\ p^2$, Si – $1s^22s^2\ p^63s^2\ p^2$,
and Ge – $1s^22s^2\ p^63s^2\ p^6\ 3d^{10}4s^2\ p^2$,

PERIODIC TABLE

IA	IIA											IIIB	IVB	VB	VIB	VIIB	VIII
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh	Uns											
				Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
				Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Electronic configurations give insight into bonding behavior and reactivity.

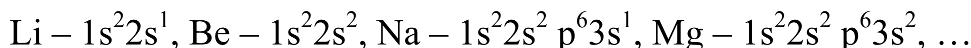
Column VIII elements have filled outer shells and contain the "Noble" Gases:



He – $1s^2$, Ne – $1s^2 2s^2 p^6$, Ar – $1s^2 2s^2 p^6 3s^2 p^6$, Kr – $1s^2 2s^2 p^6 3s^2 p^6 3d^{10} 4s^2 p^6$, ...

Electrons are not easily removed from the elements.
Elements with filled outer shells do not easily bond or react.

Column I and II elements have relatively empty outer shells (only one or two e's):



Li – $1s^2 2s^1$, Be – $1s^2 2s^2$, Na – $1s^2 2s^2 p^6 3s^1$, Mg – $1s^2 2s^2 p^6 3s^2$, …

Electrons in the outer shell are loosely bound for these elements.
Elements with one or two e's in the outer shells tend to form ions and tend to be highly reactive.

Ionic Bonding Example of Sodium Chloride (NaCl):

Ions of Na^+ and Cl^- form and these ions are electrostatically attracted.

Na^+ – $1s^2 2s^2 p^6$, (The $3s^1$ e is missing.)

Cl^- – $1s^2 2s^2 p^6 3s^2 p^6$, (An extra 3p e is present.)

An electrically neutral solid is formed when the equal numbers of Na^+ and Cl^- ions are alternately arranged.

BONDING PROPERTIES OF SOLIDS

Some Types of Bonding (for which local electron distributions tend to approximate that of Column VIII elements)

Ionic Bonding – electrons are gained and lost to create ions; oppositely-charged ions maintain regular separations (balance between the electrostatic attraction of ions and electrostatic repulsion of the outer electron distribution); the overall compound is electrically neutral.

Metallic Bonding – various forces bond atoms while the outer electron(s) are not bound locally to any particular atom; a cloud of mobile electrons exists; the overall material is electrically neutral.

Covalent Bonding – electrons are shared by adjacent atoms (and are locally bound, i.e. not mobile); the shared electrons interactions bond the host atoms; the overall material is electrically neutral.

Bonding Arrangements

Amorphous Solid – a material with no periodic structure.

Crystalline Solid – a material having a three-dimensional periodic array of atoms.

Polycrystalline Solid – a material composed of small regions of crystalline regions that are misoriented relative to one another.

Important Semiconductors as Crystalline Solids

Elemental Semiconductor – a semiconductor composed of a single species of atom through covalent bonding. They are found in column IV (periodic table) and include silicon (Si) and germanium (Ge).

Compound Semiconductor – a semiconductor composed of two or more species of atom through covalent bonding, but with some ionic aspects. They are formed from various combinations of elements in columns II, III, IV, V, and VI.

SEMICONDUCTOR CRYSTAL STRUCTURES

Electronic Configuration of Crystalline Elementary Semiconductors

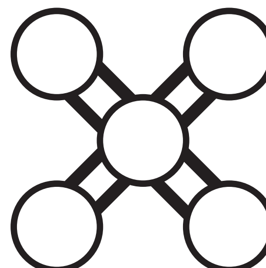
Column IV Examples:

- C – $1s^2 2s^2 p^2$
- Si – $1s^2 2s^2 p^6 3s^2 p^2$
- Ge – $1s^2 2s^2 p^6 3s^2 p^6\ 3d^{10} 4s^2 p^2$

Four electrons occur in the outer shell, e.g. $3s^2\ p^2$ for Si.

Four electrons are "needed" to fill the outer shell. (The shell would then have the electronic structure of Column VIII atoms, e.g. $3s^2\ p^6$ for Ar.)

Four covalent bonds can provide this structure through four-nearest neighbor atoms

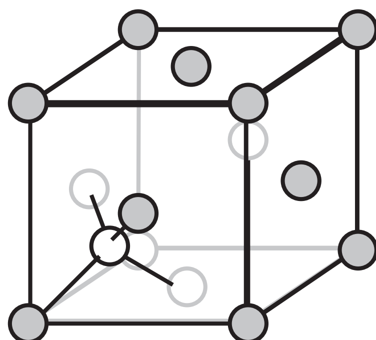


Diamond Crystal Structure

Two interpenetrating face-centered cubic (fcc) sublattices composed of the same material; each atom has four nearest neighbors.

Each component cell in a perfect crystal has the same orientation, structure, and size. The cell has dimensions of a x a x a.

- At room temperature, a_{Si} = 0.5431 nm
- For an atom at the origin (0, 0, 0) of a unit cell, a nearest neighbor is at coordinates (¼ a, ¼ a, ¼ a).



Face-Centered-Cubic sublattice with one corner of the interpenetrating sublattice

SEMICONDUCTOR CRYSTAL STRUCTURES

Electronic Configuration of Crystalline Compound Semiconductors

Binary Column III-V Examples:

- GaAs – Ga $1s^2 2s^2 p^6 3s^2 p^6 3d^{10} 4s^2 p^1$
  and As $1s^2 2s^2 p^6 3s^2 p^6 3d^{10} 4s^2 p^3$
- AlP, InSb, and InP

Other Column III-V Examples:

- Ternary – $GaAs_xP_{1-x}$ and $Al_xGa_{1-x}As$ where x is a fraction
- Quaternary – $Ga_xIn_{1-x}As_yP_{1-y}$ where x and y are fractions

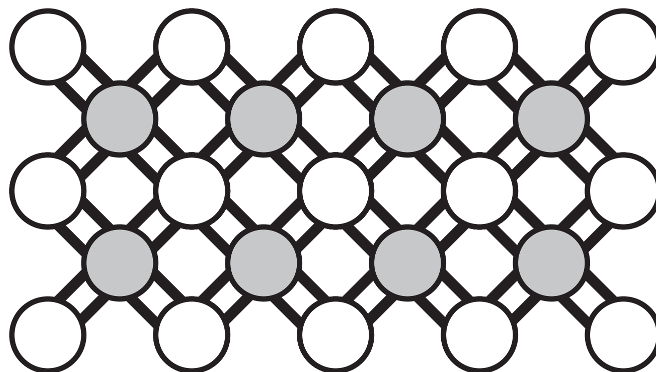
Column III-V: Three electrons in the outer shell for Column III atoms and five electrons in the outer shell for Column V atoms; Four covalent bonds can provide filled outer shells through four nearest-neighbor atoms (each nearest neighbor is of the opposite type).

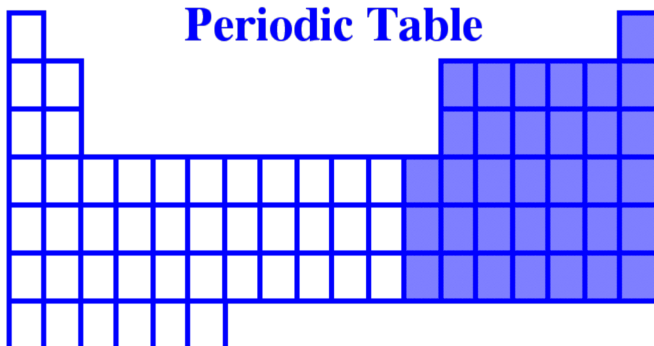
Binary Column II-VI Examples:

- ZnSe – Zn $1s^2 2s^2 p^6 3s^2 p^6 3d^{10} 4s^2$
  and Se $1s^2 2s^2 p^6 3s^2 p^6 3d^{10} 4s^2 p^4$
- CdTe and CdSe

Zincblende Crystal Structure

Two interpenetrating face-centered cubic (fcc) sublattices composed of the different materials; each atom has four nearest neighbors from the other Column.

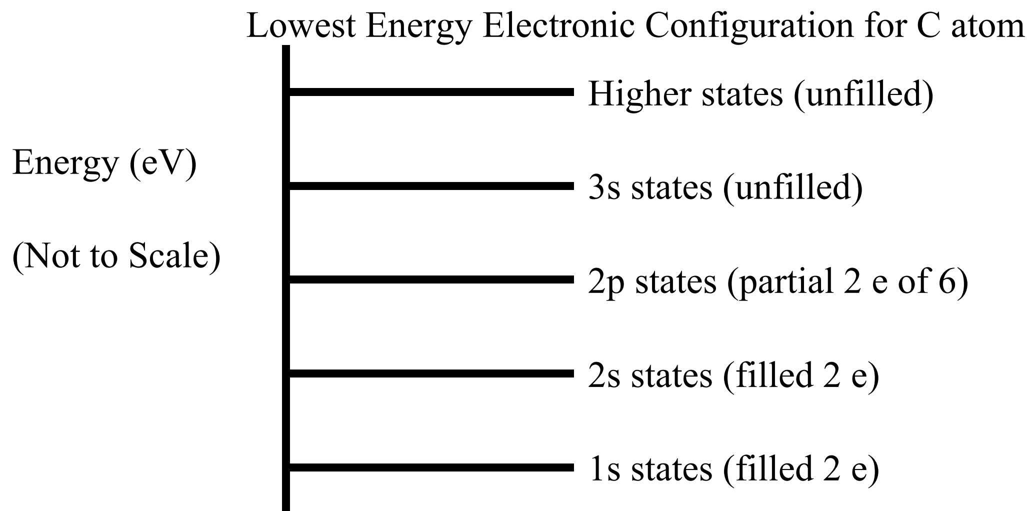




IIB	IIIB	IVB	VB	VIB	VIIB	VIII
						He
	B	C	N	O	F	Ne
	Al	Si	P	S	Cl	Ar
Zn	Ga	Ge	As	Se	Br	Kr
Cd	In	Sn	Sb	Te	I	Xe
Hg	Tl	Pb	Bi	Po	At	Rn

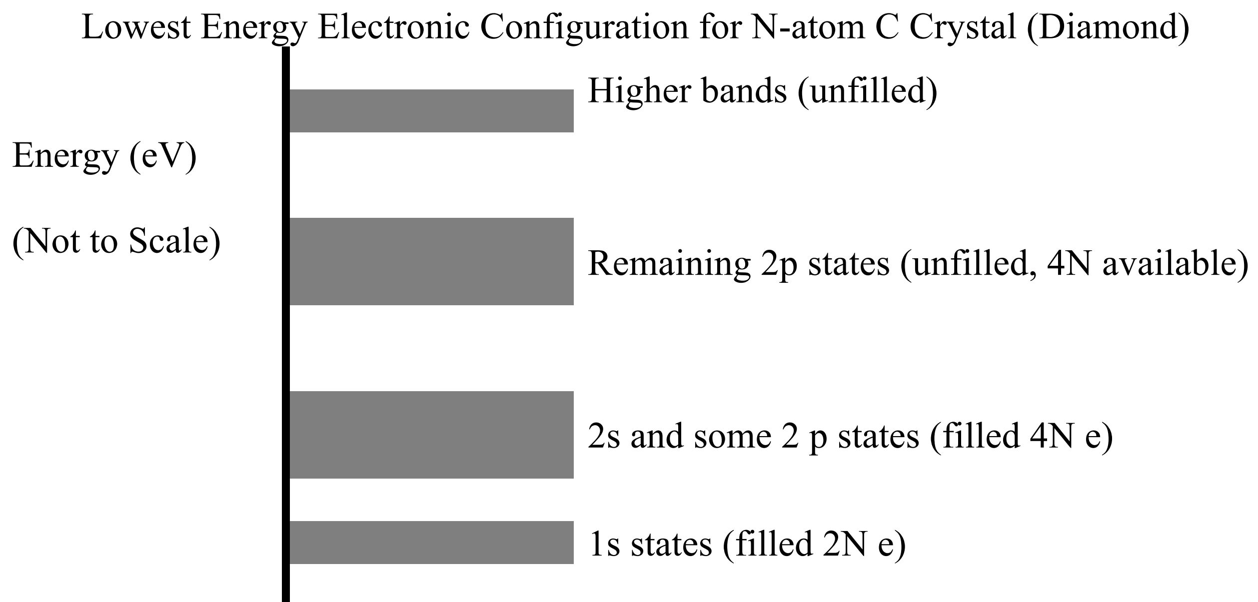
ENERGY LEVELS IN SEMICONDUCTOR CRYSTALS

Example: Energy Levels in an Isolated Carbon (C) Atom



Discrete allowed energy levels with forbidden energies between.

