# 1

# Diode Circuits

In this lab we will measure the I-V characteristics of diodes and LEDs and learn how to establish a desired bias condition (forward conduction current) using resistor networks. We will also construct several common diode circuits such as limiters, rectifiers, and voltage doublers, as well as some simple logic gates.

## Table of Contents



# Pre-lab Preparation

### *Before Coming to the Lab*

Read through the lab experiment to familiarize yourself with the components and assembly sequence. Before coming to the lab, each lab group should obtain a parts kit from the ECE Shop. If you have not yet done so, remember to purchase a soldering iron (one for each group) stand, and roll of solder, as well as small tools (wire cutter/stripper, needle-nose pliers, screwdriver, etc.). Beginning in 2007, all ECE labs will use lead-free solder, and this requires a somewhat more expensive soldering iron.

### *Parts List*

The ECE2 lab is stocked with resistors so do not be alarmed if you kits does not include the resistors listed below.

| Laboratory #1 | |
|---|---|
| **Diode Circuits** | |
| | |
| **Qty** | **Description** |
| | |
| 2 | LED, Green diffused, 5mm (T1 3/4) 20mA |
| 2 | LED, Red diffused, 5mm (T1 3/4) 20mA |
| 2 | 1N4148 Switching Diodes |
| 2 | 1N400x Rectifier Diodes |
| 1 | LF351 op-amp |
| 2 | 0.1uF capacitor (CKO5 low-volt. Ceramic) |
| 2 | Electrolytic Capacitors 1uFd / 50V, \| Radial \| |
| 2 | Electrolytic Capacitors 10uFd / 50V, \| Radial \| |
| 2 | Electrolytic Capacitors 100uFd / 25V, \| Radial \| |
| 2 | 100 Ohm 1/4W, Resistor |
| 4 | 470 Ohm 1/4W, Resistor |
| 4 | 1K Ohm 1/4W, Resistor |
| 2 | 10 Kohm 1/4W, Resistor |
| 2 | PC Mount Tactile push-buitton switch (PB1) |

# Background information

Diodes allow current to flow in one direction only, effectively an electronic "one-way street". Unlike resistors, capacitors, or inductors, the inherent asymmetry of diodes requires that we distinguish between the two ends of the device. One end is called the *anode* (from Greek *anodos* meaning upward path) and the other is the *cathode* (from the Greek *kathodos* meaning "downward path"). The diode conducts when the anode is biased positively with respect to the cathode. The term *diode* (literally "two paths" but often taken to mean "two electrodes") always refers to devices that have this one-way characteristic. The term originated in the context of vacuum tubes[1] where the cathode was a heated tungsten filament, and the anode a positively-biased conducting plate for collecting electrons that boil off the cathode. As you might guess, a vacuum-tube "triode" then has three plates, a "pentode" has five, etc. Semiconductor diodes always include special marks on the packages to help identify the leads, as shown in Figure 1-1. The circuit schematic symbol forms an arrow that points in the direction of current flow when the anode is biased positively with respect to the cathode, the "forward conduction region".

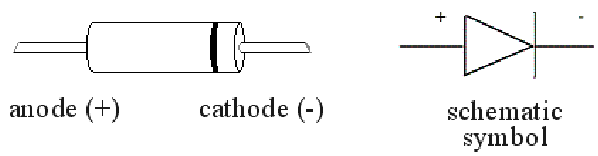



Figure 1-1 – A typical wire-lead diode package with identifying mark, and schematic symbol.

### *Current-Voltage Characteristics and Modeling*

The current voltage characteristic of a typical semiconductor diode is shown in Figure 1-2 (you will learn the detailed physics of semiconductor diode operation next year in ECE132). Above the forward threshold voltage $V_t$ the current increases exponentially. Under reverse bias only a tiny reverse saturation current flows until breakdown is encountered at which point the current increases rapidly as shown.

