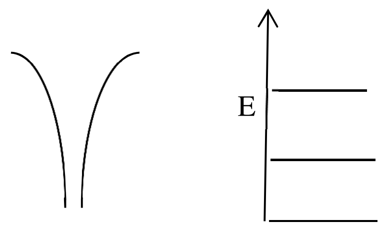
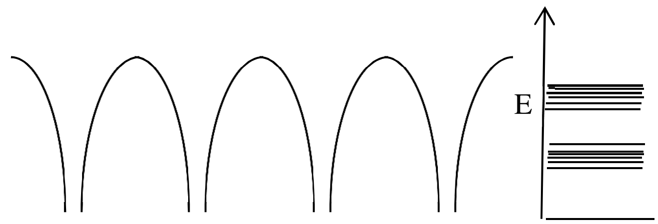
Diodes:
As you may recall from modern physics, if we look at a nucleus-plus-electron system, the system has discrete energy states. In contrast to that, when we have a collection of atoms in a regular array, such as a crystal, we observe many states so close together that, given thermal excitation, we can consider them continuous bands of states.

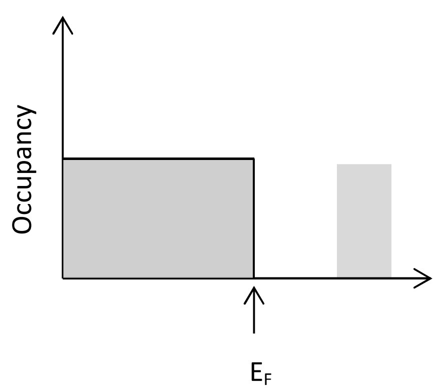


Cartoon of electrostatic potential and energy levels of isolated atom



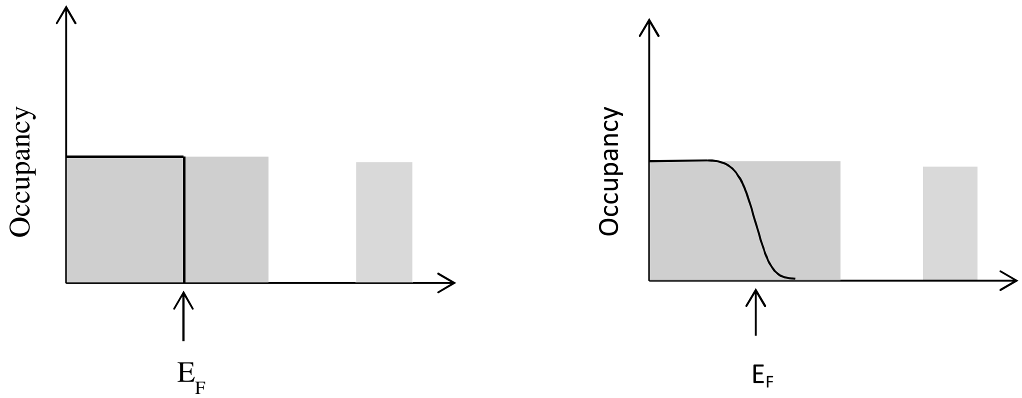
Cartoon of electrostatic potential and energy levels of regular array of atoms

These in some sense represent states electrons can be put into, but there are only a finite number of electrons so not every state/level has to be occupied. So consider an array of nuclei, imagine holding in place while adding electrons, and add electrons until the system is electrically neutral. We define the energy of the last filled state (at a temperature of 0K-- no thermal excitation) the Fermi energy, E_F. If that energy corresponds to having completely filled a band of states, then there are no nearby states for electrons to move to if we apply a potential difference across the sample. If electrons can move, the conductivity is low and we have an insulator. The energy from the top of the last band with at least some filled states to the bottom of the next higher energy band is called the bandgap. In insulators this is typically a few electron volts (eV) of energy. Since a typical room temperature the thermal energy is about 1/40 of an electron volt, it's not surprising that electrons are not easily excited thermally to the next higher band. A different way of representing how filled the states and the band are can be obtained by drawing a graph of probability of a state having electron in it versus the energy of that state:



Cartoon of band structure. Gray area represent available states. Black curve represents occupancy of those states. E_F represents the highest filled state at Temp= 0 K. Since that is the highest state in the band, this is not a conductor.

