ECE 241L Fundamentals of Electrical Engineering

NAME ______________________

Experiment 4 Diodes & Diode Circuits

PARTNER ______________________

A. Objectives:

Objectives:
I. Measure and plot the forward diode characteristic
II. Measure the reverse diode current
III. Investigate diode rectification circuits
IV. Investigate clipping and clamping circuits

B. Equipment:

Breadboard, wire, resistors, capacitors, 1N4001 diode
Oscilloscope: Tektronix TDS3043 Digital Storage Scope
Function Generator: Tektronix AFG310/320 Arbitrary Function Generator
Digital Volt-Ohm Meter (DVM): Fluke 189 (or equivalent)

C. Introductory Notes:

Semiconductors, diodes, and LEDs

Semiconductors such as **Silicon** have high resistivity that decreases with temperature as electrons normally bound in the crystal lattice are released due to thermal energy. This effect is used in devices called **Thermistors** to measure temperature. Semiconductors are also very sensitive to infinitesimally small amounts of alloying elements called "doping". The Silicon crystal has 4 valence electrons binding each atom to its neighbor. Without doping, the resistivity is very high. However, if a doping element with 5 valence electrons is introduced, the 5th electron is essentially free to conduct electric current. This is called an "n-type" material. Conversely, if an element with 3 valence electrons is introduced it leaves a "hole" in the lattice that propagates like a positively charged bubble and also can carry electric current. This is called a "p-type" material. The entire history of electronics was changed when an amplifying and switching device using this effect, called the "transistor," was invented by Brattain, Bardeen, and Shockley in 1947.

If "p" and "n" materials are welded together they form a circuit element called a **p-n junction** which will conduct positive current from "p" to "n" but not in the other direction. This device is called a "rectifier" (meaning it conducts in the "right" direction only), and also called a "diode" (meaning a device with two electrodes). A rectifier is used to convert alternating current into direct current, an essential feature of electronic circuits. The electrical characteristics of diodes can be described with a graph of current vs. voltage that has a typical "L" shape. In the forward direction the voltage drop is almost constant, independent of the current. In the reverse direction the current is almost constant, independent of the voltage, and nearly zero. Therefore these are "non-ohmic" circuit elements. The theoretical relationship is not i = v/R , but an exponential equation as given below.

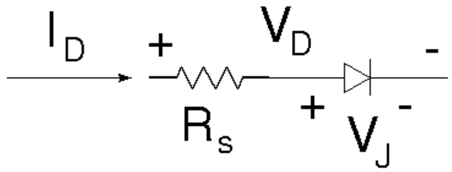
$i = I_o[\exp(+v/V_t) - 1]$ where I_o = reverse saturation current
V_t = thermal voltage, typically about 25 millivolts

(Note: This is an approximate form, and more accurate variations are presented below.)
Semiconductors can generate light. A **light-emitting diode** "LED" made of a semiconductor alloy of Gallium and Arsenic will radiate light when current flows in the forward direction. Semiconductors are also sensitive to light. A **photodiode** p-n junction will conduct in the reverse direction if light shines on it.

Diode Characteristic

To analyze electronic circuits, the engineer needs to know the parameters that describe the behavior of the electronic devices in the circuit. In this experiment you will learn how to measure and calculate several parameters of a simple diode model. Diodes are non-linear devices, i.e. the relationship between voltage and current is non-linear. Consequently, the signal-transmission behavior of these devices is dependent on the bias conditions (i.e. condition when no signal is applied) of the device. This aspect of diodes will be explored by investigating the small-signal, low frequency equivalent resistance of the diode.

The *dc* behavior of a real forward-biased diode may be modeled as an ideal diode (p-n junction) in series with a small resistor R_s, which represents both the bulk resistance of the semiconductor material and the resistance of the ohmic contacts to the semiconductor.



