Physics 310
Lecture 4 – Transformers, Diodes, and Power Supplies

Mon. 2/8	**Ch 5 – the rest**: Diodes, & Diode-based Devices	
Wed. 2/10	**Lab 4:** Transformers, Diodes, & Power Supplies	**HW4**: A* & Ch4 pr 1,2,5; Ch5 pr 3,12
Thurs. 2/11	**Quiz** Ch 4 & 5, more of the same	
Fri. 2/12	**Ch 8.1-.9:** Transistors	**Lab 4 Notebook**

Equipment:
- **Lab 4 Handout**
- **Ch 4/5 ppt.**
- **Jr-Seminar folk** – pizza & soda in the fridge

Announcements:
- Unavailable Tuesday and Wed before class – at AAPT
- Lab 4 pre-lab requires additional component models; available on website, loaded on the machines in this room and 131.

`Do all real diodes always have an associated voltage drop of 0.6V?`

`What is the effect on devices when a diode and capacitor is reversed causing a negative voltage?`

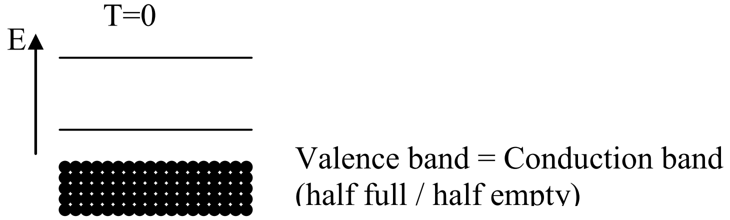
`What is important to know about regulators? The book gives veriest regulator series, but do we need to know the different kind of series and when they are meant to be used? – it's more there as a resource than for you to memorize.`

1. Why are diodes important? And how do they complicate things?
2. What are rectifiers and how do they work?
3. Could you do a sample problem from the latter half of chapter five? I'm not sure how it all fits together.

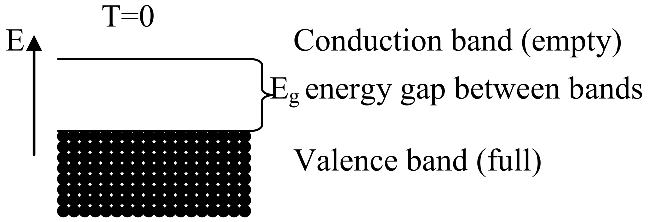
From last time
5-1 Semiconductors: Physical Model

Energy Bands

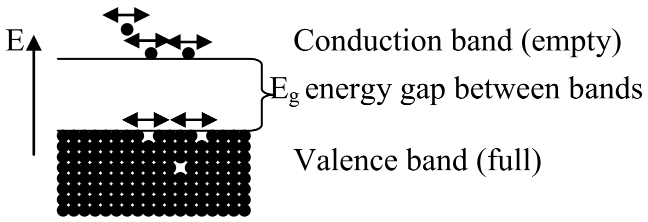
Conductor at low T



Insulator or Semiconductor at low T



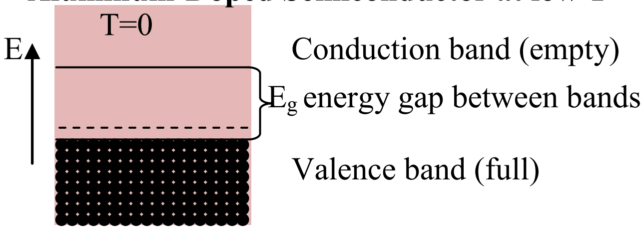
Insulator or Semiconductor at high T



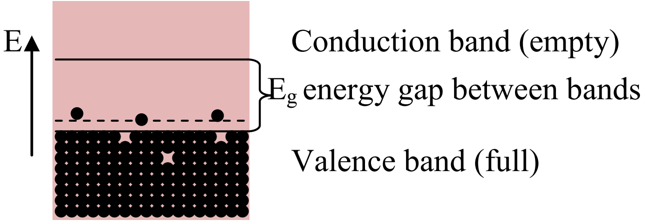
Physics 310
Lecture 4 – Transformers, Diodes, and Power Supplies

