LAB #3: DIODE CHARACTERISTICS AND APPLICATIONS

Updated July 30, 2003

Objective:

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

Components:

1 × 6.3-V CT transformer, 4 × 1N4001 power rectifier diodes, 2 × 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, 1 × 10 kΩ potentiometer, and resistors: 1 × 100 Ω, 2 × 1 kΩ, 2 × 10 kΩ, 6 × 100 kΩ, 1 × 1 MΩ (all 5%, ¼ W).

Instrumentation:

A dual-output power supply, a waveform generator (sine-wave), a digital multi-meter, and a dual-trace oscilloscope.

PART I – THEORETICAL BACKGROUND

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

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

where

- I_s is a scale factor known as the *saturation current*. For low-power diodes, it is typically in the fA range (1 fA = 10^{-15} A).
- V_T is a scale factor known as the *thermal voltage*. At room temperature, $V_T \cong 26$ mV.
- n is an empirical constant called the *emission coefficient*. It is the range of 1 for integrated-circuit diodes to 2 for discrete diodes.

For $v > 0$ the diode is said to be *forward biased*, and for $v < 0$ it is said to be *reverse biased*. When a diode is forward biased at nontrivially low currents (in practice for $v > 4V_T \cong 0.1$ V), the above equation tends to the true *exponential function*, also called the *ideal diode equation*,

$$i_D = I_s e^{v_D/nV_T} \tag{2}$$

where we use subscript D to signify forward-bias operation. The exponential characteristic exhibits some convenient features, two of which are summarized by engineers via the following rules of thumb:

- To change I_D by an *octave* we need to change V_D by 18-mV
- To change I_D by a *decade* we need to change V_D by 60-mV

Note that the above rules are independent of the particular *operating point* $Q(I_D, V_D)$ on the *i-v* curve.

Turning Eq. (2) around gives

$$v_D = 2.303 n V_T \log_{10}\left(\frac{i_D}{I_s}\right) \quad (3)$$

indicating that if we perform a set of *v-i* measurements on a *pn* diode and then plot them on *semi-logarithmic* scales with v_D on the *linear* axis and i_D on the *logarithmic* axis, the resulting curve is a *straight line* with *slope* $2.303nV_T$/decade. This is very convenient when we want to characterize a diode experimentally. Indeed, given a set of measured data, we can easily find the *best fit straight line*, and then calculate Eq. (3) at *two distinct points* on this line to establish two equations in the unknowns nV_T and I_s, which we finally solve to find the values of nV_T and I_s experimentally.

Equation (3) indicates that since i_D appears in the argument of the logarithm, v_D will not change that much over a substantial range of values of i_D. For instance, over a 100:1 range of variation of i_D, for a diode with $n = 1$, v_D will change only by $2 \times 60 = 120$ mV. This feature forms the basis of the *constant voltage-drop* diode model, also called the *large-signal* diode model, which is utilized in DC bias analysis as a quick – if approximate – alternative to exact but lengthy iterative calculations. For low-power silicon diodes, this drop is typically

$$V_{D(\mathrm{on})} = 0.7 \text{ V} \quad (4)$$

We observe that I_s is a strong function of temperature; moreover, V_T is linearly proportional to absolute temperature. Consequently, Eqs. (1) through (3) are temperature sensitive. Mercifully, it is possible for engineers to summarize the overall thermal behaviour of a forward-biased *pn* junction via a simple rule of thumb:

- At room temperature, V_D exhibits a thermal coefficient of about –2 mV/°C

Once we know V_D at some reference temperature T_0, we can estimate it at any other temperature T using

$$V_D(T) \cong V_D(T_0) - (2 \text{ mV}) \times (T - T_0) \quad (5)$$

When a diode is *reverse biased* ($v < 0$), Eq. (1) no longer holds. Rather, the diode exhibits two distinct regions of operation. At moderately low reverse voltages, a diode conducts a current I_R called the *reverse current*, which is orders of magnitude higher than I_s. In fact, I_R is typically in the pA to nA range (1 pA = 10^{-12} A, 1 nA = 10^{-9} A). Moreover, I_R is a strong function of temperature. As a rule of thumb,

- I_R doubles for every 10°C rise in temperature

Once we know V_D at some reference temperature T_0, we can estimate it at any other temperature T using

$$I_R(T) \cong I_R(T_0) \times 2^{(T-T_0)/10} \quad (6)$$

As the reverse bias voltage is increased further, a point is reached, called the *breakdown voltage* (BV), at which the reverse current shoots up in magnitude from the negligible value I_R just discussed to substantially higher values. The name stems from the fact that the *i-v* curve bends, or breaks down. This does not necessarily imply a destructive process – in fact, one always limits the reverse current within safety levels by interposing a suitable resistor in *series* between the driving voltage source and the reverse-biased *pn* junction. Figure 1 shows the complete *i-v* characteristic of a typical *pn* junction.