Diode parameters of interest in this experiment include: the series resistance R_s, the reverse saturation current I_s, the emission coefficient n_e and the small signal *ac* (or *dynamic*) resistance r_d. These parameters may be determined from the *dc* transfer curve I_D vs. V_D. Theoretically, the current I_D in a p-n junction is related to the junction voltage V_J by the equation

$$I_D = I_S(e^{V_j/(n_e V_T)} - 1)$$

Equation 1 - P-N Junction DC Transfer Curve

where:
I_S = reverse saturation current
n_e = ideality or emission coefficient (usually between 1.0 and 2.0)
V_T = the thermal voltage (kT/q = 0.025852 V @ T = 300 K)
k = Boltzmann's constant (1.38066 10^{-23} J/K)
T = temperature in K
q = magnitude of the electronic charge (1.60218 10^{-19} C)

When the diode is forward-biased ($V_J > 0$) by more than a few V_T, the exponential term is large compared to 1, and this equation can be approximated as

$$I_D \approx I_S e^{V_j/n_e V_T}$$

The total diode junction voltage is the terminal voltage less the drop across the series resistance,

$$V_J = V_D - I_D R_S$$

so

$$I_D \approx I_S e^{(V_D - I_D R_S)/n_e V_T}$$

Equation 2 - Diode DC Transfer Curve for $V_j >> V_T$

which can also be expressed as (taking the natural log of Equation 2)

$$\ln I_D = \ln I_S + \frac{V_D}{n_e V_T} - \frac{I_D R_S}{n_e V_T}$$

Equation 3

The bulk series resistance of the diode is normally quite small (usually less than 10Ω. Therefore, at low currents (e.g. $I_D <$ 1mA), the voltage drop across R_s is small compared to the voltage drop $V_J \approx V_D$ across the p-n junction, so that Equation 3 can be approximated as

$$\ln I_D = \ln I_S + \frac{V_D}{n_e V_T}$$

Equation 4

Note that the slope of this curve is inversely related to one of the diode model parameters, n_e. If we can determine the slope of this curve, we have identified n_e.

The natural log of actual current in a real diode as a function of diode terminal voltage is shown in Figure 1. From this characteristic curve we can see that the natural log of diode current deviates from the linear scaling predicted by Equation 4 at both high and low diode terminal voltages.