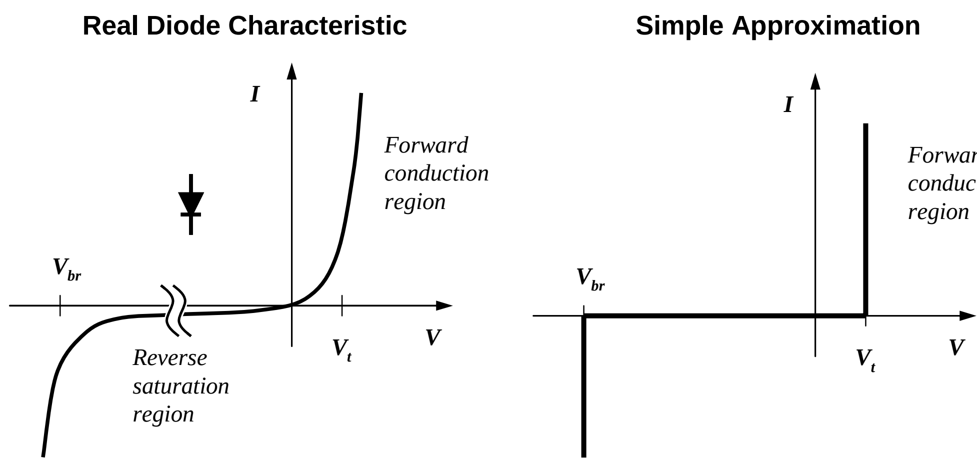



Figure 1-2 – Diode *I-V* characteristic and simple approximation for DC analysis. Note that the reverse saturation current is exaggerated for clarity, and the reverse breakdown voltage $V_{br}$ is usually much large than the forward turn-on $V_t$.

[1] Apparently the term "diode" was coined by British physicist William Henry Eccles in 1919 [1]

A mathematical model for the I-V characteristics of most semiconductor diodes is

$$I = I_s\left[e^{qV/nkT} - 1\right] \qquad (1.1)$$

where $n$ is the ideality factor, $I_s$ is the reverse saturation current, and $kT/q \approx 26$ mV at room temperature.

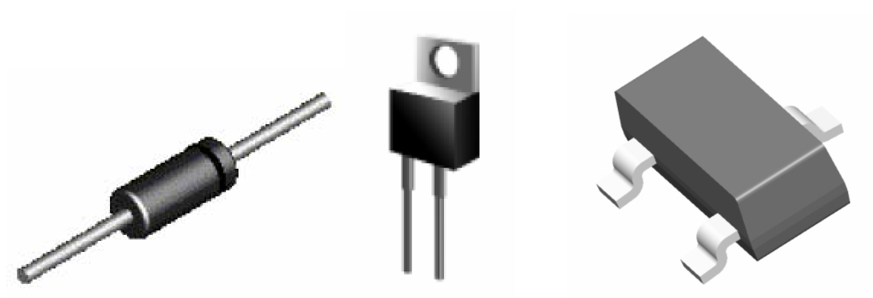
In most circuit analyses we can often get by with a much simpler phenomenological model that treats turn-on and breakdown as abrupt transitions, and neglects the reverse saturation current. In this case there are basically three parameters that describe the operation: $V_t$, $V_{br}$, and the maximum current that the device can sustain during operation. In later work (2C and 137AB) we will add to this model to account for some additional affects that are relevant to high-speed operation

The impact of these model parameters varies with application. For example, in the AM "crystal" radio that you built in ECE2A the signal levels are very small so a diode with a small turn-on voltage is desirable. In a power-supply application, devices that can sustain large forward currents and reverse voltages are often preferred.

The turn-on voltage is largely governed by the choice of semiconductor material and the device design. Silicon-based PN junction diodes have threshold voltages of ~0.6-0.8V; Germanium diodes have $V_t \approx 0.2\,\text{V}$. The current-handling capacity is often limited by thermal considerations (too much current and/or poor heatsinking and the device can be destroyed) but this can be manipulated by geometrical factors such as the device cross section, so devices of various sizes with a wide range of current-handling capacities are available.

### *Diode Selection*

In this lab we will use two types of diodes: the 1N4148, and one selected from the 1N400x family (x is a number between 1 and 7).[2] These are very common and inexpensive parts. In fact, if you look up the 1N4148 on the web you will see that they are so cheap that the suppliers make you buy them in packages of ten at a minimum.



(a) (b) (c)

Figure 1-3 – Some common diode packages: (a) DO-35/DO-41 axial-lead package ("DO=diode outline"); (b) TO-220 through-hole ("TO=transistor outline"); (c) SOT-23 surface-mount package ("SOT=small outline transistor"). Package name conventions describe the resulting physical footprint on a PCB board, not necessarily the electrical function.

[2] Any part number beginning with "1N" is *always* a diode. However, not all diode part numbers begin with "1N"!

The 1N4148 is usually listed under the heading of "small-signal diodes" or "switching" diodes. The 1N400x is usually listed under the heading of "rectifier" diodes. What is the difference between the two? The key difference is in their voltage and current handling capability. Look at the data sheet for each (on the course web site): the 1N4148 can handle currents of up to 300 mA and peak reverse voltages of 75V, and the 400x can handle up to 1A and voltages ranging from 60V (1N4001) to 1200V (1N4007). So the 4148 tends to be used in applications where the currents are small, for example in an audio amplifier circuit. The 400x, on the other hand, is designed for abuse and is a good choice in power-supply applications. There are lots of other diodes available on the market; this discussion is just intended to make you aware that diode selection involves a number of considerations beyond threshold voltage. Often packaging and availability are important considerations too.

