Physics 15b: Lab 4: Diodes and Rectifiers

DUE Friday, April 6, 2007.

Help Labs This lab is another that you can do in your dorm room, if you like. We will offer "help labs," though, as usual:

- Wednesday 6-9 p.m.

- Thursday 3-9 p.m.

You are welcome at any of the help lab hours.

Contents

1 Purpose

1. Study the use of diodes as rectifiers.
2. Understand AC currents and voltages.

An Attempt to Lure You into Trying an Oscilloscope

As soon as you start working with time-varying voltages, as you do today, a voltmeter becomes an inadequate aid. An oscilloscope, an instrument that can plot voltage versus time, is exactly what you need, to show you the details of a waveform; a voltmeter can show you only a time-averaged version of that information. We'd give you each a 'scope to take home if we (or you) could afford it. Instead, we invite you to come to help lab and use the scopes that live there.

Here and there in these notes, we've planted advertisements for use of an oscilloscope. These points are labelled "**Scope opportunity:**", and are meant to make you yearn to see the offered waveform on a scope screen. You can do that at help lab, of course and we hope that some of you will. You are not obliged to come in, of course.

---

[1]Revisions: number figures; correct reference to 'fig on p. 4' in 3.2; add hint re what meter would read for half-wave (question 1.1) (3/05).

2   Introduction to Rectifiers

Before we get to the building and lab experiments, let's consider the circuits you soon will try.

2.1   Half-wave rectifier

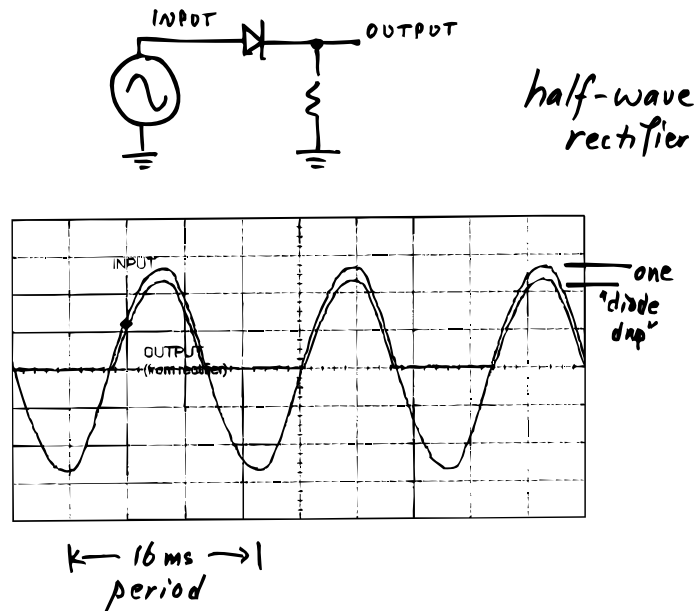The simplest rectifier circuit (called a *half-wave* rectifier) is shown below:

Figure 1: halfwave rectifier: first look

The difference between V_{in} and V_{out} reflects, of course, the fact that the diode conducts in only one direction.

QUESTION 1: Suppose the amplitude of the a.c.voltage is V_0 (i.e., $V = V_0 \, \mathrm{Sin}(\omega t)$). What is the average d.c. voltage at the rectifier's output? This is what your meter would read, on "DC volts," since it is insensitive to the fast variation of the output voltage. *Hint*: this average is one that the meter forms mechanically; it is an average in a sense simpler than the "V_{rms}" (root-mean-square) discussed in sec. 2.3, below. V_{rms} is appropriate when power is our concern; here voltage is what interests us, so an integral of the voltage waveform is sufficient, adjusted appropriately to reflect the fact that the half-wave rectifier delivers an output of zero, for half of each cycle."

The *a.c.* scales on your meter are really d.c. scales preceded by a half-wave rectifier. The calibration is arranged so they directly read a low-frequency sine wave as a "root-mean-square" a.c. voltage, a notion that is discussed below. On *"AC,"* the meter will also read a d.c. voltage, but incorrectly.

