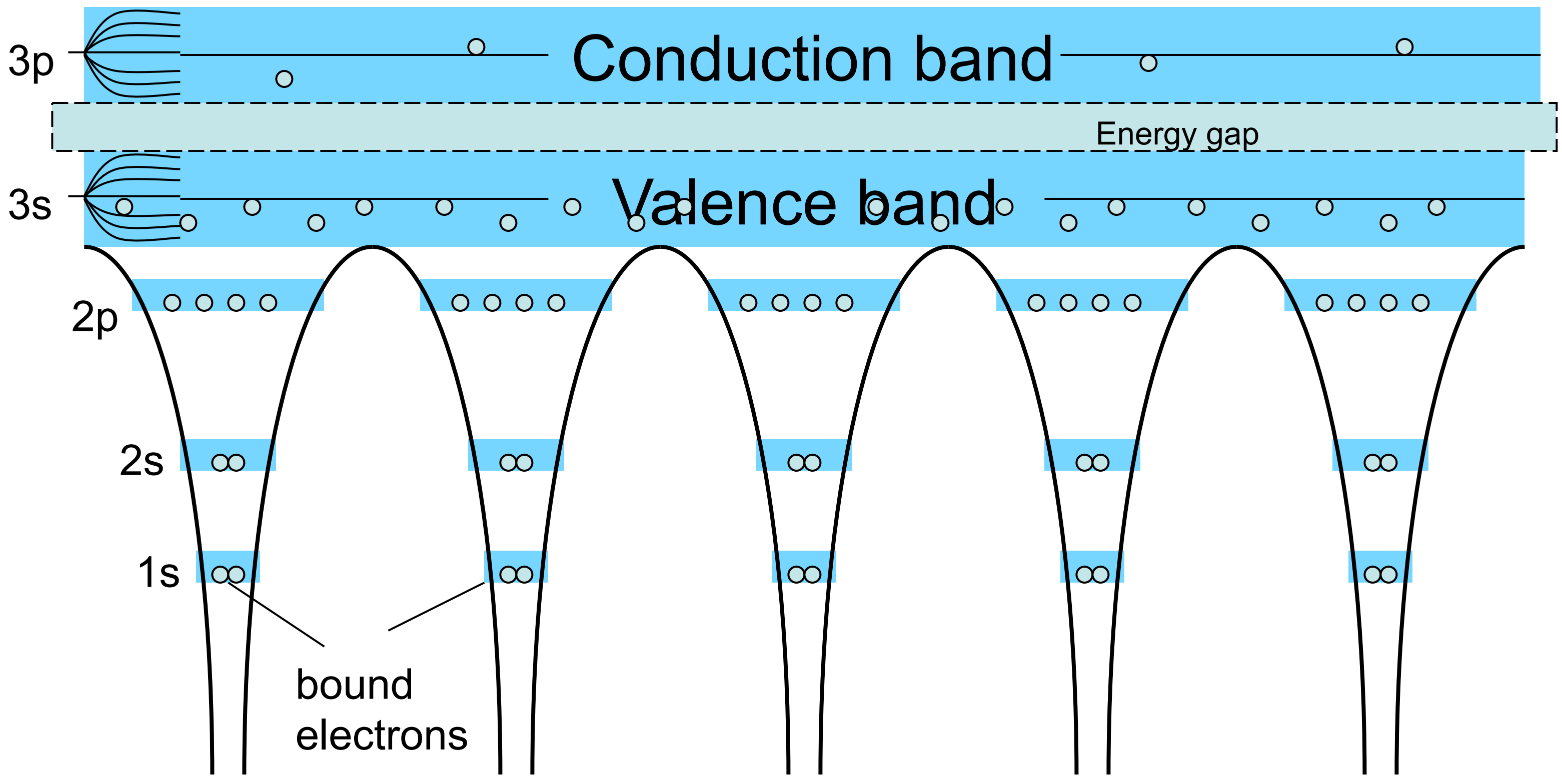
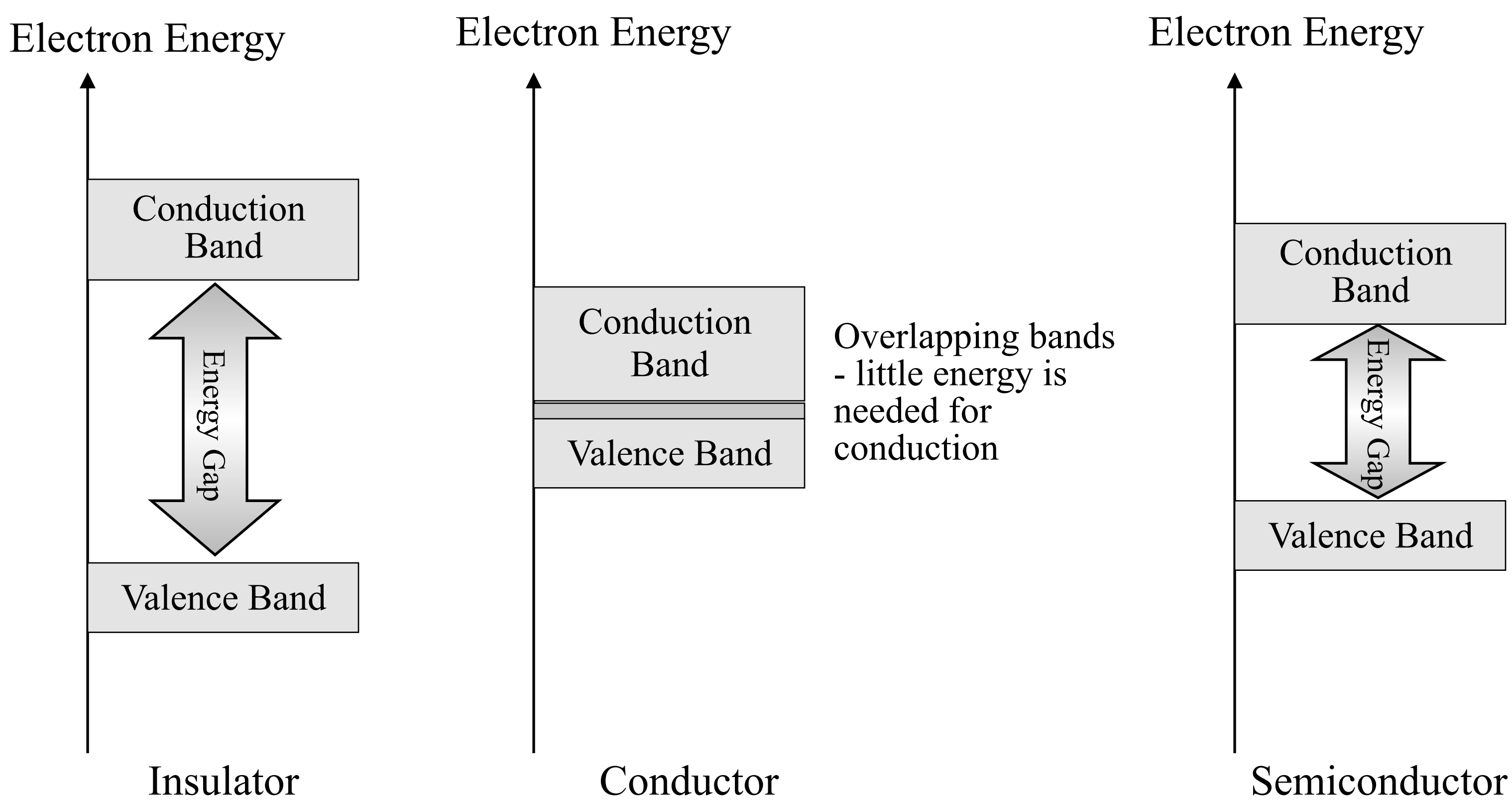
Chapter-5: Introduction to Semi-Conductors and Diode Circuits



When atoms form a crystalline structure (metals, semiconductors,) the valence electrons loose their attraction to a local atom and form an band of ~equivalent charges- **valence band**. The **conduction band** lies within or above the valence band.

Energy Bands



Transition Metals

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1 1.008 H Hydrogen																	2 4.0026 He Helium
3 6.939 Li Lithium	4 9.012 Be Beryllium											5 10.811 B Boron	6 12.011 C Carbon	7 14.007 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Florine	10 20.183 Ne Neon
11 22.989 Na Sodium	12 24.312 Mg Magnesium											13 26.981 Al Aluminum	14 28.086 Si Silicon	15 30.974 P Phosphorus	16 32.064 S Sulfur	17 35.453 Cl Chlorine	18 39.948 Ar Argon
19 39.102 K Potassium	20 40.08 Ca Calcium	21 44.956 Sc Scandium	22 47.90 Ti Titanium	23 50.942 V Vanadium	24 51.996 Cr Chromium	25 54.938 Mn Manganese	26 55.847 Fe Iron	27 58.933 Co Cobalt	28 58.71 Ni Nickel	29 63.54 Cu Copper	30 65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.922 As Arsenic	34 78.96 Se Selenium	35 79.909 Br Bromine	36 83.80 Kr Krypton
37 85.47 Rb Rubidium	38 87.62 Sr Strontium	39 88.905 Y Yttrium	40 91.22 Zr Zirconium	41 92.906 Nb Niobium	42 95.94 Mo Molybde-num	43 99 Tc Technitium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.4 Pd Palladium	47 107.87 Ag Silver	48 112.40 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony	52 127.60 Te Tellurium	53 126.904 I Iodine	54 131.30 Xe Xenon
55 132.90 Cs Cesium	56 137.34 Ba Barium	57 138.91 La Lanthanum	72 178.49 Hf Hafnium	73 180.95 Ta Tantalum	74 183.85 W Tungsten	75 186.2 Re Rhenium	76 190.2 Os Osmium	77 192.2 Ir Iridium	78 195.09 Pt Platinum	79 196.967 Au Gold	80 200.59 Hg Mercury	81 204.37 Tl Thallium	82 207.19 Pb Lead	83 208.98 Bi Bismuth	84 210 Po Polonium	85 210 At Astatine	86 222 Rn Radon
87 223 Fr Francium	88 226 Ra Radium	89 227 Ac Actinium	104 Rf	105 Ha	106 Sg	107 Uns	108 Uno	109 Une	110 Uun								