When designed to operate in the breakdown region, a diode is referred to as a *Zener diode*, and its voltage and current are denoted as $-v_Z$ and $-i_Z$. In breakdown, the diode curve is *approximately linear*, or

$$v_Z = V_{Z0} + r_z i_Z \quad (7)$$

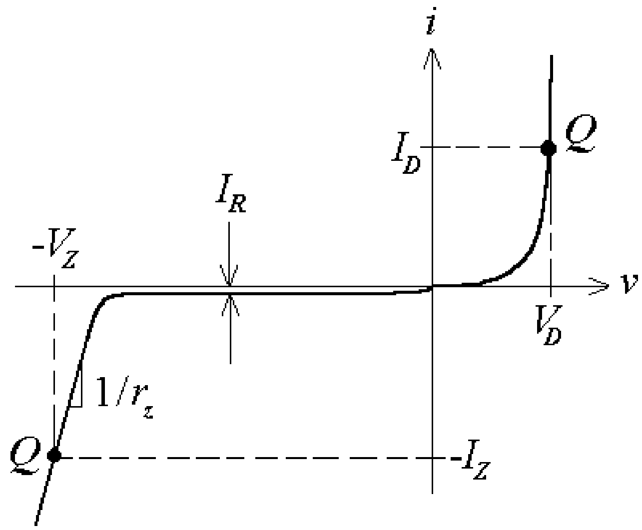

Fig. 1 - The complete *i-v* characteristic of a *pn* junction diode.

where V_{Z0} is the extrapolated value of v_Z in the limit $i_Z \to 0$, 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 -v* curve there. The smaller r_z, the steeper the curve, and the closer the diode behavior to that of an *ideal voltage source*. This feature is exploited on purpose in *voltage-regulation* applications.

Diode circuits are readily simulated using PSpice. The PSpice library contains models for popular junction diodes, such as the 1N4148 rectifier diode and the 1N750 4.7-V zener diode. Figure 2 shows a PSpice circuit to simulate a simple half-wave rectifier, and Fig. 3 depicts the input and output waveforms. You can simulate this circuit by downloading its appropriate files from the Web. To this end, go to `http://online.sfsu.edu/~sfranco/CoursesAndLabs/Labs/301Labs.html`, and once there, click on **PSpice Examples**. Then, follow the instructions contained in the **Readme** file.

PART II – EXPERIMENTAL PART

Diodes are usually equipped with *band* identifying the *cathode* terminal (the other terminal is, of course, the *anode*). If in doubt, you can always find out experimentally using your multi-meter. You are also encouraged to download the data sheets of the diodes you are using from the Web. For instance, go to, `http://www.google.com`, and search "1N4001", "1N4148", and "1N4733".

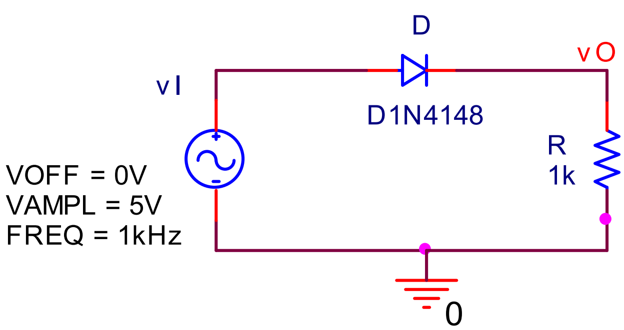

Fig. 2 – Simple *half-wave rectifier*.

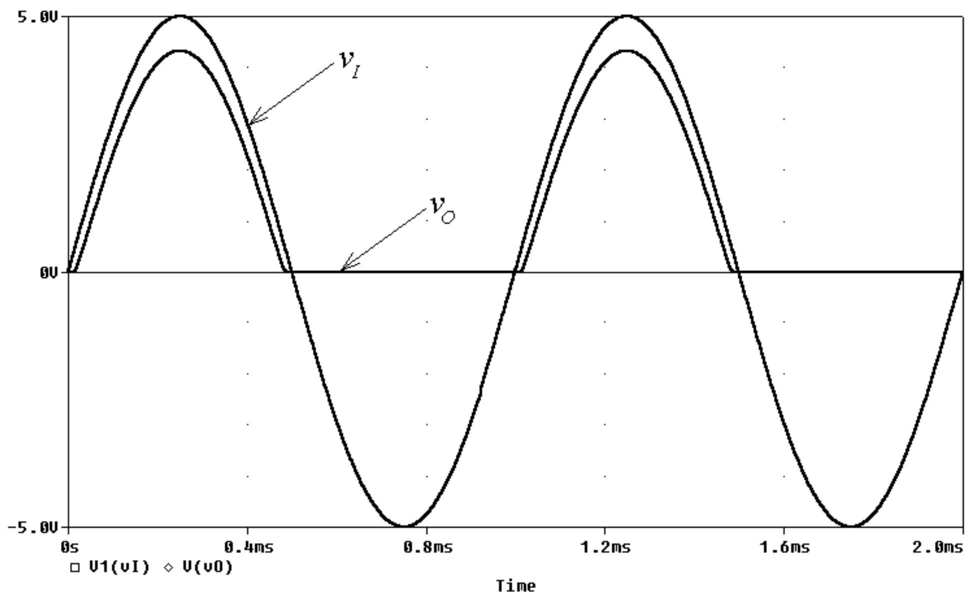

Fig. 3 – Waveforms for the circuit of Fig. 2.

Henceforth, steps shall be identified by letters as follows: **C** for calculations, **M** for measurements, and **S** for SPICE simulation. Moreover, all data must be expressed in the form $X \pm \Delta X$ (e.g. I_s = 1.6 fA ± 0.1 fA), where ΔX represents the estimated uncertainty of your measurement.