The output of the half-wave rectifier is a rapidly fluctuating voltage, but a capacitor can be used to smooth the output. As you know from your experience in Lab 3, the capacitor serves as a charge-storage device which, once charged to a particular voltage across its terminals, can take a long time to discharge. The *time-constant, RC* is long relative to the time between re-charging pulses that come from the rectified waveform, in the figure below.

The figure shows the half-wave rectifier with capacitor added. We have ignored the startup period - a fraction of a second - when the capacitor charges. The constant-voltage dash-dot line indicates the output voltage when no current is drawn from the d.c. output (if R were removed). If a current is drawn, partially discharging the capacitor

on each cycle, the output will look like the dashed line: bumpy, but still much smoother than without the capacitor. Because it is used to filter out the a.c. component of the d.c. output, a capacitor used in this way is called a "filter" capacitor.
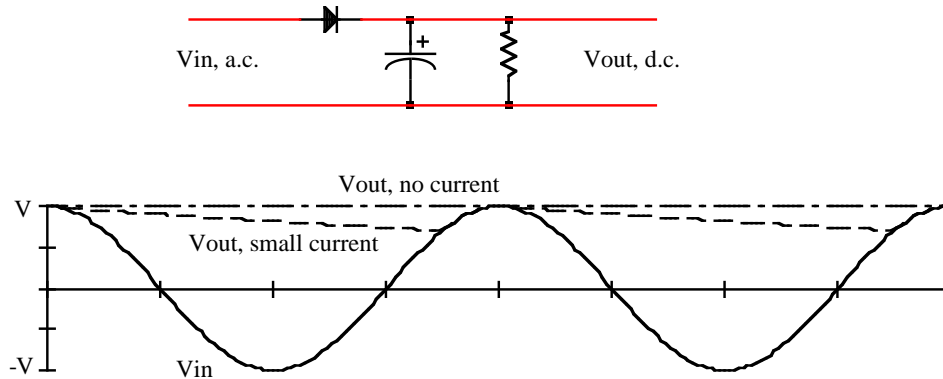

Figure 2: Half-wave rectifier

QUESTION 2: Assume you hook your voltmeter across the output, and its R is so large that the capacitor discharges a negligible amount each cycle. If the input amplitude were V_0, what would the meter read?

2.2   Full-wave rectifier

In a power supply using a half-wave rectifier, the capacitor is charged once for each cycle of the a.c. voltage. With four diodes, a "bridge" rectifier can be constructed which is active on both half cycles:
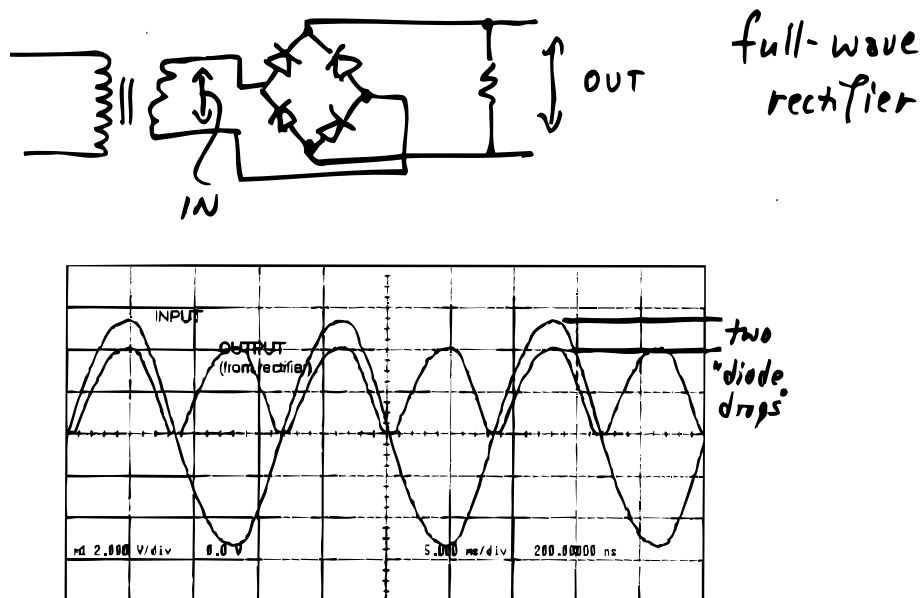