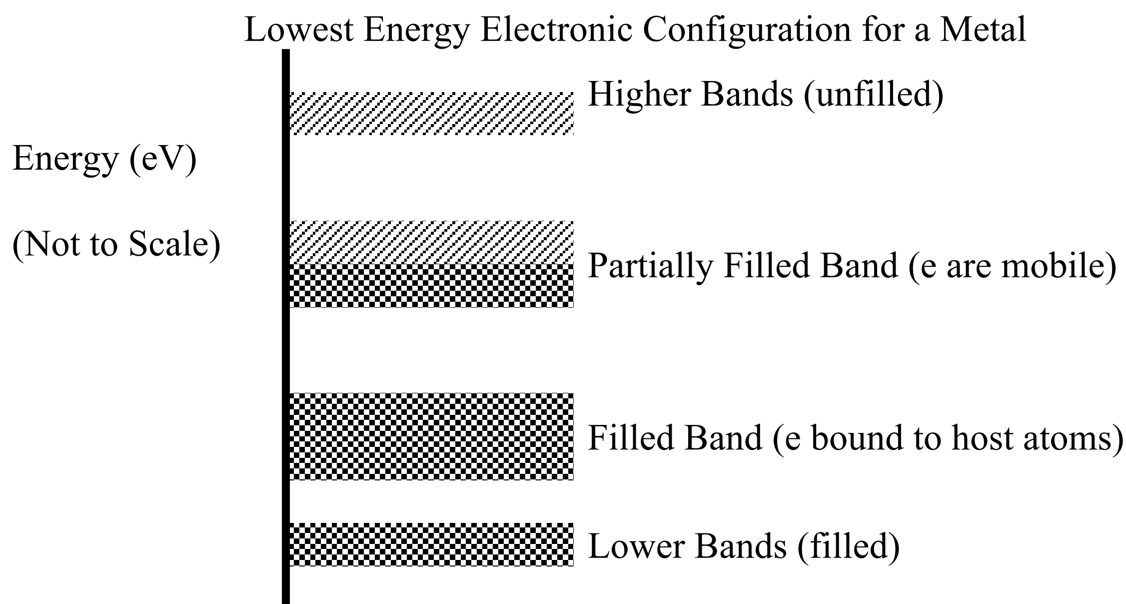
Example: Energy Levels in a Crystal of N Carbon (C) Atoms



Discrete allowed energy bands with forbidden energy gaps between.

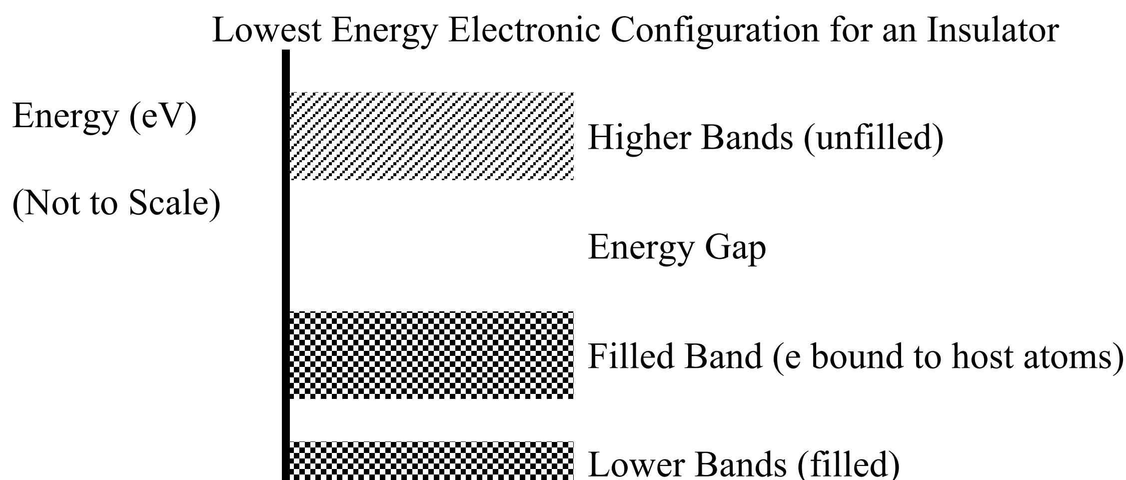
ENERGY BANDS

Energy Bands for a Metal



Electrons in the partially-filled band can easily move with little needed energy. Many states with similar energies are available. Electrons in lower bands must gain an energy equal to or greater than the gap to move.

Energy Bands for an Insulator

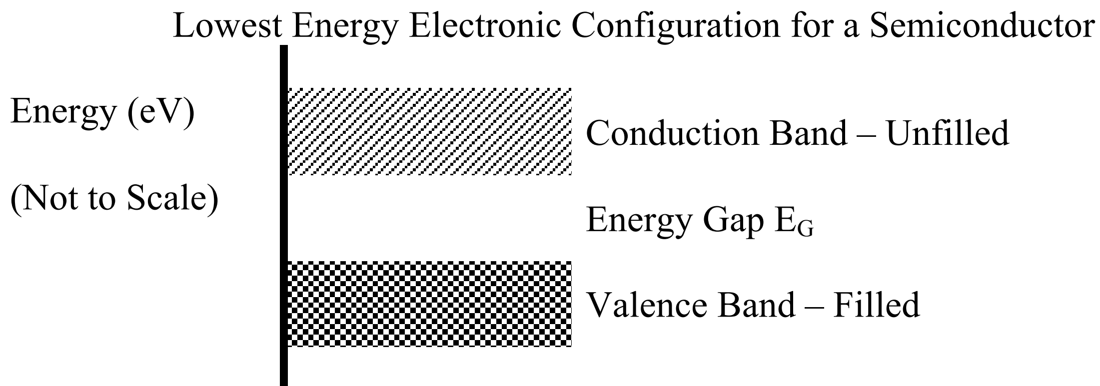


Electrons in the filled band cannot easily move. Conduction can only occur if electrons gain an energy equal to or greater than the gap to move to a higher band.

SEMICONDUCTOR BEHAVIOR

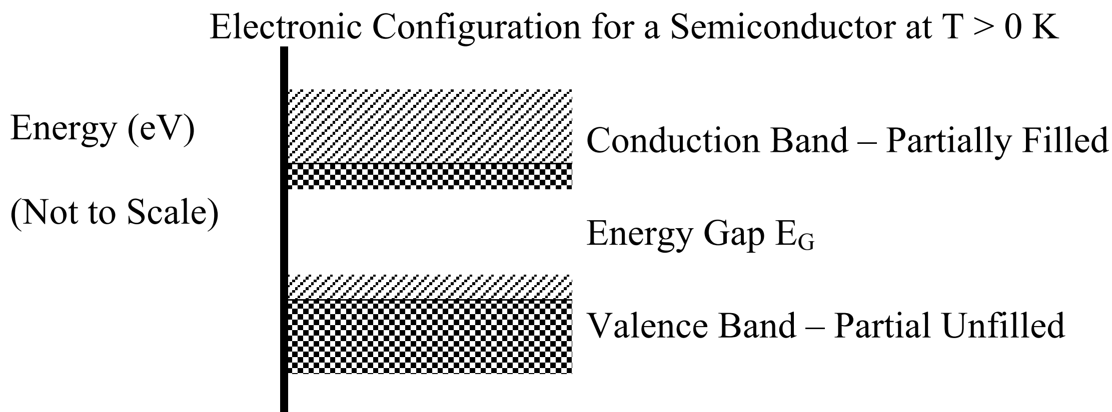
Energy Bands for a Semiconductor

Lowest Energy Electronic Configuration for a Semiconductor



Semiconductors act like insulators for low temperatures T.

Electronic Configuration for a Semiconductor at T > 0 K



Thermal excitation – Thermal energy moves a few electrons to the higher band. Electrons can now move in **both** the conduction and valence bands.

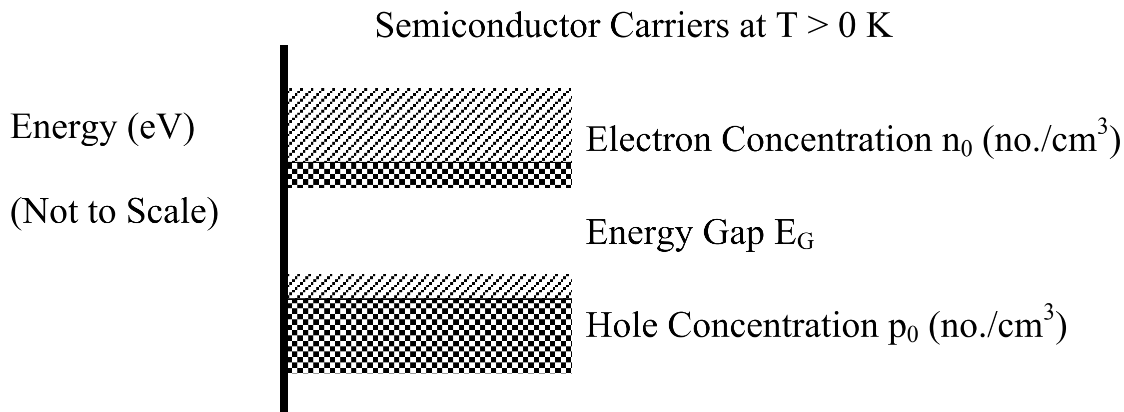
Difference between a semiconductor and an insulator – The size of the energy gap E_G. (For operating temperatures, the thermal excitation is enough to provide "significant" mobile electrons.)

Definitions:

- Valence Band – the highest filled energy band in a semiconductor at T = 0 K.
- Conduction Band – the lowest unfilled energy band in a semiconductor at T = 0 K.
- Energy Gap – the energy difference between the top of the valence band and the bottom of the conduction band. (Preferred unit eV)

ELECTRON BEHAVIOR

Semiconductor Carriers (only mobile electrons contribute to conductivity)



Electron behavior is governed by the quantum-mechanical environment of crystals.

Conduction Band – electrons are mobile. Their movement can be handled mathematically as a negatively-charged particle if an effective mass m_n^* is used rather than the true electron mass.

Valence Band – electrons are mobile, but there are many electrons and just a few empty states. The movement of charge can be handled mathematically if the empty states or holes are treated as positively-charged particles with an effective mass m_p^*.

Lower Bands – electrons are localized to the host atom and do not contribute to conductivity.

Electron-hole pairs (electrons in the conduction band and holes in the valence band) are continuously formed due to thermal excitation. However, electrons decay (downward band-to-band transitions) continuously as well.

Definitions:

General Conditions – the carrier concentrations may vary and are labeled n and p (units no./cm^3 or cm^{-3}).

Steady-State Conditions – the carrier concentrations are unchanging, i.e. transients have died out, and are labeled n and p (units no./cm^3 or cm^{-3}). External conditions such as electric fields may be present.

Equilibrium Conditions – the carrier concentrations are unchanging and are labeled n_o and p_0 (units no./cm^3 or cm^{-3}). Relevant conditions only include temperature and impurities.

INTRINSIC SEMICONDUCTORS

Intrinsic Semiconductor – a semiconductor containing no impurity atoms or an insignificant amount of impurity atoms such that its properties are native to the material. For each thermally-induced electron transition, one electron-hole pair is created. Hence, at equilibrium

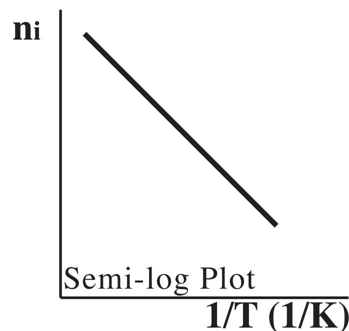
$$n_0 = p_0 = n_i$$

The equilibrium intrinsic concentration n_i is only dependent on material (specifically the magnitude of E_G) and temperature.