On the subject of packaging, the parts we use in ECE2 are "wire-lead" parts designed for "through-hole" mounting, as opposed to "surface mount" parts which have tiny leads or sometimes no leads at all. A few popular diode packages are shown in Figure 1-3. Through-hole parts have wire leads that are design to poke through a PCB board. These are great for educational and important for some legacy circuits, but nowadays most electronics is designed for tiny surface-mount parts and automated assembly.

### Light-Emitting Diodes and Displays

Light emitting diodes (LEDs) are diodes made with direct bandgap semiconductors (GaAs, GaN, etc.) and designed to generate light when enough current passes through the device. LEDs are functional similar to any diode, but they typically have a much larger threshold voltage (~2V for red and green LEDs, and upwards of 4V for blue and white LEDs). The packaging is also necessarily different, with a variety of sizes and lens configurations for various display requirements. In addition to the maximum forward current $I_f$ and the forward voltage drop $V_f$, the brightness is obviously an important factor and is specified in units of millicandela (mcd) at some forward current level.

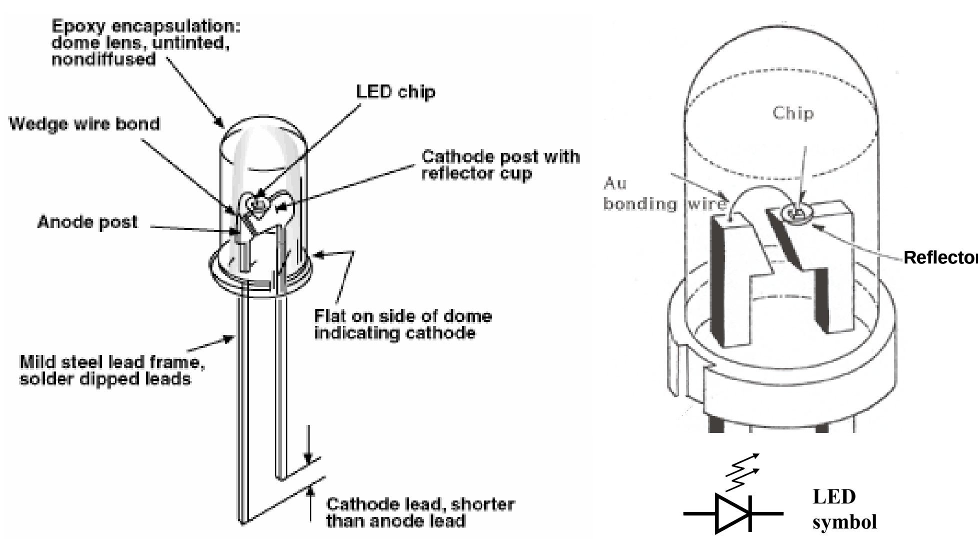
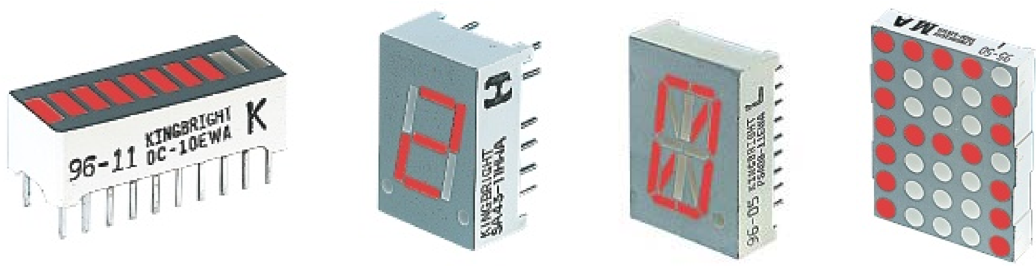



Figure 1-4 – Anatomy of a plastic 5mm diameter (T1¾) LED.

As a practical note, the cathode leg of the LED is the shorter of the two, as shown in Figure 1-4. If for some reason the two legs have been cut to the same length, you can often tell which is which by looking inside the device through the side of the plastic lens: the cathode leg is the one connected to the big piece of metal on which the diode chip is mounted. On circuit schematics, LED symbols are the same as a regular diode with little arrows to suggest light emission, and occasionally the color is printed beside the symbol if relevant.

