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

$$i = I_s (e^{v/V_T} - 1)$$

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, $V_T \approx 26$ 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 $v > 4V_T \approx 0.1$ V), the above equation tends to the true exponential function, also called the ideal diode equation,

$$i_D = I_s e^{v_D/V_T}$$

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
\[ v_D = 2.303 nV_T \log_{10} \left( \frac{i_D}{I_s} \right) \]  
\[ \text{(3)} \]

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 2.303\( nV_T/\text{decade} \). 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 \( 2 \times 60 = 120 \text{ mV} \). 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 \( V_{D(on)} = 0.7 \text{ V} \)
\[ \text{(4)} \]

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:

\[ \text{At room temperature, } V_D \text{ exhibits a thermal coefficient of about } -2 \text{ mV/}^\circ\text{C} \]

Once we know \( V_D \) at some reference temperature \( T_0 \), we can estimate it at any other temperature \( T \) using
\[ V_D(T) \approx V_D(T_0) - (2 \text{ mV}) \times (T - T_0) \]  
\[ \text{(5)} \]

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 \( (1 \text{ pA} = 10^{-12} \text{ A}, 1 \text{ nA} = 10^{-9} \text{ A}) \). Moreover, \( I_R \) is a strong function of temperature. As a rule of thumb,

\[ I_R \text{ doubles for every } 10^\circ\text{C rise in temperature} \]

Once we know \( V_D \) at some reference temperature \( T_0 \), we can estimate it at any other temperature \( T \) using
\[ I_R(T) \approx I_R(T_0) \times 2^{(T-T_0)/10} \]  
\[ \text{(6)} \]

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
\[ V_Z = V_{Z0} + r_Z i_Z \]  
\[ \text{(7)} \]
where \( V_Z \) 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. 1** - The complete \( i-v \) characteristic of a \( pn \) junction diode.

**Fig. 2** – Simple half-wave rectifier.
Henceforth, steps shall be identified by letters as follows: C for calculations, M for measurements, and S for SPICE simulation.

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 ($R = 100 \, \Omega$) 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 (X-Y mode), 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 $V_{D(on)}$, $V_{Z0}$, 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. 5a. 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. 5b. 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 $R$):

- $I_D = 1.0\ \mu A$ (1 MΩ)
- $I_D = 10\ \mu A$ (1 MΩ)
- $I_D = 100\ \mu A$ (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 $\mu A$ to 1.0 mA), and find the corresponding voltage span $\Delta V_D$. Considering that $\Delta V_D = 3 \times 2.303nV_T$, 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.](image)
S4: Create a LTSpice diode model with the above values of \( n \) and \( I_s \). Hence, using LTSpice 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.

**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 (\( R = 1 \) k\( \Omega \)) and \( I_{Z2} = 20 \) mA (\( R = 100 \) \( \Omega \)). 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 \( v_o \).
S7: By a procedure similar to that in connection with Fig. 2, simulate the circuit of Step M6 via LTSpice, 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-$\mu$F 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

![Diagram of Zener Diode Regulator](image)
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 \( 0 < i_L < 10 \text{ mA} \).

**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 \( 10 \text{ mA} \) of load current with no less than \( 5 \text{ mA} \) 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

\[
\text{Line Regulation} \approx \frac{r_s}{R_s + r_z} \tag{8a}
\]

\[
\text{Load Regulation} \approx -\frac{R}{\|r_z} \tag{8b}
\]

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 \( 500 \Omega \) for \( R_L \) (use \( 2 \times 1 \text{k} \Omega \) 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. (8a)? 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 \( I_L \approx 10 \text{ mA} \)), 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. (8b)? 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 \( V_{D(on)} \) 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 LTSpice. The resulting waveforms of Fig. 11 reveal that the circuit gives

\[
V_O = -V_I \quad \text{for} \quad V_I > 0 \tag{9a}
\]

\[
V_O = 0 \quad \text{for} \quad V_I < 0 \tag{9b}
\]

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.
C14: Analyze the circuit of Fig. 10, and prove that Eq. (9) holds. **Hint:** You can gain additional insight by directing LTSpice 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

\[
v_O = |v_I|
\]  

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 \( v_I > 0 \).

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**Fig. 10** – Precision half-wave rectifier.

**Fig. 11** – Waveforms for the circuit of Fig. 10.
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 \( V_O = V_{im} / \sqrt{2} = 0.707 V_{im} \), 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 \( 100 \) k\( \Omega \) to \( 110 \) k\( \Omega \).