ENGR 301 – Electrical Measurements

Experiment # 3: Diode Characteristics and Applications

Objective:

To characterize a *rectifier diode* and a *zener diode*. To investigate basic power-supplies concepts such as *rectification*, *filtering*, and *regulation*. To investigate basic *op amp rectifiers*. To compare *measured* and *simulated* diode circuits.

Components:

1 × 6.3 V CT transformer, 4 × 1N4001 power rectifier diodes, 4 × 1N4148 low-power rectifier diodes, 1 × 1N4733 5.1 V, 1 W zener diode, 2 × 741C op amps, 2 × 0.1 μF capacitors, 1 × 100 μF capacitor, and miscellaneous resistors: 1 × 100 Ω, 2 × 1 kΩ, 1 × 10 kΩ, and 6 × 100 kΩ (all 1%, ¼ W).

Instrumentation:

A dual ±15-V regulated power supply, a signal generator (sinewave), a digital multimeter, and a dual-trace oscilloscope.

References:

1. Sedra, Adel S., and Smith, Kenneth C., *Microelectronics*, 4th Ed, Oxford University Press, 1997.
2. Roberts, Gordon W., and Sedra, Adel S., *SPICE*, 2nd Ed., Oxford University Press, 1997.

Theoretical Background:

A *pn* junction diode exhibits the well-known *i*-*v* characteristic

$$i = I_S\left(e^{\frac{v}{nV_T}} - 1\right) \tag{1}$$

where I_S , a current scale factor, is called the *saturation current;* V_T, a voltage scale factor, is called the *thermal voltage*; n, an empirical constant called the *emission coefficient*, is in the range of 1 for integrated-circuit diodes to 2 for discrete diodes.

Engineers use the following two rules of thumb to characterize the behavior of a forward-biased diode with $n = 1$ at room temperature: (a) To effect an **octave** change in *i*, we must change *v* by **18 mV**; (b) To effect a **decade** change in *i*, we must change *v* by **60 mV**.

The parameter I_S is a strong function of temperature; moreover, it depends on diode area. As a rule of thumb, **I_S doubles for every 5°C rise in temperature**. For low-power IC diodes, I_S is typically in the range of fAs (1 fA = 10^{-15} A), though there are diodes with I_S in the range of pAs or even nAs. The parameter V_T is linearly proportional to absolute temperature, and its room-temperature value is $V_T \cong 26$ mV. The thermal behavior of a junction diode is also expressed by the following popular rule of thumb: For a junction diode operating at constant current *i*, **the diode voltage drop *v* decreases (increases) by 2 mV for every 1°C rise (drop) in temperature.**

When a diode is *forward biased* at nontrivially low currents, we have exp (v/nV_T) >> 1, so Eq. (1) can be approximated as $i = I_S e^{v/nV_T}$. This is readily turned around to yield $v = nV_T \ln (i/I_S)$, or

$$v = 2.303nV_T \log_{10} (i/I_S) \tag{2}$$

This equation indicates that if we perform a set of *i*-*v* measurements on a *pn* diode and then plot them on semilogarithmic paper, with *v* on the linear axis and *i* on the logarithmic axis, the resulting curve is a straight line such that for every decade change in current, voltage changes by $2.303nV_T$. We can exploit this to find the values of I_S and nV_T experimentally.

When a diode is *reverse biased*, Eq. (1) no longer holds. Rather, the diode exhibits two regions of operation:

(a) At moderately low reverse voltages, a diode conducts a current I_R called the *reverse current*. Typically, I_R is orders of magnitude larger than I_S, and it is likewise a strong function of temperature. As a rule of thumb, **I_R doubles for every 10°C rise in temperature**.

(b) As the reverse bias voltage is increased, a point is reached at which the diode becomes strongly conductive, and is said to be operating in the *breakdown region*. In this case it is notationally convenient to reverse the reference direction of current and the reference polarity of voltage by letting $i_Z = -i$ and $v_Z = -v$. The resulting v_Z-i_Z characteristic is approximately linear, or

$$v_Z = V_{Z0} + r_z i_Z \quad (3)$$

where V_{Z0} is the extrapolated value of v_Z in the limit $i_Z \rightarrow 0$, and r_z is the *dynamic resistance* of the diode in the breakdown region. Its reciprocal $1/r_z$ is the slope of the i_Z -v_Z characteristic. The smaller r_z, the steeper the i_Z -v_Z curve, and the closer the diode behavior to an ideal voltage source. This feature is exploited on purpose in voltage-regulation applications.