Displaying the Diode *i-v* Curve on the Oscilloscope:

Figure 4 shows a simple arrangement to visualize the complete *i-v* curve of a diode on the oscilloscope. The function of the transformer is to provide a *repetitive* voltage drive, with the 1-kΩ series resistor providing a current-limiting function for the diode. In order to convert the current waveform to a voltage waveform for the oscilloscope, we sense *i* with the small (R = 100 Ω) series resistor shown. The oscilloscope is operated in the *x-y* mode, with the diode voltage *v* going to Ch. 1, and the voltage $-Ri$,

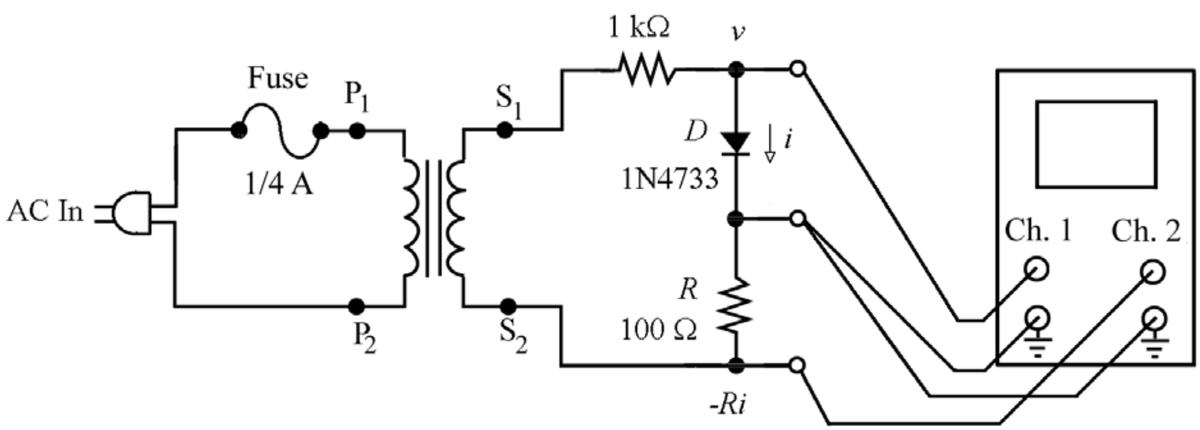

Fig. 4 – Displaying the *diode curve* with an oscilloscope operating in the *x-y* mode. (Note: Ch. 2 must be set in the *Invert Mode*.)

proportional to the diode current i, going to Ch. 2. To avoid displaying the curve upside-down because of the negative sign, we use Ch. 2 in the *Invert Mode*.

MC1: With power off, assemble the circuit of Fig. 4. Also, configure the oscilloscope for *x-y* operation, with Ch. 2 in the *Invert Mode*. Adjust the position of the beam (dot) so that it is *right at the center* of the screen. Next, apply power, and play with the channel sensitivities until you obtain a curve of the type of Fig. 1. Hence, use this curve for a *first estimate* of $V_{D(\text{on})}$, V_{Z0}, and r_z for this particular diode sample.

Forward-Region Characterization:

This characteristic shall be investigated by measuring v_D for different values of i_D using the test circuit of Fig. 5. Here, V_S is a variable DC source which, together with R, is used to establish prescribed values of I_D. To perform each pair of V_D–I_D measurements, proceed as follows:

- With power off, configure your multi-meter as a *digital current meter* (DCM) and insert in *series* between R and D as in Fig. 5*a*. Next, apply power and adjust V_S for the desired value of I_D.
- With power off, remove your multi-meter, connect R to D, configure your multi-meter as a *digital voltmeter* (DVM) and connect it in *parallel* with D, as in Fig. 5*b*. Next, apply power and measure V_D.

M2: In the circuit of Fig. 5 measure V_D for the following values of I_D (shown within parentheses are the corresponding recommended values of R):

- I_D = 1.0 μA (1 MΩ)
- I_D = 10 μA (1 MΩ)
- I_D = 100 μA (100 kΩ)
- I_D = 1.0 mA (10 kΩ)

As you measure V_D, use as many digits as your DVM will allow (why?). Hence, plot your data on a *semi-logarithmic* graph, with v_D on the *linear* axis and i_D on the *logarithmic* axis.

C3: Find the *best-fit straight line* over the above-specified 3-decade interval (1.0 μA to 1.0 mA), and find the corresponding voltage span ΔV_D. Considering that $\Delta V_D = 3 \times 2.303 nV_T$, find nV_T. Assuming $V_T = 26$ mV, what is the experimental value of n? Finally, pick a convenient operating point Q somewhere between the extremes, substitute the values of its coordinates V_{DQ} and I_{DQ} into Eq. (2), along with the value of nV_T just found, and solve for the experimental value of I_s. Are your findings typical?

