EXPERIMENT 2: DIODES AND THEIR APPLICATIONS

I. DESCRIPTION AND OBJECTIVE

In this experiment, you will study the current-voltage characteristics of diodes, build rectifier circuits and study small signal dynamic resistance of a diode.

II. GENERAL CIRCUIT DISCUSSION

A diode is a two-terminal element, usually made by using a pn junction (the operation of which is explained in detail in EE178 Device Electronics class). In this lab, we are concerned only with the external (voltage-current) characteristics of diodes, their application in AC to DC conversion and their small signal dynamic resistance and how it changes with the operating bias of the diode.

The symbol for a diode is shown in Fig. 1(a). Which terminal is which matters very much in a diode. Usually, the terminal indicated by a horizontal line in Fig. 1(a), called the cathode, is marked on a real diode; see, for example, Fig. 1(b). We define the voltage \(v_D\) and the current \(i_D\) of a diode as shown in the figure. These two quantities are related, as shown in figure Fig. 1(c). When the voltage \(v_D\) is positive, the diode is said to be forward-biased; a large current can then flow, and the diode is said to conduct. When the voltage \(v_D\) is negative, the diode is said to be reverse-biased; the diode current is extremely small, and for our purposes it is assumed to be zero; the diode is then said to be turned off. Thus, the diode effectively conducts current in only one direction (downward in Fig. 1); it “refuses” to conduct current in the other direction. This property turns out to be very useful, as you will find out in this experiment.

![Fig. 1](image-url)
III. Large Signal Operation (Rectification)

In the forward bias region (positive voltage $v_D$), $i_D$ turns out to be exponentially related to $v_D$. For typically used values of the current, the resulting steepness of the $i_D - v_D$ characteristic curve means that a large range of current variation can be obtained by varying the voltage in a narrow range, as indicated in Fig. 1(c). For this reason, for commonly used current values the forward-biased diode voltage $v_D$ is sometimes considered to be approximately constant. A typical value often used for this voltage is 0.7 V. We will assume this value in the discussion, but it should be kept in mind that other values may be more reasonable, depending on the diode type and current range used.

Consider now the circuit of Fig. 2. The output voltage $v$ cannot be negative since this would require a negative value for $i_D$, which cannot pass through the diode. The voltage $v$ can be positive, though, and this will occur when $i_D$ is positive (i.e., when the diode conducts). In this case, $v_D$ will be approximately equal to 0.7 V (see above). From Kirchoff’s voltage law, we have $v_D + v = v_S$, and thus the output will be $v = v_S - v_D$. These observations should help you interpret what you will be measuring.

Assume now that $v_S$ in Fig. 2 is a sinusoidal voltage. From the above observations, it can be seen that the output voltage waveform $v$ is as shown in Fig. 3. The negative parts of each input cycle are cut off, since $v$ cannot be negative. The positive parts of each input cycle appear at the output, but are lowered by the voltage of the forward-biased diode (assumed to be about 0.7 V in the figure). The circuit in Fig. 2 is called a rectifier.

The output voltage $v$ in Fig. 3 has only one polarity, in contrast to the input voltage. However, it is not a DC voltage, as it is not constant with time. We can obtain a voltage that is almost DC by adding a capacitor to the circuit, as shown in Fig. 4. This results in the behavior shown in Fig. 5, as will now be explained. When the diode conducts, $v = v_S - v_D$, and the capacitor charges up to this value. Let the peak value of the input voltage be $V_p$. Near the peaks of the input voltage, the capacitor voltage is approximately $v = V_p - 0.7$ V. When $v_S$ decreases below its peak value, the value of $v_D = v_S - v$ decreases since $v$ is held almost constant by the capacitor. Thus the diode becomes cut off, and its current reduces practically to zero; it now behaves virtually as an open circuit. The capacitor is then effectively connected only to the resistor and begins discharging through it. If the RC time constant is large, the discharge will be slow, as shown in Fig. 5. At some later point, the input rises again and reaches a value about 0.7
V higher than the value of \( v \); then the diode starts conducting again, and \( v = v_S - v_D \approx v_S - 0.7V \). The output thus starts following the rising input (while staying below it by about 0.7 V). The capacitor charges up again, and the whole cycle is repeated. It can be seen that, for the circuit of Fig. 4, the output voltage is almost DC; it is constant within a small variation, called the ripple. The ripple can be made very small by choosing an appropriate RC time constant.

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**RECTIFIERS**

1. Connect the function generator to the circuit, as shown in Fig. 8. Use a sinusoidal voltage with a frequency of 1 kHz and an amplitude of 4V. Observe both the generator and the resistor voltage waveforms, using the two channels of the scope. Be very careful with the grounds. (The ground of the scope should be attached to the grounded terminal of the function generator; otherwise, the generator may be damaged. You may want to consult the Lab 0 chapter on ground connections.) Use DC input coupling on the scope for both channels. You need to think about how you would trigger to obtain a stable display. Adjust the time/div control so that you can observe several cycles on the screen. Keep a record of the waveforms obtained. The circuit you have just studied is a rectifier.
2. To help keep the output constant, add a 1 µF capacitor in parallel, as shown in Fig. 9. Explain what you see. **CAUTION: If a polarity is indicated on the capacitor available to you, be sure to deserve it.**

3. What is the average value of the waveform v?

4. What is the ripple (variation) of the waveform v in volts? What is the ripple as a percentage of the average value found in step 1?