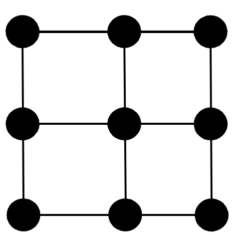
If the Fermi energy is well below the top of an energy band, then there are many free states available for electrons to move into and therefore they are free to do so under the influence of an external for such as an applied electric field. This means we have something more like a conductor.



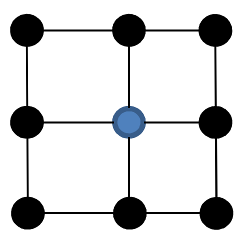
Cartoon of band structure: Conductor. Gray area represent available states. Black curve represents occupancy of those states. E_F represents the highest filled state at Temp= 0 K (the situation depicted in the left graph). Since this is in the middle of the band, this is a conductor. The band in which E_F lies in this case is called the conduction band. In the right graph, we show the effect of being at finite temperature (T>0 K): thermal energy enables some electrons to be excited from field to unfilled states in the conduction band.

<u>Semiconductors</u>: Like insulators but smaller band gap. Pure semiconductors conduct poorly @ room temperature, ≈ not at all when cold. Conduct better @ hot.

Can affect energy level structure by *doping*:

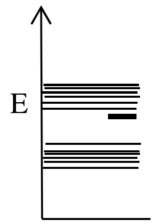


Schematic of a piece of a Si crystal lattice. Dots represent Si atoms, rods represent bonds to neighboring Si atoms. Si has valence 4.

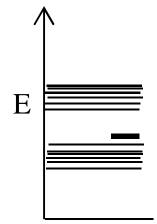


Schematic of a piece of a Si crystal lattice doped with an electron donor making it n-type Si. The valence of the dopant is 5 so while it is neutral, it has one more electron than neighboring Si atoms can keep busy. This electron is more mobile and can be available for conduction.

Similarly, the dopant could have valence 3 and be “short” one electron to share with neighboring Si’s. This makes a “p-type” semiconductor, this “vacancy” can be filled by a neighboring atom’s electron, effectively “moving” from the original atom to the one that just had an electron hop into the vacancy. This “hole” can be treated to a large extent as if it were a charge carrier of its own with effectively a positive charge. Dopant concentrations (dopants per volume compared to Si per volume) are usually in the range of 10^{-9} to 10^{-4}.This difference in valencies affects the band structure, which is why we do it.

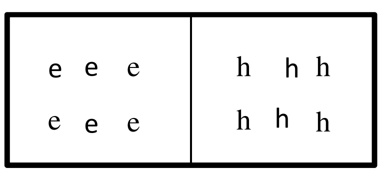


n-type Si creates "electron donor" states just below conduction band.

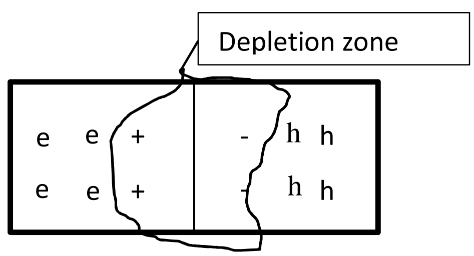


p-type Si creates "electron acceptor" states just above valence band.

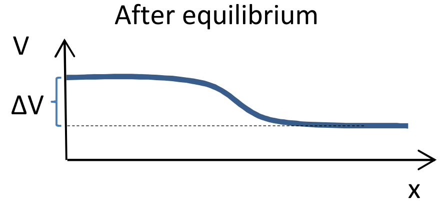
Now imagine we butt a piece of n-Si next to p-Si. At the interface (junction) holes in p-Si are filled by e's from n-Si. Once this starts, the n-Si (losing electrons) becomes net positive, which makes it less likely for more e's to leave. Eventually equilibrium is achieved where by the tendency (through diffusion) of e's to wander around and find holes to fill is exactly balanced by the charge imbalance and the resulting ΔV created which opposes further diffusion of e, h to junction.