P-type (doped) semiconductor

Aluminum-Doped Semiconductor at low T

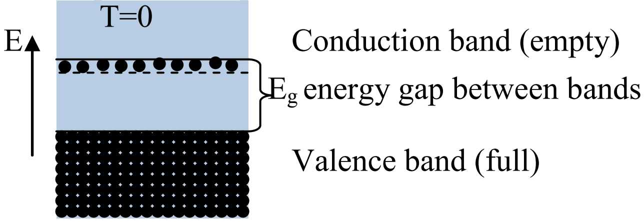


Aluminum-Doped Semiconductor at normal T

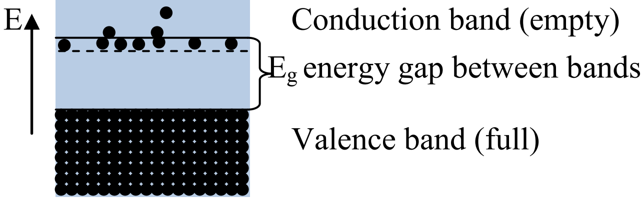


N-type (doped) semiconductor

Phosphorus-Doped Semiconductor at low T

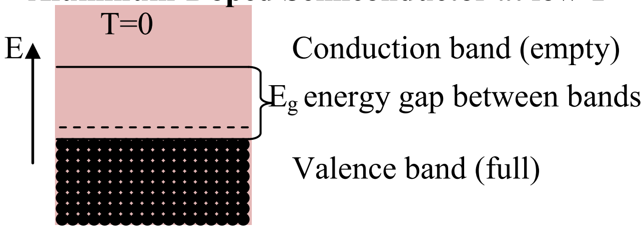


Phosphorus-Doped Semiconductor at normal T



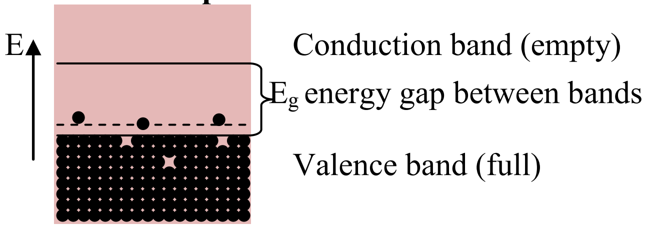
P-type (doped) semiconductor

Aluminum-Doped Semiconductor at low T



At regular temperatures, the conduction band is out of reach of the valence electrons – thermal jostlings just aren't enough to kick them up that high. However, these states at the aluminum atoms are accessible. We call these states "acceptor" states since they can "accept" valance electrons. Their energy level is then called the "acceptor band." At modest temperatures, some number of electrons will be in this "acceptor band."

Aluminum-Doped Semiconductor at normal T

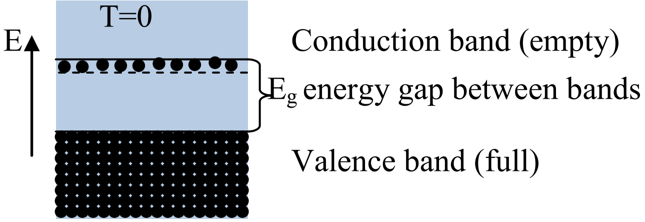


By accepting the electrons, the acceptor band has left "holes" behind in the valance band. Other electrons in the valance band are free to move into the holes, and thus leave holes behind them. In this way the electron holes can wander through the material. A mobile lack of electrons is electrically the same as a mobile positive charge. Thus, such material is called "p-type" for the mobile **p**ositive charges. So, if you apply a voltage across this chuck of doped semiconductor, holes will flow / current will flow, not as well as in a metal (there are far more mobile charge carriers in a metal than in a doped semiconductor) but they'll flow.

N-type (doped) semiconductor

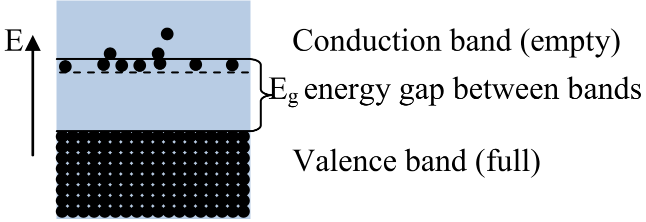
Alternatively, say we "doped" our semiconductor with Phosphorus. Phosphorus atoms have one more proton and one more electron than do silicon atoms. However, when surrounded by silicon in a solid, phosphorus atoms reach out to form just four bonds. So a phosphorus atom has one more outer electron than it can incorporate in the solid's valance band. Of course, it's got the protons to hold it, but just barely. Each Phosphorus atom has an additional energy level just below the bottom of the conduction band.

Phosphorus-Doped Semiconductor at low T



At very low temperatures, all the phosphorus atoms would hold onto their extra electrons; however, at normal temperatures, random thermal jostelings would have kicked a fair number of these extra electrons into to the conduction band. Since the phosphorus acts to provide or "donate" electrons, they're known as "donors", and the energy level is called the "donor band."

Phosphorus-Doped Semiconductor at normal T

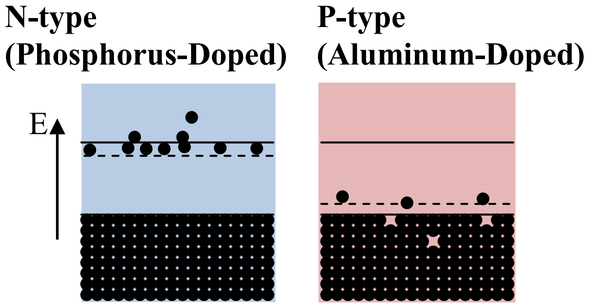


Because this kind of doping produces mobile electrons in the conduction band, and because electrons are negatively charged, this is called "n-type" semiconductor for the **n**egative electrons. Just like the "p-type" semiconductor, "n-type" semiconductor will conduct electricity.

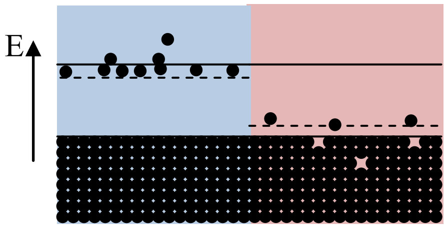
This Time

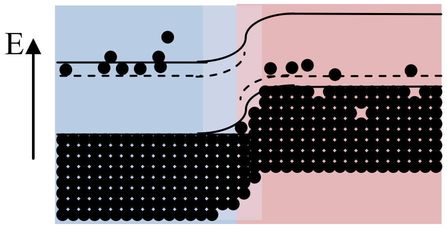
P-N Junction: Diode

Things get really interesting when you mate P and N type semiconductors.



