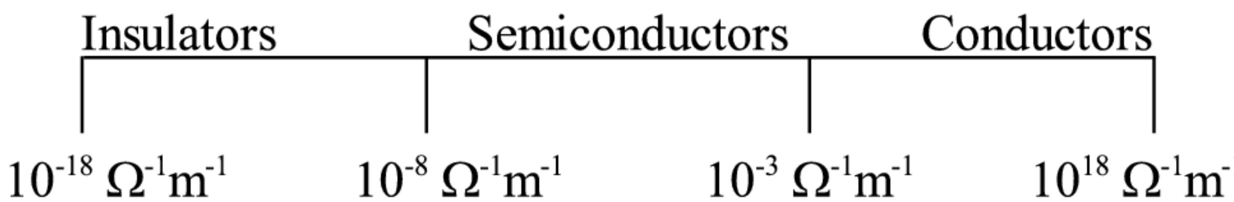
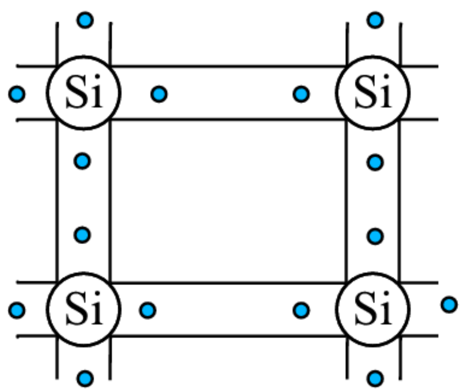
Brief introduction to Semiconductors

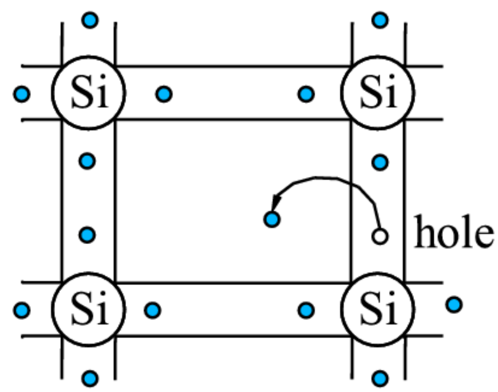
Conductivity $\sigma[\Omega^{-1}m^{-1}]=\frac{1}{\rho}$ Resistivity Note: Resistance $=\frac{\rho L}{A}$



(conductivity for Si depends on doping, Cu ~ 6E7 Sm^{-1})

Think of a crystal matrix of silicon atoms (Si has 4 valence electrons).





T=0 all electrons are bound in valence bonds

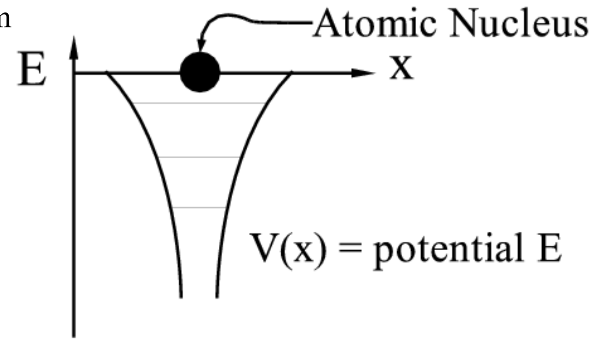
no carriers available for conduction

eg. Silicon, Germanium are tetravalent elements

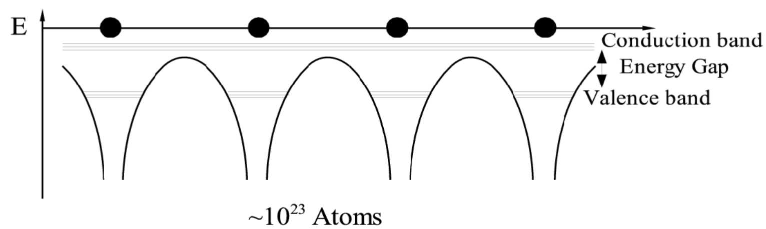
For T> 0 thermal fluctuations can break electrons free creating electron-hole pairs

Both can move throughout the lattice and therefore conduct current.