Nonmetals

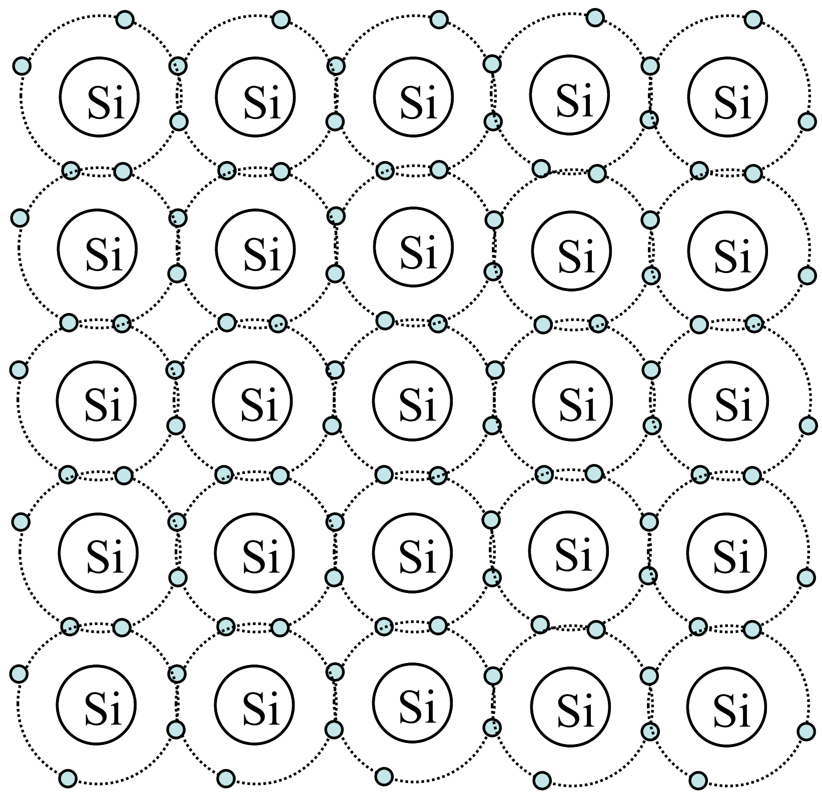
Metalloids (semimetals)

Lanthanides	58 140.12 Ce Cerium	59 140.91 Pr Praseodym-ium	60 144.24 Nd Neodym-ium	61 147 Pm Prome-thium	62 150.35 Sm Samarium	63 151.96 Eu Europium	64 157.25 Gd Gadolin-ium	65 158.92 Tb Terbium	66 162.50 Dy Dyspro-sium	67 164.93 Ho Holmium	68 167.26 Er Erbium	69 168.93 Tm Thulium	70 173.04 Yb Ytterbium	71 174.97 Lu Lutetium
Actinides	90 232.04 Th Thorium	91 231 Pa Procat-inium	92 238.03 U Uranium	93 237 Np Neptunium	94 242 Pu Plutonium	95 243 Am Americium	96 247 Cm Curium	97 247 Bk Berkelium	98 249 Cf Califor-nium	99 254 Es Einstein-ium	100 253 Fm Fermium	101 256 Md Mendelev-ium	102 253 No Nobelium	103 257 Lr Lawren-cium

Group IVA Elemental Semiconductors

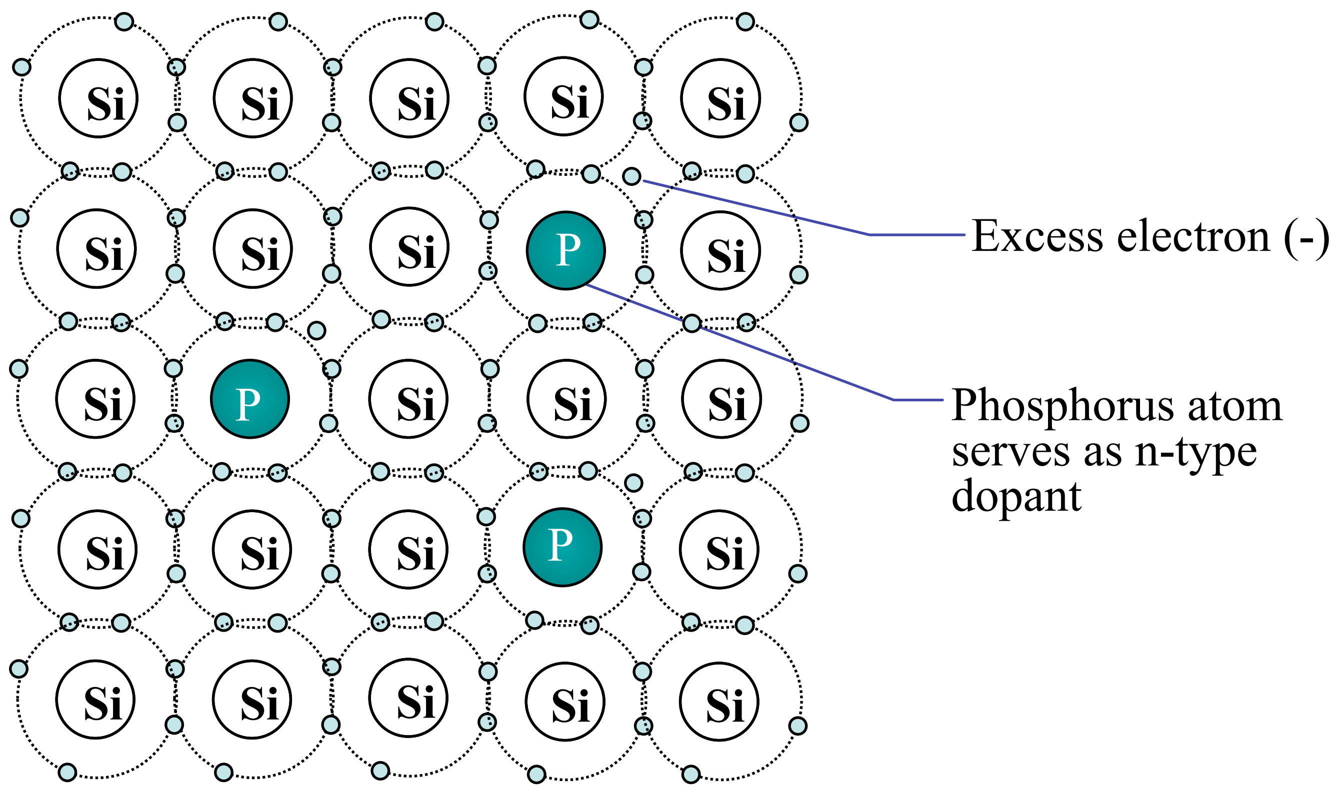
Carbon	C	6	•Very Expensive **diamond** •Band Gap Large: 6V •Difficult to produce without high contamination
Silicon	Si	14	•Cheap •Ultra High Purity •Oxide is amazingly perfect for IC applications
Germanium	Ge	32	•High Mobility (good) •High Purity Material (good) •Oxide is porous to water/hydrogen (disasterous!)
Tin	Sn	50	•Only "White Tin" is semiconductor •Converts to metallic form under moderate heat
Lead	Pb	82	•Only "White Lead" is semiconductor •Converts to metallic form under moderate heat

Covalent Bonding of Pure Silicon



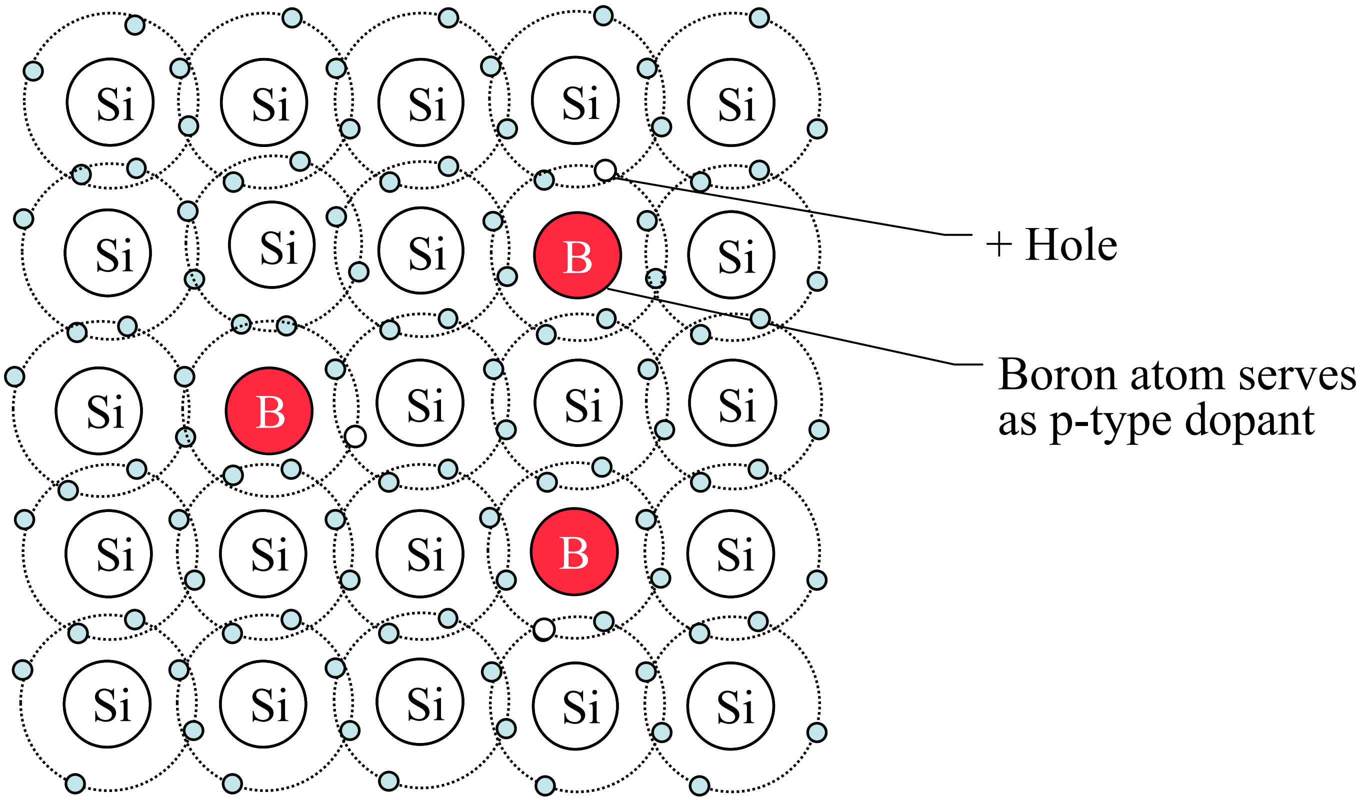
Silicon atoms share valence electrons
to form insulator-like bonds.