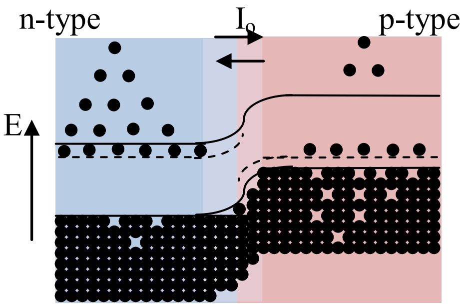
Physics 310
Lecture 4 – Transformers, Diodes, and Power Supplies





Electrons in the donor band find lower and unoccupied energy states they can drop into in the acceptor band; i.e., they leave their phosphorus atoms and hook up with the aluminum atoms. But, that leaves one unbalanced proton at each vacated phosphorus atoms on the N-side and one additional electron at each occupied aluminum atom on the P-side. This sets up an electric field much like a capacitor. The capacitor like fringe field gets larger and larger as it charges more and more until no more electrons want to migrate.
This is analogous to plugging a battery (built in energy difference) into a capacitor (ability to store separated charge).

Now, before we make use of this device, it's important to get a feel for the population distribution of electrons. In general, the probability that a particular electron state is occupied is proportional to $e^{-E/kT}$. The higher the energy, the likelihood that the state is occupied dies exponentially. Right around the donor – acceptor level, roughly half the states are occupied, so below it the states get more and more occupied and above it they get less and less occupied. Just so we can see that, I'll exaggerate the electron and hole populations.



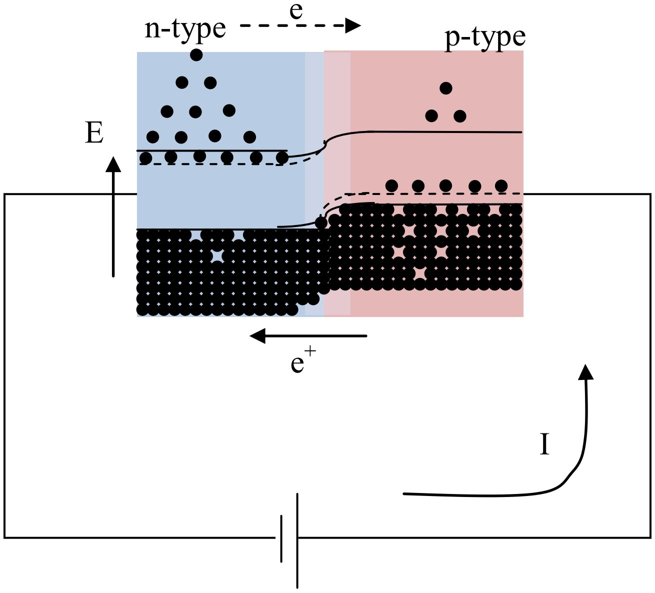
These stacks of electrons and holes are to represent their exponentially decreasing populations the further you get from the donor/acceptor level.

The electrons who have energies above the bottom of the conduction band are free to roam; similarly, holes with energies below the top of the valance band are free to roam. They will do just that until there are just as many of them at any given accessible energy. That's why the peaks of the electron stacks are the same on both sides / the bottoms of the hole stacks are the same on both sides.

Physics 310
Lecture 4 – Transformers, Diodes, and Power Supplies

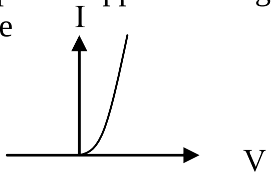
Forward Bias

Now say we hook this diode up to a battery with the positive voltage on the p-side and the negative voltage on the n-side. Since we're dealing with negatively charged electrons, this makes the p-side's energy more *negative* /less positive.



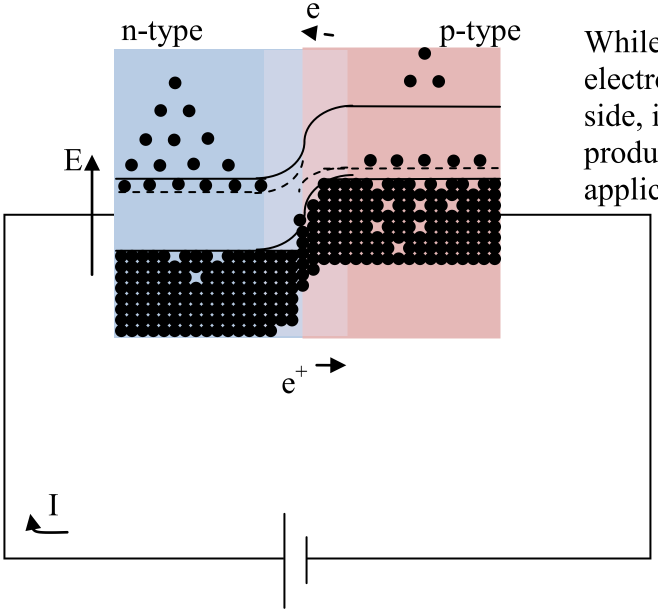
Now, there are electrons in states on the left that have higher energies than do some unoccupied ones on the right, so the electrons can migrate left to right across the junction. Since the thing's wired up to an external circuit, the electrons can keep on going. So we keep pumping more electrons on one side and taking them off the other – a current is sustained. Not only that, but if we vary the applied voltage, then the levels shift more and make more and more electrons capable of wandering across the junction, and not just 'more' but 'exponentially more since the populations scale with $e^{-E/kT}$.