- As temperature T increases, the intrinsic concentration n_i increases.
- As the energy gap E_G increases, the intrinsic concentration n_i decreases.

$$n_i = 2(2\pi kT/h^2)^{3/2} (m_n^* m_p^*)^{3/4} \exp(-E_G/2kT)$$

E_G has a slight temperature dependence



Common Semiconductors

- Silicon (Si) at 300 K
  Bandgap: $E_G = 1.12$ eV $n_i = 1.5 \times 10^{10}$ cm^{-3}
- Germanium (Ge) at 300 K
  Bandgap: $E_G = 0.67$ eV $n_i = 2.3 \times 10^{13}$ cm^{-3}
- Gallium Arsenic (GaAs) at 300 K
  Bandgap: $E_G = 1.42$ eV $n_i = 2.1 \times 10^{6}$ cm^{-3}

Room Temperature RT: T = 300 K (Note for RT: kT = 0.0259 eV)

Example: n_i(Si at T = 300 K) = 1.5×10^{10} cm^{-3}

n_i(Si at T = 250 K) ~ 1×10^{8} cm^{-3}

EXTRINSIC SEMICONDUCTORS

Extrinsic Semiconductor – a semiconductor in which impurities control electrical properties. Impurities typically lie on lattice sites, i.e. they replace a host atom in the crystal. Donor impurities increase the concentration of electrons in the conduction band and acceptor impurities increase the concentration of holes in the valence band.

Donors for Elemental Semiconductors:

- Donors have valence electrons for all four covalent bonds and extra electron(s).
- Common donors are Column V atoms to replace Column IV host atoms. These donors have 5 valence electrons.
- Common donors – P $1s^22s^2\,p^63s^2\,p^3$ and As $1s^22s^2p^63s^2p^63d^{10}4s^2p^3$.

Acceptors for Elemental Semiconductors:

- Acceptors have insufficient valence electrons for all four covalent bonds.
- Common acceptors are Column III atoms to replace Column IV host atoms. These acceptors have 3 valence electrons.
- Common acceptors – B $1s^22s^2p^1$, Al $1s^22s^2\,p^63s^2\,p^1$, and Ga $1s^22s^2p^63s^2p^63d^{10}4s^2\,p^1$.

Donors for Compound Semiconductors:

- Donors have valence electrons for all four covalent bonds and extra electron(s).
- In Binary III-V semiconductors, common donors are Column VI atoms to replace Column V host atoms or Column IV atoms to replace Column III host atoms. These donors have one more valence electron than the host atoms that are replaced.

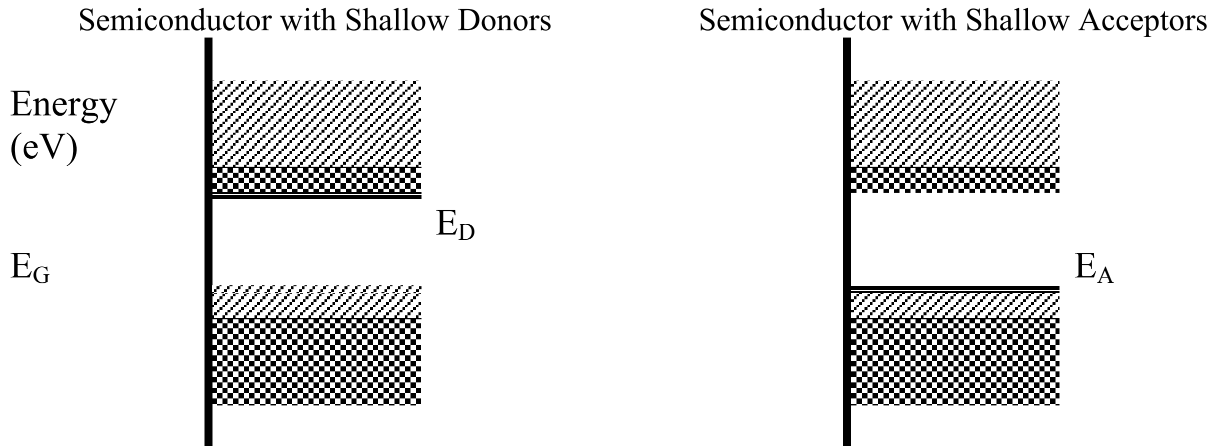
Acceptors for Compound Semiconductors:

- Acceptors have insufficient valence electrons for all four covalent bonds.
- In Binary III-V semiconductors, common acceptors are Column II atoms to replace Column III host atoms or Column IV atoms to replace Column V host atoms. These acceptors have one less valence electron than the host atoms that are replaced.

Example: Si (column IV) can be a donor or an acceptor depending on whether it replaces Ga or As in the host GaAs crystal.

CARRIERS IN EXTRINSIC SEMICONDUCTORS

Common dopants are "shallow" in that they introduce new, localized energy levels that are near the edges of the energy gap



At 0 K, the dopant levels E_D are full, i.e. the extra valence electron is bound to the donor.
At 0 K, the dopant levels E_A are empty, i.e. the missing electron in the covalent bond is localized to the acceptor.

At low temperatures (the energy difference E_C - E_D is small), the donors are ionized such that electrons are given to the conduction band with no mobile hole created in the valence band.
At low temperatures (the energy difference $E_A – E_V$ is small), the acceptors are ionized such that electrons are taken from the valence band with no mobile electron given to the conduction band.

The equilibrium carrier concentrations may be no longer balanced ($n_0 \neq p_0$) and are dependent on doping concentration N_D or N_A as well as E_G and T.

- After the dopants are ionized ($N_D \sim N_D^+$ and $N_A \sim N_A^-$), further temperature increases do not create more carriers from the dopants.
- As temperature T increases, the band-to-band transitions increase.

Hence at equilibrium

$$n_0 + N_a^- = p_0 + N_d^+$$

Other dopants such as those two extra electrons or two missing electrons exhibit more complex behvior. Only a portion of the dopants may ionize at operating temperatures and the fraction ionized may vary with doping level.

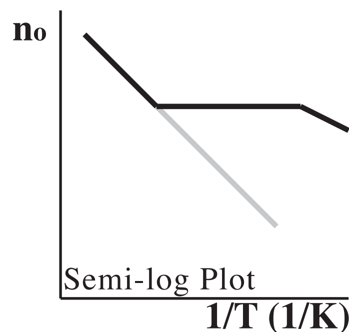
EQUILIBRIUM CARRIER CONCENTRATIONS

Consider a semiconductor at temperature T with shallow donors of concentration N_D and shallow acceptors of N_A. Electrons (in the conduction band) and holes (in the valence band) are provided by ionized dopants and thermal transitions. The decay rate is dependent on the electron and hole concentrations. At equilibrium, the simultaneous equations are:

$n_0 + N_a^- = p_0 + N_d^+$ $\qquad\qquad$ $n_0 p_0 = n_i^2$

Possible situations:

$n_0 > p_0$	n-type material (electrons are the majority carrier) necessary condition $N_a^- < N_d^+$
$n_0 < p_0$	p-type material (holes are the majority carrier) necessary condition $N_a^- > N_d^+$
$n_0 = p_0$	intrinsic behavior (thermal electron-hole generation dominates)



Definitions:

- Intrinsic Temperature Range – $n_0 = p_0 = n_i >> |N_a^- - N_d^+|$
- Extrinsic Temperature Range – $n_i << |N_a^- - N_d^+|$ and
  $n_0 \sim [N_d^+ - N_a^-]$ or $p_0 \sim [N_a^- - N_d^+]$
- Ionization Temperature Range – $[N_a > N_a^-]$ and/or $[N_d > N_d^+]$

CARRIER CONCENTRATION EXAMPLES

Consider a semiconductor at temperature T with shallow donors of concentration N_D and shallow acceptors of concentration N_A. Assume complete dopant ionization and $N_d^+ > N_a^-$.

The equations are

$$n_0 + N_a^- = p_0 + N_d^+ \qquad\qquad n_0 p_0 = n_i^2$$

Solve for the majority carrier (n_0 since $N_d^+ > N_a^-$). Substitute for a single equation in n_0.

$$n_0 - (N_d^+ - N_a^-) - p_0 = 0 \qquad\qquad p_0 = n_i^2/n_0$$
$$n_0 - (N_d^+ - N_a^-) - (n_i^2/n_0) = 0$$
$$n_0^2 - (N_d^+ - N_a^-)\, n_0 - (n_i^2) = 0$$

This quadratic equation has two solutions. One solution gives a negative n_0 which is not a physical possibility. The other solution is

$$n_0 = -(1/2)[-(N_d^+ - N_a^-)] + (1/2)\sqrt{\{[-(N_d^+ - N_a^-)]^2 - 4(-n_i^2)\}}$$
$$n_0 = (1/2)(N_d^+ - N_a^-) + (1/2)\sqrt{[(N_d^+ - N_a^-)^2 + 4(n_i^2)]}$$

Given this majority carrier concentration, the minority carrier concentration is

$$p_0 = n_i^2/n_0 = n_i^2/\{(1/2)(N_d^+ - N_a^-) + (1/2)\sqrt{[(N_d^+ - N_a^-)^2 + 4(n_i^2)]}\}$$

Note special conditions

If $n_i >> [N_d^+ - N_a^-]$, then

$$n_0 = (1/2)(N_d^+ - N_a^-) + (1/2)\sqrt{[(N_d^+ - N_a^-)^2 + 4(n_i^2)]}$$
$$n_0 \sim (1/2)(N_d^+ - N_a^-) + (1/2)[2(n_i)] = (1/2)(N_d^+ - N_a^-) + (n_i)$$
$$n_0 \sim (n_i)$$

If $n_i << [N_d^+ - N_a^-]$, then

$$n_0 = (1/2)(N_d^+ - N_a^-) + (1/2)\sqrt{[(N_d^+ - N_a^-)^2 + 4(n_i^2)]}$$
$$n_0 \sim (1/2)(N_d^+ - N_a^-) + (1/2)\sqrt{[(N_d^+ - N_a^-)^2]}$$
$$n_0 \sim (1/2)(N_d^+ - N_a^-) + (1/2)(N_d^+ - N_a^-) = (N_d^+ - N_a^-)$$

CARRIER CONCENTRATION IN SILICON

Consider a Silicon (Si) sample at room temperature (T = 300 K) with shallow acceptors of concentration $N_A = 1.0 \times 10^{12}$ cm^{-3}. Assume complete dopant ionization $N_a = N_a^-$. Note $n_i = 1.5 \times 10^{10}$ cm^{-3}.

The equations are

$$n_0 + N_a^- = p_0 \qquad\qquad n_0 p_0 = n_i^2$$

Solve for the majority carrier p_0. Substitute for a single equation in p_0.

$$p_0 - (N_a^-) - n_0 = 0 \qquad\qquad n_0 = n_i^2/p_0$$
$$p_0 - (N_a^-) - (n_i^2/p_0) = 0 \quad \text{or} \quad p_0^2 - (N_a^-)\, p_0 - (n_i^2) = 0$$

Taking the physical solution of this quadratic equation.

$$p_0 = -(1/2)[-(N_a^-)] + (1/2)\sqrt{\{[-(N_a^-)]^2 - 4(-n_i^2)\}}$$
$$p_0 = (1/2)(N_a^-) + (1/2)\sqrt{[(N_a^-)^2 + 4(n_i^2)]}$$
$$p_0 = (1/2)(10^{12}) + (1/2)\sqrt{[(10^{12})^2 + 4(1.5 \times 10^{10})^2]}$$
$$p_0 = 1.00 \times 10^{12} \text{ cm}^{-3} \quad (\text{or } p_0 = 1.000225 \times 10^{12} \text{ cm}^{-3})$$

The minority carrier concentration is

$$n_0 = n_i^2/p_0 = (1.5 \times 10^{10})^2/(1.00 \times 10^{12}) = 2.25 \times 10^8 \text{ cm}^{-3}$$

Carrier concentrations are controlled by the dopant concentrations. The Silicon atoms per unit volume are

$$N_{Si} = (8 \text{ atoms per unit cell}) / (0.5431 \times 10^{-7} \text{ cm})^3$$
$$N_{Si} = 4.99 \times 10^{22} \text{ cm}^{-3}$$

Note that for RT dopant concentrations in excess of one donor or acceptor atom per every ~4×10^{12} silicon atoms are enough to determine the crystal carrier concentrations. For this example it is one acceptor atom per every 4.99×10^{10} silicon atoms.

FERMI LEVELS IN SEMICONDUCTORS

The mathematics of the electron behavior in the semiconductor follows Fermi-Dirac statistics. Electron and hole concentrations are determined by the probability of available energy states being filled or empty.

Fermi Level E_F – the energy level at which an available state has a 0.5 probability of being filled. (Note that no electrons can be present in the band gap even though a finite probability may exist, i.e. electron concentration equals probability times the density of available states.)