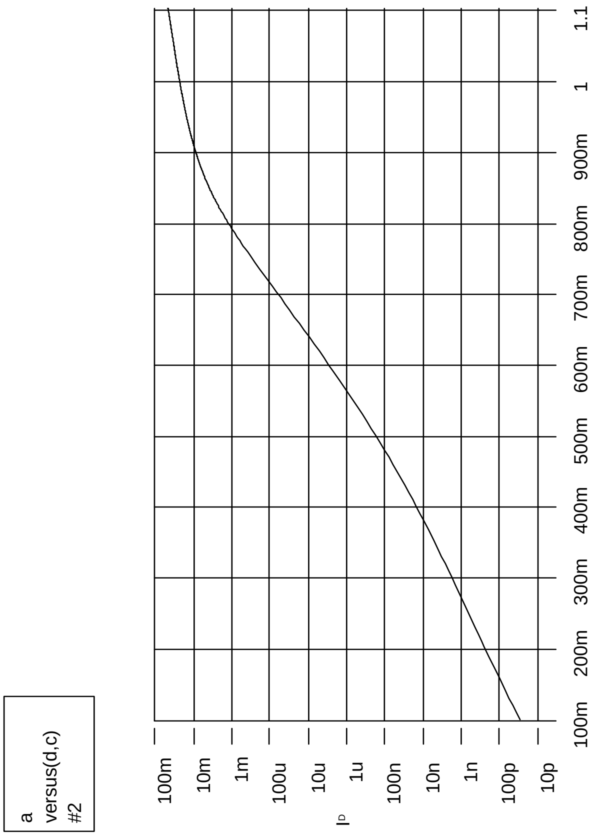


Figure 1 - Measured ln(ID) vs. VD

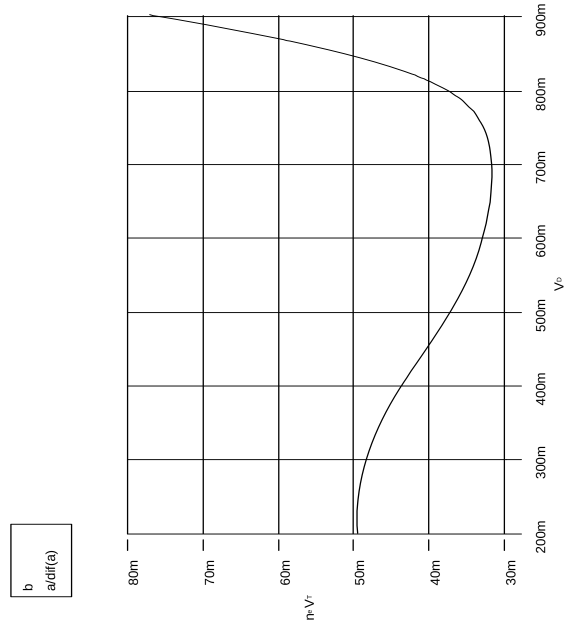


Figure 2 $\frac{I_D}{\frac{\partial I_D}{\partial V_D}}$ **From Figure 1**

At high currents, the series resistance term in Equation 3 causes the diode current to drop below the prediction of Equation 4, i.e. some of the voltage drop is consumed in overcoming the series resistance, and is not dropped across the p-n junction. As such, the slope of the curve is lower than that predicted by Equation 4

At low currents, effects in the space-charge layer in the pn-junction result in extra current in the junction which causes the current to be higher than predicted by the ideal diode equation, and the slope is also lower than predicted by Equation 4.

The best place to determine n_e, is where the above effects are minimized. This will occur where the slope of the $\ln(I_D)$ vs. V_D curve is at it's maximum. From Equation 2,

$$\frac{\partial I_D}{\partial V_D} = \frac{1}{n_e V_T} I_s e^{(V_D - I_D R_D)} = \frac{I_D}{n_e V_T}$$

$$or$$

$$n_e V_T = \frac{I_D}{\frac{\partial I_D}{\partial V_D}}$$

A plot of $\frac{I_D}{\frac{\partial I_D}{\partial V_D}}$ for the data of Figure 1 is shown in Figure 2. The influence of diode resistance and space charge effects are clearly shown in this figure at high and low diode voltages. If the diode had been ideal, following

Equation 2, the graph would have been a horizontal line. The minimum value in this graph can be used to determine $n_e V_T$ and hence the emission coefficient n_e.
Once n_e is known we can determine the saturation current I_S, using Equation 4 and data taken from Figure 1. The $\ln(I_D)$ data must be taken at the same voltage used to estimate n_e.

At high current levels the data from Figure 1 in Equation 3 can be used to calculate R_S, since n_e and I_S are known.

$$R_S = \frac{n_e V_T}{I_D}\left[\ln(I_S) - \ln(I_D) + \frac{V_D}{n_e V_T}\right]$$

The small signal, or dynamic resistance is the resistance seen by small current variations around a DC bias point (otherwise known as operating point.) If a diode voltage is applied that contains both DC and AC components, $V_d(t) = V_D + v_d(t)$, a time varying current will flow through the diode, like

$$I_d(t) = I_D + i_d(t) = I_s e^{\frac{(V_D + v_d(t))}{n_e V_T}} = I_s e^{\frac{V_D}{n_e V_T}} e^{\frac{v_d(t)}{n_e V_T}}$$

$$I_D = I_s e^{\frac{V_D}{n_e V_T}}$$

so

$$I_D + i_d(t) = I_D e^{\frac{v_d(t)}{n_e V_T}}$$

Expanding the exponential in a series expansion, and retaining only linear terms in v_d,