Diode circuits are readily simulated using PSpice. The file `Eval.lib` that comes with the student version of PSpice contains models for popular junction diodes, including the 1N4148 rectifier diode and the 1N750 4.7-V zener diode. For instance, to invoke a 1N4148 diode from the built-in library, we use a command of the type

```
DXXX A C D1N4148
```

where `DXXX` is the name of the specific diode (such as `D1`), and `A` and `C` are the anode and cathode nodes, in that specific order. Shown below is the PSpice code for the simple diode circuit of Fig. 1.

```
Half-Wave Rectifier
.lib eval.lib
vI 1 0 sin(0v 10V 1kHz)
D1 1 2 D1N4148
R 2 0 1k
.tran 10us 4ms
.probe
.end
```

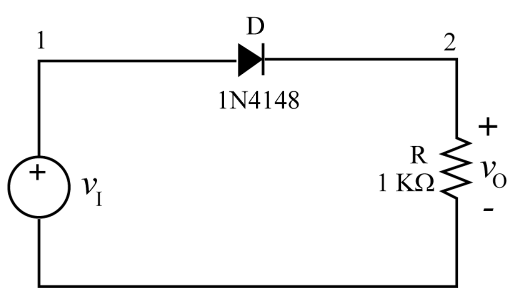

Fig. 1 - Half-wave rectifier.

The response is shown in Fig. 2.

Experimental Setup:

Diodes usually come with a *band* identifying the *cathode* terminal (the other terminal is, of course, the anode). If in doubt, you can determine experimentally which terminal is which by measuring the diode with an ohmmeter (the diode must be out of the circuit, and the ammeter's scale should be set in the kΩ range). Then, if the display *blinks* (indicating overrange resistance), the *cathode* is the one connected to the red cable of the ohmmeter; if the display shows some *finite resistance*, then the *cathode* is the one connected to the black cable. To make sure, try out both connections and verify that they give consistent results.

Henceforth, steps shall be identified by letters as follows: **C** for calculations, **M** for measurements, and **S** for SPICE simulation. Moreover, each measured value should be expressed in the form $X \pm \Delta X$ (e.g. v = 650.5 mV ± 0.1 mV), where ΔX represents the estimated uncertainty of your measurement, something you have to figure out based on your learning in ENGR 300.

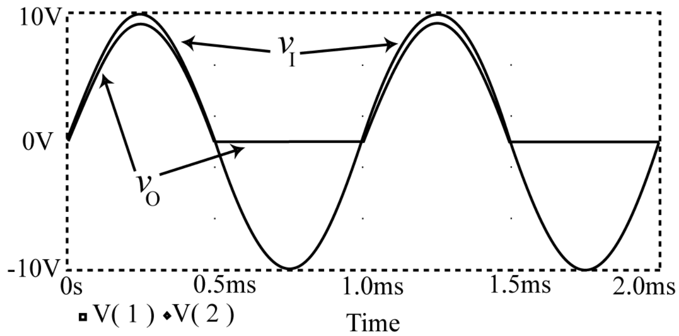

Fig. 2 - Half-wave rectifier waveforms.

Forward-Region Characteristic:

This characteristic shall be obtained by Here v_S is a variable DC source which, together with R, is used to establish prescribed values of i. To perform your i and v measurements, first configure your digital multimeter (DMM) as an *ammeter in series* between the resistance and the diode to set i, then as a *voltmeter in parallel* with the diode to measure v. In case your ammeter has been put it out of service by abuse, you can still use your DMM to perform current measurements as follows: Before inserting R in the circuit, measure it with the ohmmeter; then insert R, and while monitoring with measuring v for different values of i using the circuit of Fig. 3.voltmeter the voltage v_R across the terminals of R, adjust v_S for the desired value of i (for instance, to obtain i = 100 µA with R = 98 kΩ, adjust v_S until $v_R = R \times i = 98 \times 0.100 = 9.8$ V).