E_F in a given semiconductor may be used as a measure of the equilibrium carrier concentrations. It is always expressed with respect to the middle of the bandgap (E_i) or to either band edge.

- E_F at the middle of the bandgap ($E_F = E_i$) – the semiconductor has intrinsic behavior with $n_0 = p_0$. (Note that E_i is not precisely at the middle of the bandgap, but for the purposes of this course it is assume to be. The reasons are beyond the scope of the course.)
- E_F at the above the middle of the bandgap ($E_F - E_i > 0$) – the semiconductor has extrinsic n-type behavior with $n_0 > p_0$.
- E_F at the below the middle of the bandgap ($E_F - E_i < 0$) – the semiconductor has extrinsic p-type behavior with $n_0 < p_0$.

Carrier concentrations as a function of E_F and T.

$$n_0 = n_i \exp[(E_F - E_i)/kT] \quad \text{or} \quad (E_F - E_i) = kT \ln(n_0/n_i)$$

$$p_0 = n_i \exp[-(E_F - E_i)/kT] \quad \text{or} \quad (E_F - E_i) = - kT \ln(p_0/n_i)$$

Note at room temperature kT = 0.0259 eV

Example: Si (E_G = 1.12 eV) at room temperature with $N_a^- = 1.00 \times 10^{12}$ cm^{-3}

$$p_0 = 1.00 \times 10^{12} \text{ cm}^{-3} \quad \text{and} \quad n_0 = 2.25 \times 10^{8} \text{ cm}^{-3}$$

$$(E_F - E_i) = (0.0259 \text{ eV}) \ln(2.25 \times 10^{8} \text{ cm}^{-3}/1.5 \times 10^{10} \text{ cm}^{-3})$$
$$(E_F - E_i) = - 0.109 \text{ eV}$$

or

$$(E_F - E_i) = - (0.0259 \text{ eV}) \ln(1.00 \times 10^{12} \text{ cm}^{-3}/1.5 \times 10^{10} \text{ cm}^{-3})$$
$$(E_F - E_i) = - 0.109 \text{ eV}$$

CARRIER DRIFT IN SEMICONDUCTORS

Drift – the net movement of charge due to an electric field. Electrons move randomly in the material and a subject to scattering interactions with lattice atoms, impurity atoms, other electrons, etc. With no electric field, the net movement of charge is balanced in all directions. With an electric field, an average net velocity is created on the carriers.

For an electric field E,

Electrons (in the conduction band): the average velocity is
$\langle v \rangle = -\mu_n E$ (the field and the movement are in opposite directions)

Holes (in the valence band): the average velocity is
$\langle v \rangle = \mu_p E$ (the field and the movement are in the same direction)

where μ_n and μ_p are the mobilities with units cm^2 /Vs.

The electron current density (A/cm^2) is: $J_n = (-q)n_0(-\mu_n E) = qn_0\mu_n E$

The hole current density (A/cm^2) is: $J_p = (+q)p_0(+\mu_p E) = qp_0\mu_p E$

The total current density accounts for both electron drift and hole drift.

$$J = q(n_0\mu_n + p_0\mu_p)E = \sigma E$$

Hence, the conductivity is $\sigma = q(n_0\mu_n + p_0\mu_p)$ $(\Omega\text{-cm})^{-1}$

The mobilities are a measure of how easy the carriers can move through the material. The electrons and holes have different quantum-mechanical environments and consequently have different mobilities.

- $\mu_n > \mu_p$: electrons move in the crystal more easily than holes.
- $\mu_n(N_{dopants} = 0) > \mu_n(N_{dopants} > 0)$ and
  $\mu_p(N_{dopants} = 0) > \mu_p(N_{dopants} > 0)$:
  mobilities are reduces as the impurity concentration increases.
- Listed mobilities may generally be used for $N_{dopants} < 10^{14}$ cm^{-3}.
  The mobilities decrease for larger impurity concentrations.

CARRIER DIFFUSION IN SEMICONDUCTORS

Diffusion – the net movement of charge due to concentration gradient. Due to their random movement, electrons will migrate from regions of high concentration to regions of low concentration. The net movement is proportional to the gradient magnitude.

For a one-dimensional gradient in x,

Electrons (in the conduction band): the current density (A/cm^2) is

$J_n = (-q)(D_n)(-dn/dx)$

$J_n = qD_n\, dn/dx$ (current is in the same direction of the gradient)

Holes (in the valence band): the current density (A/cm^2) is

$J_p = (+q)(D_p)(-dp/dx)$

$J_p = -qD_p\, dp/dx$ (current is in the opposite direction of the gradient)

where D_n and D_p are the diffusion coefficients with units cm^2 / s.

The total current density accounts for electron diffusion and hole diffusion.

$J = qD_n\, dn/dx - qD_p\, dp/dx$ for one-dimension

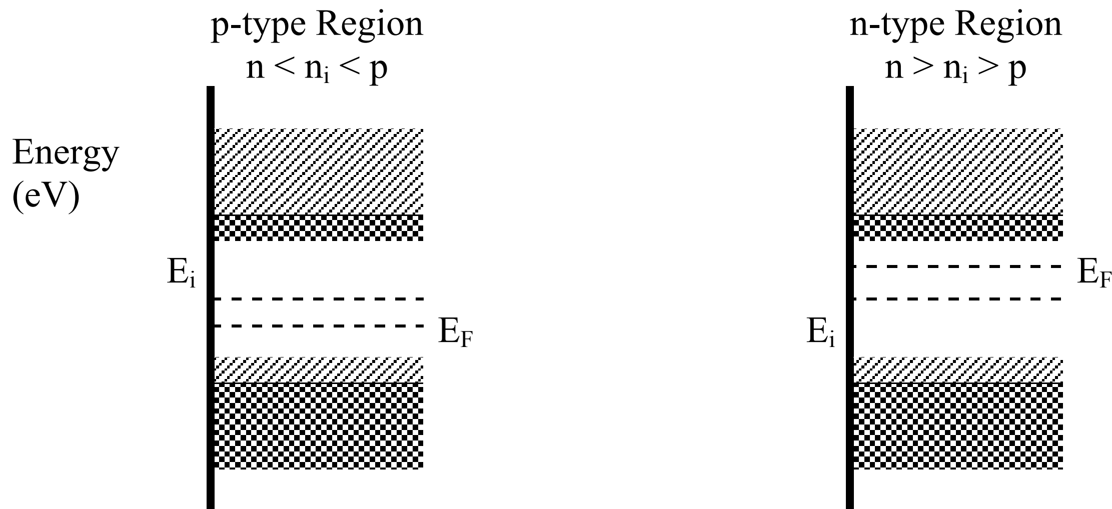
$$J = qD_n (\mathbf{a_x}\, d/dx + \mathbf{a_y}\, d/dy + \mathbf{a_z}\, d/dz)n - qD_p (\mathbf{a_x}\, d/dx + \mathbf{a_y}\, d/dy + \mathbf{a_z}\, d/dz)p \quad \text{for three-dimensions}$$

The diffusion coefficients are a measure of how easy the carriers can move through the material and are related to the mobilities. The different quantum-mechanical environments for the electrons and holes give different diffusion coefficients. The relation is known as the Einstein relation.

$D_n / \mu_n = kT/q$ and $D_p / \mu_p = kT/q$

ABRUPT PN JUNCTIONS IN SEMICONDUCTORS

Interface between a p-type region and an n-type region forms a pn junction.



For equilibrium, the Fermi level E_F for a semiconductor is constant and the total current density is zero.

At the interface,

n (p side) < n (n side): a gradient exists and electrons flow.
p (p side) > p (n side): a gradient exists and holes flow.

Depletion region around the interface

p side: mobile holes are depleted leaving immobile acceptors N_a^-
n side: mobile electrons are depleted leaving immobile donors N_d^+

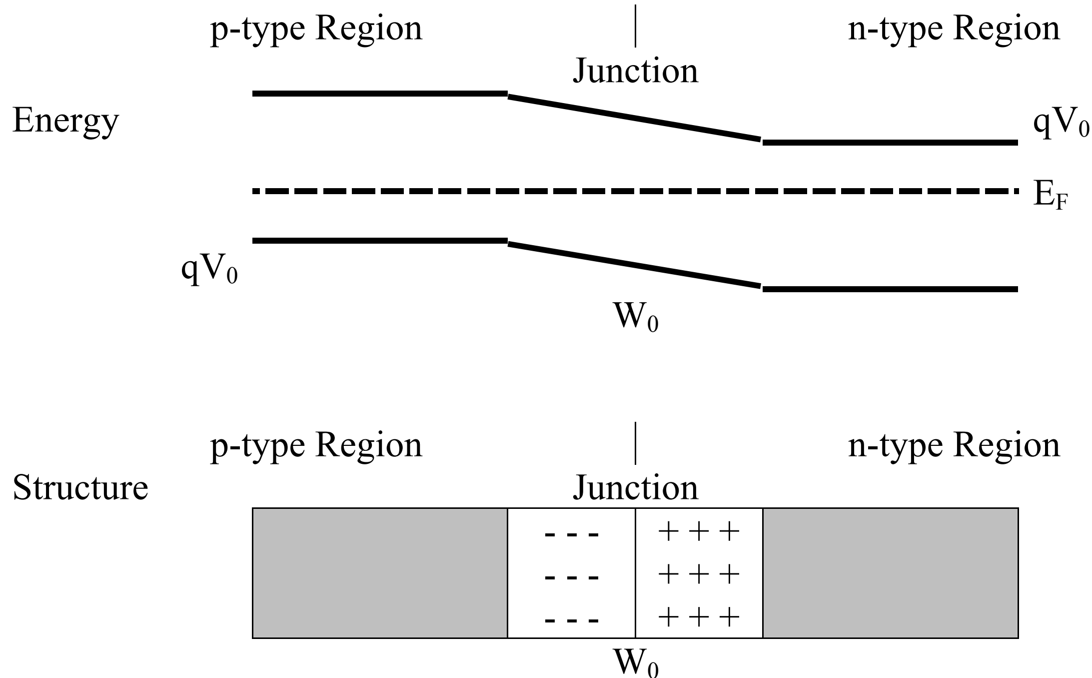
Electric Dipole is created between the negatively-charged region on the p-side and the positively-charged region on the n-side. The electric field produces a drift current in the opposite direction. Hence, the diffusion and drift currents are balanced.

$$J_n(x) = 0 = + q\mu_n n_0(x)\, E(x) + qD_n\, dn/dx$$
$$J_p(x) = 0 = + q\mu_p p_0(x)\, E(x) - qD_p\, dp/dx$$

A built-in or contact potential V_0 is created across the depletion region which corresponds to an energy difference qV_0.

PN JUNCTIONS AT EQUILIBRIUM

Doping concentrations determine the contact potential V_0 and the equilibrium depletion width W_0. Note for equilibrium, I = 0 A and J = 0 A/cm^2.