LEDs are used in lots of applications and come in a variety of packages. Standard wire-lead LED packages like those in Figure 1-4 are usually organized by the diameter of the lens and its color. The most common package sizes are 3mm (T1) and 5mm (T1¾). LEDs are also available in some very tiny surface mount packages. LED *displays* include multiple LEDs arranged in a fixed pattern with shaped lenses, the most familiar pattern being the 7-segment displays for showing numbers (digits 0-9). Figure 1-5 illustrates some of the popular designs. You will use some 7-segment displays in ECE2 and later in ECE 152A.




(a) (b) (c) (d)

Figure 1-5 – A few common LED-based displays. (a) Bargraph; (b) 7-segment; (c) Starburst; (d) Dot matrix.

## References

[1] On diodes: http://en.wikipedia.org/wiki/Diode

[2] On LEDs: http://www.kpsec.freeuk.com/components/led.htm

[3] Interesting discussion on digital logic: http://www.play-hookey.com/digital/

[4] A useful site on voltage multipliers: http://www.play-hookey.com/ac_theory/ps_v_multipliers.html

# In-Lab Procedure

Follow the instructions below CAREFULLY.

- □ Each critical step begins with a check box like the one at the left. When you complete a step, check the associated box. Document your results with each step for inclusion in your lab report.

## 1.1 Diode I-V Curves and Biasing

### *Diode Forward I-V Characteristics*

- □ Using the 1N4148, set up the circuit in Figure 1-6 using the DC Power Supply as the voltage source. You can use your hand-held DMM (or the oscilloscope) to measure the diode voltage, and use the bench DMM as the ammeter.
- □ Adjust the power supply output until the Ammeter (the DMM measuring current) reads a current of 10µA through the diode. Record the voltage drop across the diode at this current.

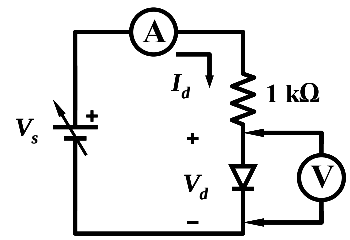


Figure 1-6 – Circuit for diode I-V measurements.

- □ Repeat for 20µA, 50µA, 0.1mA, 0.2mA, 0.5mA, 1mA, 2mA, etc. up to 20mA. You will plot this data in your lab report as described below. How much does the forward voltage drop change for a factor of 10 change in current ?
- □ Record I-V curves for both the 1N4148 and the 1N4005 using the procedure above.

In your lab report,use Excel to generate a nice I-V curve, and fit your data to the exponential function (1.1) to determine the ideality factor and saturation current. (Note: a handout is posted on the web explaining how to use Excel if you are not familiar with the program.)

### *Diode Biasing*

Your measurements will have demonstrated that the forward voltage drop does not change much over a large range of currents, so we can safely assume a constant drop for bias circuit calculations.

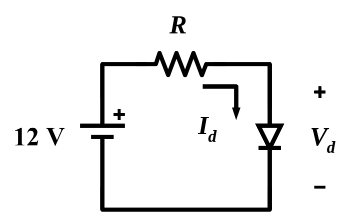


Figure 1-7 – Simple diode bias circuit

- □ For the circuit in Figure 1-7, determine the value of resistance that will give a diode current of ~10mA, assuming a diode forward drop of 0.7V. Choose the nearest value resistor you can find and verify your design for both the 1N4148 and 1N4005.
- □ Now do the same for the Red and Green LEDs: find a bias resistor that will give a forward current ~20mA, assuming a forward drop of ~2V. Verify your design by recording the actual current and voltage in the circuit. Is this current sufficient to generate a reasonable level of brightness for the LED?

### *Diodes in Series and Parallel*

Since forward-biased diodes have a relatively constant voltage drop, series combinations are sometimes used in circuits to shift the DC level up or down by a fixed amount. Consider the circuit in Figure 1-8; can you predict the output voltage?

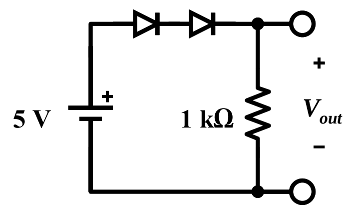



Figure 1-8 – Series-connected diodes

- □ Construct the circuit in Figure 1-8 using 1N4148s or 1N4005s, and record the output voltage in each case. Decrease the resistance in the circuit by a factor of two by adding an identical resistor in parallel; record the output voltages again.
- □ Figure 1-9 shows another circuit with series-connected diodes. What is the output voltage this time? Construct using 1N4148s and 1N4005s (leave out the load resistor $R_L$ for now), and record the output voltage. Vary the supply voltage ±2V and record how much the output voltage changes.