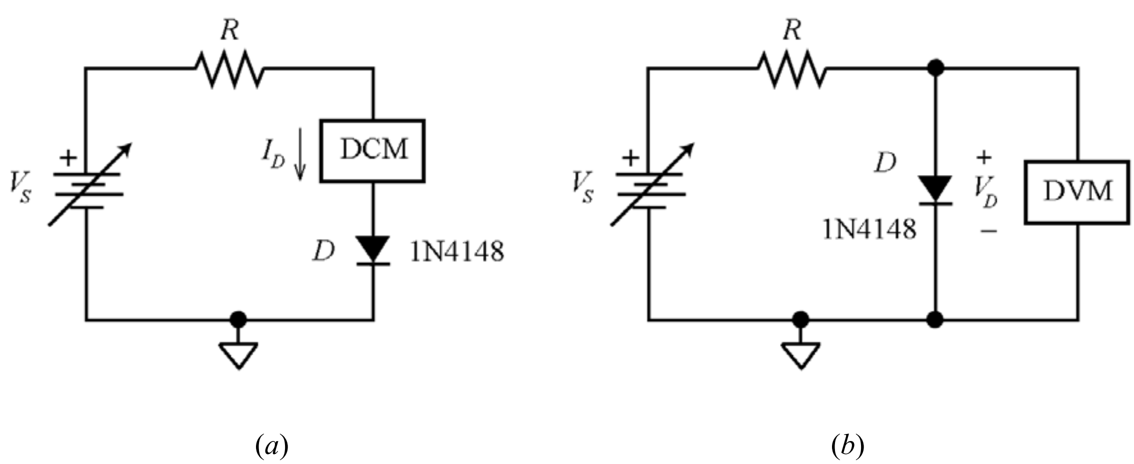

Fig. 5. – Test circuit to investigate the diode characteristic in the *forward region*.

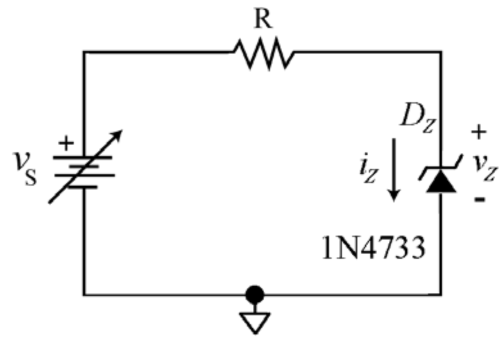

Fig. 6. – Test circuit to investigate the diode characteristic in the *breakdown region*.

S4: Create a PSpice diode model with the above values of n and I_s. Hence, using PSpice as a curve tracer, perform a DC Sweep to plot the diode's v_D-i_D curve both on *linear* and on *semi-log* scales. How does the semi-log curve compare with the experimental one you derived? Justify any differences.

Note: To create a diode model for your sample, select the diode in your PSpice schematic, then click **Edit → PSpice Model** and change the parameters to correspond to those found experimentally.

Breakdown-Region Characterization:

Sufficiently to the left of the breakdown knee, the diode curve is approximately straight so we characterize it by measuring v_Z for *two* different values of i_Z using the circuit of Fig. 6.

MC5: In the circuit of Fig. 6 measure V_Z for I_{Z1} = 5 mA (R = 1 kΩ) and I_{Z2} = 20 mA (R = 100 Ω). As you measure V_Z, use as many digits as your DVM will allow (why?). Next, denoting the corresponding voltages as V_{Z1} and V_{Z2}, calculate the *dynamic resistance* of the diode as $r_z = (V_{Z2} - V_{Z1})/(I_{Z2} - I_{Z1})$. Finally, use Eq. (7) to find the extrapolated value of V_{Z0}.

Basic Rectifier Principles

In the following investigations we shall use a *center-tapped transformer* (see Fig. 7). Before proceeding, observe the waveforms at the secondary nodes S_1 and S_2 with the oscilloscope (CT to the oscilloscope's ground, S_1 to Ch. 1, S_2 to Ch. 2, Trigger from Ch.1), and verify that they are *out of phase* with each other.

M6: With power off, assemble the circuit of Fig. 7, *but without connecting D_2 yet*. Next, apply power, and observe v_{S1} with Ch. 1 and v_O with Ch. 2 of the oscilloscope, and record both waveforms. Hence, use the AC voltmeter to measure the *RMS value* V_{rms} of v_O.

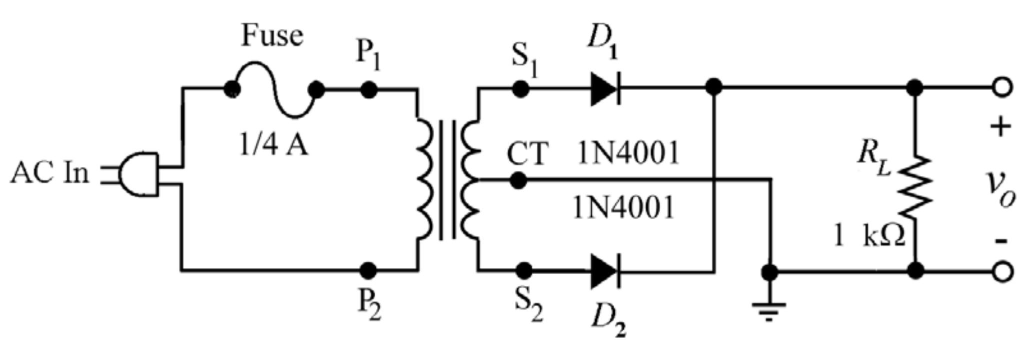

Fig. 7 – Basic rectifier circuit.