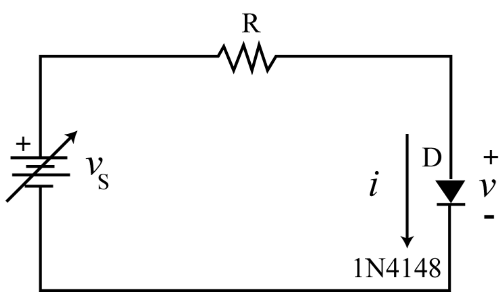

Fig. 3 - Circuit to find the diode characteristics.

M1: In the circuit of Fig. 3 measure v for the following values of i (shown within parentheses are the corresponding recommended values of R): i = 10 µA (1 MΩ), i = 100 µA (100 kΩ), i = 1 mA (10 kΩ), and i = 10 mA (1 kΩ). As you measure v, use as many digits as your DVM will allow (why?). Hence, plot your data on semilogarithmic paper (v on the linear scale, i on the log scale), with each datum shown as a rectangle with dimensions reflecting the uncertainties of the corresponding measurements, as learned in ENGR 300.

C2: Draw a best-fit straight line (if you can, do this by computer, using your ENGR 308 learning). Measure its slope, and hence find the value of nV_T. Assuming V_T = 26 mV, what is the experimental value of n? Finally, find the experimental value of I_S. Are your findings typical? Comment.

S3: Create a PSpice diode model with the above values of n and I_S. Hence, using PSpice as a curve tracer, plot the diode i-v curve both on linear and semilog scales. How does the semilog curve compare with the experimental one you derived? To create a diode model for a specific sample, such as `our_diode`, we use the statement

```
.model our_diode D (Is=Ival n=nval)
```

where `Ival` and `nval` are the measured values of I_S and n. Then, to invoke a specific diode of that class, say D1, we use the statement: `D1 A C our_diode`

Breakdown-Region Characteristic:

This characteristic shall be obtained by measuring v_Z for different values of i_Z using the circuit of Fig. 4. The suggestions given above in connection with the measurements of Fig. 3 still hold.

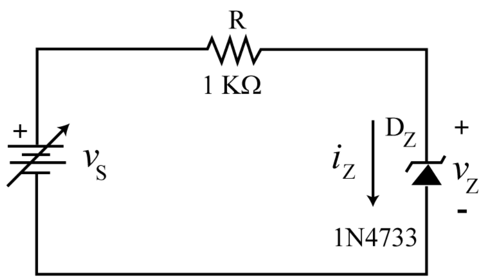

Fig. 4 - Circuit to investigate a zener diode.

M4: In the circuit of Fig. 4 measure v_Z for two different values of i_Z, say i_{Z1} = 5 mA and i_{Z2} = 10 mA. Denoting the corresponding voltages as v_{Z1} and v_{Z2}, calculate the dynamic resistance of the diode as $r_Z = (v_{Z2} - v_{Z1})/(i_{Z2} - i_{Z1})$. Hence, use Eq. (3) to find the extrapolated value V_{Z0}.

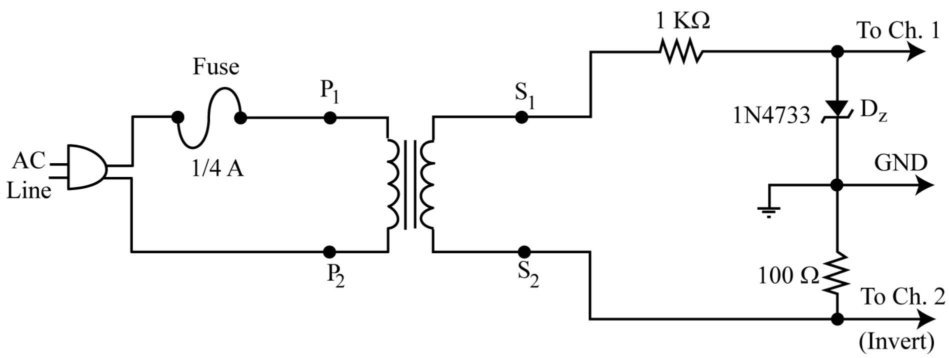

Fig. 5 – Circuit to display the entire *i-v* curve of a zener diode.