Electrons in N-Type Silicon with Phosphorus Dopant



Donor atoms provide excess electrons to form n-type silicon.

Holes in p-Type Silicon with Boron Dopant

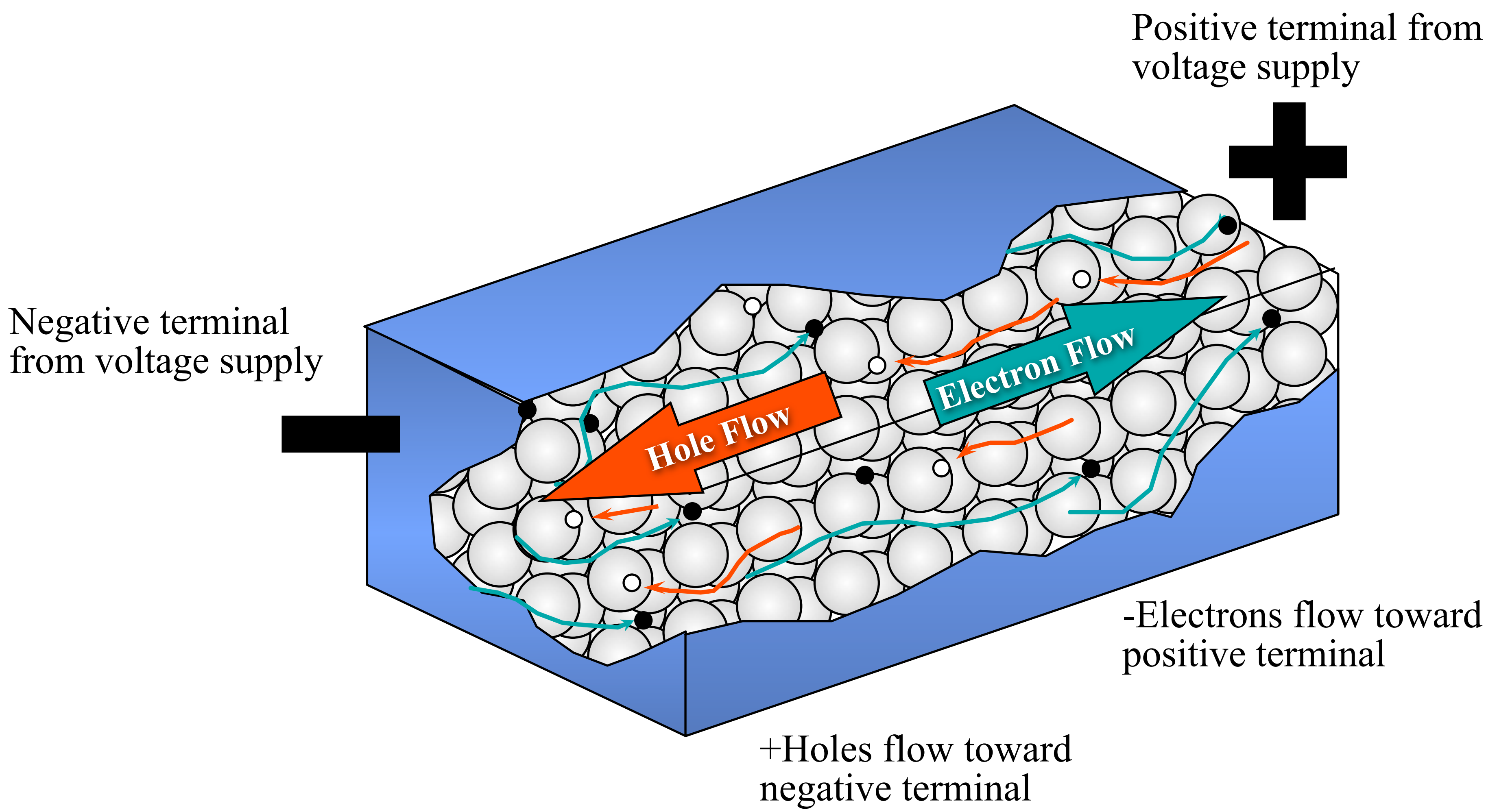


Acceptor atoms provide a deficiency of electrons to form p-type silicon.

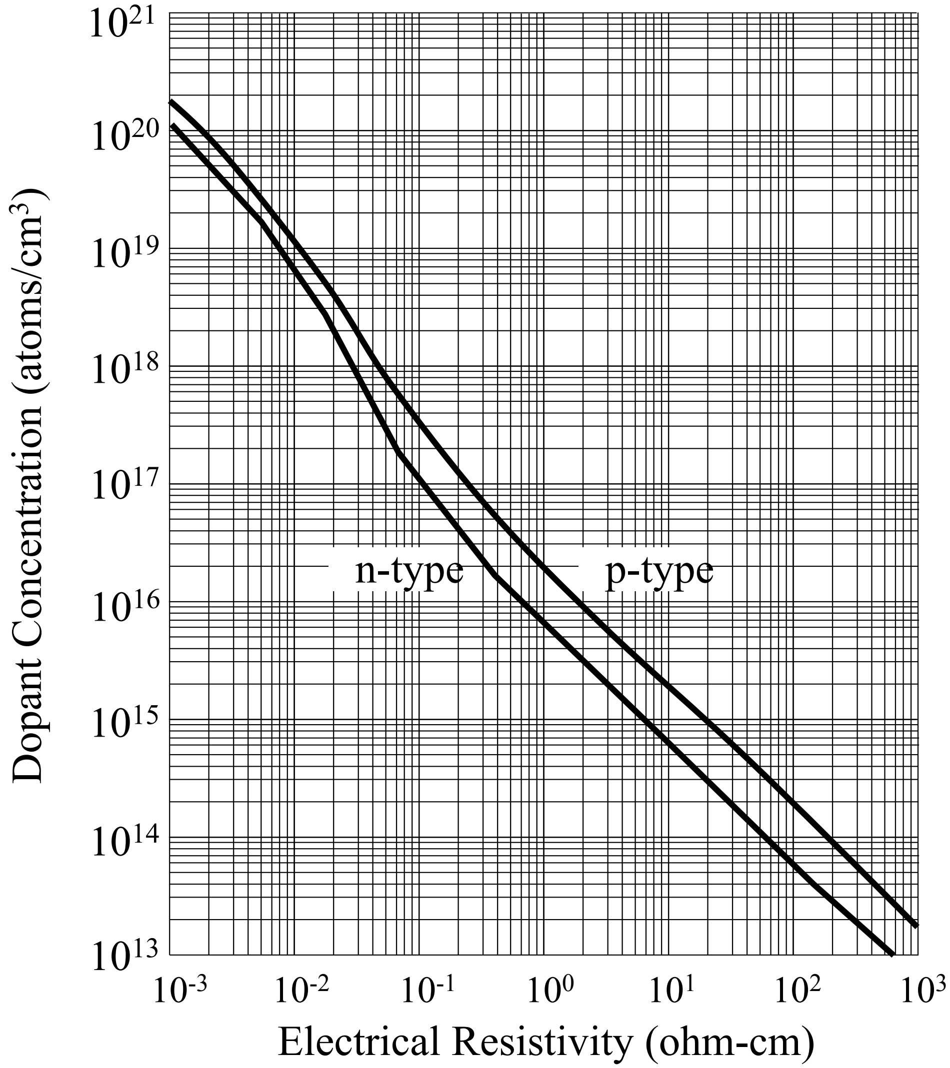
Silicon Dopants

Acceptor Impurities	Semiconductor	Donor Impurities
Group III (p-type)	**Group IV**	**Group V (n-type)**
Boron 5	Carbon 6	***Nitrogen 7***
Aluminum 13	**Silicon 14**	**Phosphorus 15**
Gallium 31	Germanium 32	**Arsenic 33**
Indium 49		Antimony 51

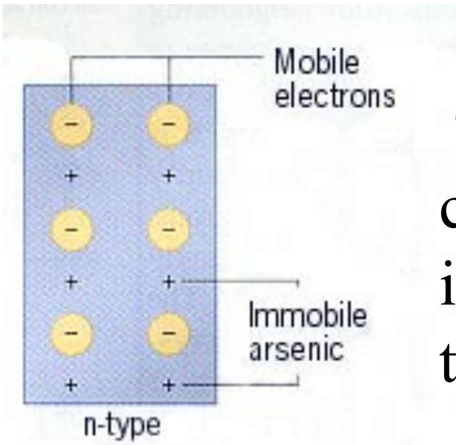
Conduction in n and p-Type Silicon



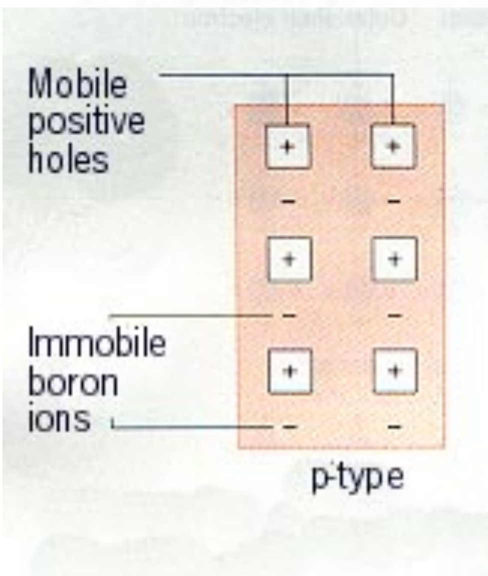
Silicon Resistivity Versus Dopant Concentration



n- and p-Type Silicon



The dominant charge carrier in n-type Si is the electron.