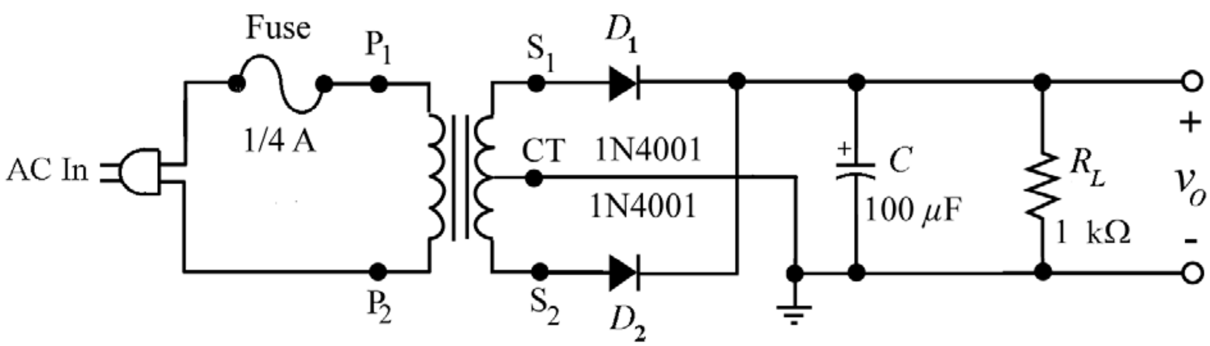

Fig. 8 – Simple DC power supply

S7: By a procedure similar to that in connection with Fig. 2, simulate the circuit of Step M6 via PSpice, and plot both v_O and its RMS value V_{rms} for about half a dozen periods. To plot v_O, select the trace V(VO), and to plot V_{rms}, select the trace RMS(V(V(0))). How does this value of V_{rms} compare with the measured value of Step M6? Justify any differences.

MS8: Repeat the last two steps, *but with D_2 now in place*. Compare with the case of a single diode, and comment.

Basic DC Power Supply:

As we know, the rectifier of Fig. 7 can be turned into a simple DC supply by connecting a filter capacitor C in parallel with the output load R_L, in the manner depicted in Fig. 8.

C9: Using the information available from Step MS8, predict the ripple V_{ro} as well as the average value V_O of the output for the circuit of Fig. 8.

M10: With power off, insert the 100-μF capacitor (this capacitor is a polarized type, so make sure you connect it with the polarity as shown!) Next, apply power, and use the DC voltmeter to measure the *average* V_O of the output, and use the oscilloscope to observe and measure the output *ripple* V_{ro}. (For best visualization on the screen, switch to the AC mode and adjust the vertical sensitivity accordingly.) Compare with the predicted values of Step C9, and account for any differences.

Zener Diode Regulator:

As we know, with a Zener diode we can reduce the output ripple significantly, while simultaneously

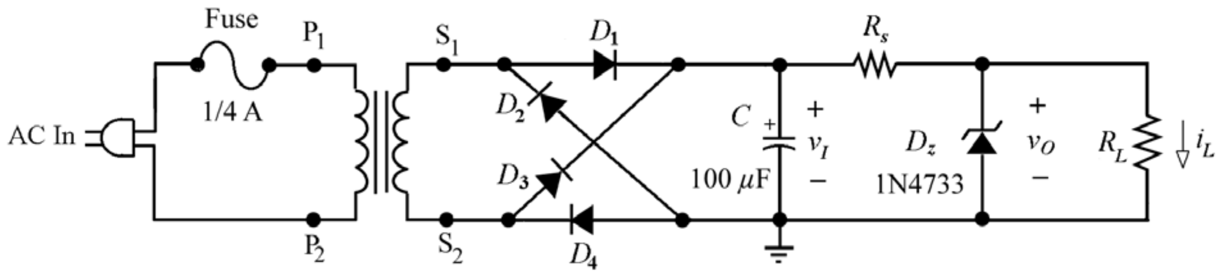

Fig. 9 – Shunt regulator. (D_1–D_4: 1N4001).

making the circuit less sensitive to variations in the load current i_L. The shunt regulator of Fig. 9 is designed to function as a DC power supply of about 5 V, and we are going to find R_s for proper operation over the load-current range $0 < i_L < 10$ mA.

C11: Based on the observations and measurements of the previous steps, calculate a suitable value for R_s in Fig. 9 that will ensure *up to* 10 mA of load current with *no less than* 5 mA of Zener-diode current under all input conditions, including when v_I reaches its *minima*. Then, obtain from the stockroom a standard resistor closest to the calculated value, and use this value to predict the *Line Regulation* and the *Load Regulation*, which in the present case take on the forms

$$\text{Line Regulation} \cong \frac{r_z}{R_s + r_z} \tag{8a}$$

$$\text{Load Regulation} \cong -R_s // r_z \tag{8b}$$

The *Line Regulation*, in V/V, allows us to estimate the rate of change of the regulated output v_O with the unregulated input v_I, and the *Load Regulation*, in V/A, allows us to estimate the rate of change of the regulated output v_O with the load current i_L. Both regulations are figures of merit of a regulator. Ideally we'd want them to be zero to signify a regulated voltage that is completely insensitive to variations in either the voltage supplying it, or in the load drawing current from it.

M12: With power off, assemble the circuit of Fig. 9, using the resistor obtained in Step C11 for R_s, and using 500 Ω for R_L (use 2 × 1 kΩ resistors connected in parallel.) Apply power, and measure both the *input ripple* V_{ri} and the *output ripple* V_{ro} with the oscilloscope. The *ratio* V_{ro}/V_{ri} provides the experimental value of the *Line Regulation*. How does it compare with the predicted value of Eq. (8*a*)? Justify any possible differences.

M13: Using the DC voltmeter, measure the *average value* V_O of the output, first with $R_L = 500\ \Omega$ (corresponding to the maximum load current $I_L \cong 10$ mA), then with $R_L = \infty$ (corresponding to the minimum load current $I_L = 0$). The ratio $\Delta V_O / \Delta I_L$ provides the experimental value of the *Load Regulation*. How does it compare with the predicted value of Eq. (8*b*)? Justify any possible differences.