Equilibrium carrier concentrations

p side: n_{p0} and p_{p0} calculated from donors N_{dp}^+ and acceptors N_{ap}^-

n side: n_{n0} and p_{n0} calculated from donors N_{dn}^+ and acceptors N_{an}^-

Contact Potential V_0

$$V_0 = (kT/q)\ \ln(n_{n0}/n_{p0}) = (kT/q)\ \ln(p_{p0}/p_{n0})$$

$$V_0 = (kT/q)\ \ln[(N_{ap}^- - N_{dp}^+)(N_{dn}^+ - N_{an}^-)/n_i^2] \text{ for extrinsic doping}$$

or

$$(n_{n0}/n_{p0}) = (p_{p0}/p_{n0}) = \exp(qV_0/kT)$$

Relation to Fermi levels on each side of the junction

$$qV_0 = (kT)\ \ln(n_{n0}/n_{p0}) = (kT)\ \ln[(n_{n0}/n_i)(n_i/n_{p0})]$$

$$qV_0 = (kT)\ [\ln(n_{n0}/n_i) + \ln(n_i/n_{p0})] = (kT)\ \ln(n_{n0}/n_i) - (kT)\ \ln(n_{p0}/n_i)$$

$$qV_0 = (E_F - E_{in}) - (E_F - E_{ip})$$

$$qV_0 = E_{ip} - E_{in}$$

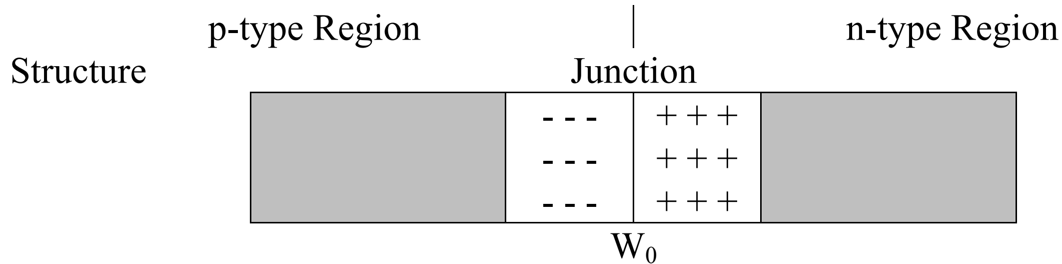
DEPLETION APPROXIMATION FOR PN JUNCTIONS

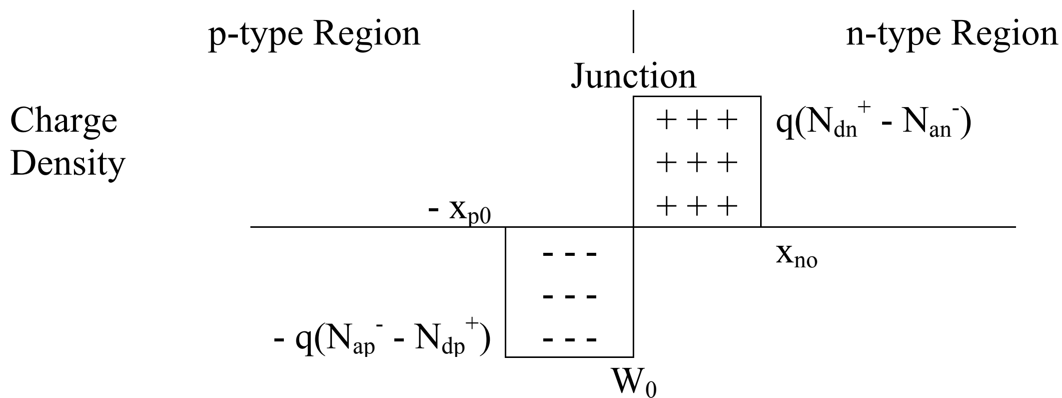
Depletion approximation – assume that the uncompensated dopant charge in the depletion region is uniform and equal to:

p side: $Q_- = - q(N_{ap}^- - N_{dp}^+)A\, x_{p0} = - q(N_{ap}^-)_{Eff}\, A\, x_{p0}$

n side: $Q_+ = + q(N_{dn}^+ - N_{an}^-)A\, x_{n0} = + q(N_{dn}^+)_{Eff}\, A\, x_{n0}$

where A is the cross-sectional area, x_{po} is the extension into the p side, and x_{no} is the extension into the n side..





Hence,

$|Q_-| = |Q_+|$; $(N_{ap}^- - N_{dp}^+)\, x_{p0} = (N_{dn}^+ - N_{an}^-)\, x_{n0}$;

or $(N_{ap}^-)_{Eff}\, x_{p0} = (N_{dn}^+)_{Eff}\, x_{n0}$;

$$W_0 = \{(2\varepsilon_r\varepsilon_0 V_0/q) [(N_{ap}^-)_{Eff} + (N_{dn}^+)_{Eff}] / [(N_{ap}^-)_{Eff} (N_{dn}^+)_{Eff}]\}^{1/2}$$

where ε_r = relative permitivitty and $\varepsilon_0 = 8.854 \times 10^{-14}$ F/cm.

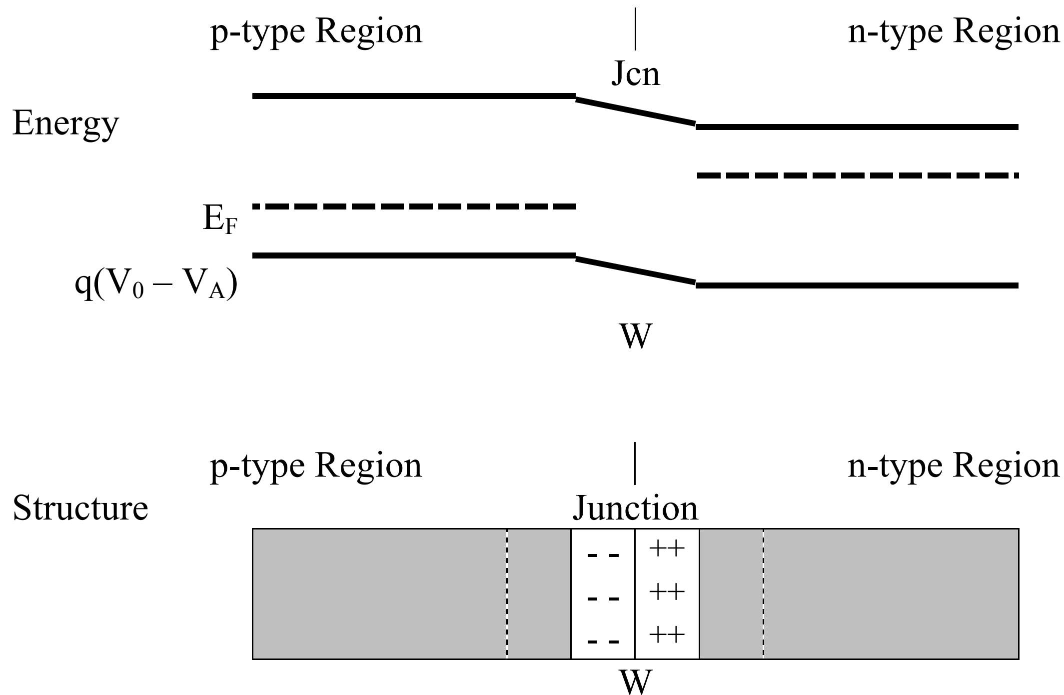
Examples

If $(N_{ap}^-)_{Eff} = (N_{dn}^+)_{Eff}$, then $x_{p0} = x_{n0}$

If $(N_{ap}^-)_{Eff} = 100\, (N_{dn}^+)_{Eff}$, then $100\, x_{p0} = x_{n0}$

If $(N_{ap}^-)_{Eff} = 10^6\, (N_{dn}^+)_{Eff}$, then $10^6\, x_{p0} = x_{n0}$

Forward Bias – a positive external voltage V_A is applied with the positive polarity at the p side and the negative polarity at the n side. For this non-equilibrium case, the Fermi level is non-continuous and $I \neq 0$.



Electrical Behavior:

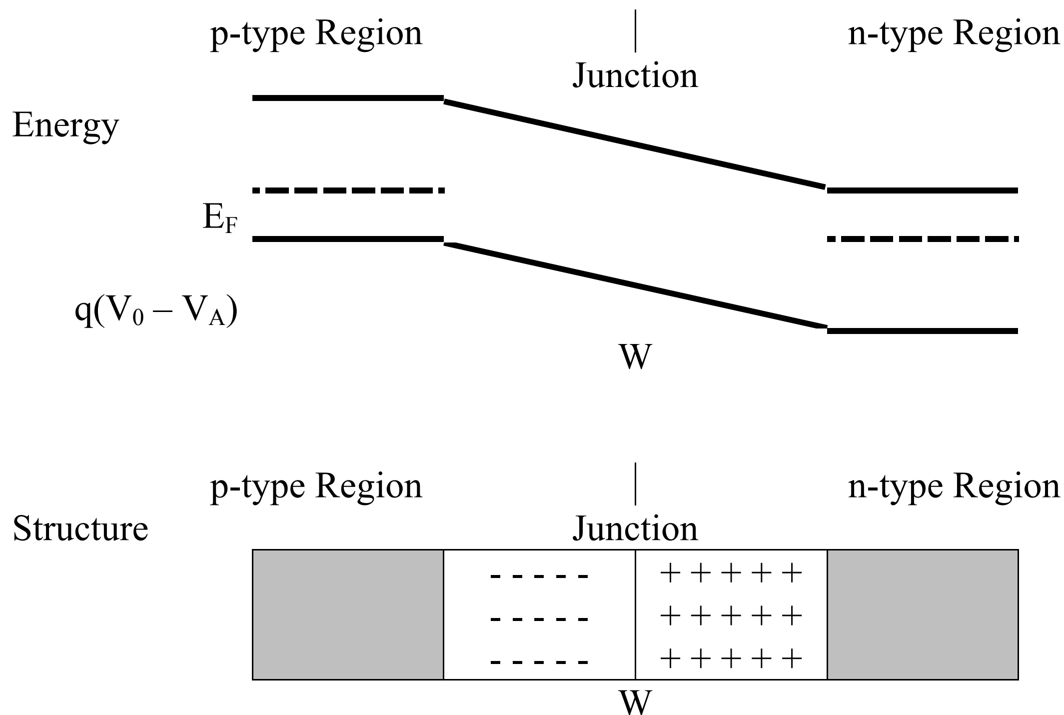
- Applied voltage V_A is in opposition to V_0 and the electric field at the junction is smaller than at equilibrium.
- Diffusion current dominates drift. The current is a strong function of the applied voltage V_A. (Many electrons and holes for available for movement, hence, a large current can result.)
- The depletion width W is smaller than W_0.
- The potential difference in the energy bands is less at $q(V_0 – V_A)$ and the applied voltage approaches a limit of V_0.
- The Fermi level difference is qV_A.

Forward Bias Equations

$$W = \{[2\varepsilon_r\varepsilon_0 (V_0 - V_A)/q] [(N_{ap}^-)_{Eff} + (N_{dn}^+)_{Eff}] / [(N_{ap}^-)_{Eff} (N_{dn}^+)_{Eff}]\}^{1/2}$$

PN JUNCTIONS UNDER REVERSE BIAS

Reverse Bias – a negative external voltage V_A is applied with the positive polarity at the p side and the negative polarity at the n side, i.e. $V_A = -|V_A|$. For this non-equilibrium case, the Fermi level is non-continuous and $I \neq 0$.



Electrical Behavior:

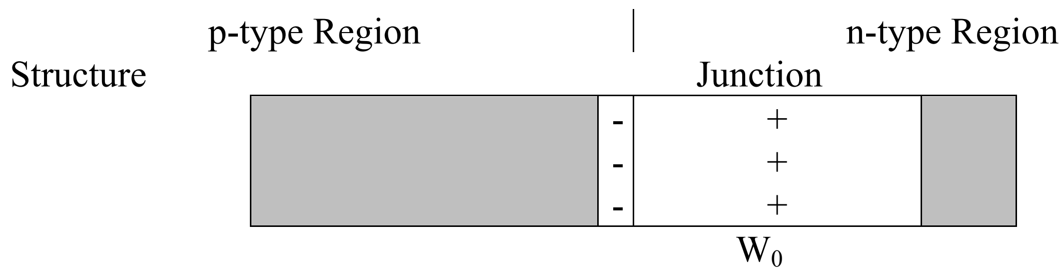
- Applied voltage V_A reinforces V_0 and the electric field at the junction is larger than at equilibrium.
- Drift current dominates diffusion. The current is relatively independent of the applied voltage V_A. (Few electrons and holes for available for movement, hence, a small, constant current results.)
- The depletion width W is larger than W_0.
- The potential difference in the energy bands is greater at $q(V_0 – V_A)$.
- The Fermi level difference is qV_A.

Forward Bias Equations

$$W = \{[2\varepsilon_r\varepsilon_0 (V_0 - V_A)/q]\ [(N_{ap}^-)_{Eff} + (N_{dn}^+)_{Eff}\ ] / [(N_{ap}^-)_{Eff}\ (N_{dn}^+)_{Eff}\ ]\}^{1/2}$$

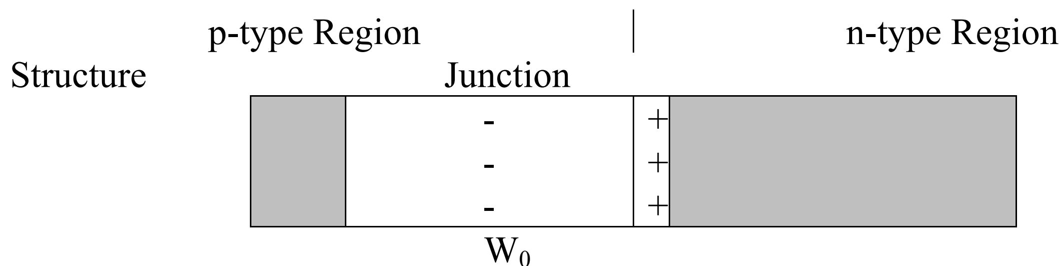
P+N JUNCTIONS AND PN+ JUNCTIONS

When one side of a junction is doped significantly more than the other, the junction may be referred to as a p+n or pn+ (or n+p) structure. The reasons to design such a junction may be compensation doping during fabrication, control of the size and placement of the depletion region W, and current domination by electron or hole flow.