The dominant charge carrier in p-type Si is the hole

Important Facts:

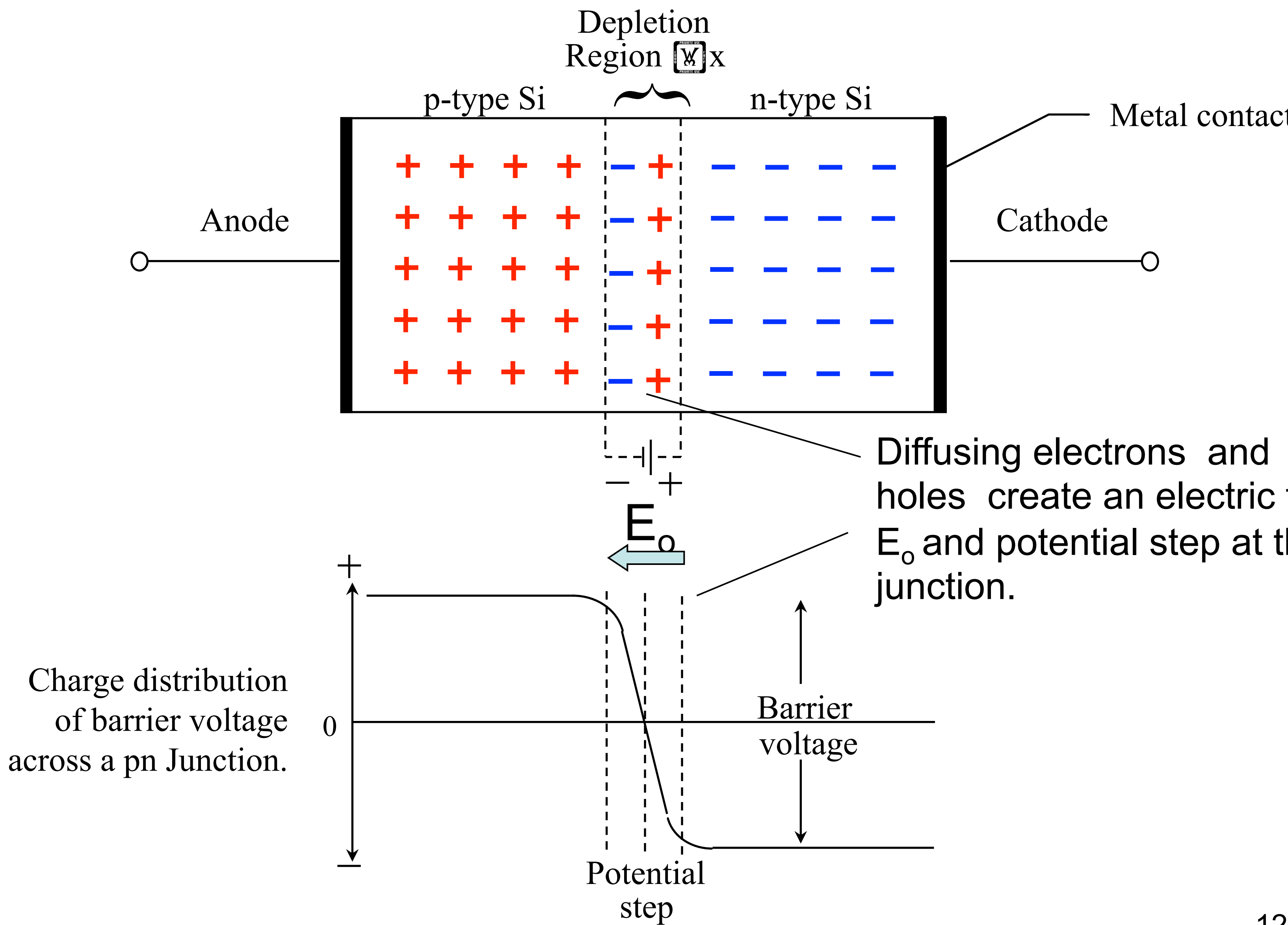
Not shown are the silicon atoms, which are present in vastly greater numbers than either arsenic or boron.

Typical doping concentrations are 10^{16} arsenic or boron atoms per cm^3.

The concentration of silicon atoms is about 10^{22} atoms per cm^3.

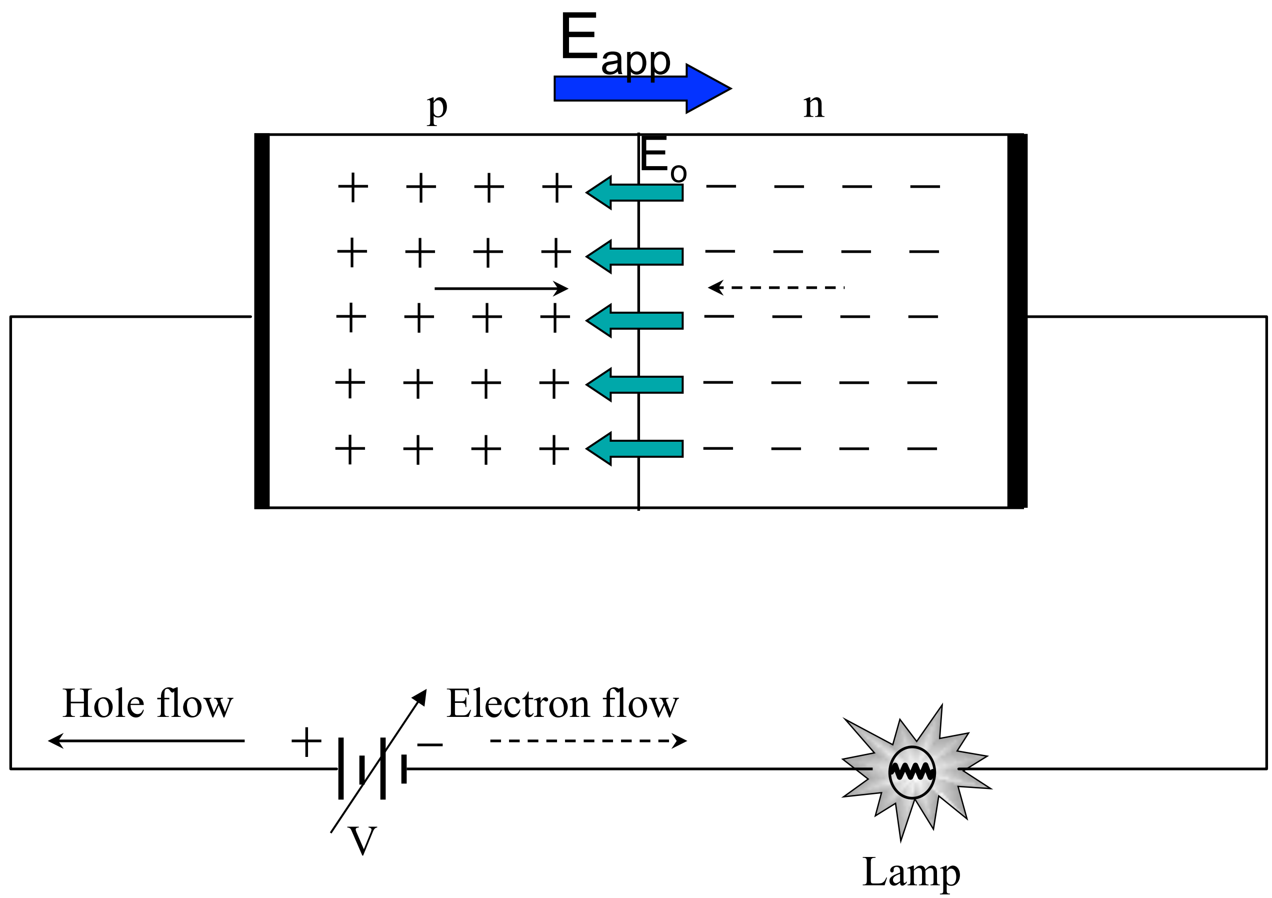
For every "dopant" atom, there are about a million silicon atoms.