Figure 3: Full-wave rectifier

The bridge can be seen to be two half-wave rectifiers, which conduct on different half-cycles of the a.c. to give the full-wave output voltage:
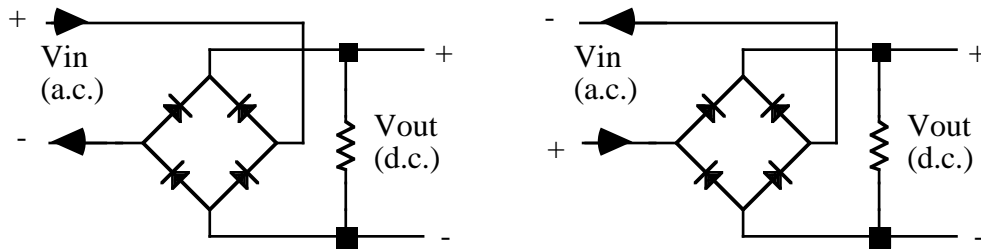
Figure 4: Full-wave rectifier, showing both possible input polarities

Compared to our original half-wave rectifier, these have an extra diode in the path for each polarity of input, but they work the same way. If the second diode were left out, when the two circuits were combined in the bridge the a.c. input would be shorted. You can figure this out for yourself if you like.

When there is no filter capacitor, the bridge should produce twice the average output voltage of the half-wave rectifier. With the filter, the advantage of the bridge is that it is better for producing steady voltages when there are large currents, because it recharges the capacitor twice as frequently.

2.3 A. C. Arithmetic

Suppose we have a sine wave a.c. voltage with amplitude V_0, $V = V_0 sin(\omega t)$. If this voltage is applied to a resistor, the average power dissipated is the mean value of $I^2 R$, or, via Ohms law, the mean value of V^2/R. Therefore, the algebraic function of the a.c. voltage that plays the same role as a d.c. voltage in dissipating power is the square root of the mean square voltage. This is abbreviated as the root mean square a.c. voltage, or V_{rms}. On your a.c. meter it is simply a.c. volts. Your meter is designed to directly read V_{rms} if a sinusoidal a.c. voltage at a frequency near 60 hertz is applied.

The relationship of V_{rms} to the amplitude V_0 is easily found by doing the integral to find the average value of V^2, and then taking the square root:

$$V_{rms} = \left(\frac{\int_0^T V_0^2 sin^2(\omega t) dt}{T} \right)^{1/2} = \frac{V_0}{\sqrt{2}} = 0.707 V_0 \tag{1}$$

The d.c. voltage recorded by your meter will be simply the average voltage it measures. For example, for the full-wave rectifier we need to average a half sine-wave over a half cycle:

$$V_{avg} = \frac{\int_0^{T/2} V_0 sin(\omega t) dt}{T/2} = \frac{2V_0}{\pi} = 0.636 V_0 \tag{2}$$

Clearly, the half-wave rectifier has half this average output voltage, because half the time the output is zero. Compare with your answer to the first question above.

3 Experiment: Building a DC Power Supply

3.1 12V AC Transformer

Connecting the transformer.Do not plug in the transformer until you are ready to make use of it in part 3. Connect

it to two *tie points* on your perforated circuit board for later use. The tie points are small steel gadgets, and one is shown a little larger than actual size below:

Figure 5: "tie point" that plugs into perf board

You should poke two of them through holes in a corner of your circuit board which are separated by three empty holes, oriented as shown.
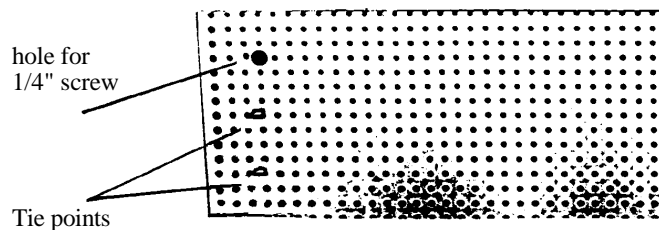

hole for
1/4" screw

Tie points

Figure 6: perf board circuit input points

Now go back and pry the two "leaves" on the upper half apart using something thin like a razor blade. You only need to use two, so don't worry if you chalk a few up to practice.