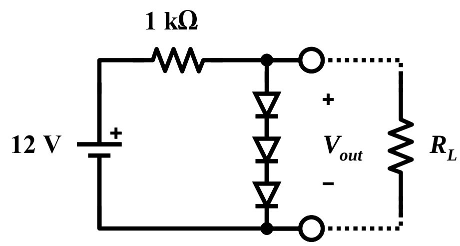



Figure 1-9 – Series clamp.

It is important to remember that diodes only maintain the ~0.7V forward voltage drop if the circuit permits enough current to flow through them. In the two circuits you just constructed, the bias resistors were chosen to insure proper operation.

- □ Using the decade box at your bench, place a load resistor across the output of the circuit as shown in Figure 1-9. Starting with a load resistance of 1kΩ, steadily decrease the resistance until the output voltage deviates by more than 20%. Can you understand what is happening? For large load resistance the diodes "clamp" the output at 3 forward voltage drops, but at some critical load resistance this is no longer possible, and the circuit behaves more like a resistive voltage divider.
- □ Naturally you can cascade LEDs in series too, they just have a larger threshold voltage and often need a specific minimum current for good visibility. In the circuit of Figure 1-10, what supply voltage is required to keep the devices biased at ~15mA? Build the circuit to verify your prediction.

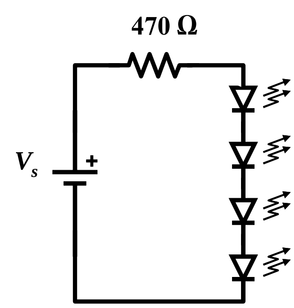



Figure 1-10 – LEDs in series

Using diodes in parallel as shown in Figure 1-11 is not commonly done. You might think this topology would be useful for splitting a large current among devices with small current handling capacity, but unless the diodes are very well matched, one device ends up carrying most of the current. This is because the diode current depends exponentially on the ideality factor and temperature, so small changes in device or environmental parameters can lead to rather large changes in current from one device to the next. As a general rule ***diodes or LEDs in parallel each one should have its own bias resistor.*** An exception is within an integrated circuit where we can

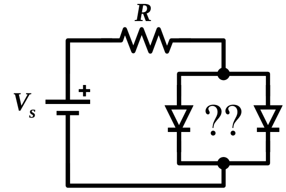
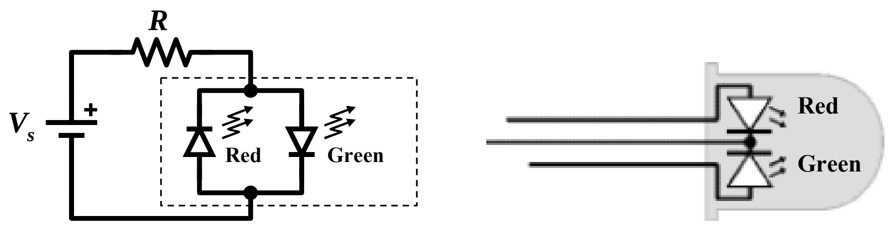



Figure 1-11 – Some issues here.

often count on the devices being well matched, but even in that case it is probably better to simply use one large diode than a bunch of smaller ones in parallel..

On the other hand, there is some merit to the use of *anti-parallel* diodes, that is, diodes that are in parallel but with an opposite orientation of cathodes. We will build a limiter circuit that uses this approach later. Figure 1-12a shows the use of antiparallel LEDs to create a polarity indicator, which gives a visual display of the polarity of the supply voltage. Such devices are packaged and sold as "bi-color" LEDs. A variant of this idea is the bicolor/tri-state LED shown in Figure 1-12b; this three terminal device includes two LEDs of different color that can be switched on and off independently.




(a) (b)

Figure 1-12 – (a) A current polarity indicator using two LEDs (dashed box represents a part packaged and sold as a "bi-color" LED). (b) Configuration for bi-color/tri-state LED.

## 1.2 Diode Logic

In ECE 15A you should be starting to learn about combinational logic. Devices that implement various binary logic functions (AND, OR, NOT, etc.) are called "logic gates" and are the basic building blocks of all digital electronics. In this section of the lab, you will build two simple logic gates using diodes. In doing so, you will quickly realize why nobody builds logic gates this way!

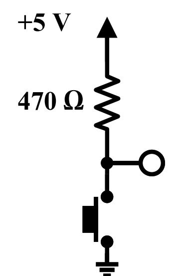
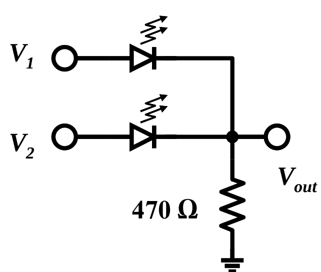



Figure 1-13 – Circuit to generate logic levels.