Open-Circuit Condition of a p-n Junction Diode



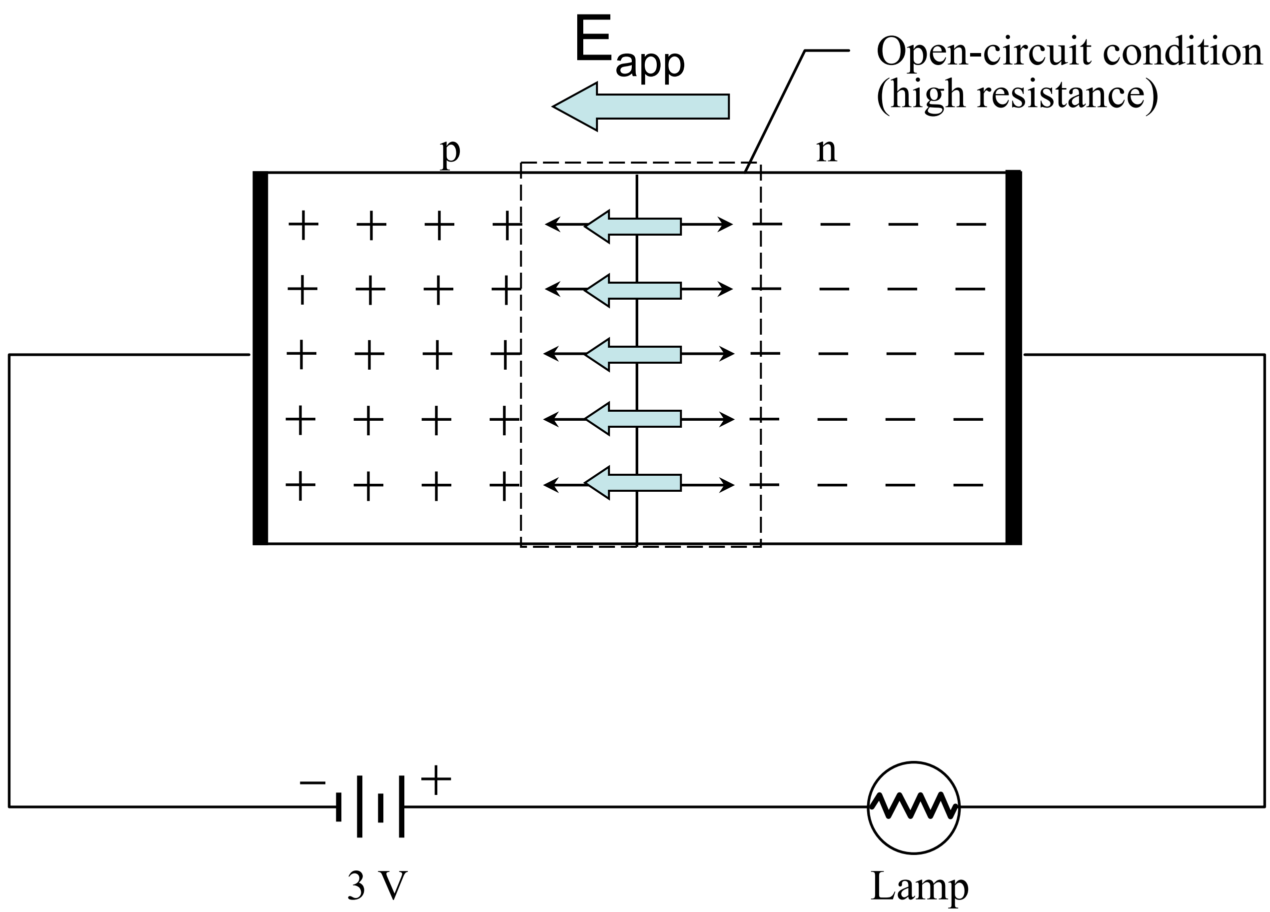
Diffusing electrons and holes create an electric field E_o and potential step at the junction.

Forward-Biased PN Junction Diode



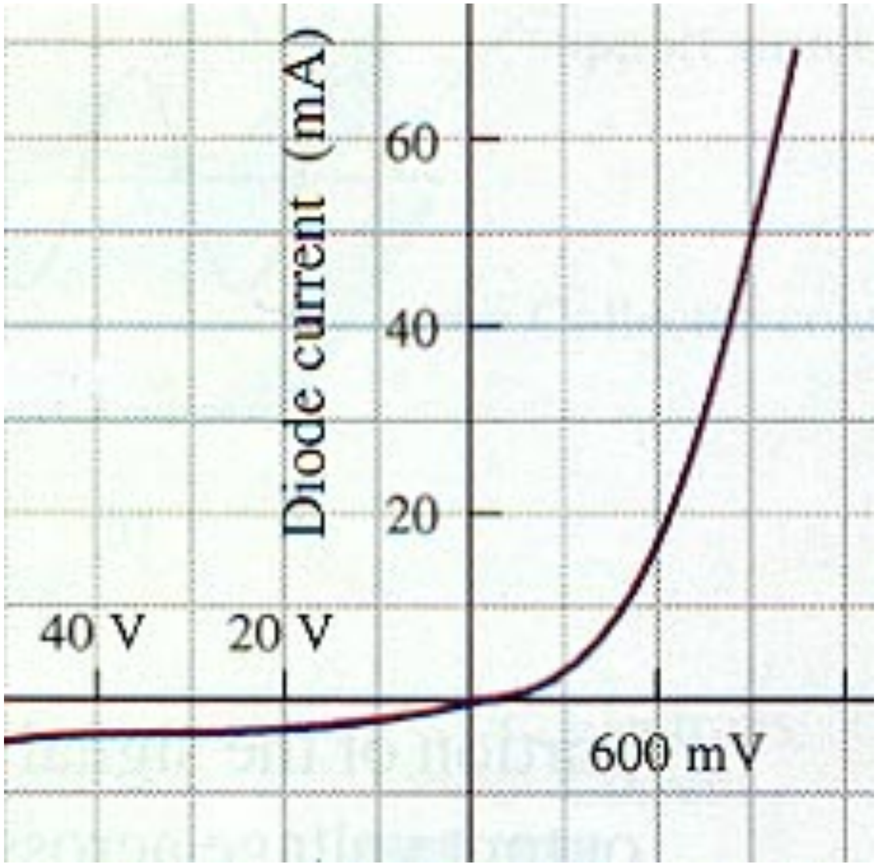
In **forward bias** the applied E-field cancels internal electric field and charges begin flowing across the junction when $E_{app} > E_o$ or $V_{app} > \sim 0.6V$.

Reverse-Biased PN Junction Diode



In the **reverse bias** the external E-field increases the size of the depletion zone until all charge carries are near the contacts - **fully depleted**.

I-V Characteristic Curve



Reverse current exaggerated; typical reverse saturation current: $I_S \sim 10^{-(6-12)}$A.

This is the "characteristic" curve of a pn junction diode. It shows the slow, then abrupt, rise of current as the voltage is raised.

Under reverse bias, even very large voltages will cause only very small currents, essentially *constant* reverse bias currents.

Shockley Diode Law (Ideal)

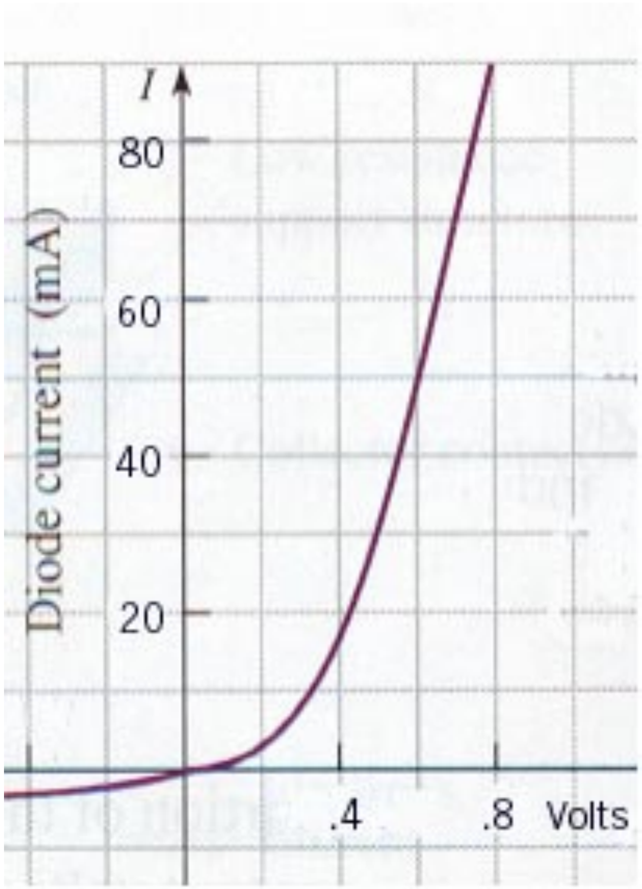
$$I = I_S(e^{+eV_D/kT} - 1) \sim I_S \ e^{+eV_D/kT}$$

$$I_S = reverse\ bias\ saturation\ current$$

$$V_D = diode\ voltage$$

$$kT = 0.025eV\ at\ 300^o K$$

Turn-On Voltage



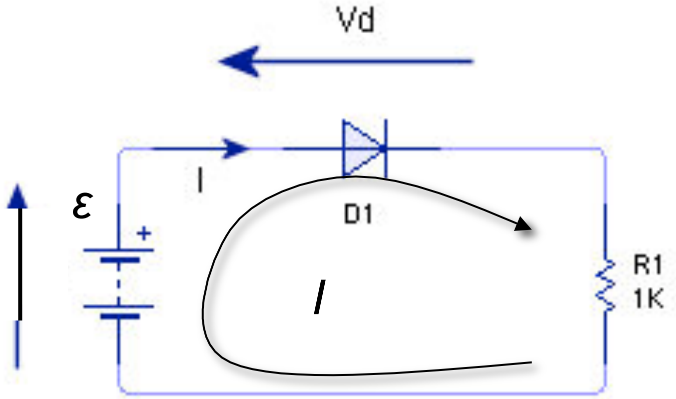
A pn junction diode "turns on" at about 0.6 V, but that varies according to the doping concentration, diode type.

Notice the sharp rise in current near the turn-on voltage. This behavior will be exploited later in the construction of the transistor amplifier.

$Use\ the\ Shockley\ Equation\ to\ \det er\min e\ the\ \ forward\ \ diode\ current\ \ V_D = 1\ V\ \ T = 300^0 K\ \ and\ \ I_S = 10\,pA.$

$I = 10\,pA\ \exp(1eV / 0.025eV) = \ 2.4e9A$!!