M5: Assemble the circuit of Fig. 5 to observe the complete *i-v* characteristic of the zener diode (for safety, be sure to connect the ¼-A fuse in series with the primary, as shown). Here, the oscilloscope is used in the *x-y* Mode (see ENGR 206), with the anode voltage *v* as the *x* axis (Ch1. 1, 1 V/div, DC), and the cathode current *i*, sensed across the 100-Ω resistor, as the *y* axis (Ch. 2, Inverted, 0.2 V/div, DC). Before connecting the oscilloscope to your circuit, adjust the offsets of the two channels so that the origin of the *x-y* display (dot) is at the center of the screen. Also, keep the beam intensity suitably low to avoid burning out the phosphor on the CRT.

C6: Once you have displayed the *i-v* characteristic, develop large-signal diode models (with actual element values) for the three regions of operation, namely, *forward*, *cutoff*, and *breakdown*.

Simple DC Power Supply:

For the following investigations, refer to Fig. 6. Before assembling the circuit downstream of the secondary, observe the waveforms at nodes S_1 and S_2 with the oscilloscope (center tap to ground of the oscilloscope, v_{S1} to Ch. 1, v_{S2} to Ch. 2, Trigger from Ch.1, Chop Mode), and verify that they are out of phase with each other. What are their amplitudes V_{m1} and V_{m2}?

MC7: Assemble the circuit of Fig. 6, but without interconnecting D_2 and C yet. Observe v_{S1} and v_O with Ch.1 and Ch. 2 of the oscilloscope, and use the information provided by Ch. 2 to predict the average (or DC) value V_O of v_O (show your calculations!). Then, measure V_O with the DC voltmeter, compare with the predicted value, and account for any discrepancies. What is the maximum reverse voltage (PIV) that D_1 must withstand?

MC8: Now connect *C*, but with D_2 still disconnected. Predict the output ripple as well as the new DC value of v_O (show your calculations!). Observe the ripple with Ch. 2 (switch it to the AC mode for this observation,), measure V_O with the DC voltmeter, compare with your predictions, and comment. What is now the PIV for D_1?

MC9: Repeat first Step MC7, and then Step MC8, but also with D_2 in place. Hence, summarize the advantages of using also D_2.

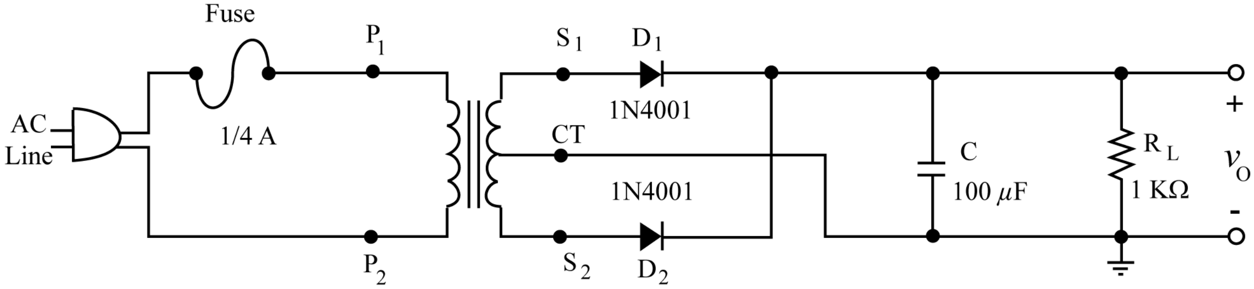

Fig. 6 – Simple DC power supply

Zener Diode Regulator:

For the following investigations, refer to Fig. 7, which is intended to be a DC power supply of about 5 V with a maximum current rating of about 10 mA, or $0 < I_L < 10$ mA.