A plot of applied voltage against current looks like

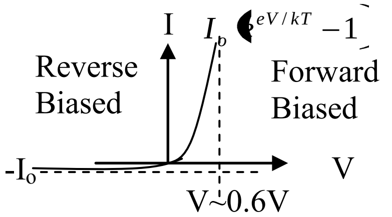


Reverse Bias

Now say that we wire the positive terminal of a power supply to the n-side of the diode and the negative terminal to the p-side. For negatively charged electrons, that makes the p-side more positive.

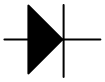


While it's true that a very small population of electrons on the p-side can now migrate to the n-side, it's small enough that the current it produces is miniscule, and negligible for most applications.



Someone asked about this 0.6V value – all semi-conductors have voltages around this value, but it depends on the exact material it's made of: Si, Ge, and GaAs are most common.

For most application's, that's the end of the storey. Perhaps it's easiest to think of the effective resistance of the diode, $\frac{dV}{dI}=R$; at most positive voltages this is virtually 0 and at most negative voltages this is virtually infinite. Thus, the diode then acts like a one-way switch: current can flow forward but not backwards. That's a very handy device. The symbol is rather suggestive of the function, coming from one side, it's an arrow; coming from the other it's a wall.



Here's the *single most important thing for you to know about a diode*. The resistance of a diode for any given voltage across it is $\frac{dv}{di} = R(v)$, look at the plot, for reasonable reverse voltages $R(v_{reverse}) = \frac{dv}{di} \approx \infty$ and for reasonable forward voltages, $R(v_{forward}) = \frac{dv}{di} \approx 0$.

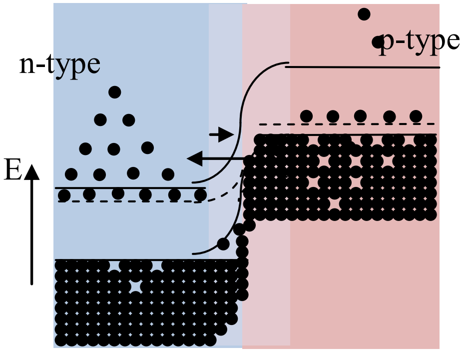
So, for reverse bias, it's like the diode is an open switch / a broken wire; for forward bias, it's like the diode is a closed switch / a wire.

One small additional detail is that, as you can see from how the current takes off exponentially, a wide range of currents corresponds to a fairly narrow range of voltages. In fact, for most reasonable currents, the voltage drop is on order of 0.6V for a silicon-based diode (for diodes of other materials it's different, but it's always round-about this.) This corresponds to essentially leveling the bands across the junction – valance/conduction on left is at same level as valance/conduction on right. In many cases, it's sufficient to model a diode as simply having this constant drop across it.

Zeener Breakdown

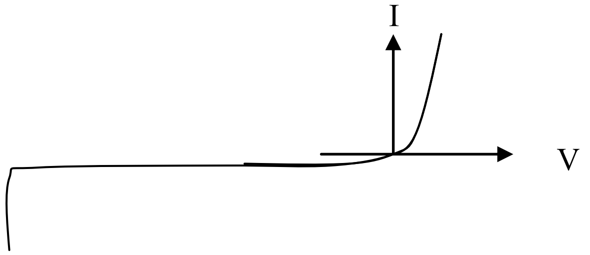
Before we start focusing on applications, we'll use this energy-band model to look at a rather extreme and useful situation. Say you apply a *huge* reverse bias to the diode. Its near infinite resistance will give way or "break down." That can happen one of two ways, depending on the details of the diode.

The book describes what's known as the "Avalanche breakdown" mechanism, though the authors call it a "Zeener breakdown." The "avalanche" occurs because the bias is so great that those very few electrons that do migrate from the p to the n side acquire *so* much energy that when they have regular resistive kinds of collisions, they impart a *lot* of energy – enough to free up more electrons, who get accelerated, have collisions and free up *more* electrons…You can get an 'avalanche' of electrons.

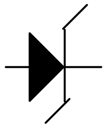


The other mechanism characterizes a true "Zeener" breakdown. If applied voltage bends the bands so much that the top of the valance band in the p-type is above the bottom of the conduction band in the n-type, and the gap is significantly narrowed, then electrons can tunnel straight from the p valance to the n conduction. The strength of the tunneling current (like the tunneling probability itself) depends exponentially on the width of the gap which, for high voltages depends roughly linearly on the voltage. So the current grows exponentially with the voltage.

Regardless of the mechanism, the current vs. voltage plot looks like



Diodes that have been specifically designed for this effect are called Zeener Diodes. The symbol for this device is that of a diode where the 'wall' looks like a backwards "Z."



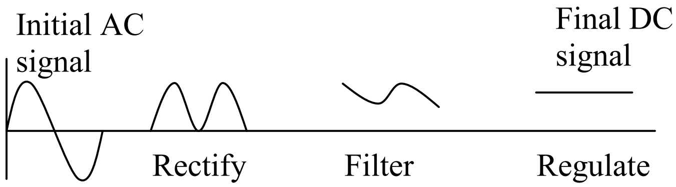
So, for a Zeener diode, the addition to the "single most important thing" about a diode is that, if the there's a *big enough* reverse voltage, then the "resistance" slams to zero again, and the diode's like a simple wire with its negligible resistance.