Solving Diode Equation by Iteration

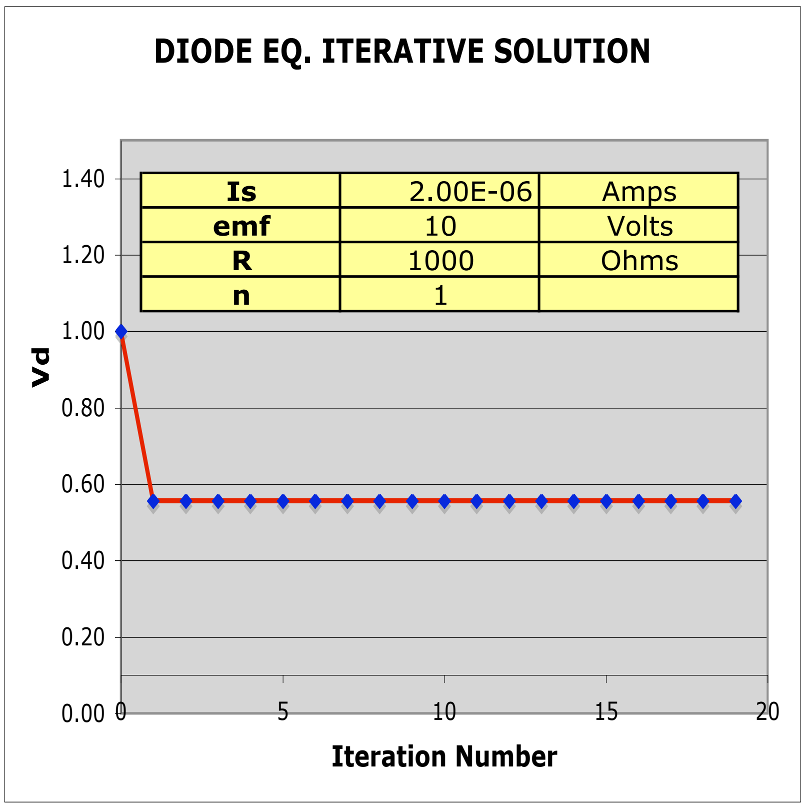


$$\varepsilon - V_d - IR = 0 \qquad \textit{Kirchhoff's law}$$

$$I = \frac{\varepsilon - V_d}{R} = I_S\left(e^{eV_d/nkT} - 1\right) \qquad n \equiv \textit{diode realty factor } n \sim 1.5$$

$$\frac{eV_d}{nkT} = \ln\left(\frac{I}{I_S} + 1\right)$$

$$V_d = \left(\frac{n}{e}\right) kT \ln\left(\frac{\varepsilon - V_d}{I_S R} + 1\right) \qquad \textit{Solve by iteration}$$



Is	2.00E-06	Amps
emf	10	Volts
R	1000	Ohms
n	1	

$$V_d^{(1)} = \left(\frac{n}{e}\right) kT \ln\left(\frac{\varepsilon - V_d^{(0)}}{I_S R} + 1\right)$$

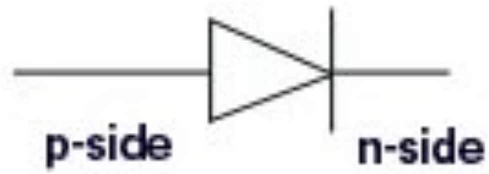
$$V_d^{(2)} = \left(\frac{n}{e}\right) kT \ln\left(\frac{\varepsilon - V_d^{(1)}}{I_S R} + 1\right)$$

.

$$\textit{Stop when } V_d^{(N+1)} \sim V_d^{(N)}$$

http://en.wikipedia.org/wiki/Diode_modelling#Shockley_diode_model

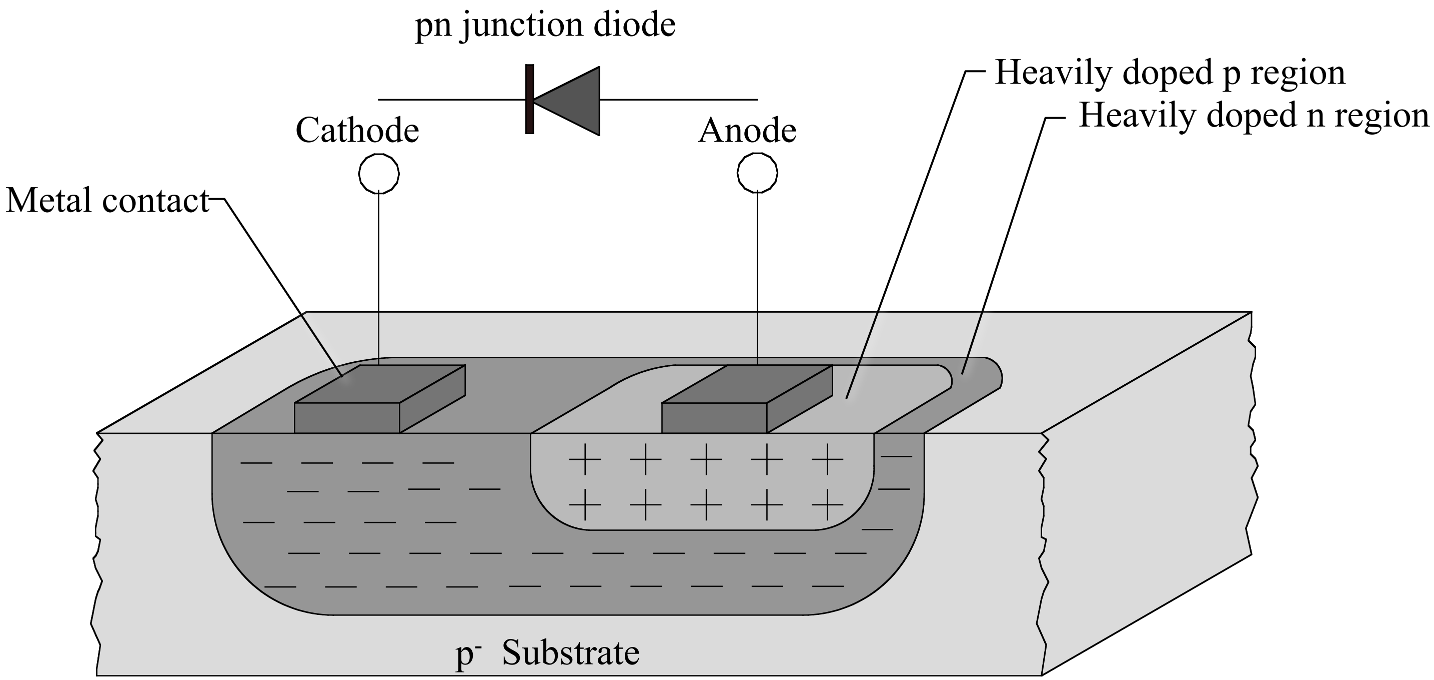
A PN Junction Diode and Its Symbol



Black band corresponds to the "point" in the diode symbol on the right.

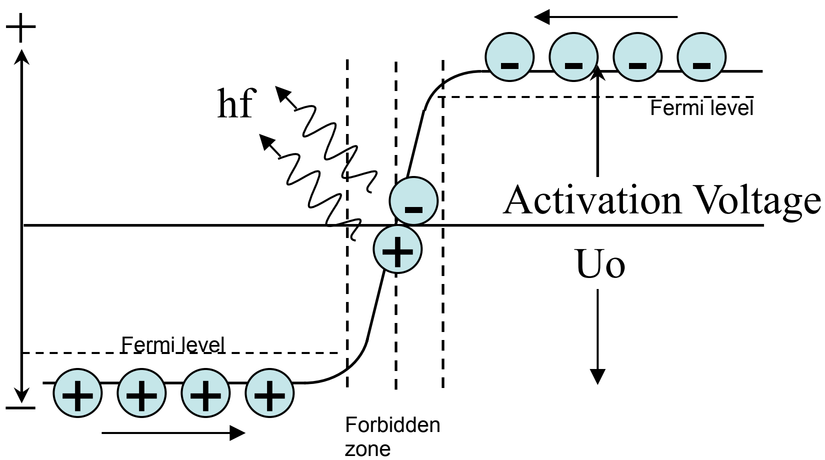
It points as "point" is spelled, with "p" first, and"n" later.

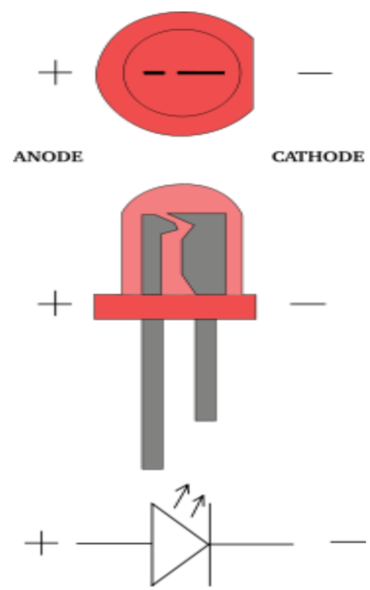
Basic Symbol and Structure of the pn Junction Diode



Light Emitting Diodes

As electrons and holes pass thru the forward biased junction, some annihilate and release hf = eUo of activation energy in to light.





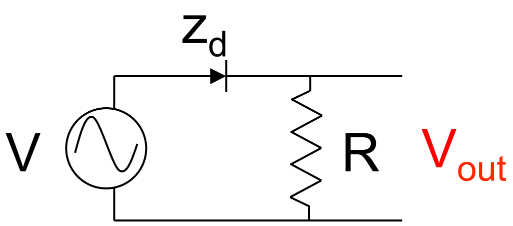
Activation Energy

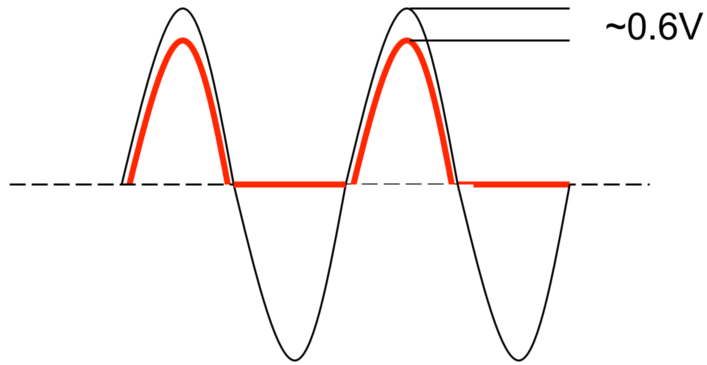
Color	Potential Difference (Vf)
Infrared	1.6 V
Red	1.8 V to 2.1 V
Orange	2.2 V
Yellow	2.4 V
Green	2.6 V
Blue	3.0 V to 3.5 V
White	3.0 V to 3.5 V
Ultraviolet	3.5 V

$E = hc/\lambda = 1240$ eV-nm / λ(nm)

