Laboratory 10: Diodes

Concept

Diodes are extraordinarily useful simple pn junction devices which exhibit highly nonlinear I versus V curves. Among the many types are small signal Si and Ge diodes, high power diodes, Schottky-barrier diodes, tunnel diodes, Zener diodes, silicon controlled rectifiers, varactors, light emitting diodes, laser diodes and photodiodes. Analysis of the $I(V)$ curve and and its dependence upon temperature and exposure to light provides insights into the underlying physics. Among the important applications are half-wave and full-wave bridges, the peak detection circuit, RF detectors, sensitive light detection, thermometry, lighting and optical communications.

Helpful hints and warnings

Diodes can be destroyed when the internal temperature of the pn junction excedes 150°C. Thus, the dissipated power $P = IV_d$, where $V_d \simeq 0.7$ V is the forward-biased potential across the diode, must be kept below the specified limit. Including a current-limiting resistor in series with the diode will prevent overheating. For example, using a potential of 10 V across a series combination of a diode and a resistor for a diode capable of withstanding a maximum of 20 mA would require a resistance of at least 10 V /20 mA = 500 Ω .

Experimental Instructions

I. Diode Equation Measurements of Si, Schottky-Barrier, Zener and Light-Emitting Diodes

The current through a diode as a function of the potential applied across the diode V and temperature T depends upon two parameters: $I_\circ$ called the saturation or reverse-bias current current and an effective carrier charge q. The functional form is

$$I(t) = I_\circ(T)\left(e^{qV(t)/kT} - 1\right) ,$$

where k is Boltzmann's constant. This is called the *diode equation*. Note that $V(t)$ is the potential across the diode, not the potential across a circuit of which the diode is only a part. Also, note that $I(t)$ is the diode current in the time domain with the assumption that it is varying slowly with respect to the time scale of the internal response of the diode.

As $V(t)$ increases above 0, $I(t)$ grows rapidly. The maximum current from the specification sheet is on the order of 1 amp, but in the circuit below the current is limited by either the value of R_f or the maximum current provided at the output of the op amp. Thus, $V(t)$ can never be much more than 0.7 V. As for negative values of $V(t)$, the limit from the specification sheet is of the order of 80 V, unless a Zener diode is the device under test (DUT). Thus, $V(t)$ should be an asymmetric bipolar ramp from a function generator.

The experimental goal is to build a circuit to accurately measure I and V without incurring significant errors from the input offset potential and input bias current of the op amp. Then, the quantities $I_\circ(T)$ and q can be determined for small signal Si diodes, Schottky-barrier diodes, Zener diodes and LEDs can be determined. The reverse current $I_\circ$ is a function of temperature, the bandgap of the material, doping levels and other parameters. The effective charge q is a function of the bandgap, dopants and other parameters.

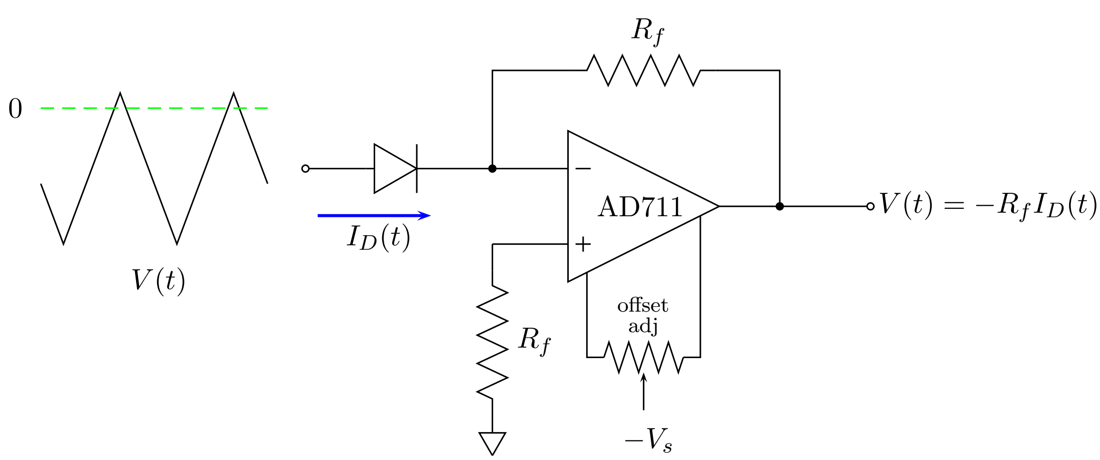


Figure 1: Measuring the behavior of a diode with an asymmetric bipolar ramp signal and a transimpedance amplifier.