$$I_D + i_d(t) \approx I_D\left(1 + \frac{v_d(t)}{n_e V_T}\right) = I_D + v_d(t)\frac{I_D}{n_e V_T}$$

so the variation around the bias point (I_D, V_D) is

$$i_d(t) \approx v_d(t)\frac{I_D}{n_e V_T}$$

The coefficient of v_d is the small signal conductance of the diode to small changes in current around it's operating point. Note that the conductance of the diode increases linearly with the bias current in the diode. The small signal resistance of the diode is the inverse of the conductance, or, alternatively, the inverse slope of the diode V-I characteristic at the operating point, $r_d = \frac{\partial v_d}{\partial i_d} \approx \frac{n_e V_T}{I_D}$,

Plotting the *dc* transfer curve for forward bias on linear scales, Figure 3, permits us to illustrate the meaning of the *small-signal* diode resistance r_d. In small-signal operation, a forward-biased diode acts like a resistor r_d, where r_d is given by the slope of the *dc* transfer curve in the operating point established by the *DC* values I_D and V_D. From the figure it should be clear that the small-signal parameter r_d is a function of the operating point, since the slope of the diode characteristic curve changes with the bias point: different values of *DC* bias result in different values of the small-signal resistance. This is true for all small-signal parameters in non-linear devices.

The slope of the characteristic curve at the bias point can be estimated by taking a centered difference around the bias point, i.e.

$$r_d = \frac{\partial v_d}{\partial i_d} \approx \frac{\Delta V_d}{\Delta I_d}$$

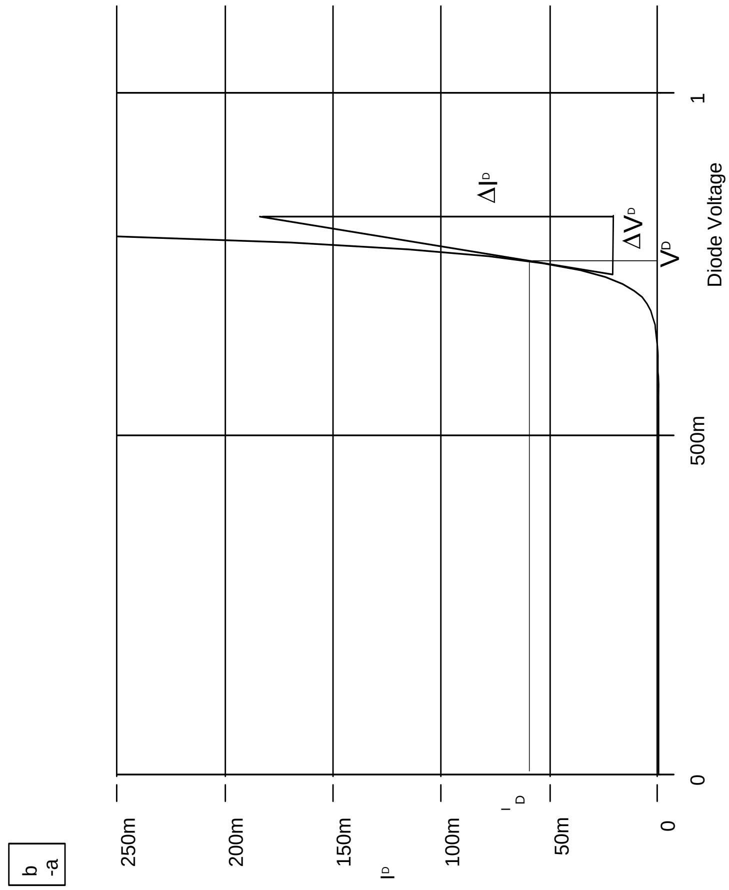
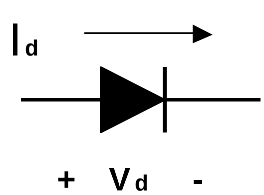


Figure 3 Diode characteristic and incremental resistance

Diode Circuit Models

The semiconductor diode is a simple exmple of nonlinear circuit elements that can be created using the properties of semiconductor p-n junctions. While the nonlinear V-I relationships allow the design of very useful nonlinear circuits, the nonlinearities complicate the circuit analysis by excluding fundamental linear analysis methods like superposition, Laplace Transforms, and transfer function descriptions. In general, circuit equations describing circuits with nonlinear elements are nonlinear ordinary differential equations, and can require advanced analytic solution techniques, or numerical solution via a circuit simulator.