Red light of 650nm would correspond to Uo = 1240/650 eV = 1.9 eV

Simple Diode Circuit

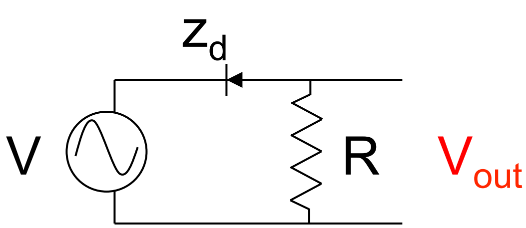


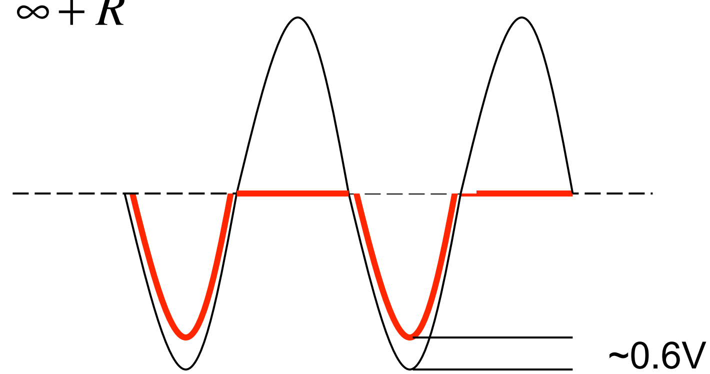


$$V_{diode} \simeq 0.6V$$

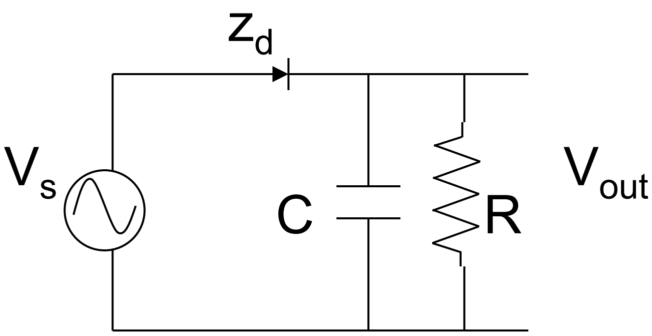
$$V > V_{diode} \qquad z_d = r \;\; and \;\; V_{OUT} = (\frac{R}{r+R})V = (\frac{1}{1+r/R})V \simeq (1 - r/R)\; V \simeq V - V_{diode}$$

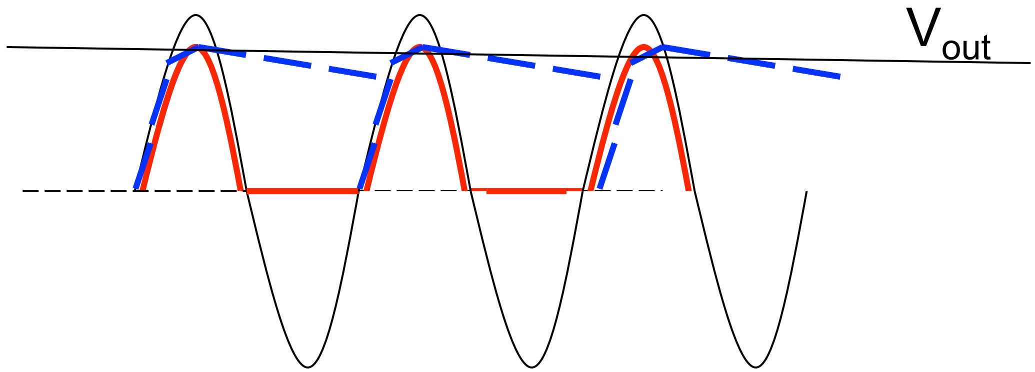
$$V < V_{diode} \qquad z_d = \infty \;\; and \;\; V_{OUT} = (\frac{R}{\infty + R})V = 0$$





Half Wave Rectifier - AC-to-DC Conversion





AC - DC Converter

Capacitor charges to peak voltage $V_{OUT} \sim V_S - 0.6V$

Voltage decays on down-cycle $V_{OUT} = V_S\ e^{-t/RC}$

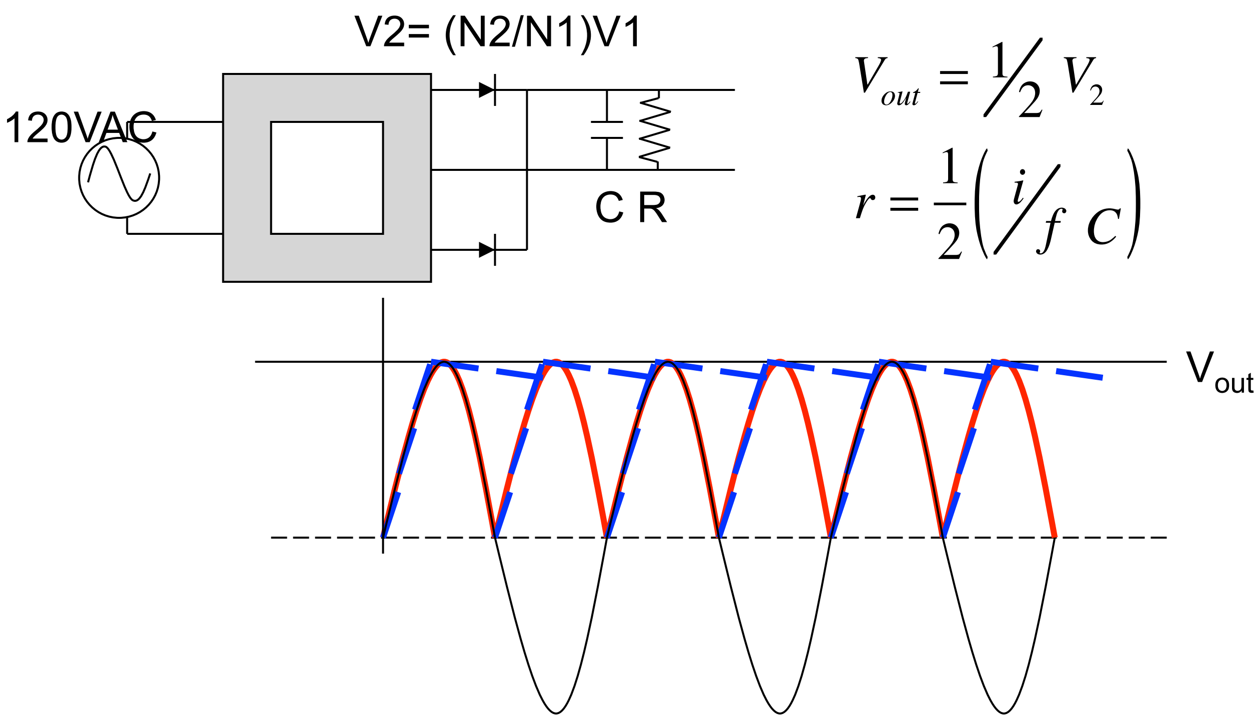
$$V_{OUT}(t) = V_S\ (1 - t/RC + \ldots\quad) \qquad t/RC << 1$$

$$\Delta V = V_{OUT}(t) - V_S = \frac{V_S}{R}\frac{t}{C} = \frac{i}{f\ C} \quad ripple\ voltage$$

$r = \Delta V / V_{OUT}$ *ripple factor*

$V_{OUT} \cong V_S - 0.6V$ *We have produced a DC voltage from AC input.*

Full Wave Rectifier - AC-to-DC Conversion



$$V_{out} = \frac{1}{2} V_2$$

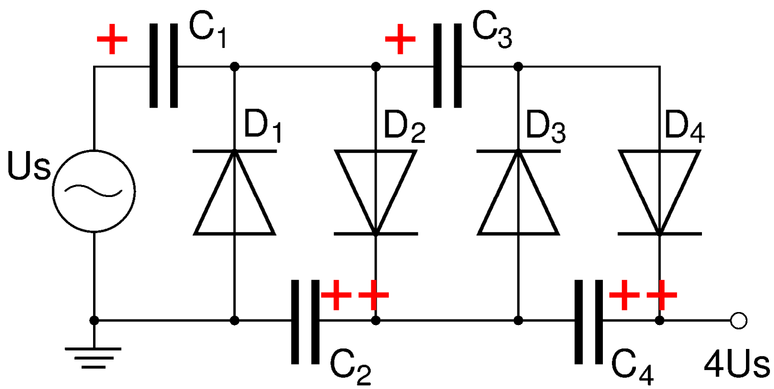
$$r = \frac{1}{2}\left(\frac{i}{f\ C} \right)$$

- In a Full Wave Rectifier two diodes act to rectify both positive and negative cycles.

- A transformer is generally used to isolate the 120VAC (20A) from the secondary.

- Less power wasted and a reduced ripple factor:

Cockroft -Walton Voltage Multipliers



4-stage Multiplier

1. On the positive halfcycle C1,C2,C,C4 charge to +Us thru D2 and D4. D1 and D3 are blocking.

2. On the negative halfcycle C1,C3, charge to -Us, but C2 and C4 can not discharge.

3. On the 2nd cycle C1,C2,C,C4 charge again to +Us thru D2 and D4. and C2 and C4 coming each chargeing to 2 Us.

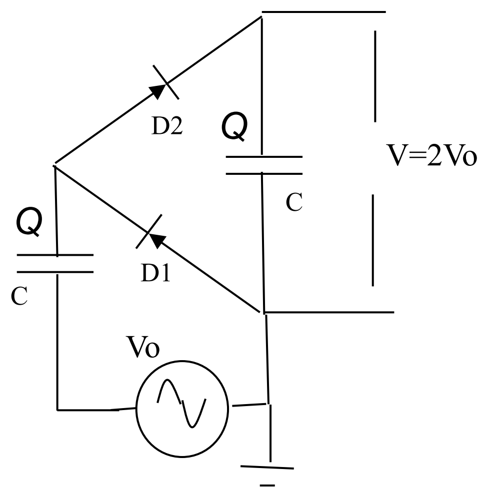
4. The total potential difference across the output C2+C4 is Vout= +4Us.