In binary logic there are two states, implemented electronically with two different voltages, a "High" voltage state and a "Low" voltage state. The voltages vary with logic family, although the low state is almost universally ground (0 Volts). In this lab we'll take the high state to be +5V. So a binary "0" is represented by voltages near zero volts, and a binary "1" is represented by voltages near +5 Volts. The simple switch circuit in Figure 1-13 can be used to generate the logic high and low states.

□ Build two of the switches in Figure 1-13 and construct the circuit in Figure 1-14; ordinary diodes would be fine here but using LEDs is more interesting and also highlights one of the problems with this kind of logic circuit (the diode voltage drop).

□ Before the next step, contemplate how you will decide whether a certain output




Truth Table

| $V_1$ | $V_2$ | Vout |
|---|---|---|
| 0 | 0 | |
| 0 | 1 | |
| 1 | 0 | |
| 1 | 1 | |

Figure 1-14 – A diode logic gate. Fill out the truth table based your measurements: what kind of gate is this?

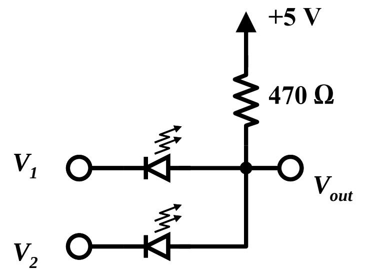
voltage is "high" or "low"; for example, is +2V high or low? Is 0.5V high or low? There must be some threshold for making an unambiguous decision.

- □ With two logic inputs $V_1$ and $V_2$ there are clearly four possible permutations of high and low inputs. Using the DMM, record the output voltage for each of the four combinations of inputs on a truth table like that in Figure 1-14.

You can immediately appreciate the critical problem with simple diode logic gates: as the signals travel through the gate, the high-state becomes corrupted by the diode voltage drop. For a single gate this is not a problem, but cascading gates would clearly be difficult. Eventually the high state becomes indistinguishable from the low-state.

The gate in Figure 1-14 implements the logical "OR" function, since the output goes high whenever one OR the other input is high (or both). Another gate is shown in Figure 1-15, what kind of gate is this?

- □ Build the circuit in Figure 1-15 and make a truth table to describe its function.




Truth Table

| $V_1$ | $V_2$ | **Vout** |
|---|---|---|
| 0 | 0 | |
| 0 | 1 | |
| 1 | 0 | |
| 1 | 1 | |

Figure 1-15 – Another diode logic gate. Fill out the truth table based your measurements: what kind of gate is this?

*For your lab report*: can you think of a way to make an inverter with diode logic (an inverter performs the logical NOT operation, where a high input gives a low output, and vice versa). Hint: the answer to this question is another strike against diode logic!

## 1.3 Clipping Circuits and Rectifiers

### *Clippers or Limiters*

Thus far we have been working with DC signals, let's switch gears now to AC signals. Consider the circuit in Figure 1-16 with a sinusoidal input voltage. If the signal exceeds the diode forward voltage drop, the diodes will conduct and clamp the output to ±0.7V. This is sometimes called a "clipper" circuit because the tops of the sinusoidal waveforms (signals exceeding 0.7V in magnitude) appear to be clipped off. It is also called a "limiter" for obvious reasons. This is useful in some applications, for example at the input of a sensitive high-gain amplifiers where the input signal needs to be limited to prevent overdriving the amplifier.

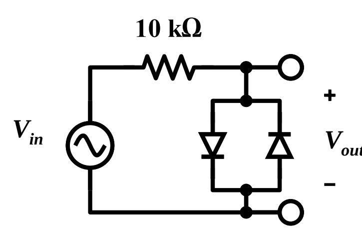



Figure 1-16 – A simple bipolar limiter

- □ Construct the circuit in Figure 1-16 using the 1N4148s.
- □ Set the function generator to produce a 4VPP (peak to peak) sine wave at a frequency of 400Hz to drive the circuit.
- □ Set up the oscilloscope to measure $V_{in}$ on CH1 and $V_{out}$ on CH2

□ Record/sketch the input and output voltages shown on the oscilloscope. (Make sure you align the axis of CH1 with the axis of CH2 and use identical vertical scales.) Label your graph and note the maximum and minimum values of the input and output signals.