Since $I_\circ \approxeq 10^{-9}$ A, R_f will need to be 1 MΩ or more when the diode is reversed-biased. However, to measure as much as of the forward-biased behavior as possible, R_f should be much smaller but greater than $(V_s - 2)/I_{max}$, where I_{max} is the maximum current that can be provided by the op amp.

a. Derive the expression for V_{out} in terms of I_D with and without R_f on the noninverting input. Include V_{io}, the input offset potential, and I_b, the input bias current, both of which are zero-frequency or DC effects. The problem with adding R_f is that the potential V_- is no longer zero but rather $-R_f I_b$, so the potential across the diode would then be $V + R_f I_b$. This will be of little significance if $R_f I_b << V$. Without the second R_f in the circuit, $V_- = 0$ but $V_{out} = -R_f (I - I_b)$. This is of no consequence if $I >> I_b$.

b. Build this circuit using a TL071C, AD711 or LF356 op amp, all of which have an input resistance > 1 GΩ . Choose the values of R_f to satisfy the experimental goals. Set up the function generator to deliver the asymmetric bipolar ramp signal at a low repetition rate of about 100 Hz. Use DC coupling on both channels of the oscilloscope, and trigger the oscilloscope with the TTL ouput of the function generator. Observe the signals in both yt and xy modes. Use the data acquisition program to record V and V_{out} traces, and save the plots and the data. Remember to maximize the signal to noise ratio by using the entire digitization range on the oscilloscope and averaging over multiple sweeps.

c. Begin with a small signal Si pn junction diode in a glass envelope. Using $R_f \approxeq 10$ MΩ , focus on the reverse current first. Measure room temperature ($T \approxeq 293$ K) using an AD590, record V and V_{out} and determine $I_\circ(293\text{ K})$. Then, using the smaller value of R_f , record V and V_{out} and solve for q. Take the same data when the temperature is about 230 K using a cup with dry ice and an AD590 temperature sensor. Determine $I_\circ$ and q. Interpret the temperature dependence of these two quantities. Plot the experimental and theoretical $I(V)$ curves using these values, and discuss any deviations.

d. Increase the ramp repetition rate and determine at what rate the diode behaves in a significantly different fashion. Also, try a sine waveform at 100 Hz and beyond. Explain the low and high frequency behaviors.

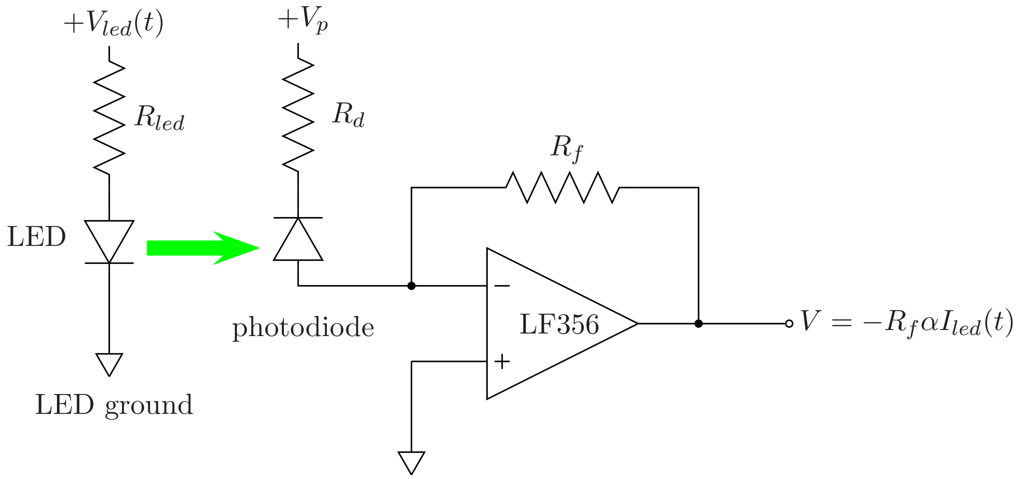
e. Use a magnifier to see the pn junction. At room temperature, apply a constant reverse bias of about -10 V and shine light from an LED flashlight on the pn junction. Try to measure a change in $I_\circ$ using the largest value of R_f . Interpret your results.

f. Determine $I_\circ$ and q for a Schottky-barrier diode and an LED at room temperature. Plot the experimental and theoretical $I(V)$ curves using these values, and discuss any deviations. Explain the observed differences among the three types of diodes.

g. Record the $I(V)$ curve for a 5 V Zener diode and discuss the observed behavior.

II. Detection of an LED Signal with a Photodiode

An optical signal from an LED, whether oscillatory or constant, can be detected over a considerable distance using a photodiode and a transimpedance amplifier. Since the transmitting and receiving circuits need not have power sources or a ground in common, they are said to be *optically isolated.*



a. Build this circuit being careful to limit the current through the LED to 15 mA or less. The LED should be a high brightness type. Several types of photodiodes are available, with areas ranging from 0.1 mm^2 to 25 mm^2. The optical power detected is proportional to the area, so the larger area devices are more sensitive, but they exhibit more dark current. Apply a bias of -5 to -10 V, that is, operate the photodiode in the reverse-bias regime.

b. Record the dark current from the photodiode. The photodiode detects room lights, so shield it with a tent of black paper.