Applications

Okay, now let's think about ways these get used in circuits.

5-4 Rectifiers and Singe-Voltage Power Supplies

While a lot of circuits require DC power, there are lots of advantages to generating and transmitting electricity in AC rather than DC: at the power plant, it's easier to generate AC than DC voltage, using transformers AC can be conveniently stepped up or down in voltage, there's less resistive heating and thermal loss of power when it's transmitted with high voltage rather than high current (note: when reasoning this out, it's important to differentiate between the power line's "voltage" amplitude relative to ground and the voltage drop along its length. It's the latter, not the former that relates to resistive heating and thus energy dissipation.) These add to make AC the obvious choice for electrical power generation and transmission. However, a lot of circuits require DC voltages. So, we need a way to generate DC voltages from AC voltages. Between inputting a sinusoidal AC voltage and outputting a steady DC voltage output, there are three main steps.

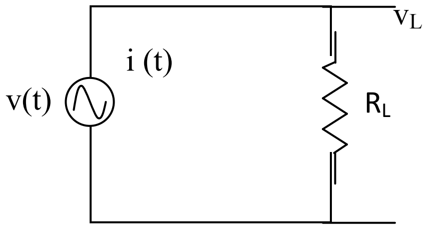


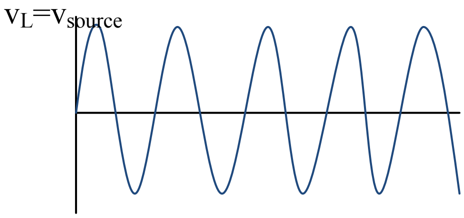
Diodes are useful in this process.

Physics 310
Lecture 4 – Transformers, Diodes, and Power Supplies

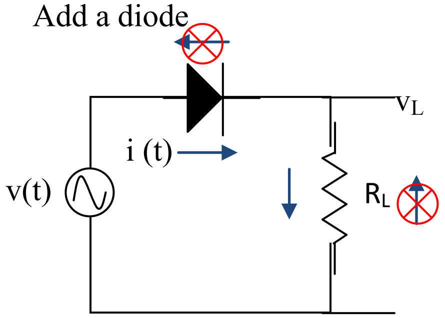
Half-Wave Rectifier

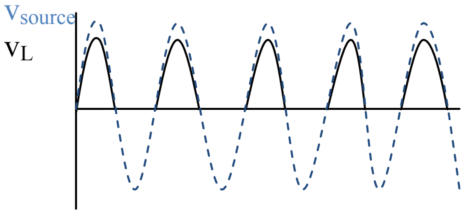
We'll build up the circuit and see how, with each added component, the output voltage changes.





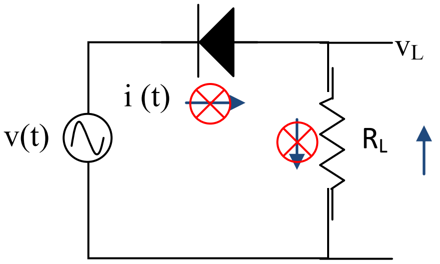
Add a diode

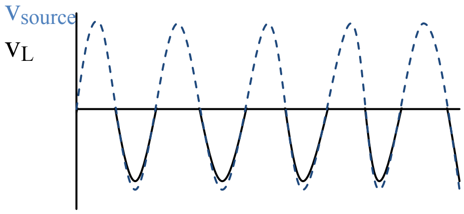




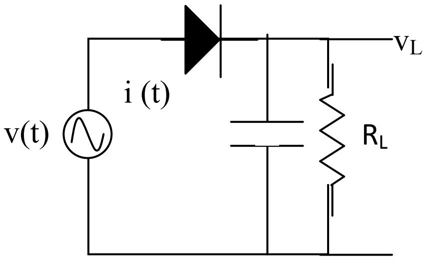
When the diode doesn't let current pass on through the resistive load, then there's no corresponding voltage drop across the load; it's all across the diode. Think of it like that one-way switch.

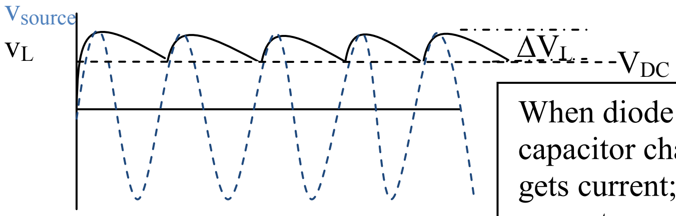
Or, if the Diode faced the other way





Add a capacitor across the resistor to make this *filter* the signal





When diode let's current flow, capacitor charges and resistor gets current; when diode blocks current, capacitor discharges and resistor gets exponentially-decaying current.

When the Diode *Passes* Current: In broad strokes, the capacitor and resistor are parallel across the supply + diode, so the voltage across them will just be that across the supply – 0.6V drop of the diode.

A little more specifically, we could apply what we'd learned in Ch. 3 to see that the impedance of the combination is, from what we learned in Ch. 3,

$$Z = \frac{1}{\frac{1}{R} + \frac{1}{Z_C}} = \frac{1}{\frac{1}{R} + jC\omega} = \frac{e^{-\tan^{-1}(RC\omega)}}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(C\omega\right)^2}}$$

So there will be a frequency dependent damping and phase shift.