Energy levels are discrete for a single, isolated atom



In a crystal, many atoms are in close proximity. The energy levels are split ~n-fold. The discrete levels become nearly continuous, within bands.



Conduction band: ~composed of excited states of the single atoms
Valence band: ~ ground state of the single atom

Forbidden Energy Gap (Band Gap) exists between valence and conduction bands O(1eV) in Semiconductors. This is the energy required to break one of the bonds.

Insulators: Large gap, difficult to to jump to conduction bandpass

Semiconductors: Thermal excitations at room temp., moderate applied potentials can bridge gap

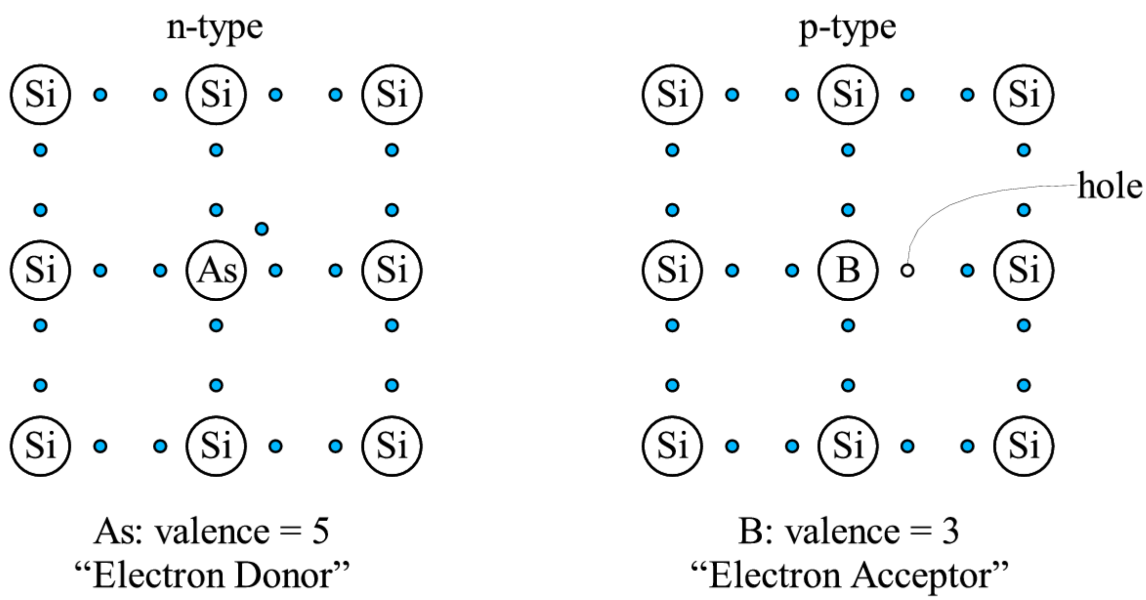
Conductor: Conduction and valence bands overlap charge flows freely w/ applied potentials

Intrinsic semiconductors: no impurities

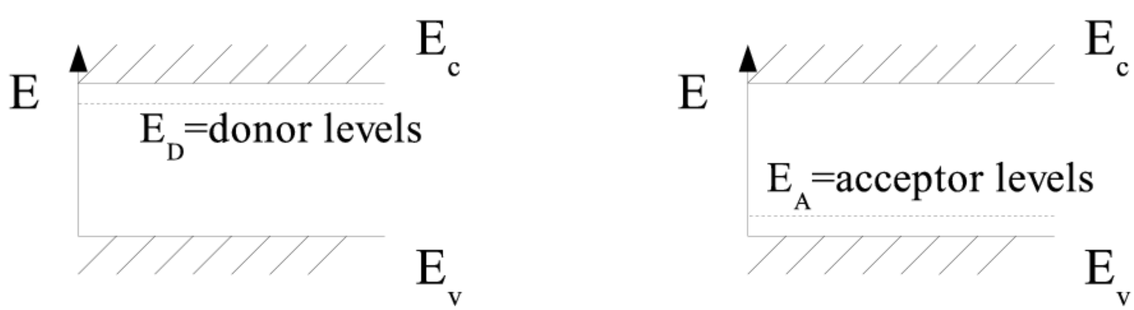
Extrinsic semiconductors: impurities introduced with different valence that underlying crystal.