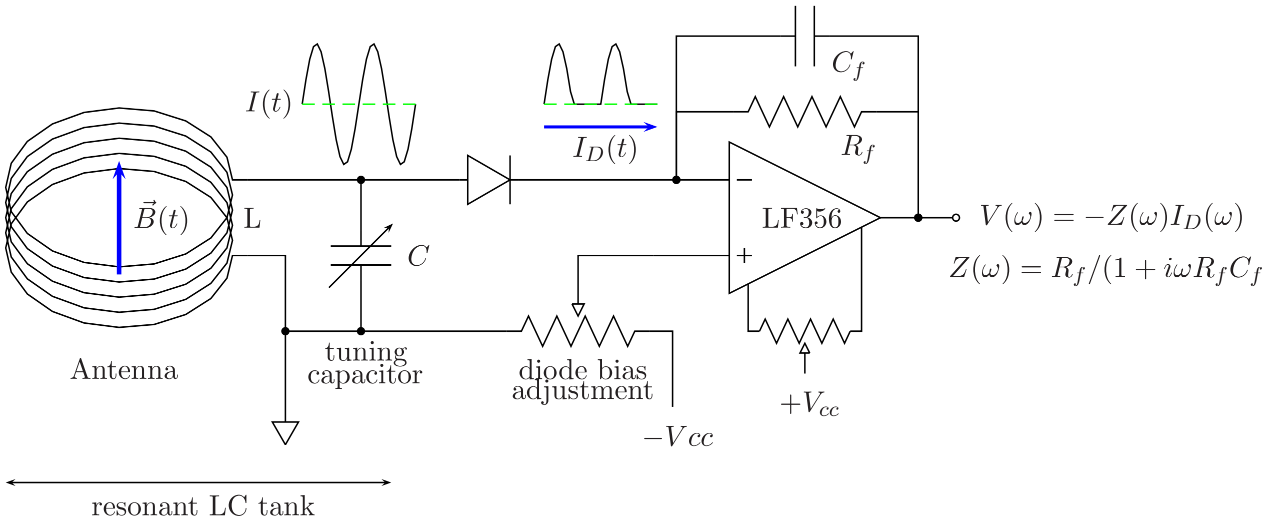
c. Apply a constant current to the LED and measure the output of the transimpedance amplifier as you vary the distance between the LED and the photodiode. After subtracting the dark current from these measurements, determine how the intensity of the LED emission varies with distance. Intensity is power/area.

d. Drive the LED with a function generator and determine the maximum frequency at which a square wave can be transmitted. What device parameters or phenomena limit the frequency response of your communication system?

e. Consider the entire circuit from R_{led} to the output pin of the op amp to be a "black box" with $V_{led}(\omega)$ as the input, $V(\omega)$ as the output and a response function $A(\omega)$ in the frequency domain. Use the response function scan program to determine $A(\omega)$ within the range 10 Hz to 10 MHz. Plot the power spectrum in dB and the phase. What is the characteristic or -3 dB frequency?

III. Detection of a High-Frequency RF Signal with a Diode and an Op Amp

A radio frequency, or RF, signal can be detected using an op amp with a much lower frequency response. The concept is to use a diode to *rectify* the current from an antenna and then amplify the time-average of this unipolar current. An antenna which responds to the oscillating magnetic field can be a simple coil with many loops. Adding a capacitor in parallel to the coil allows a larger signal to build in the LC tank tuned to the frequency of the RF radiation. Since the required 0.7 V potential difference across the Si diode can be hard to achieve when the RF signal is weak, the Si diode can be forward-biased slightly or a different type of diode requiring a small forward bias, such as a Schottky-barrier diode, can be used.



a. Build this circuit using an SD101C or equivalent Schottky-barrier diode, $R_f = 1\ \text{M}\Omega$ and $C_f = 1$ nF. Do not include the tuning capacitor. Begin with zero forward bias across the diode, that is, connect V_+ to ground.

b. Measure the power and frequency of you cell phone or laboratory walkie-talkie on the spectrum analyzer. Then, keeping the source at least one wavelength away from the coil, try to detect a signal with your circuit. Does the orientation of your antenna relative to the antenna of the RF source matter? Explain your observations.

c. At what distance from the RF source can you just barely detect a signal? how does the signal vary with distance?

d. Explain how this circuit functions.

e. Time permitting, make a resonant LC tank using a ceramic or air capacitor. The antenna coil will need to be just a few loops. Does this improve the sensitivity of your circuit?