When the Diode *Blocks* Current: it's like we threw open a switch at that point in the circuit. Now, the capacitor discharges through the resistor. While decaying, we can treat this just as an RC circuit.

$$I = C\frac{dV}{dt} \Rightarrow \frac{I}{C}\Delta t \approx \Delta V$$

The output signal is periodic, with period and frequency of the source voltage, $\tau = \frac{1}{f}$, looking over that time interval,

$$\frac{I}{fC} \approx \Delta V$$

Alternative approach. The above is just an estimate; here's another estimate. Assume that the moment the source voltage drops from the peak the left of the diode is at a higher voltage than the right, so the diode shuts off. From then until the voltage gets back up near the peak, roughly a full period, T=1/f, later, the capacitor simply discharges across the resistor.

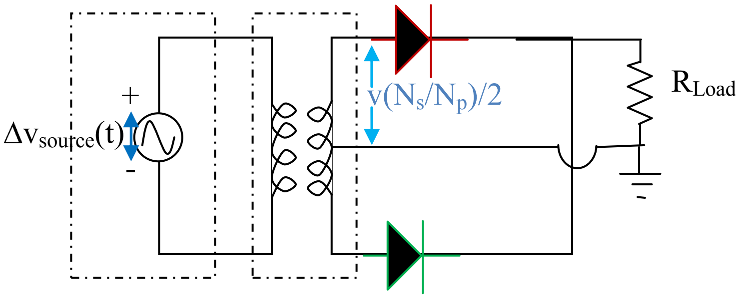
So, $v_{\min} \approx v_{peek} e^{-T/RC} = v_{peek} e^{-1/fRC} \Rightarrow \frac{1}{RfC} = \ln\left(\frac{v_{peek}}{v_{\min}}\right)$

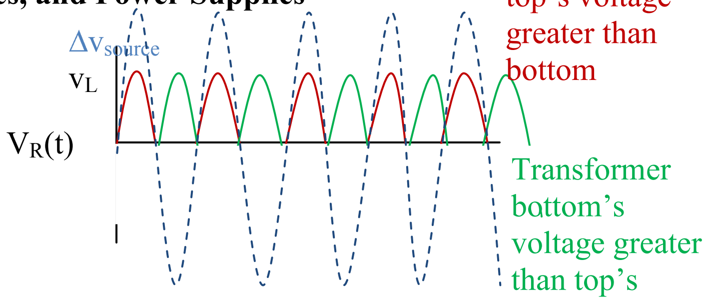
A "ripple factor" is defined – the ratio of the voltage "ripple's" amplitude to the offset in the voltage:

Ripple factor= $\frac{\Delta V}{V_{DC}}$, or, in terms of rms, $\frac{V_{rms}}{V_{DC}} \approx \frac{1}{\sqrt{2}}\frac{\Delta V}{V_{DC}}$ (this is *approximate* since the factor of $\sqrt{2}$ only holds for sinusoidal functions)

Group Problem (2nd on 4a sheets)

Full Wave Rectifier

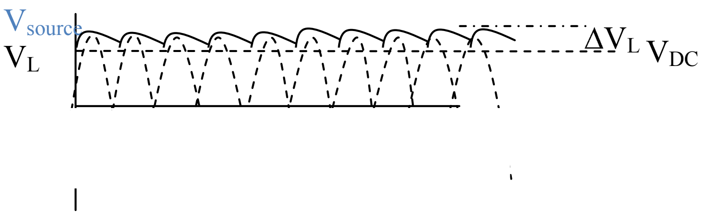




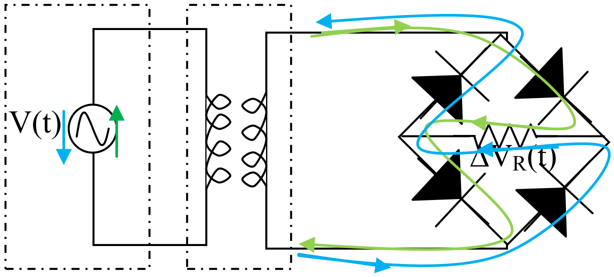
Anchoring the center of the transformer and end of the resistor at ground does a couple of things – it allows current to flow through just one diode at a time (and on to ground), it also means that the voltage drop across the resistor is only half of that across the whole secondary coil of the transformer; that fact, along with the ratio of coils in the secondary to that in the primary (and the voltage drop across the diode) determines the size of the voltage across the resistor.

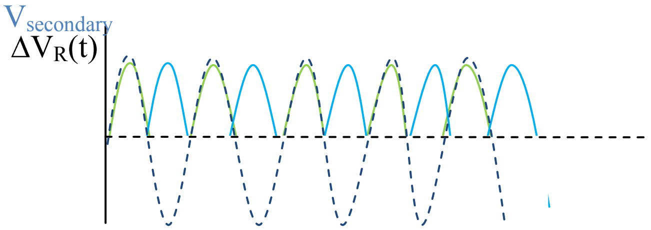
Filter

Putting a capacitor across the resistor would create a rippled signal, but with half the period / twice the frequency, of the previous case. Having less time to decay, also means less decay and so *less ripple*