You also need to add "legs" to your circuit board. Take the four 1-inch aluminum standoffs from bin 7, along with the four 1/4" #4-40 screws. Attach the standoffs to the screws, through the 4 larger holes in each corner of the circuit board. Now the components of the circuits you make can go on the top of the board, and most of the wiring can go on the bottom. The legs reduce the risk of short-circuiting the wiring if you lay the board on a conducting object (like your pliers, or a metal desk-top).

Next, you need to install your fuse holder in series with either one of the transformer wires. Separate the two wires by pulling them apart, and cut one off short to allow for the fuse holder:

Fuse holder

To transformer

Figure 7: stripped wire and fuse holder

It will be easiest if you make the solder joint to the fuse holder by stripping each wire about 1/2 inch, twisting them, making hooks which hold them together, and then tinning and soldering the joint. When you are through, wrap some scotch tape around the exposed solder joint for insulation. This is **NOT** approved insulation for household a.c. or other high voltages, but is OK for your low voltage transformer.

If you'd like to do a classier job, pick up some heat-shrink tubing at help lab: slip this over a wire before you start soldering; keep the tubing at least an inch away from the heated joint. Then, when the joint has cooled, slide the tubing over it, and use the hot iron to heat the tubing *without touching the tubing* (hold the iron as close as you can, but try not to bump the heat-shrink). The heat shrink will conform to the underlying joint.

Having done this, tin the large ends of the tie points, the transformer wire, and the fuse holder wire, and solder the wires to the tie points. Install your two ampere fuse in the holder. You open the holder by twisting it counter-

clockwise; you close it by pushing it closed against a spring when the fuse is in, and then twisting clockwise to lock. If you short the transformer by connecting a conductor, or a diode, across the two tie points, the fuse will protect it by "blowing". A fuse blows when its current rating is exceeded. That is, the little wire in the fuse is made of a special alloy that heats up and melts very quickly when more than the rated current passes through it. The melted wire falls away and the connection between the two sides of the fuse is broken (it becomes an open circuit). If the fuse blows, you can get a new one from the help lab or borrow one from a friend. If you have to live dangerously, remove the burned-out fuse, and push the wires into the fuse holder ends so you can connect them with a clip lead. Now you have no protection, so try not to short your transformer again until you get a new fuse. We replace dead transformers for free, but we'd like to keep the mortality rate low.

3.2 A half-wave rectifier

Review figure 2, which shows a half-wave rectifier smoothed by a capacitor. Your voltmeter's resistance will stand in place of the R shown in that drawing. Make a half-wave rectifier with your high voltage diode, check the circuit and then plug in the transformer and measure the d.c. output voltage. You can use clip leads. On the d.c. setting, your meter reads the average d.c. voltage. Re-measure the rms a.c. voltage at the input (V_{in}), and compare the measured output voltage with what you would expect on the basis of the remarks in the background section.

Scope opportunity: input and output of the rectifier are more interesting if you see the waveforms. An oscilloscope, available in help lab (it comes accompanied by human scope instructor!), will show you those waveforms. Do these *peak* voltages that the scope shows you fit your expectations?

Add the 1000 microfarad filter capacitor across the output of your half-wave rectifier, *being careful to observe the proper polarity*. While most capacitors are symmetric, large-valued capacitors (above about 1 microfarad) usually are *polarized*. This 1000 μF cap is an "electrolytic" type, and is polarized. Electrolytic capacitors contain (as the name would suggest) electrolytic material between the capacitor's plates; the electrolyte can store lots of charge.