Characteristics of p+n Junction: $N_{apEff}^{-} >> N_{dnEff}^{+}$:

- The depletion width W is primarily in the lightly doped n-type region, i.e. then $x_{p0} < x_{n0}$.
- Variations in the depletion width W with bias are most significant in the lightly doped n-type region.
- Forward-bias current across the junction is primarily hole current.



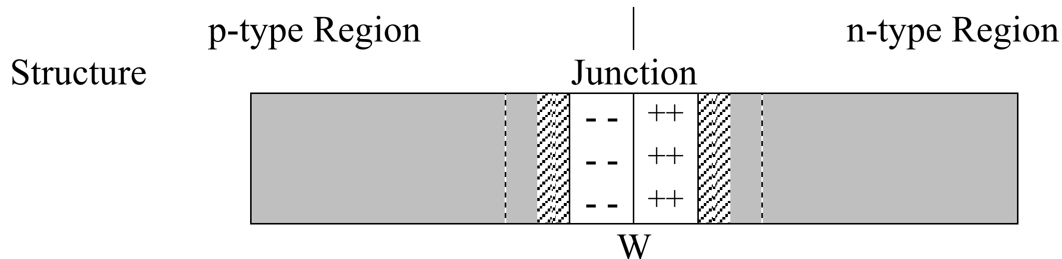
Characteristics of pn+ Junction: $N_{apEff}^{-} << N_{dnEff}^{+}$:

- The depletion width W is primarily in the lightly doped p-type region, i.e. then $x_{p0} > x_{n0}$.
- Variations in the depletion width W with bias are most significant in the lightly doped p-type region.
- Forward-bias current across the junction is primarily electron current.

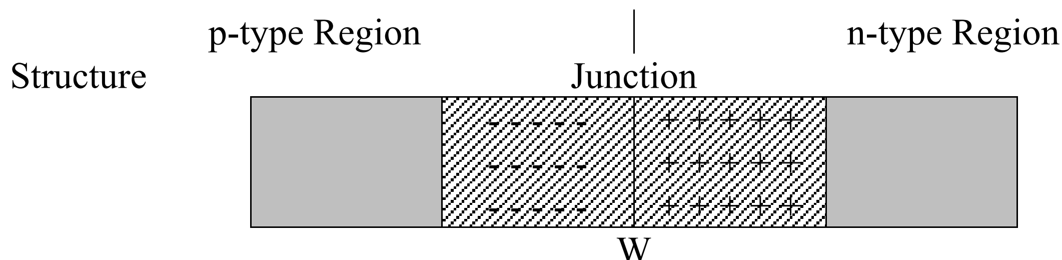
CAPACITANCE IN PN JUNCTIONS

Capacitance is $C = |\Delta Q/\Delta V|$ where the V is the applied voltage.

Capacitance for Forward Bias Conditions – called charge storage or diffusion capacitance C_S. The charge for this capacitance is injected carriers just beyond the edge of the depletion region W. Note that holes are injected into the n-type region and create an excess carrier concentration near the edge of W. Electrons are injected into the p-type region and create an excess carrier concentration near the edge of W. (The charge in the depletion region is reduced as the applied voltage increases and is not a dominant effect.)

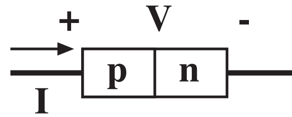


Capacitance for Reverse Bias Conditions – called junction capacitance C_J. The charge for this capacitance is the dipole charge in the depletion region. Note that this region is large and is a strong function of applied voltage. (Electrons at the edge of W in the p-type region and holes at the edge of W in the n-type region are depleted, i.e. a negative injection. These changes in the minority carrier concentrations are not a dominant effect.)

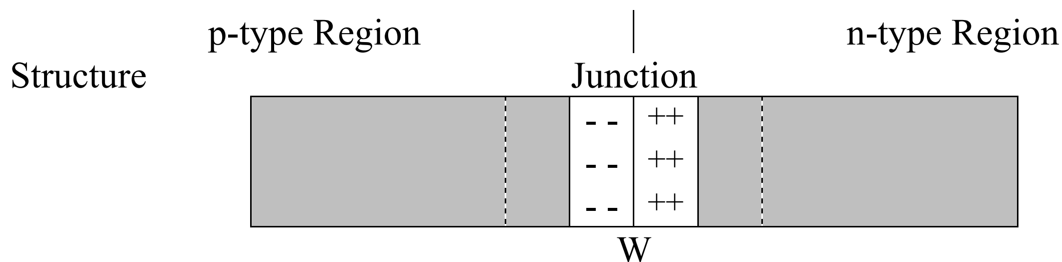


SUMMARY OF BIAS BEHAVIOR FOR PN JUNCTIONS

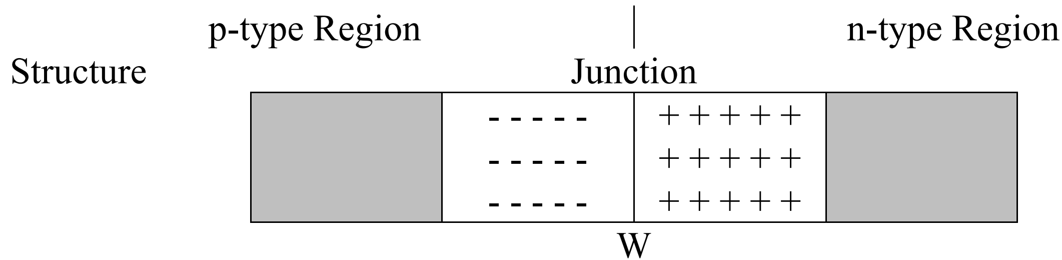
The structure behaves differently for positive and negative polarities of the applied voltage V.



Forward Bias – a positive external voltage V produces a large and increasing current especially as the voltage approaches the contact potential V_0. Diffusion current dominates drift. The depletion width W is smaller than W_0.



Reverse Bias – a negative external voltage V produces a small and relatively constant current. Drift current dominates diffusion. The depletion width W is larger than W_0.



Characteristics:

- The peak electric field is located at the junction.
- The potential difference in the energy bands is $q(V_0 – V)$.
- The Fermi level difference is $q|V|$.
- $W = \{[2\varepsilon_r\varepsilon_0 (V_0 - V)/q]\, [(N_{ap}^-)_{Eff} + (N_{dn}^+)_{Eff}] / [(N_{ap}^-)_{Eff} (N_{dn}^+)_{Eff}]\}^{1/2}$

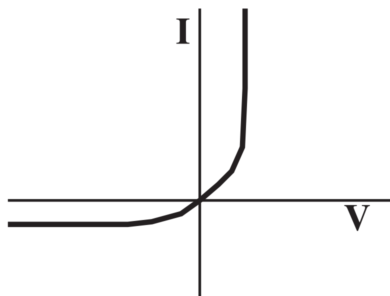
PN JUNCTION DIODES

Diode – a two-terminal device with p-type and n-type regions in which the electrical behavior differs for forward and reverse bias.

IV Characteristic – the current-voltage behavior is different for forward bias (positive V, or V_A in the semiconductor development,) and for reverse bias (negative V).

Forward Bias: A large current is possible as the applied voltage approaches the device turn-on voltage (approximately V_0 in the semiconductor development).

Reverse Bias: Only a small current is possible (the magnitude is known as the reserve saturation current I_0).



Diode Equation resulting from the depletion approximation for an abrupt junction.

$$I = I_0 \, [\exp(qV/kT) - 1]$$

Forward bias with $V >> 0$

$$I \sim I_0 \exp(qV/kT)$$

Reverse bias with $V << 0$

$$I \sim -I_0$$

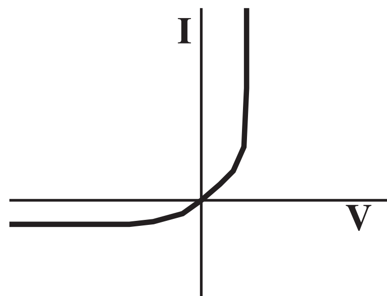
Note that the diode equation curve does not approach a turn-on voltage. Modifications are needed for this equation

FORWARD-BIAS MODIFICATIONS TO THE DIODE EQUATION

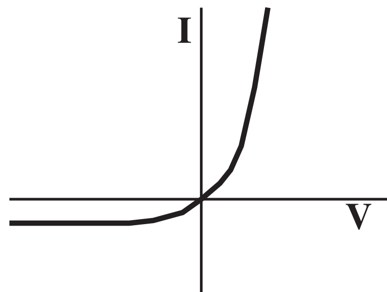
Diode Equation: $I = I_0 [\exp(qV/kT) - 1]$

Modifications for the diode equation to better represent the forward-bias diode current-voltage characteristic:

- Turn-on Voltage – As the applied voltage V approaches the internal contact potential V_0, the energy bands flatten and the depletion region approaches zero. V_0 is the limiting voltage for the theoretical junction.



- Ohmic Effects – As the current increases, additional factors must be considered. For instance, the resistance of the p-type and n-type regions away from the junction becomes significant. The overall voltage across the structure can be greater than V_0.



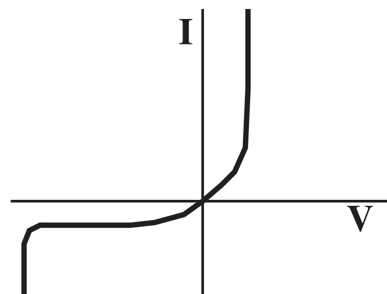
- Other modifications – Other improvements to the diode equation are possible, but these are beyond the scope of this class.

REVERSE-BIAS MODIFICATIONS TO THE DIODE EQUATION

Diode Equation: $I = I_0 [\exp(qV/kT) - 1]$

Modifications for the diode equation to better represent the reverse-bias diode current-voltage characteristic:

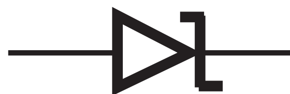
- Reverse Bias Breakdown – As a negative applied voltage V becomes larger in magnitude, physical mechanisms known as avalanche breakdown and tunneling occur. The magnitude of the current can increase greatly beyond a given voltage.



Reverse bias breakdown may be a device limitation or a useful effect. Some diodes are designed to operate with an abrupt breakdown.

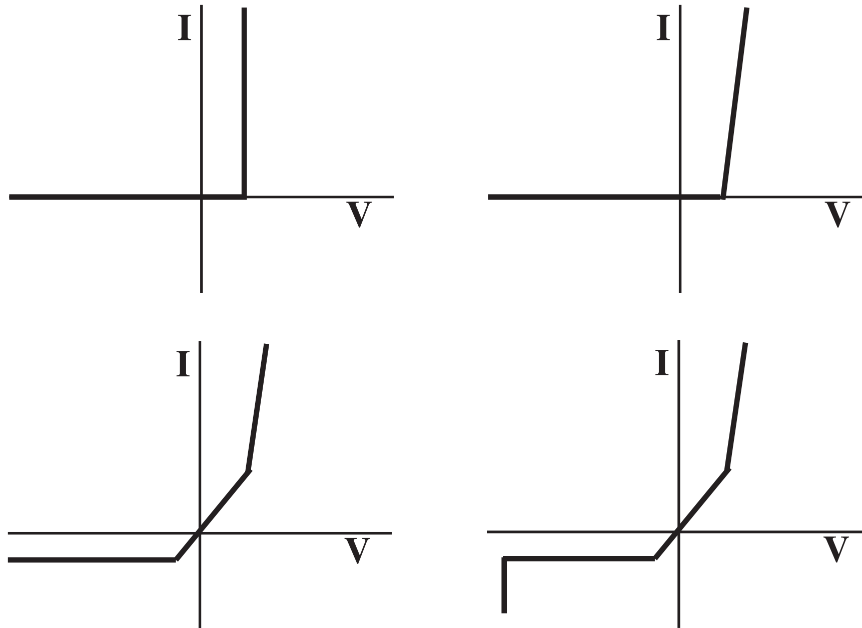
- Other modifications – Other improvements to the diode equation are possible, but these are beyond the scope of this class.

Diodes with intentional (and typically abrupt) breakdown characteristics may be represented with a special circuit symbol. The specific breakdown voltage is determined by the specific mechanism and the design structure.