Bridge Rectifier

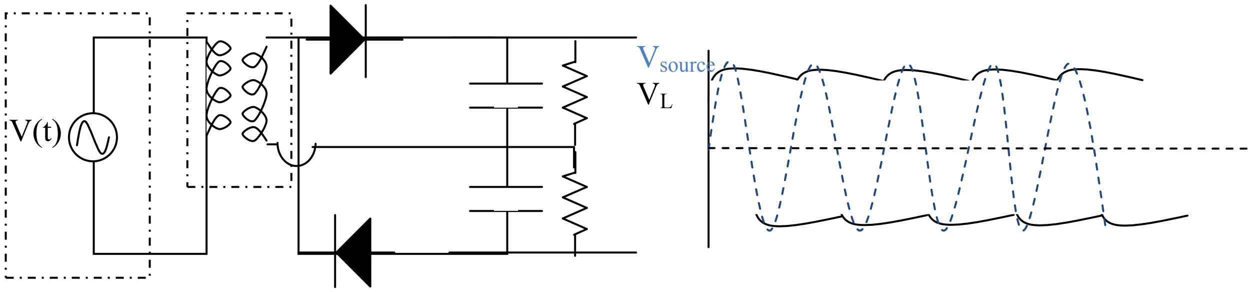




In this configuration, the right side of the load resistor will remain positive relative to the left side. The voltage across it looks very much like that for the other full-wave rectifier. The distinction is that resistor now gets (nearly) the full voltage drop of the secondary coil across it (minus the two small drops across the two diode through which the current is flowing); another distinction is that the resulting voltage is *relative to the left end of the resistor* not relative to ground.

Group Problem (1 from sheet 4a)

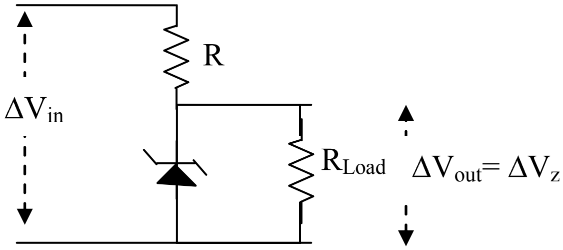
5-6 Voltage Doublers



Thanks to the transformer, the output's ground is floating; if we anchor the lower output terminal to ground, then the whole pattern shifts up. The "Doubler" is relative to what you'd get if you just used a rectifier. The positive terminal is the input's full peak-to-peak height above the negative terminal; whereas, for a simple rectifier, the positive terminal's voltage is just the input's amplitude above the negative terminal.

5-10 Zeener Voltage Regulator

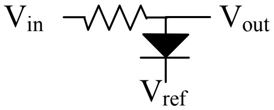
So far, all of these circuits are highly dependent on the input voltage – if the input voltage is increased or decreased, so is the output voltage. A "regulator" is much less dependent; as long as the input voltage is greater than some minimum, the output holds pretty steady. This is a very desirable behavior in power supplies. Recall that the Zeener diode has a very precipitous I-V plot; it goes asymptotic to some back voltage, V_z. We can make use of that feature in a regulator.



Functionally, the Zeener's like a battery, it will maintain the voltage as long as $\Delta V_{in} > \Delta V_z$.

5-8 Diode Clipper / Voltage Limiter

Often, you have a bit of circuitry that has some range of voltages it can accept; too large (positive or negative) an input voltage would fry the circuit. In that case, you really want to limit the possible input. Here's a snippet of a circuit that can do just that.

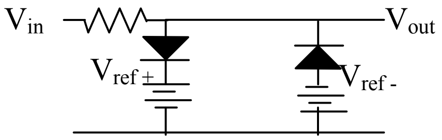


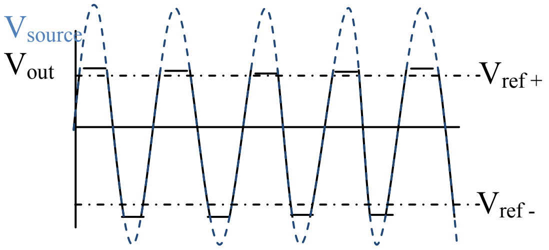
Clearly, this is just a morsel of a larger circuit; what the morsel does is force $V_{out} \leq V_{ref} + \Delta V_{diode}$ (where the drop across a silicon diode is around 0.6V).

Here's a very simple situation for thinking about how this works: imagine that the load (whatever V_{out} is connected to) draws negligible current. Then, if V_{in} is inside this range,

$V_{in} < V_{ref}$, virtually no current is drawn through the resistor or diode, and $V_{out} = V_{in}$. But, if V_{in} is outside this range, then current flows through the diode, forcing $V_{out} = V_{ref} + \Delta V_{diode}$, and there's a corresponding voltage drop across the resistor.

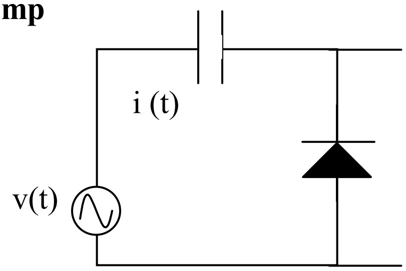
Here's a bi-polar limiter (that is, it enforces both a max and a min.)