Doped semiconductors

Two examples of doped (extrinsic) semiconductors with impurities of different valence values than the silicon atoms. The addition of dopants can greatly increase the conductivity of the material. (allows for adjustment of distance between the valence and conduction bands)

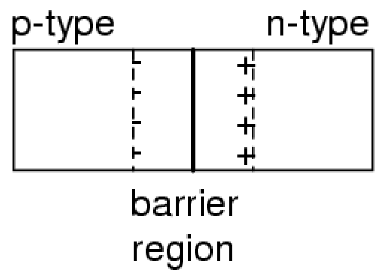


Donors put energy levels just below conduction band (in the gap)
Acceptors put energy levels just above the valence band.



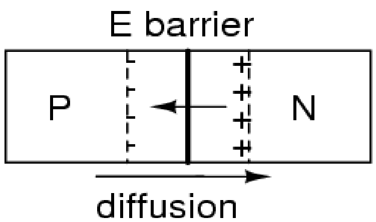
A hole jumping into the valence band is like an electron jumping into the conduction band. Electrons are easily excited (thermally) from E_D to the conduction band for n-type material. In p-type material, they are easily excited from the valence band to E_A.

P-N Junction

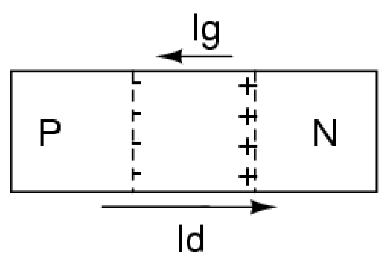


Charges diffuse due to thermal effects. Holes diffuse from p-side to n-side, electrons diffuse from n-side to p-side.

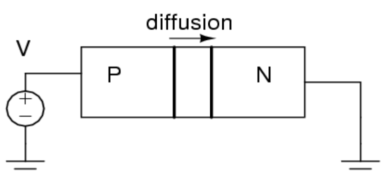
This diffusive flow creates an equilibrium state.



Electron/hole pairs created within the gap flow opposite to the diffusion from P to N.



At equilibrium: $|I_d|-|I_g|=0=I$ (no net current flow!)
define: $|I_d|=|I_g|=I_0$



Applying a forward voltage ($V_P > V_N$) to the diode causes charges to diffuse from the P to N nodes of the device.

$$I=I_d-I_g=I_d-I_0$$

Boltzman factor: $\frac{N}{N_0}=\exp\left[\frac{-(E-E_0)}{k_T}\right]$

ratio of charge carriers in higher state compared to those in state E_0

$E-E_0$ represents a step in potential energy $E-E_0=-qV$

N_0 = #carriers at state E_0

N = # carriers at state E

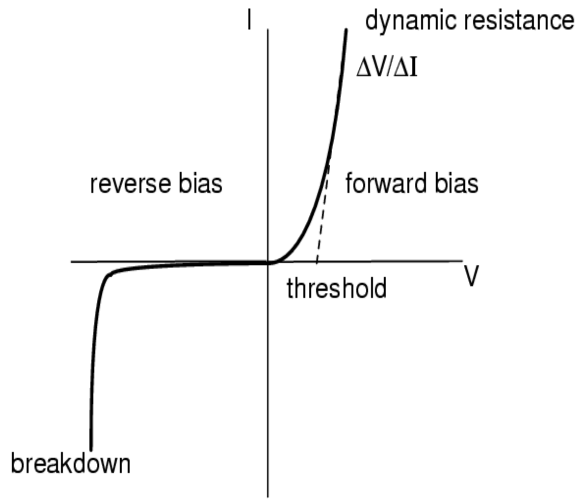
current is proportional to charge carriers: $\frac{N}{N_0}=\frac{I_d}{I_0}\rightarrow\frac{I_d}{I_0}=\exp(qV/kT)$