"Polarized", here, means that if you apply any DC voltage across the cap, you must observe the indicated polarity. If you get it backwards, you'll almost surely destroy the cap. It's likely to turn into a short, and that result will puzzle you. At its most dramatic, a reversed hookup can make the capacitor explode! The capacitor has a light-colored stripe with <u>minus</u> signs on it, to indicate the lead which should go to the minus side of your rectifier (see fig.9).
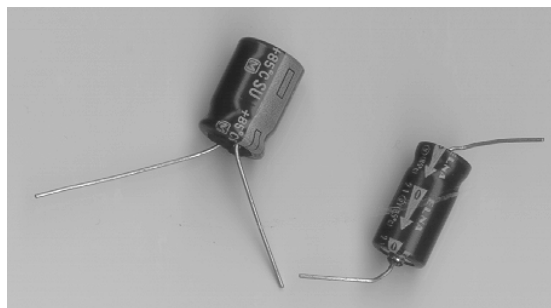

Figure 8: Polarized capacitors

Again measure the d.c. output voltage. Compare with what you would expect.

Another Scope opportunity: Take a look at the effect of the filter capacitor on the circuit output. If you're ambitious, try calculating the expected "ripple", and compare it against what you see.

Here's a note on calculating the ripple:

you need only the formula $I = CdV/dt$, which you'll recall as the dynamic version of $Q = CV$. To use that formula, you need only recognize its elements:

- I is the load current (here, $V_{peak}/R_{in-meter}$);

- dV or delta-V is the *ripple*;

- dt or delta-t is the time during which the capacitor discharges: roughly, the time between recharge peaks coming from the rectifier: here, 1/60Hz, or about 16ms.

For more on designing power supplies, see Horowitz I& Hill, <u>The Art of Electronics</u> (2d ed., 1989), pp. 44-47, 329-330.

3.3   Bridge rectifier

This is the first component of a regulated adjustable power supply you will finish next week. Unplug the transformer. Install your BR86D bridge rectifier (black sugar-cube shaped device with four leads) on the circuit board, sticking its leads through holes from the top side. See the sketch below. Let the + lead be nearest the edge of the circuit board.
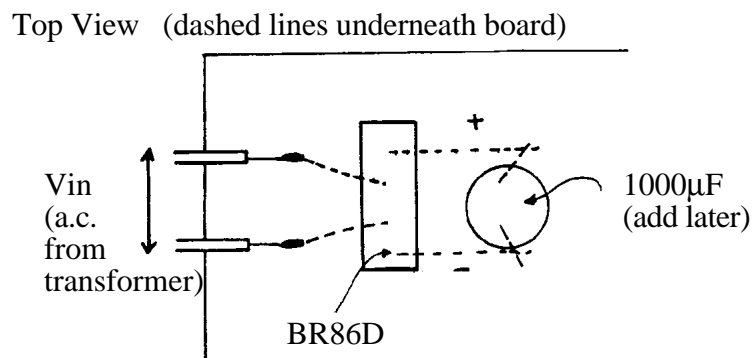

Figure 9: bridge rectifier

Bend each of the a.c leads of the BR86D to a tie point (note the labels on the device), solder them, and cut off the excess. Bend the + and - leads (the outer ones) in the opposite direction and clip to them to measure the output voltage. Plug in the transformer, measure the output voltage, and compare with what you expect.

Scope opportunity: The output waveform shows (vividly!) the improvement that you know the full-wave bridge offers.

3.4   Ripple

Then unplug the transformer and install a 1000 microfarad filter capacitor from the top side, as shown in the sketch above, pushing its leads through holes in the board and bending them to touch the BR86D + and - d.c. output leads. <u>Be sure to get the polarity right</u>. The light-colored stripe has minus signs on it to indicate the lead that goes to the more negative voltage. Then tin and solder the capacitor leads to the BR86D outputs. Plug in the transformer, measure the d.c. voltage, and check against your expectations.

Scope opportunity: The filtered output of the rectifier is dull on a scope–until you add a "load" so that ripple

reappears. Try that: use the smallest resistor you can get away with. Recall that the heating power of the output is now more than V_{rms}, which was its value before rectification. Now you need to consider V_{peak} across R_{load}. The most convenient *power* formula probably is $P = V^2/R$.

With a substantial load R discharging the filter capacitor, you should see ripple revealing the full-wave shape of the rectifier's output, as in the sketch in fig.11 of these lab notes.

If your measurements of the output voltages are systematically different from the values you expect, you should think about why that might be.