### *Half-Wave Rectifier*

If we flip the resistor and diode around we get the configuration shown in Figure 1-17. When driven by a sinusoidal signal this is called a half-wave rectifier. Put it together on your breadboard using a 1N4005:

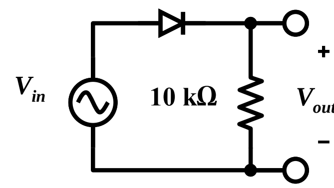



Figure 1-17 – Half-wave rectifier

□ Set the function generator to produce an 8VPP sine wave at a frequency of 400Hz.

□ Set up the oscilloscope to measure Vin on CH1 and Vout on CH2. Record/sketch the input and output voltages shown on the oscilloscope. (Make sure you align the axis of CH1 with the axis of CH2.) Label your graph and note the maximum and minimum values of the input and output signals. You should observe something like the waveforms shown in Figure 1-18.

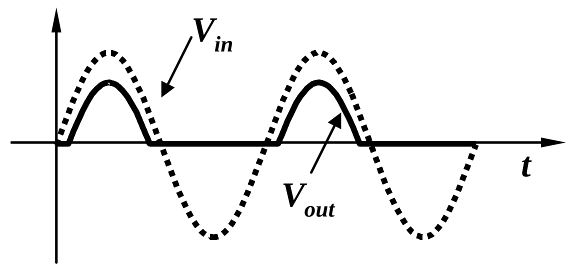



Figure 1-18 – Input and output waveforms for a half-wave rectifier

□ Decrease the amplitude to 2V p-p: do you see evidence of the diode forward voltage drop? Describe.

"Rectifier" is an old term that describes the process of converting AC signals into DC. It may not be obvious that this is happening, but by allowing only positive voltages to pass through, a waveform with an average DC level is produced. The most common use of rectifiers is in DC power supplies, but you also used one in the construction of your AM radio. Figure 1-19 shows another use of a rectifier as a simple dimmer in a lighting circuit.

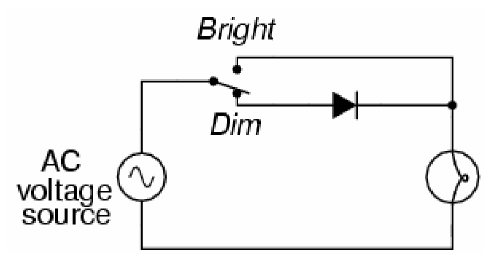



Figure 1-19 – Using a rectifier diode to implement a simple dimmer switch for a lighting circuit.

### *Capacitive Smoothing*

In DC supplies, we need to smooth out the rectified AC signal to obtain a signal that more closely resembles a constant output voltage. This can be done with a capacitive load.

□ Connect a 1μF capacitor across the circuit output (parallel to the 10kΩ resistor). ***Be sure to hook up the capacitor with the correct polarity!!*** How does the waveform change? Explore the influence of frequency on the waveform. Can you explain the results in terms of the RC time constant of the load?

□ Repeat with a 10uF and 100μF capacitor. Describe the results..

### *Full Wave Rectifier*

By adding two more diodes as in Figure 1-20 we can make a circuit that gives a positive output for all parts of the input waveform, as shown in Figure 1-21.

You do not need to build this circuit here, because we will return to it in the next lab where we will build a linear power supply. If you have time after completing this lab, you might find it instructive to build the full-wave rectifier using LEDs and driving it with a very low frequency input signal; the diodes will then light as they conduct, effectively illuminating the current path on each part of the AC cycle. Notice one rather important point about the full-wave rectifier: the input and output voltages do not share a common reference!

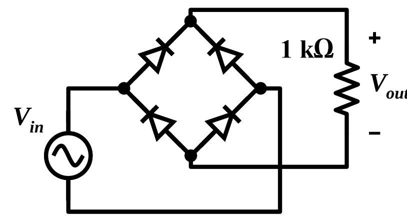



Figure 1-20 – Full-wave rectifier.

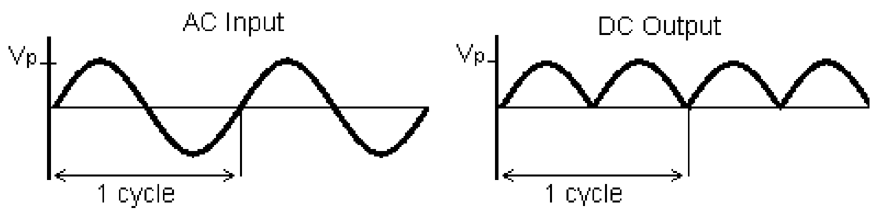



Figure 1-21 – Waveforms for a full-wave rectifier.