Using Op Amps to Improve Circuit Performance:

The performance of diode circuits can be improved significantly through the judicious use of op amps. In the following steps, we investigate two application examples, namely, **rectification** and **regulation**.

Precision Rectification:

Figure 3 indicates that the presence of the diode drop $V_{D(\text{on})}$ causes an error of about 0.7 V in the output waveform that may be undesirable especially in precision rectifier applications. This error can be nulled by placing the diode (or diodes) inside the *feedback loop* of an *op amp*. Figure 10 shows a popular *precision half-wave rectifier* using this concept. Like its basic counterpart of Fig. 2, the circuit is readily simulated via PSpice. The resulting waveforms of Fig. 11 reveal that the circuit gives

$$v_O = -v_I \qquad \text{for } v_I > 0 \tag{9a}$$

$$v_O = 0 \qquad \text{for } v_I < 0 \tag{9b}$$

without noticeable error in spite of the nonzero diode voltage drops. The circuit provides also signal inversion due to the presence of the op amp, which is made to operate in the inverting mode.

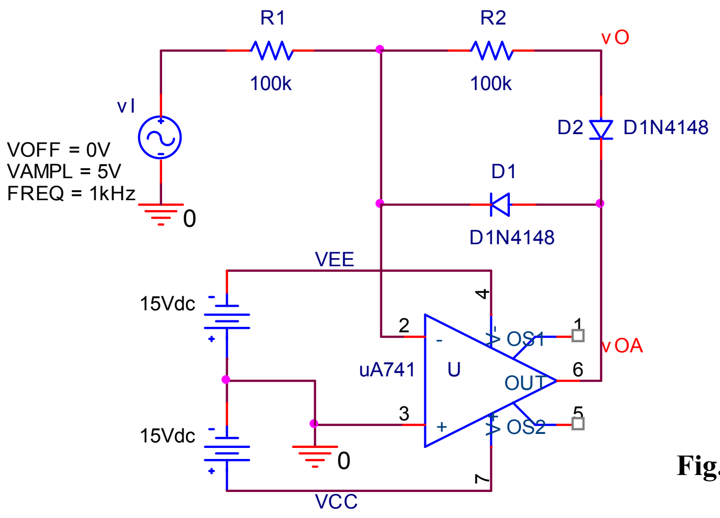

Fig. 10 – Precision half-wave rectifier.

C14: Analyze the circuit of Fig. 10, and prove that Eq. (9) holds. ***Hint:*** You can gain additional insight by directing PSpice to plot also v_{OA}, the waveform right at the op amp's output pin.

C15: By summing a signal with its inverted half-wave rectified version in a 1-to-2 ratio, as depicted in Fig. 12, we obtain *precision full-wave rectification.* Prove that this circuit yields

$$v_O = |v_I| \tag{10}$$

this being the reason why it is also called a *precision absolute-value circuit.*

Hint: Consider first the case $v_I < 0$, then the case $v_I > 0$.

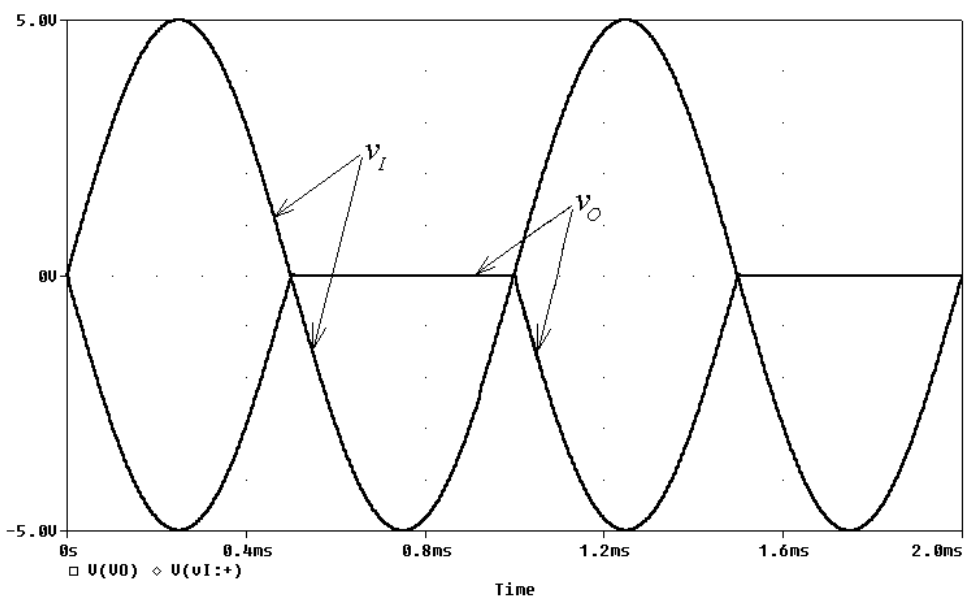

Fig. 11 – Waveforms for the circuit of Fig. 10.