Initially



After equilibrium

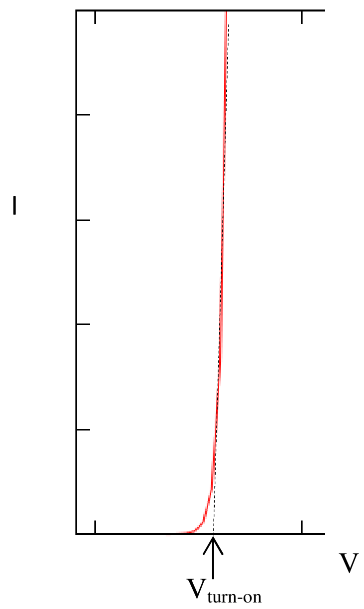


So now attach wires and apply external ΔV. If applied ΔV makes n-Si <u>more</u> positive, even less current flows since the ΔV hindering diffusion is even bigger (reverse bias).

If applied ΔV makes n-Si <u>less</u> positive, can eliminate the barrier and get <u>much</u> conduction (forward bias). In the forward bias condition, the I(V) curve is approximately

$$I(V) = I_0(e^{bV} - 1)$$

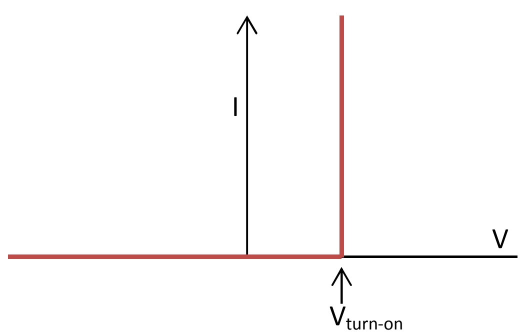
Note the b is positive so in forward bias (V>0) we have a positive exponential!



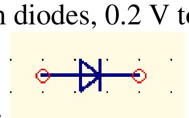
Exponential takes off so fast, your eye extrapolates roughly linearly back to I=0 and it looks as if there's some turn-on voltage.

From a practical "in the circuit" standpoint, a diode lets current flow in forward bias once $V>V_{turn-on}$, then essentially any current can flow with that ΔV. In reverse bias, approximately zero current flows. There is a limit to how large a reverse bias a diode can "stand" in the real world and if exceeded the diode "breaks down" and conducts like crazy. In most diodes except specially designed ones (called Zener diodes) such a break down irreversibly damages the diode.

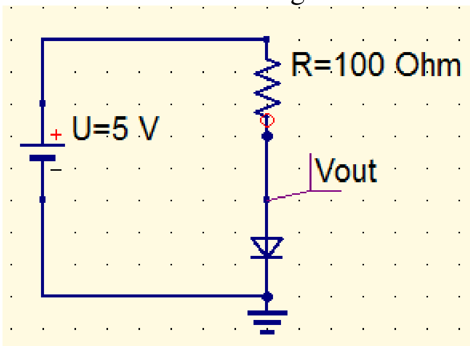
In our circuits we will treat diodes in a very ideal way: I=0 for all voltages below $V_{turn-on}$ (including reverse biases) and above $V_{turn-on}$, any current can flow without changing the potential drop across the diode:



Typical values for $V_{turn-on}$ 0.6 V to 0.7 V for silicon diodes, 0.2 V to 0.3 V for germanium diodes.

Standard diode symbol for use in circuit diagrams: . The triangle points along the wire in the direction conventional current flows when forward biased. The perpendicular bar represents the cathode (that is the end which is negatively biased in forward biased condition). Physically on most diodes (which are cylindrical glass or plastic objects) there is a black stripe to indicate which end is the cathode.