## Voltage Multipliers

### *DC Restorer Circuit*

If we take a half-wave rectifier with a capacitive load and switch the diode and capacitor around, the circuit of Figure 1-22 results. The behavior of this circuit is a little less obvious than some of the previous circuits; here the diode clamps the output so that it can never fall more than a diode drop below ground. For AC inputs that vary between $\pm V_p$, the output signal will then vary between ~0V and $2V_p$. The output signal is a level-shifted version of the input signal. This is called a DC restorer circuit. Set up the circuit using the 1N4005 (be sure to use the correct polarity on the capacitor!).

- □ Set the function generator to produce an 8VPP sine wave at a frequency of 400Hz.
- □ Set up the oscilloscope to measure Vin on CH1 and Vout on CH2
- □ Record/sketch the input and output voltages shown on the oscilloscope. (Make sure you align the axis of CH1 with the axis of CH2.) Label your graph and note the maximum and minimum values of the input and output signals.

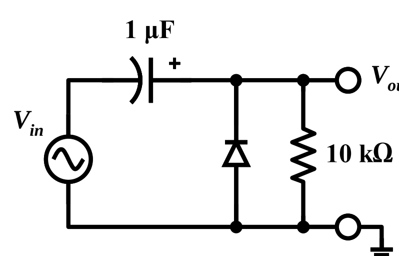



Figure 1-22 – DC restorer

### *Voltage Doubler*

How can we use the DC restorer? Well, if we follow it by a half-wave rectifier, then we should end up with twice the DC voltage that we obtained earlier! Let's try this: construct the circuit of Figure 1-23 using 1N4005s and the 1uF capacitors. Note the large load resistance.

- ☐ Set the function generator to produce an 8VPP sine wave at a frequency of 400Hz.
- ☐ Set up the oscilloscope to measure Vin on CH1 and Vout on CH2
- ☐ Record/sketch the input and output voltages shown on the oscilloscope. Label your graph and note the maximum and minimum values of the input and output signals. Of particular interest is the value of the output DC voltage relative to the peak AC input; compare this with your capacitively loaded half-wave rectifier earlier.
- ☐ Decrease the load resistance to 1kΩ; is there a degradation in the output voltage? If so, can you compensate by increasing the capacitance in the circuit?

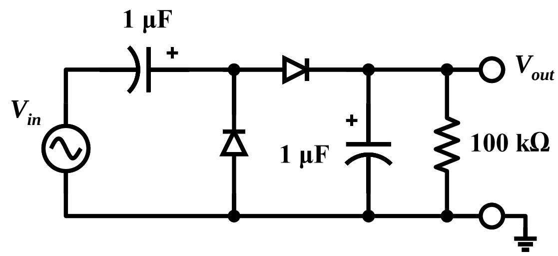



Figure 1-23 – Voltage doubler circuit.

### *Voltage Multipliers*

By cascading voltage doublers we can continue to increase the output voltage; this is illustrated in Figure 1-24.

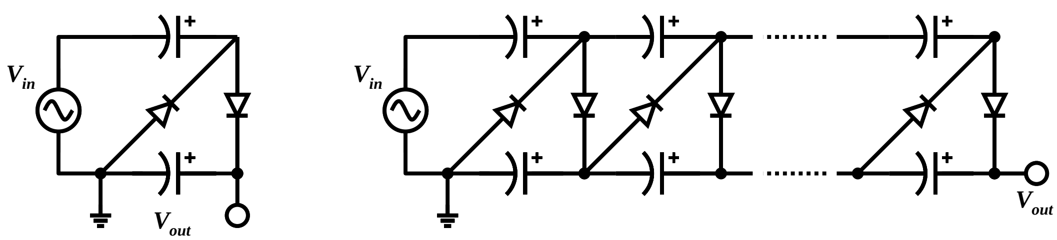



Figure 1-24 – (a) The voltage doubler of Figure 1-23, just drawn differently. (b) A cascade of *N* doublers, yielded an output voltage of $2NV_p$.

Just as a point of interest I've included a picture of a real circuit that exploits this technique, shown in Figure 1-25. This is sold as an "ion generator" kit. It uses a cascade of 15 voltage doublers. With a 120VAC input (120V rms = 170V peak) this circuit generates over 5000 V! When applied to the "comb" of five thin electrodes shown at the top, the resulting high fields can ionize the air around the electrodes. This kind of circuit finds use in static-sensitive work environments since it generates charges that can neutralize other charged objects or surfaces. Ionized air is also purported to have health benefits, but this is not supported by sound scientific evidence.

Figure 1-25 – An "ion-generator" circuit using a cascade of 15 voltage doublers. This circuit generates >5kV with a 120VAC input!