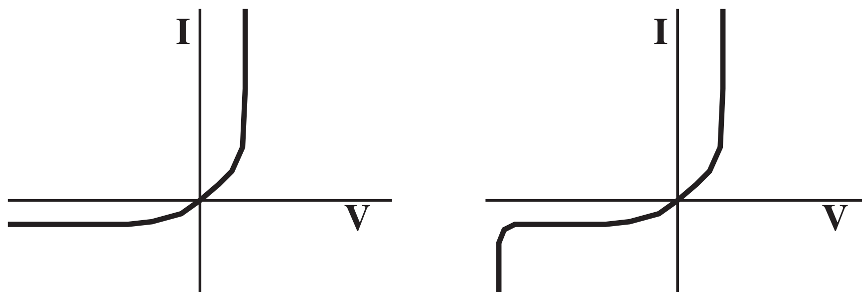


DIODE CIRCUIT MODELS

Simple Piecewise Equivalent Models – Linear approximations are sometimes used to represent the diode IV characteristics with varying degrees of accuracy. Straight lines over selected ranges may simplify an analysis.



For the purposes of this course, the following characteristics will be assumed.



- The IV characteristic near V = 0 V will be given by the diode equation
  $I = I_0 [\exp(qV/kT) - 1]$

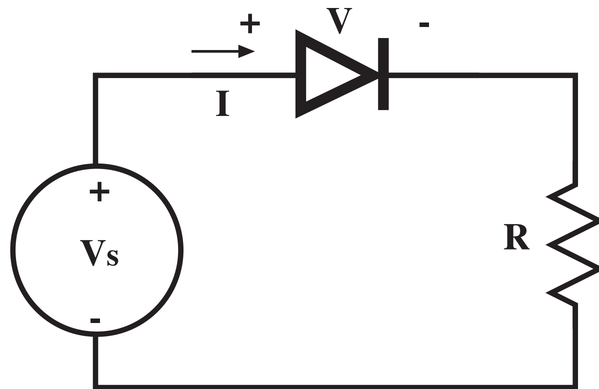
- The applied voltage V approaches an abrupt turn-on voltage.

- The reverse saturation current approaches a constant value of $-I_0$.

- The breakdown voltage, if present, is abrupt.

BASIC DIODE CIRCUIT

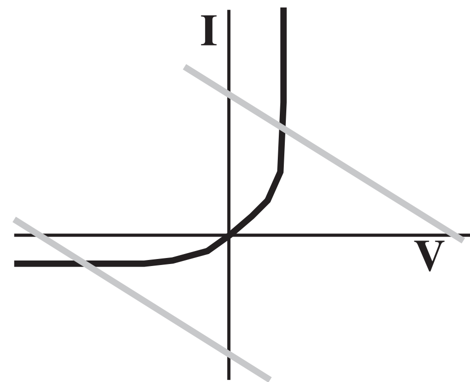
The circuit operation of a diode is illustrated in the following figure. Consider a diode with a turn-on voltage V_{to} and a reverse saturation current of I_0.



The current is shared by all of the circuit elements. KVL gives the load-line (LL) equation:

$$V = V_S - IR$$

The load-line equation and the nonlinear diode equation must be satisfied for the operating point simultaneously. Two possible graphical solutions are shown.



- Forward Bias (Positive V_S): If the operating V and I are away from the knee of the diode curve, the diode voltage is approximately $V = V_{to}$ and the current can be found by substituting V into the LL.
  $$I = (1/R)[V_S - (V_{to})]$$

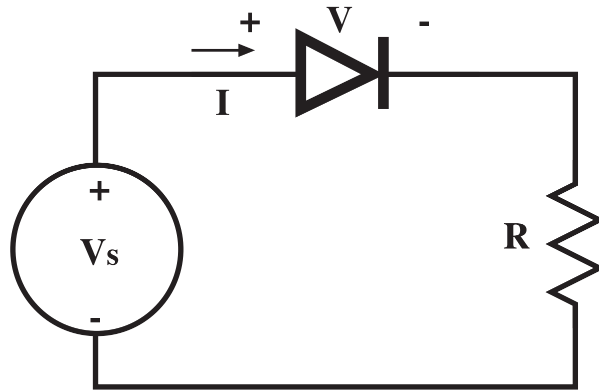
- Reverse Bias (Negative V_S): If the operating V and I are away from the knee of the diode curve, the diode current is approximately $I = - I_0$ and the voltage can be found by substituting I into the LL.
  $$V = V_S - (- I_0)R$$

Note that the intercepts of the load-line equation are:

$$I = 0 \text{ for } V = V_S \quad \text{and} \quad V = 0 \text{ for } I = V_S /R$$

BASIC BREAKDOWN DIODE CIRCUIT

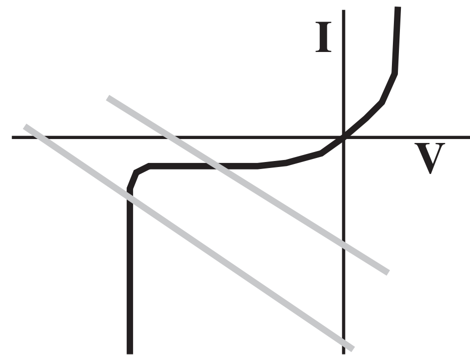
The circuit operation of a diode is illustrated in the following figure. Consider a breakdown diode with a turn-on voltage V_{to}, a reverse saturation current of I_0., and a breakdown voltage (reverse bias) of - V_{br}. .



The current is shared by all of the circuit elements for a KVL load-line (LL):

$$V = V_S - IR$$

The load-line equation and the nonlinear diode equation must be satisfied for the operating point simultaneously. Two possible graphical solutions are shown for reverse bias conditions.



- Reverse Bias (Negative V_S): If the operating V and I are between the knee of the diode curve and breakdown, the diode current is $I = - I_0$ and the voltage can be found by substituting I into the LL.
  $$V = V_S - (- I_0)R$$

- Reverse Bias Breakdown (Negative V_S): If the operating V and I are in the breakdown region, the diode voltage is approximately $V = - V_{br}$ and the current can be found by substituting I into the LL.
  $$I = (1/R)[V_S - (-V_{br})]$$

Again the intercepts of the load-line equation are:

$$I = 0 \text{ for } V = V_S \quad \text{and} \quad V = 0 \text{ for } I = V_S /R$$

DIODE AS A CLIPPER OR LIMITER

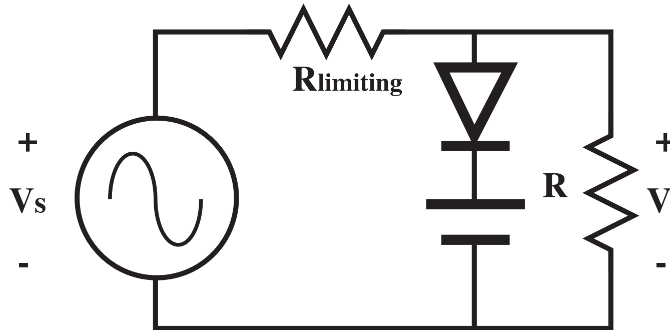
Consider a diode with a turn-on voltage V_{to} and a reverse saturation current of I_0. Assume that the constant source in series with the diode is V_P.

Diode is "on" for

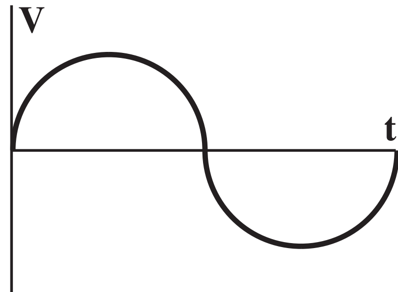
$V = V_{to} + V_P$

Diode is "off" for

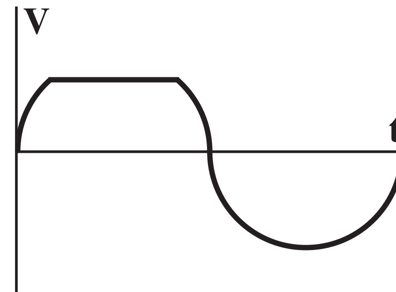
$V < V_{to} + V_P$



Output w/o Diode & Source



Desired Output Voltage

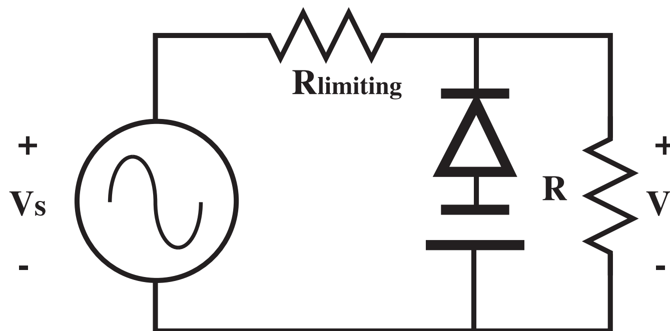


Diode is "on" for

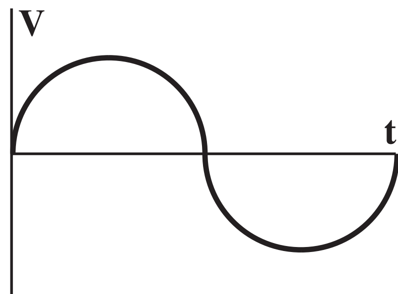
$V = -(V_{to} + V_P)$

Diode is "off" for

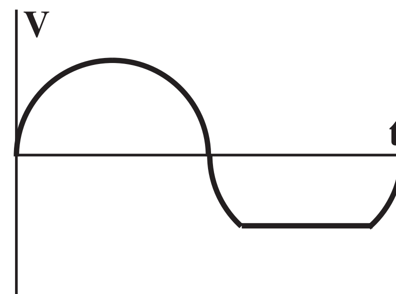
$V > -(V_{to} + V_P)$



Output w/o Diode & Source



Desired Output Voltage

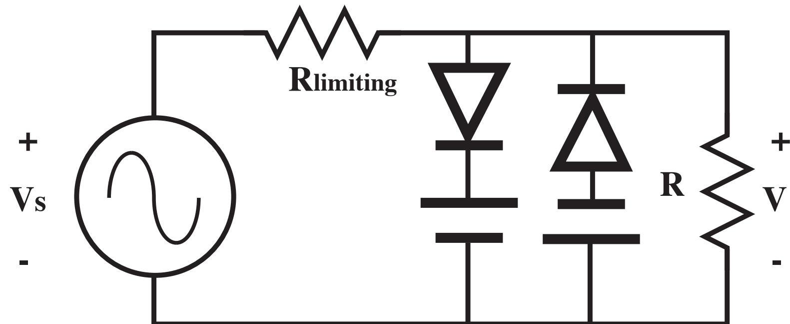


DIODE AS A DOUBLE CLIPPER OR LIMITER

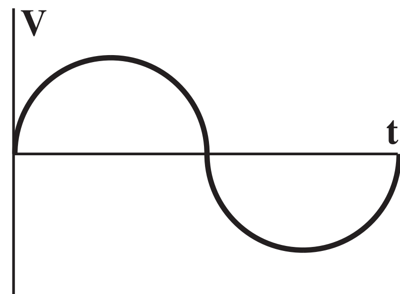
Consider diodes with a turn-on voltage V_{to} and reverse saturation currents of I_0. Assume that the constant sources in series with the diodes are V_P.

A diode is "on" for
$|V| = |V_{to} + V_P|$

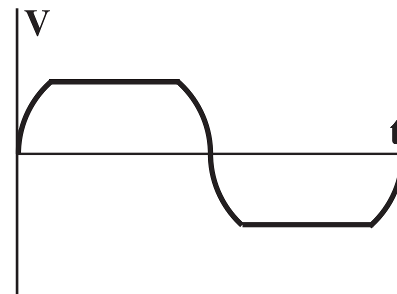
Both diodes are "off" for
$|V| < |V_{to} + V_P|$



Output w/o Diode & Source



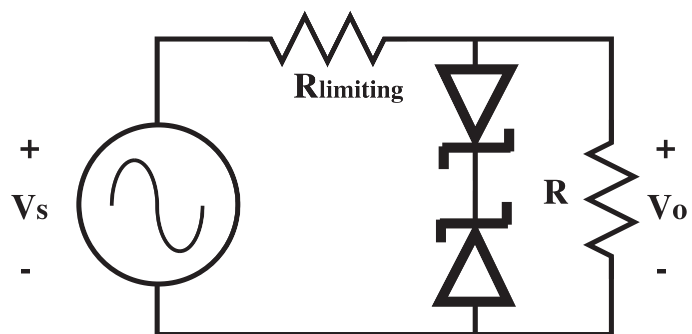
Desired Output Voltage



Similar clipping behavior is obtained using two breakdown diodes with a breakdown voltage of $V = - V_{br}$.