$I=I_d-I_0=I_0\exp(qV/kT)-I_0$

thus we have the diode equation: $I=I_0[\exp(qV/kT)-1]$ (almost correct)

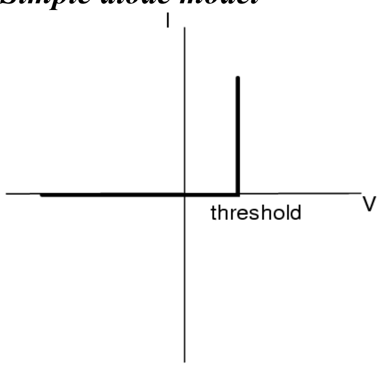
Add additional material-dependent factor to handle various recombination effects

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



Current flows freely in forward biased diode with small dynamic resistance above threshold voltage.

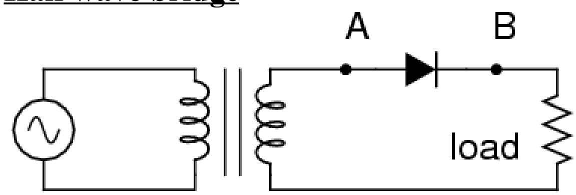
Simple diode model

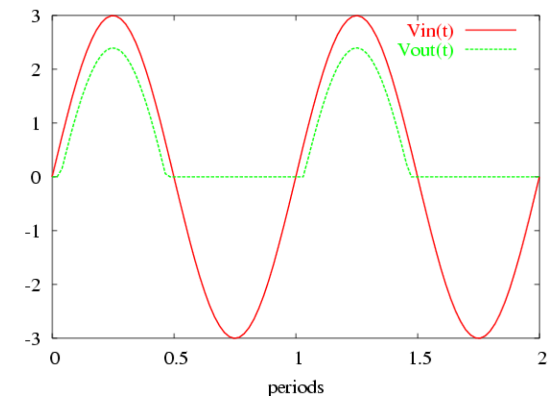


The most simple model of the diode is as a sort of switch that turns on when an applied forward voltage reaches the threshold voltage (V_{TH}) ~ 0.6V for silicon diodes.

This model is most often used to explain the operation of rectifiers (AC to ~DC conversion circuits)

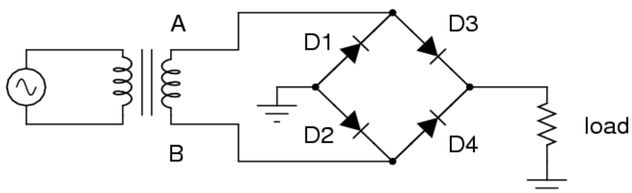
Half wave bridge

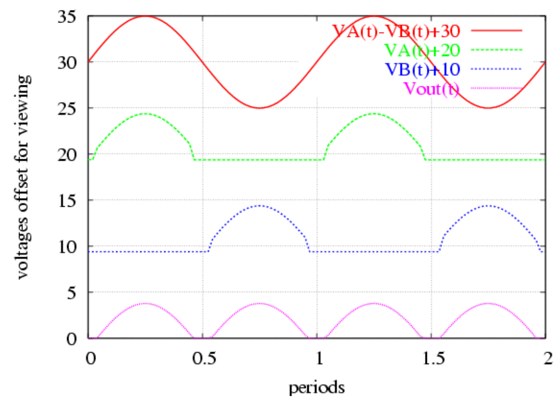




Output voltage across load is below V_A by a fixed cut in voltage = V_{TH} $\quad V_B \sim max(0, V_A - V_{TH})$