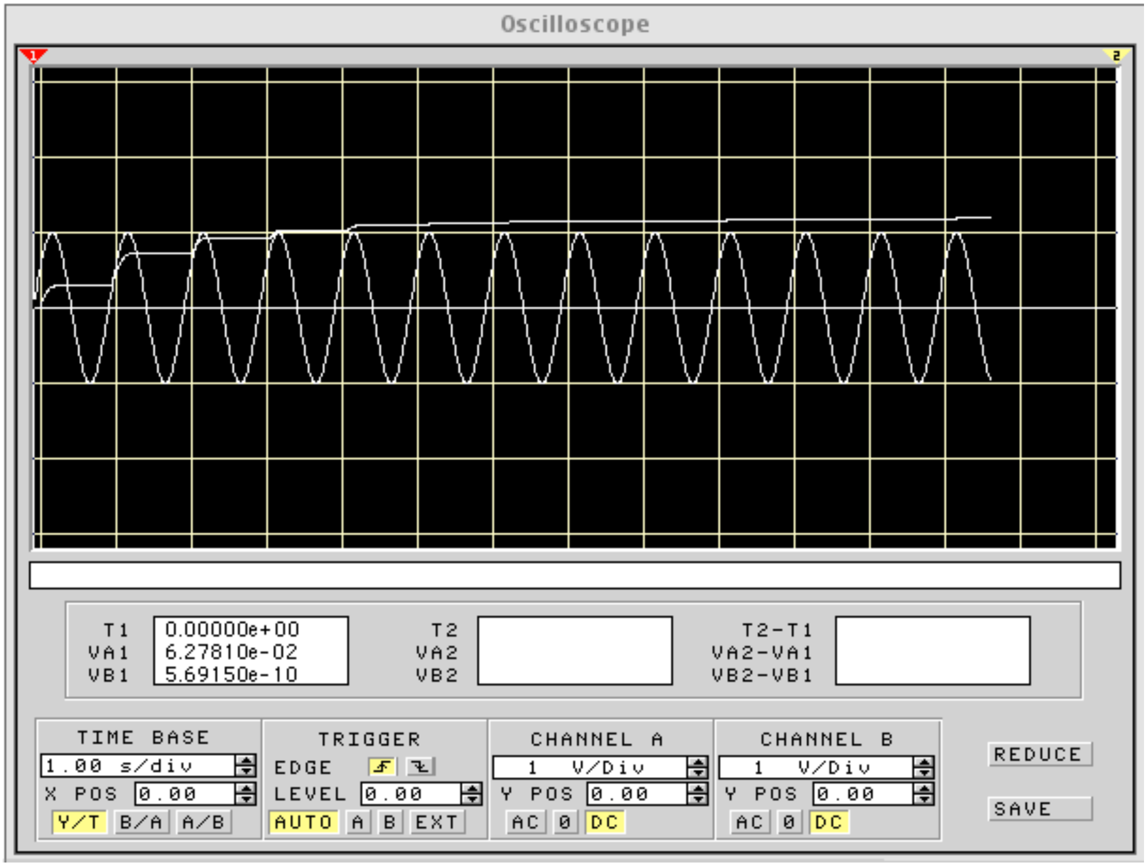
5. Practically speaking Vout < +4Urms.

6. You can hear your digital camera charge up the capacitor banks for the flash. The cockroft walton concept can only supply a short burst of charge and must be modified for high DC current use.

http://www.blazelabs.com/e-exp15.asp

Voltage Doubler Circuit





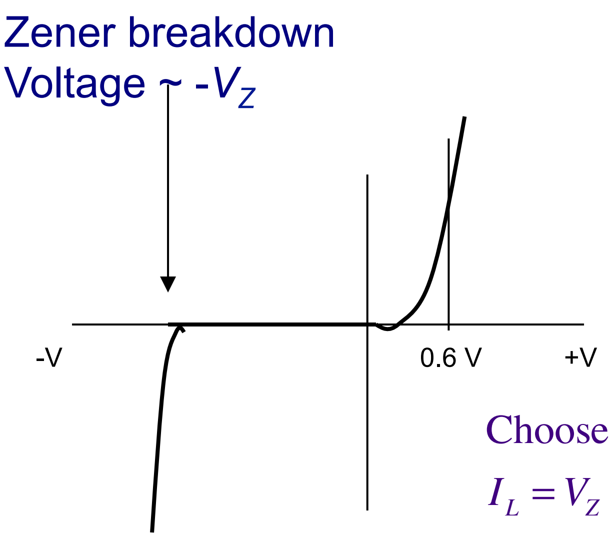
- *Capacitors are charged to Q by Vo sin(wt) after a few cycles.*
- *Charge can not leak off due to diodes. T*
- *Total Voltage sum is V=2Vo (doubler)!*

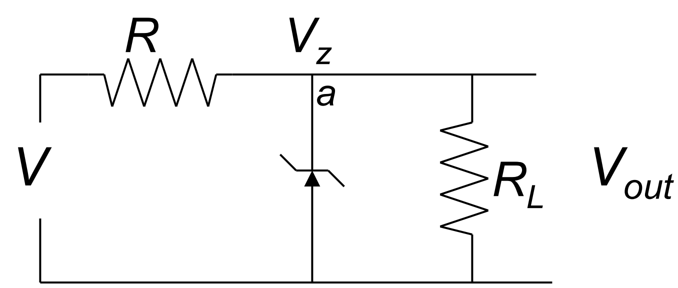
Zener Diode / Voltage regulator

•A Zener works in reverse bias mode. It is be designed to break down at the precise voltage called V_{Zener} ~10-100V eg.

• Point *a* in the circuit is fixed to the Zener voltage when Vin > Vz.

• The Zener diode is used for tight DC voltage regulation.





Choose R to limit the current thru the Zener diode ($I_{Zmax} \approx 50$ma)

$$I_L = V_Z / R_L$$

$$I = (V - V_Z) / R$$

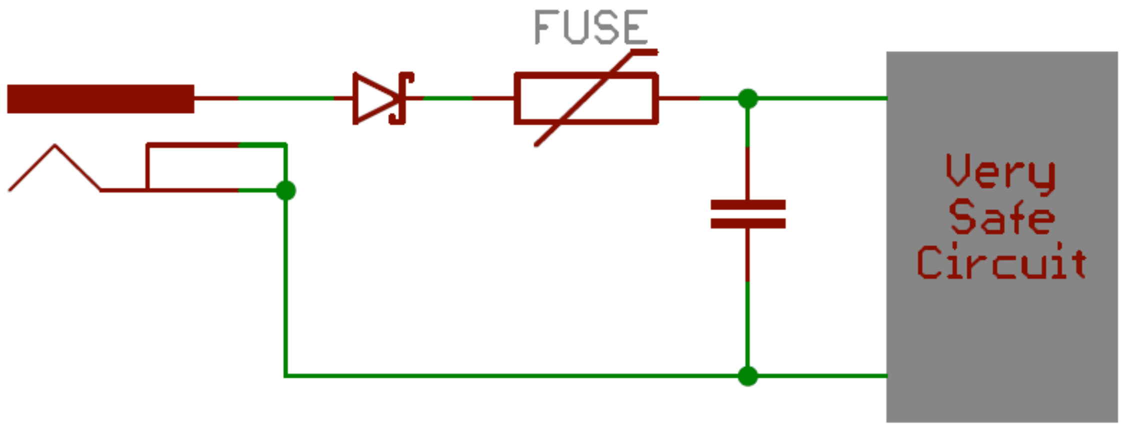
$$I_Z = I - I_L < I_{Z\max}$$

$$(V - V_Z)/R - V_Z/R_L < I_{Z\max}$$

$$(V - V_Z)/R < I_{Z\max} + V_Z/R_L$$

$$R > \frac{(V - V_Z)R_L}{I_{Z\max}R_L + V_Z} > \frac{(10V - 5V)1000\Omega}{0.005A \cdot 1000\Omega + 5V} = 91\Omega$$

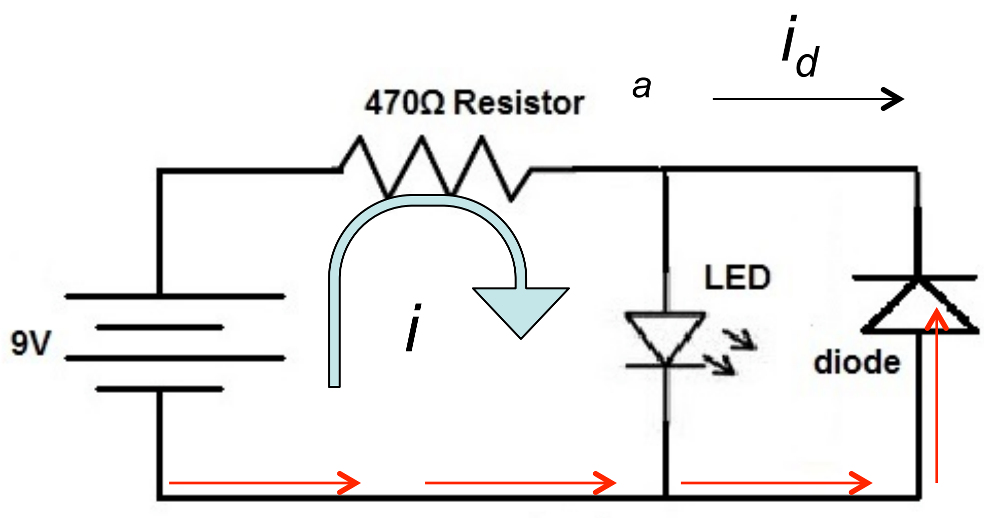
Input/Output Protection with Diodes



A diode placed in series with the positive side of the power supply is called a reverse protection diode. It ensures that current can only flow in the positive direction, and the power supply only applies a positive voltage to your circuit.

Input/Output Protection with Diodes

- *The 470Ω resistor in series with the LED limits the forward bias current flowing through the LED typically I_{limit}< 20ma.*
- *9V - 470 I – 0.6V = 0 so I = 8.4V/470Ω =18ma (safe).*
- *I_d = 0 in most cases where point a is maintained with a positive voltage.*
- *If someone attached the battery in the reverse directions the LED would blow out w/o the protection diode. The diode allows the current to bypass the LED!*



Load Protection with Diodes

- *Consider a circuit with a power supply and an inductive load (e.g. motor) on it. From the instant the switch is closed, the inductive load will accumulate stored energy. When the switch is opened this energy will generate a high reverse voltage and arc across the contacts of the switch. This could damage the switch, load and other circuit components.*

- *A power diode placed across the inductive load will provide a path for the release of energy stored in the inductor while the inductive load voltage drops to zero.*