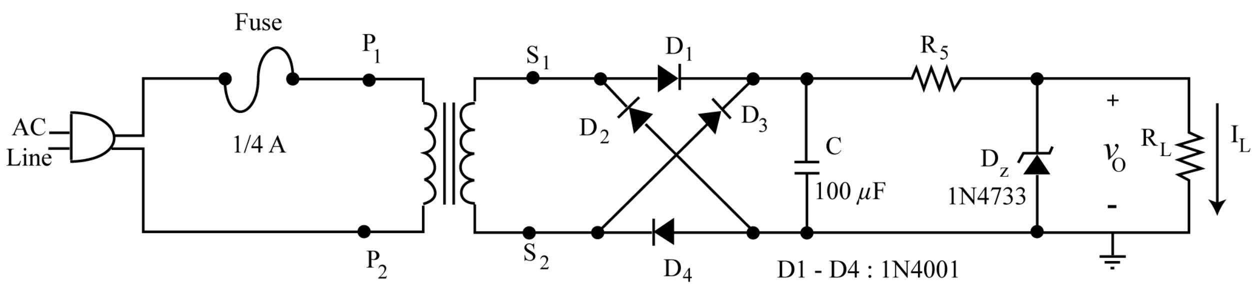

Fig. 7 – Shunt regulator

C10: Based on the observations and measurements of the previous steps, calculate a suitable value of R_s in the circuit of Fig. 7 for a maximum load current of 10 mA. Then, obtain from the stockroom a standard resistor closest to the calculated value, and predict both the *load regulation* and the output ripple of your circuit.

M11: Assemble the circuit of Fig. 7, and observe the voltage across *C* with Ch.1 of the oscilloscope, and the voltage across D_z with Ch.2 of the oscilloscope (you may alternate between the DC and AC Modes, as needed, for optimal observations). Measure the output ripple with the oscilloscope and V_O with the DC voltmeter at the following two extremes: $R_L = \infty$ (no load) and $R_L = 500\ \Omega$ (maximum load; use 2×1 kΩ Resistors in parallel). What is the measured *load regulation* of your circuit? The measured *output ripple*? Compare with the predictions of Step C10, comment.

Precision Rectifiers:

As shown in Fig. 2, the diode voltage drop results in a error which may be undesirable, especially in precision rectifier applications. This error can be nullified by placing the diode (or diodes) within the feedback loop of an op amp. Figure 8 shows a popular example of a *precision half-wave rectifier* using this concept. The circuit is readily simulated via PSpice using the following code:

```
Precision Half-Wave Rectifier
.lib eval.lib
VCC 7 0 dc 15V
VEE 4 0 dc -15V
```

```
vI 1 0 sin (0v 10V 1kHz)
R1 1 2 100k
R2 2 8 100k
D1 6 2 D1N4148
D2 8 6 D1N4148
Xoa 0 2 7 4 6 uA741
.tran 10us 2ms 0us 10us
.probe
.end
```

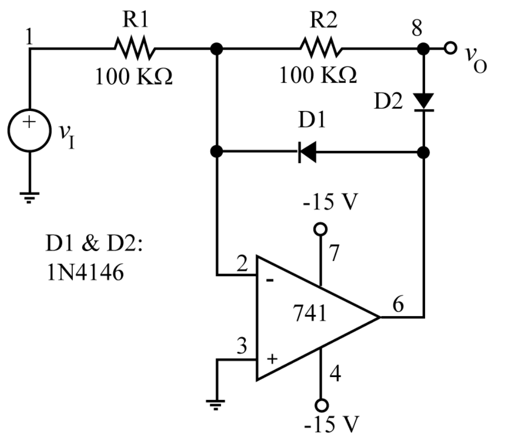

Fig. 8 - Precision half-wave rectifier.

As shown in Fig. 9, the circuit gives (*a*) $v_O = -v_I$ for $v_I > 0$, and $v_O = 0$ for $v_I < 0$, and it does so without appreciable errors due to the nonzero diode drops.

M12: Assemble the circuit of Fig. 8 (see Appendix 2 for useful tips), and confirm its behavior by monitoring v_I and v_O with Ch.1 and Ch. 2 of the oscilloscope (both Channels set on DC, Trigger from Ch. 1, Chop Mode). Next, use Ch. 2 to observe the waveform at the output of the op amp (pin 6), and justify it by analyzing the behavior of the circuit first for the case $v_I > 0$, then for the case $v_I < 0$. Finally, gradually rise the input frequency until you begin to observe appreciable distortion at the output. Hence, justify this distortion in terms of well-known op amp limitations.