Full wave bridge

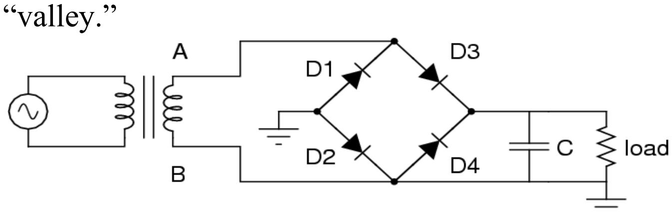


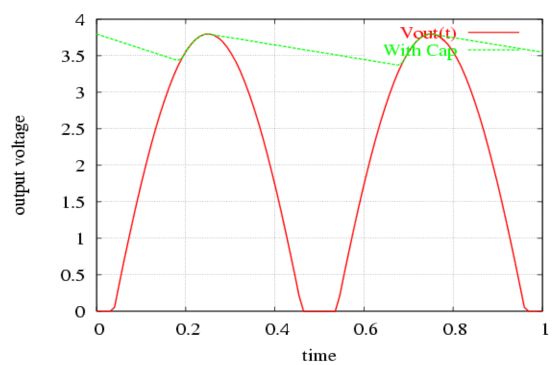


On alternate half-cycles point B (or A) is "grounded" through D2 (or D1) while A (or B) is connected to the load through D3 (or D4).

Both V_A,V_B vary between $V_{secondary}$-V_{TH} and -V_{TH}
Output voltage varies between $V_{secondary}$-2V_{TH} and ground.

The above full wave rectifier circuit still does a poor job of delivering a DC voltage. The cusps or valleys can be smoothed out by attaching a capacitor to ground. The capacitor acts as a charge reservoir that can supply current to the load over the course of the "valley."





Approximate analysis of ripple voltages (assuming constant current discharging the capacitor between the peaks): $V_{ripple} = \frac{\Delta Q}{C} = \frac{I \cdot T}{C}$

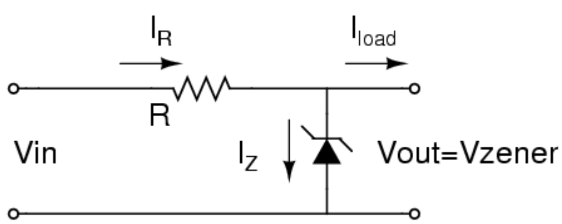
Once the value of C is set, the amount of ripple on V_{out} will vary as the load increases or decreases. The stability in the output voltage of a power supply against variations in load current is called regulation.

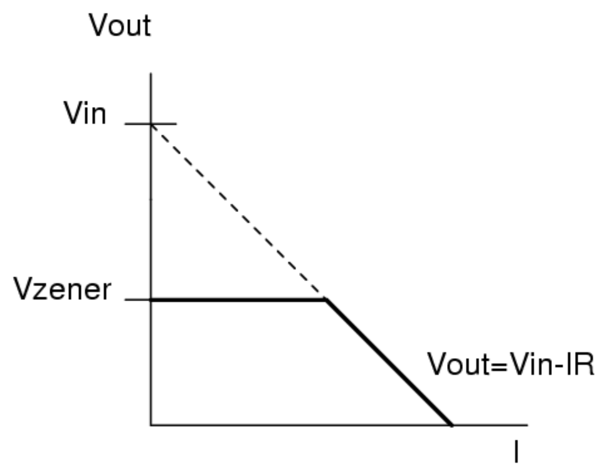
$$\%\,regulation = \frac{\langle V \rangle_{\text{no load}} - \langle V \rangle_{\text{load}}}{\langle V \rangle_{\text{no load}}}$$

In more sophisticated DC power supplies the ripple and regulation are independent. For this simple supply:

$$\%\,regulation = \frac{1/2\,V_{\text{ripple}}}{\langle V_{\text{out}} \rangle}$$

The regulation and ripple of the full wave rectifier + capacitor power supply can be improved by adding a zener diode "shunt" across the output.





The zener draws current in the reverse direction to keep Vout at Vzener. (typically at least a few mA must flow through the zener to ensure accurate regulation) The resistor limits the current through the zener diode in case the load is removed. This protects the zener from excessive current flow.