The circuit you have just made is an AC-to-DC converter—a simple power supply. It is the basis of most power supplies, which convert a 60 Hz or 50 Hz AC voltage to a DC voltage. In this experiment, we have used instead a frequency of 1 kHz for convenience in measurements.

**IV. Small Signal Operation (Dynamic Resistance)**

Consider the following well-known equation:

\[ r_d = \frac{nV_T}{I_D} \]  

where the thermal voltage \( V_T = \frac{kT}{q} = 25mV \) at room temperature. Equation [1] is the small-signal dynamic (or AC) resistance the diode exhibits when biased at a quiescent DC current \( I_D \).

Remember this equation is an approximation holding only for small time-varying AC, or small-signal, inputs limited to about 10 mV in amplitude. The diode’s current then varies nearly linearly with the small voltage changing across it, so we can treat the behavior of the diode as a linear resistor having \( r_d \) Ohms of resistance.
Figure 1. Theoretical diode circuit.

Note: Re-draw this schematic in your engineering notes and make any experimental scribbles or annotations there.

Figure 2. Practical circuit implementation.

Note: Re-draw this schematic in your engineering notes and make any experimental scribbles or annotations there.

Figure 1 shows the theoretical circuit we want to implement. Our work will be based on a practical implementation of this, shown in Figure 2. The Op-amps have been added to help maintain an approximately ideal testing environment.
Op-amp $U1$ functions as a unity-gain buffer to isolate the unwanted effects of the signal generator’s output impedance (which is typically 50 Ohms or greater). It provides the input signal for the main circuit at its output node.

Op-amp $U2$ is used in a similar manner: diode current $I_D$ will be found by calculation from the measured resistance of $R_B$ and the measured voltage drop across it for various settings of $R_D$. Without $U2$, the effective resistance seen looking back into this branch would change whenever resistance $R_4$ was changed. Op-amp $U2$ provides the biasing DC current through the resistor at its output node.

$V_{CC}$ and $V_{EE}$ should be somewhere between 10 and 15 Volts. Keep track of their actual values and make sure they remain stable as you go through the experiment. Once set, try not to keep turning them on and off; rather, remove the interconnections when you want to de-energize things to make changes. You may also want to de-couple the power supply rails to avoid small-signal feedback paths through the power supply leads. Place 100 $\mu$F (or larger) capacitors from $V_{CC}$ and $V_{EE}$ to ground where appropriate. You should have at least one to decouple $V_{CC}$ and one for $V_{EE}$.

Op-amp $U3$ is configured as a non-inverting amplifier with a voltage gain of about 11 [V/V]. It provides amplification of the small signal diode voltage $v_D$ so that the oscilloscope can read it.

Take measurements to determine the dynamic resistances $r_d$ of the diode at several DC bias conditions. How the dynamic resistance changes with DC bias? Why?

**Recommended Procedure for part IV:**

*(Hint) Build and test each amplifier separately before assembling the full circuit*

This is a complicated circuit, so assemble each of the three op-amp circuits before doing anything else. Test each one separately before connecting them together. This will help identify problems in parts of the circuit when it is simple enough to identify the source of the problem.

1. **Determine dynamic resistance $r_d$ at least three different bias points.**

A substitution procedure works best to accurately determine the dynamic resistance $r_d$. First, measure $R_I$ (nominal 100 Ohms), $R_B$ (nominal 1k) and one of the several resistances $R_D$ (between 10 and 1000 Ohms) that will be used to calibrate $r_d$. Substitute $R_D$ in place of the diode and adjust the signal generator for a small-signal sinusoidal output less than 10 $mV_{pp}$ at 1 kHz (5 to 8 $mV$ works well). The signal generators in the lab produce a minimum output voltage of 50 $mV_{pp}$ so you must design yourself a voltage divider to reduce the output voltage into the desired range. Be sure to calibrate your voltage divider (used here as an attenuator) and check the voltage that you are actually applying using the scope.
First, put a resistor $R_D$ in place of the diode with resistance between 10-1000 Ohms (again measure its actual resistance as the resistor values are different from resistor to resistor). Measure $V_X$, the output voltage of Op-amp U3. Now replace the resistor $R_D$ with the diode and adjust the current through the diode until you get the same $V_X$ as you measured with the resistor in place. The small signal resistance of the diode will now be equal to the value of $R_D$ that you chose. You now know that $r_d$ of the diode is equal to $R_D$ and you can measure the current through it, $I_D$. You now know all the components of $r_d$ given in equation 2 except for $n$, which you can now calculate. The ideality (or emission factor) $n$ that you calculate should be somewhere between 1 and 3. Repeat this procedure for 3 different $R_D$ calibration resistor values. Are the values that you calculate for $n$ all the same? Why might they be different? Assuming that the $n$ of the diode really is a constant, what is your best estimate of its value and how accurately do you think that you know it?

Investigate the effect of overdriving the diode, that is use a signal voltage of more than 10 $mV_{pp}$, try it and see what happens. It might provide insight into what is going on. This is much easier done in the lab by measurement or on a simulator than by hand calculation!