Recalling Ripple calculation, for Filtered Full-wave rectifier

Question 3: Below is a sketch showing the full-wave rectifier with the 1000μ F capacitor attached.
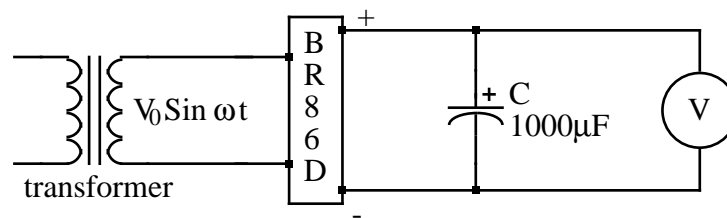

Figure 10: full-wave rectifier with filter capacitor

The expected value of the output voltage is V_0 (remember you have measured this value), if we neglected the small ripple due to the capacitor discharging between the 120Hz rechargings. Now that you can calculate V as a function of time, find an estimate of the amplitude of the ripple: that is, How much would you expect the voltage to drop if the resistance of the voltmeter is $500\,\mathrm{k}\Omega$, as it is on the 25V scale? The calculation is useful as a warmup, but this experiment is not gratifying to run, using either scope or multimeter: you are likely to find the ripple too small to measure.
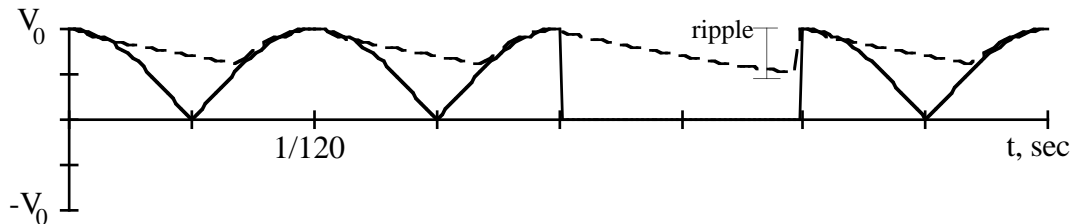

Figure 11: recapitulation of ripple calculation

We encourage you to save yourself a good deal of effort by using a couple of helpful approximations:

- rather than use the exact truth that the capacitor's *discharge* current decays exponentially, assume that the capacitor's current is constant (at the value of $V_{\mathrm{max}}/R_{\mathrm{load}}$);

- assume that the capacitor discharges for the full 1/120Hz time between rectified peaks.
  These approximations will lead you to overestimate the ripple slightly. But since ripple is not desirable, no one will get sore at you for delivering a circuit that works a little better than advertised!

Measurable Ripple

Now let's put on a heavier load–one that will evoke measurable ripple. As load, use the automobile lamp in your parts kit–the large bulb with *two* contacts on the end of its base. If you haven't done so already, solder a lead to each of these contacts, and a third lead to the brass casing.

Check resistance between the brass casing and each contact, using your ohmmeter. We want to use the contact that evinces the larger resistance. Now *load* your circuit with that lamp (across the 1000 microfarad cap).

Measure Ripple

Does your voltmeter reveal ripple? If so, how does it reveal it to you? Could you infer the ripple's magnitude from the change in the voltmeter's reading when you attach the load?

This is a fine **Scope opportunity:** the scope can show you the shape and magnitude of the ripple.

Calculate Ripple

Calculate the ripple that you would expect, if you assume that the lamp's resistance (warm) is around $35\ \Omega$. Is the result of this calculation consistent with your estimate of *observed* ripple? If not, which of our assumptions do you suppose contributes the largest error? (It's probably impossible for you to answer this question unless you happen to have looked at the waveform with an oscilloscope; so, if you haven't done that, don't worry about this question. You *are* permitted, however, to feel guilty for not having been curious enough to try using the scope.)

PROPAGANDA recapitulation: We Hope You'll Watch Ripple on a Scope This ripple waveform, like all time-dependent effects, is much more interesting when seen on an oscilloscope than when seen as a stationary needle-deflection. We hope many of you will take the chance to see both the sine wave input and the full-wave rectified output of the bridge on a scope. Once you have seen that, we think you'll agree that when you watched this behavior on meter alone you were seeing it only through a glass darkly.