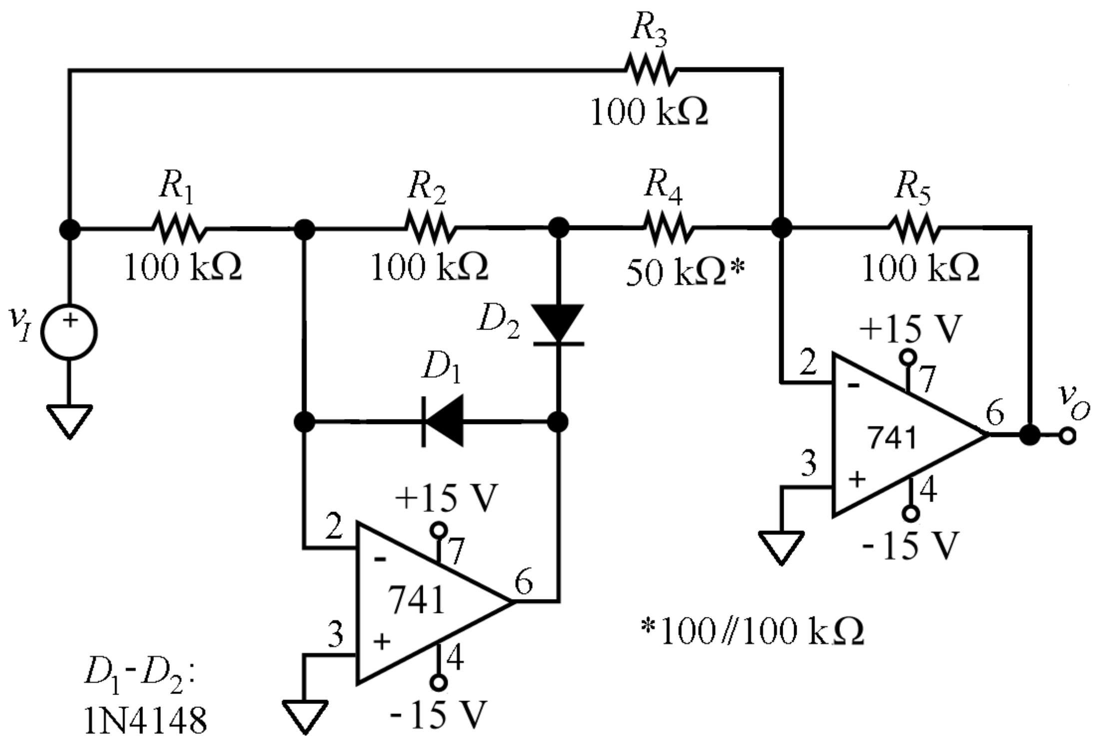

Fig. 12 – Precision full-wave rectifier.

M16: With power off, assemble the circuit of Fig. 12. Next, apply power, and while monitoring v_I with Ch.1 of the oscilloscope, adjust the waveform generator so that v_I is a 1-kHz sine-wave alternating between –5 V and +5 V. Observe v_O with Ch. 2 of the oscilloscope, and verify that v_O is indeed the *full-wave* rectified version of v_I. Vary the amplitude as well as the frequency of v_I. What happens if amplitude is raised above a certain limit? If frequency is raised above a certain limit? Justify your findings in terms of familiar op amp limitations.

The most popular application of the full-wave rectifier is in *averaging-type voltmeters.* These meters accept an AC input and produce a DC output calibrated to coincide with the RMS value of the AC input, or $V_O = V_{im}/\sqrt{2} = 0.707V_{im}$, where V_O is the DC output and V_{im} is the amplitude of the AC input. To this end, we first generate the *absolute value* of the input. Then, we *low-pass filter* it to synthesize its *average*, which for a rectified sine wave is $(2/\pi)V_{im} = 0.637V_{im}$. Finally, we raise the filtered signal from $0.637V_{im}$ to the desired value of $0.707V_{im}$ by *amplifying* it with gain 0.707/0.637 = 1.1 V/V. As shown in Fig. 13, filtering is achieved by adding a suitably large capacitance C in the feedback path of the summing amplifier, and the desired amplification is obtained by raising its feedback resistance from 100 kΩ to 110 kΩ.

M17: With power off, add C (beware of polarity!) to the circuit of Fig. 12, as well as 10-kΩ resistance in series with the existing 100 kΩ, so as to obtain the circuit of Fig. 13. Then, apply power, and verify that your circuit yields a DC output that, within an error due to resistance tolerances and op amp imperfections, coincides with the RMS value of the AC input. Verify over a range of input amplitudes and frequencies.