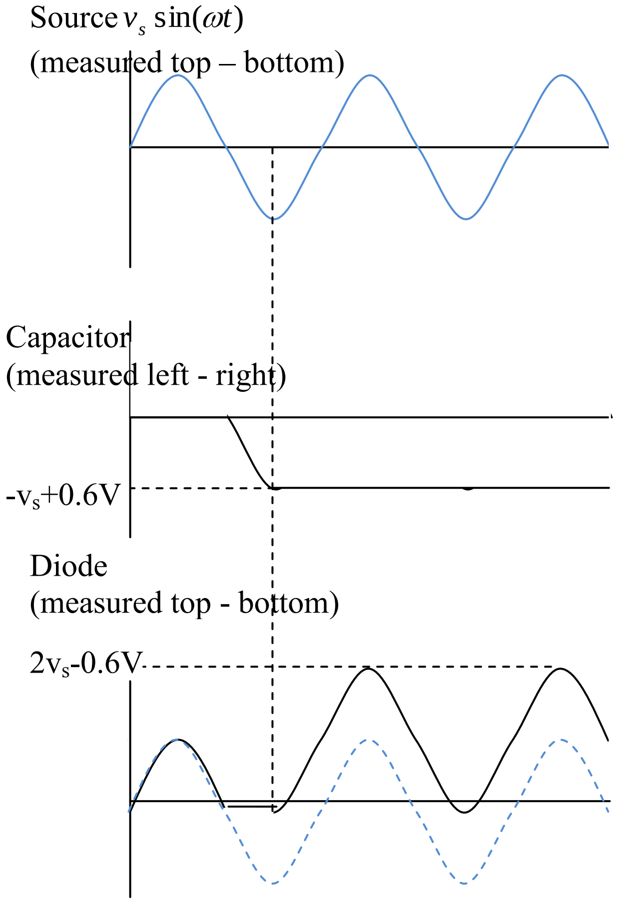




Note that the output slightly overshoot the reverence voltages, to the tune of the diode's voltage drop.

5-9 Diode Clamp





When you first turn on the circuit, during the first half cycle, current can't flow onto the capacitor's left side because it can't flow off the right side (the diode blocks flow). So, with no charge distribution across the capacitor, the left side's voltage just rides up with the right side's. With the diode acting as a broken wire (no current flows), the source's full voltage drop is across it.

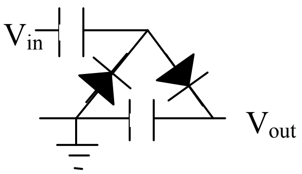
For the next quarter cycle, when the source goes negative, the left side of the capacitor goes negative and the right side wants to draw current, which it can since the diode is happy passing current in that direction. The diode's flowing current, so it just has its ~ 0.6 V drop across it.

But once the source starts heading toward positive again, the capacitor *would* normally start discharging – flowing current off the right side, but the diode prevents it. So now the capacitor is stuck with a v_s drop across it, right to left, and no way to discharge. Meanwhile, the left side is becoming more positive, so, the right side tracks with it. Ever after, the capacitor would want to pass current to the right and the diode prevents it. So the capacitor is stuck with a v_s drop and the diode acts like a broken wire. Kirchoff's loop rule says that the voltage across the diode must make up the difference between that and the source: giving an voltage that oscillates with the source, but a $+v_s$ offset.

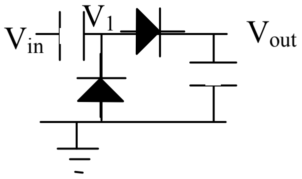
Physics 310
Lecture 4 – Transformers, Diodes, and Power Supplies

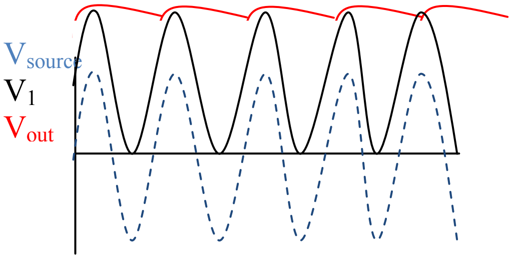
Another doubler

The book shows it as



It could be unwrapped to have a more standard form of





The first capacitor and pair of diodes act as a “clamp” (see 5-9), and the second capacitor helps to filter the signal.

Try working through problem 12 for figure D.A. (pp 98-99)

<u>Topics</u>:

Diodes – very little about solid state
- I vs. V
- voltage drop when conducting
- Zener diodes

Rectifiers
- half-wave
- full-wave
- bridge rectifier – with 4 diodes or prepackaged

Filtering Capacitors
- ripple calculation
- full-wave rectification is doubling frequency (time to repeat)
- good to put a resistor (& LED) in parallel to discharge the capacitor

Regulators
- Zener diodes
- fixed
- adjustable

Other diode circuits – diode clipper and diode clamp (skip voltage multipliers)

Study List for Quiz #4:

1. Transformers
2. Impedance matching
3. I vs. V for diodes
4. Signal rectification, filtering, and voltage regulation

Equation List: [units in square brackets]

Physics 310
Lecture 4 – Transformers, Diodes, and Power Supplies

$$\frac{v_s}{v_p} = \frac{N_s}{N_p} \qquad P_p \approx P_s \qquad \frac{Z_s}{Z_p} = \left(\frac{N_s}{N_p}\right)^2$$

$$C \approx \frac{i}{\Delta V \cdot f} \; \left[\mathrm{F} = \mathrm{A} / (\mathrm{V} \cdot \mathrm{Hz})\right] \qquad r = \frac{\Delta V}{V_{DC}} \qquad V_p = \sqrt{2} \cdot V_{rms}$$