So consider the following circuit:

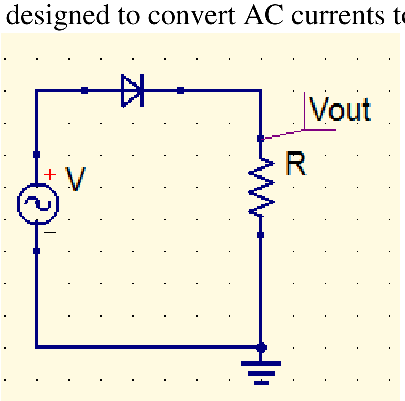


How do we analyze a circuit like this with a diode? Since it is a non-Ohmic device we need a strategy. Questions to ask yourself are can I tell if it is forward or reverse biased? Is it on or is it off? How can I tell if it is on or off? One straightforward way is to guess that it is on, analyze your circuit, and see if you get self consistent results. If you do not than your initial assumption that it was on must've been wrong.

Let's try that strategy here: assume that it is on which means that the potential difference across it must be $V_{turn\text{-}on}$, or 0.6 V.
Kirchoff Loop Law says $5V-0.6V=V_R$
So, $4.4V=V_R=iR$
$i=4.4V/100\Omega=44mA$
also, $V_{out}=V_{diode}=0.6V$

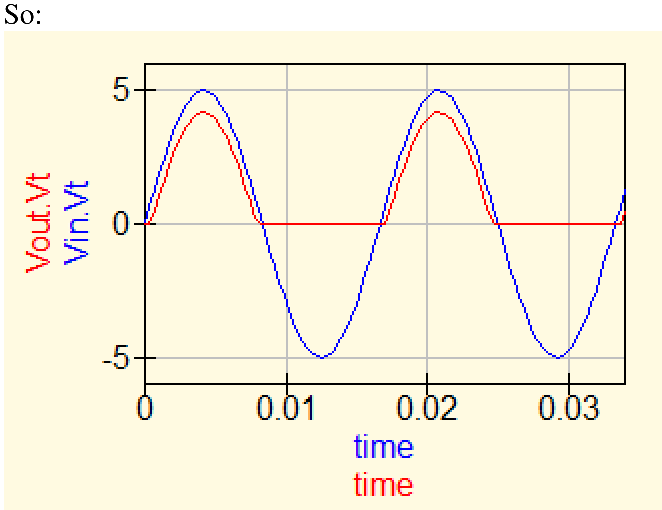
What if instead we had an AC voltage with a 5 V amplitude?
From the above analysis we know that if the diode is on, $V_{out}=0.6V$.
what if the diode is off (which we expect to be at some point during the alternating voltage cycle)?
If the diode is off no current is flowing. If no current is flowing the voltage drop across the resistor is zero. If the voltage drop across the resistor is zero, then the out is equal to the source voltage.
Okay then but when does the diode shut off? With our ideal model, any time $V_{in}<0.6V$, the diode cannot be forward biased and therefore has no current flowing and can be called "off". Similarly, once $V_{in}>0.6V$, $i>0$ and $V_{out}=0.6V$.

Because of its "one-way valve" sort of operation, a diode is often used in a circuit called a rectifier designed to convert AC currents to DC currents:



Apply the same analysis above to the circuit of the left and find V_{out} as a function of time.

If diode is off, $I_R=0$ so $V_{out}=0$. Once $V_{in} > V_{turn\text{-}on}$, $V_{out} = V_{in} - V_{turn\text{-}on}$.
So:



Now, that's clearly not a very good looking DC output, it's merely "always positive". So how do we fix that? We need to keep the output voltage high, even when the diode is off. An appropriate capacitor charged up during the time the diode is on, but then discharges through the load when the diode is off. The output voltage will decay exponentially with the RC time constant, but we can choose RC long compared to the period to get a relatively small "ripple" voltage (V_{max}-V_{min}). Note: Ripple under a given load is often a specification on power supplies.