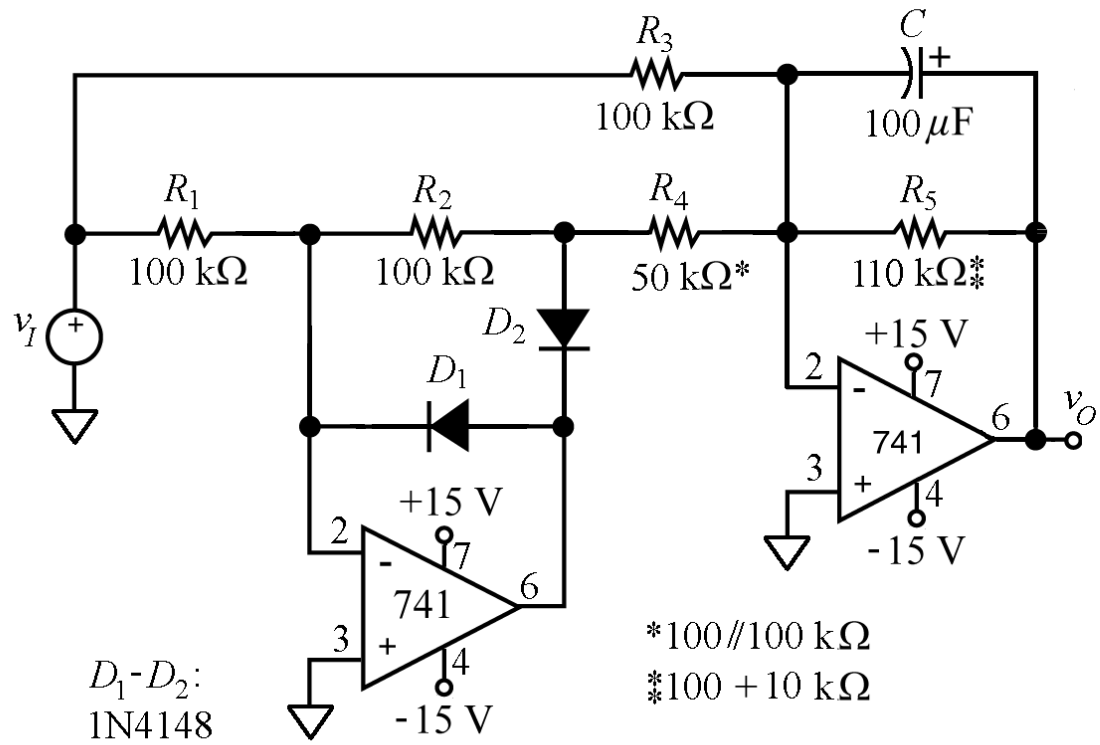

Fig. 13 – Building block for averaging-type voltmeters.

Precision Regulation:

As discussed, the drawbacks of the simple regulator of Fig. 9 are nonzero line and load regulation. If the Zener diode had $r_z = 0$, its *i-v* curve would be perfectly vertical, indicating ideal voltage-source behaviour. Both right-had terms in Eq. (8) would then drop to zero. The circuit of Fig. 14 uses an op amp to effect a dramatic improvement *both* in line and load regulation. Starting from a *raw supply voltage* V_{RAW}, the circuit amplifies the Zener-diode voltage V_Z (≅ 5 V) to produce a highly *regulated output voltage* V_{REG} according to

$$V_{REG} = \left(1 + \frac{R_2}{R_1}\right) V_Z \qquad (11)$$

The circuit is fairly insensitive to ripple and other variations in the supply voltage V_{RAW} because of the op amp's high *PSRR*. The circuit is also fairly insensitive to variations in the output current I_L because of its low output resistance. Moreover, by powering the Zener diode from the very voltage that we are trying to regulate, we are making the effects of its resistance r_z irrelevant. For this reason, the circuit is also referred to as *self-regulated voltage reference*. Finally, by varying R_2, we can adjust V_{RAW} exactly.

M18: With power off, assemble the circuit of Fig. 14, *but without* R_L *yet*. Then, apply power (V_{RAW} ≅ 15 V DC), and while monitoring V_{REG} with the DC voltmeter, adjust R_2 so that V_{REG} = 10 V. Now, verify the excellent regulation capabilities of your circuit as follows:

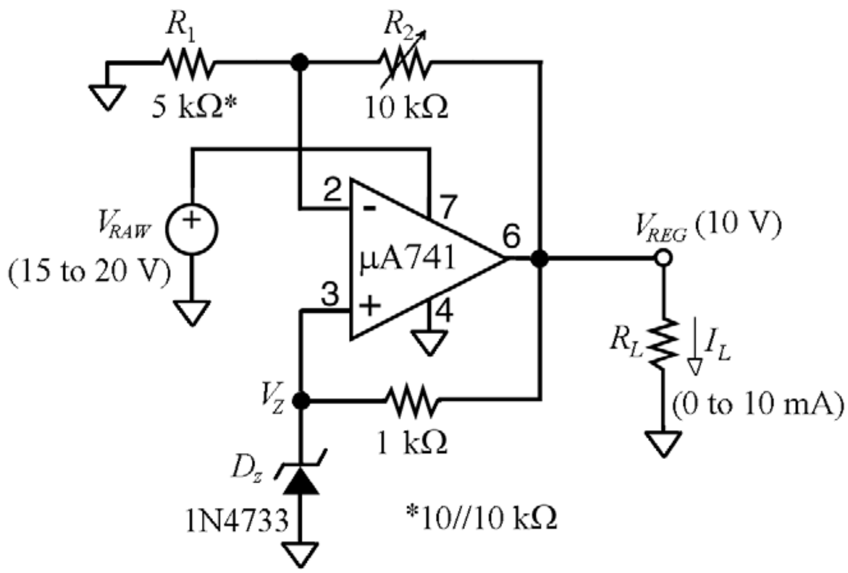

Fig. 14 – Self-regulated voltage reference.

- Vary V_{RAW} from 15 V to 20 V ($\Delta V_{RAW} = 5$ V), measure the resulting variation ΔV_{REG} with a sensitive DVM, and then calculate *Line Regulation* = $\Delta V_{REG}/\Delta V_{RAW}$. How does it compare with Step M12?
- Connect $R_L = 1$ kΩ, so that I_L changes from 0 to 10 mA ($\Delta I_L = 10$ mA), measure the resulting variation ΔV_{REG} with a sensitive DVM, and then calculate *Load Regulation* = $\Delta V_{REG}/\Delta I_L$. How does it compare with Step M13? Comment on your findings.