One diode is "on" and one diode is in breakdown for
$|V| = |V_{to} + V_{br}|$

Both diodes are "off" for
$|V| < |V_{to} + V_{br}|$

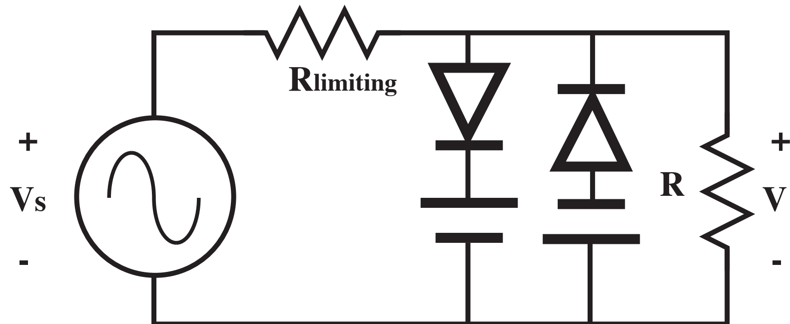


DOUBLE CLIPPER OR LIMITER EXAMPLE

Consider diodes with a turn-on voltage V_{to} and reverse saturation currents of I_0. Assume that the constant sources in series with the diodes are V_P.

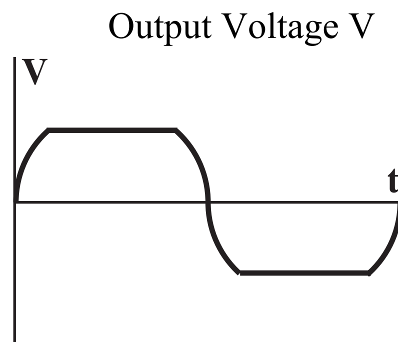
A diode is "on" for
$|V| = |V_{to} + V_P|$

Both diodes are "off" for
$|V| < |V_{to} + V_P|$



Consider a sinusoid source with
$|V_{S,Max}| > |V_{to} + V_P|$.

Output Voltage V

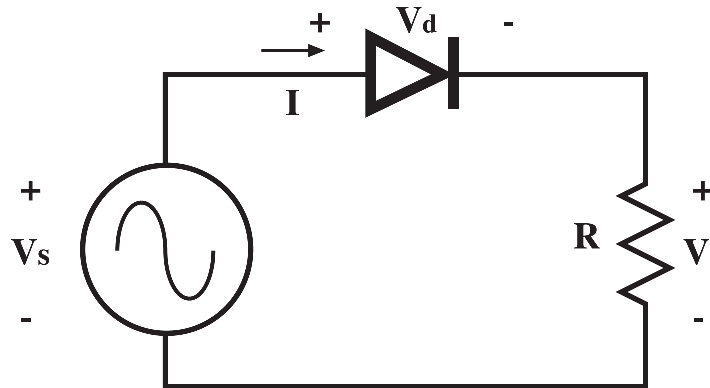


- Maximum Voltage V: For $V_S = V_{S,Max}$, one diode (diode A) is forward biased and the other (diode B) is reverse biased. Hence, diode A has a voltage $V_{d,A} = V_{to,A}$ and the output voltage $V = V_{to,A} + V_{P,A}$. Diode B has a current $I_{d,B} = - I_{0.B}$. The output voltage and current are
  $V = V_{to,A} + V_{P,A}$ and $I = V/R = (V_{to,A} + V_{P,A})/R$.
  Note that the diode A current is found from KCL at the node
  $(V – V_{S,Max})/R_{Limiting} + I_{d,A} – (-I_{0,B}) +V/R = 0$ or
  $I_{d,A} = – (V – V_{S,Max})/R_{Limiting} + (-I_{0,B}) – V/R$

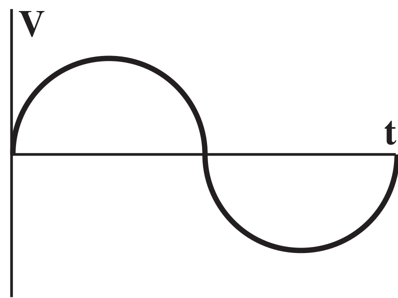
- Minimum Voltage V: For $V_S = – V_{S,Max}$, diode A is reverse biased and diode B is forward biased. Hence, diode A current $I_{d,A} = - I_{0.A}$. Diode B voltage $V_{d,A} = V_{to,A}$ and the output voltage $V = – (V_{to,B} + V_{P,B})$. The output voltage and current are
  $V = – (V_{to,A} + V_{P,A})$ and $I = V/R = – (V_{to,A} + V_{P,A})/R$.
  Note that the diode B current is found from KCL at the node
  $(V – V_{S,Max})/R_{Limiting} - I_{d,B} + (-I_{0,B}) +V/R = 0$ or
  $I_{d,B} = + [V – (-V_{S,Max})]/R_{Limiting} + (-I_{0,A}) + V/R$

DIODE AS A HALF-WAVE RECTIFIER

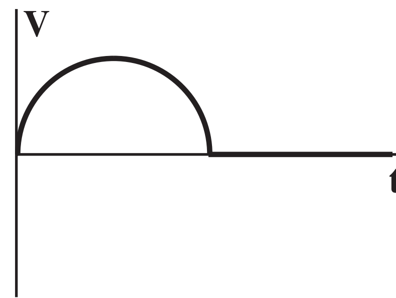
Consider a diode with a turn-on voltage V_{to} and a reverse saturation current of I_0.



Output w/o Diode

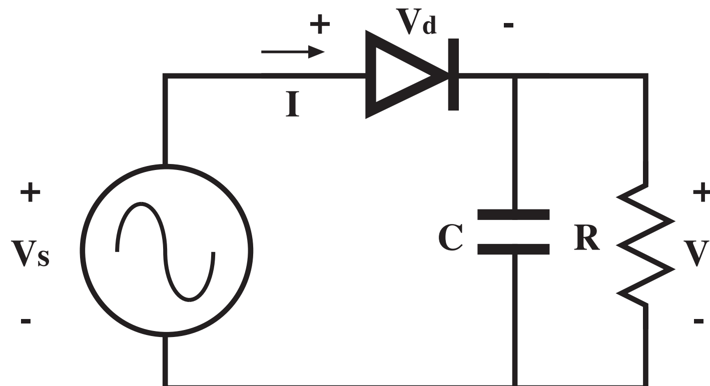


Desired Output Voltage



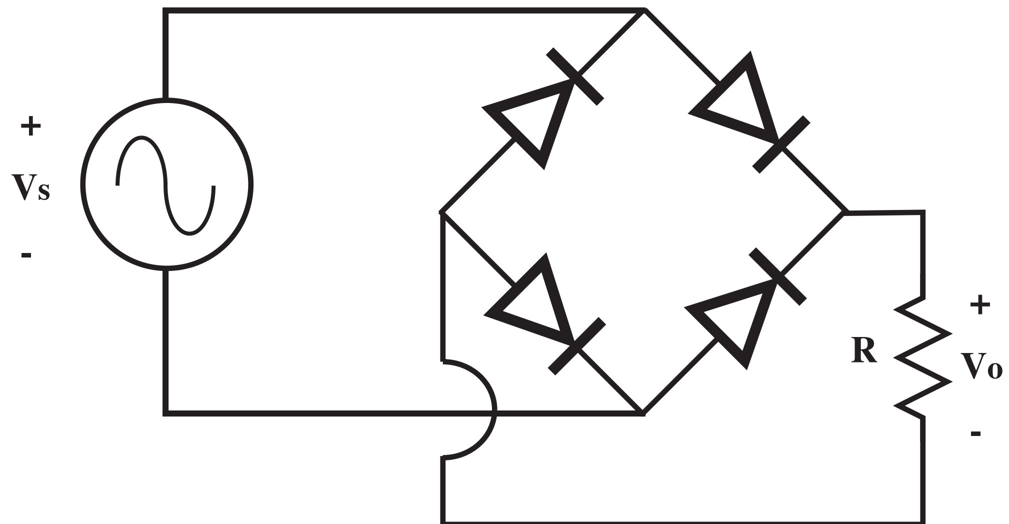
Diode is "on" when $V_S > V_{to}$, then $V = V_S - V_{to}$.
Diode is "off" when $V_S < V_{to}$. Furthermore, if the diode is reverse biased away from the diode knee, then $V = - I_0R$. Note that the effect of reverse saturation current is that the output voltage is not zero during the "off" part of the cycle.

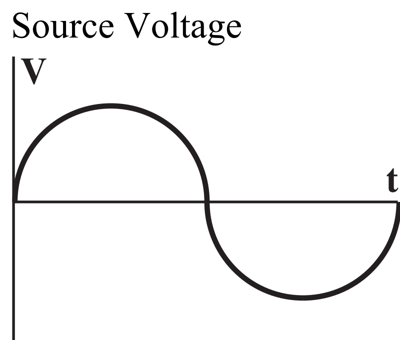
Consider the effect of placing a capacitor in parallel to the resistance R.

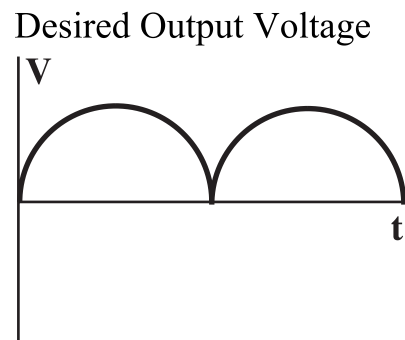


DIODE AS A FULL-WAVE RECTIFIER

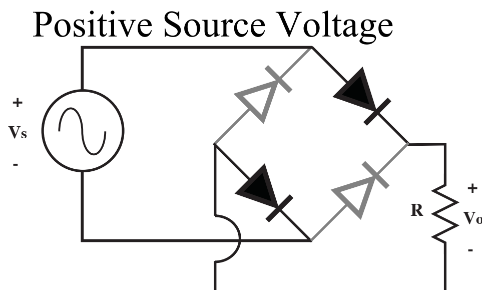
Consider diodes with turn-on voltage V_{to} and reverse saturation current of I_0.

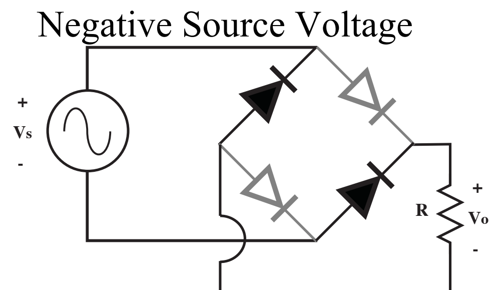






Diode is "on" when $V_S > 2V_{to}$, then $V = V_S - 2V_{to}$. (Diodes Highlighted)
Diode is "off" when $V_S < 2V_{to}$. (Diodes Shaded)



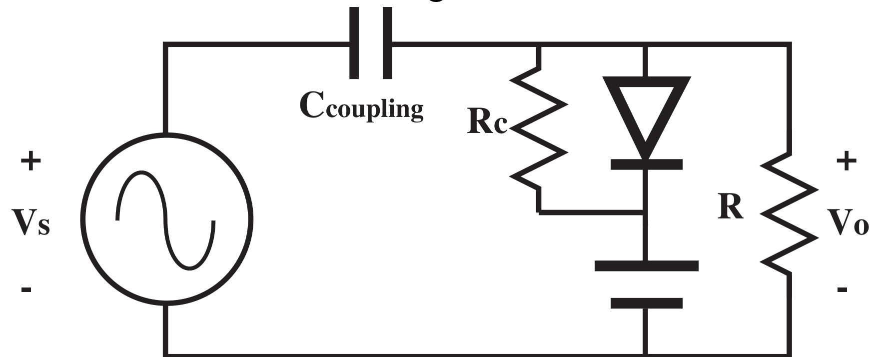


Consider the effect of the reverse saturation current.

Consider the effect of placing a capacitor in parallel to the resistance R.

OTHER DIODE CIRCUITS

Diode Clamping Circuit: The circuit serves to adjust the peak level of the input voltage to match the constant voltage V_P.



Diode Logic Circuits: The circuits are an OR gate and an AND gate, respectively