C13: By summing a signal with its half-wave rectified version in a 1:2 ratio, we obtain the *precision full-wave rectifier* of Fig. 10. Prove that its output is $v_O = (R_5/R_3) \times |v_I|$, this being the reason why the circuit is also called a *precision absolute-value circuit. Hint:* Consider first the case $v_I > 0$, then the case $v_I < 0$.

S14: Use Pspice to display the input and output waveforms of the circuit of Fig. 10 for the case in which *C* is not connected yet.

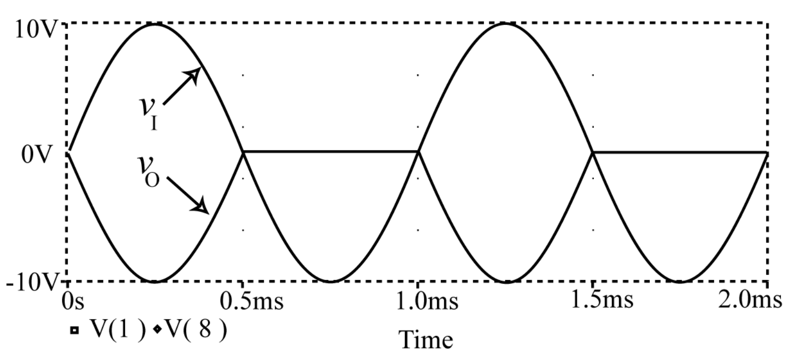

Fig. 9 - Waveforms for the precision half-wave rectifier.

M15: Assemble the circuit of Fig. 10 to confirm the waveforms of Step S14. Next, connect *C* as shown. This turns the summing op amp into a low-pass filter to yield $V_O = (R_5/R_3) \times \text{Avg}(|v_I|)$, where $\text{Avg}(|v_I|)$ denotes the average of

$|v_I|$. Recall that if v_I is a sinewave of amplitude V_m, then $\text{Avg}(|v_I|) = (2/\pi)V_m = 0.637V_m$. Amplifying this average by $R_5/R_3 = 110/100 = 1.1$ gives $V_O = 0.707V_m$, which coincides with the rms value of v_I when v_I is an ac signal. Verify that this is the case by letting v_I be a sinewave with zero DC offset, but variable amplitude and frequency; then, while monitoring v_I with the AC voltmeter and V_O with the DC voltmeter, compare the two readings for several amplitudes and frequencies of v_I, and account for possible discrepancies. The circuit of Fig. 10 forms the basis of a class of AC voltmeters known as *averaging-type ac voltmeters*. Can you justify?

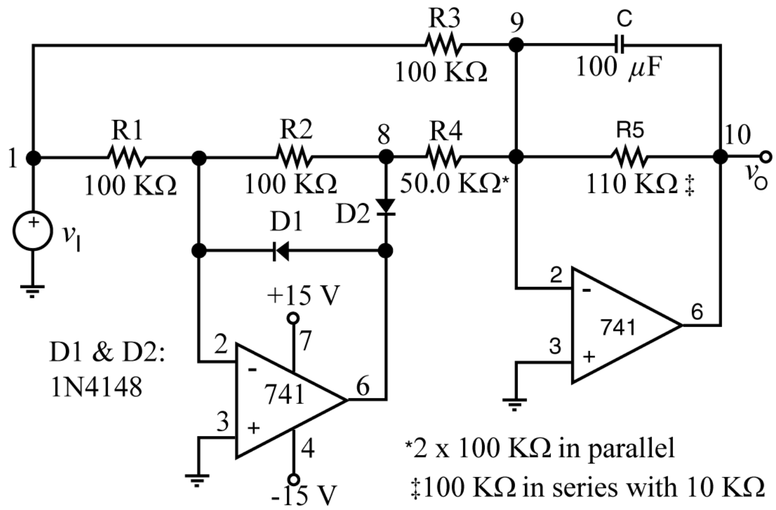

Fig. 10 - Precision full-wave rectifier with averaging capacitor filter.