Rather than abandon what we know about linear circuit analysis, very useful results (although at less accuracy that exact analyses) can be had by using linear approximations to nonlinear behavior. Replacing a nonlinear element with an approximate linear model allows linear circuit theory to be applied, but it also restricts the domain of signal amplitudes where the results are correct to withan an acceptable error. Often, several approximate linear models are needed to describe the nonlinear element over a wide range of voltages and currents. After getting approximate results from a linear model, the analyst should always check to validate the “appropriateness” of the assumed model and try to establish bounds on the error introduced by using the approximation.



Diodes are often replaced with one of 4 equivalent linear circuits of increasing complexity and accuracy. They are:

1. The "ideal" diode approximation - The diode is approximated as a "switch" which is open for $V_d < 0$, closed for $I_d > 0$, and $V_d = 0$ for $I_d \geq 0$; This is the simplest linear diode model, and is appropriate for use when the diode is in series with other circuit elements with much larger voltage drops than typical of a diode.

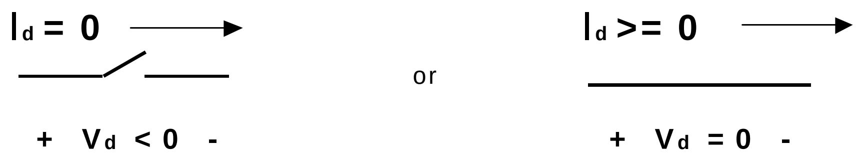


Figure 4 - Ideal Diode Approximation

2. The "constant voltage drop" approximation – The same as the ideal model, except, the switch "closes" at $V_d = V_{on}$, i.e. a "switch" which is open for $V_d < V_{on}$, closed for $I_d > 0$, and $V_d = V_{on}$ for $I_d \geq 0$; This model recognizes that a small "forward voltage" must be present for significant currents to flow through the diode. V_{on} is selected to give a "best fit" to a particular diode V-I relationship, and usually is between 0.5 V and 1 V. This model is appropriate for use when the drop across the diode is on the order of the voltage drops in series with the diode.

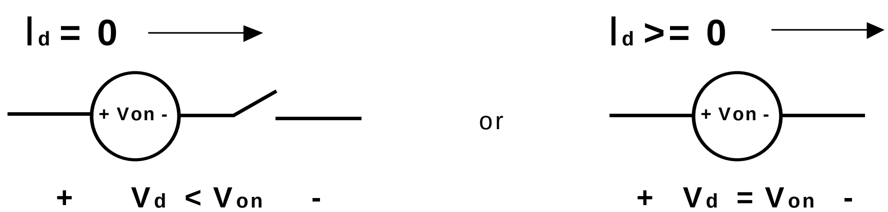


Figure 5 - Constant Voltage Drop Approximation

3. The "threshold voltage drop plus series resistance" approximation – This model reflects the fact that higher diode currents are associated with larger diode voltage drops, and approximates the nonlinear V-I relationship with a linear resistance in the vicinity of an "operating point", where the resistance is the dynamic resistance of the diode at the bias voltage. This model is most often used in coupled bias point and small signal AC analysis, where the diode resistance is on the order of the resistances in series with the diode. V_{on} and R_d are selected to give a "best fit" over a region of the forward biased diode characteristic. V_{on} is usually in the 0.5 V to 1 V range and R_d can vary from below 1 ohm and up to about 50 ohms, depending on the device.

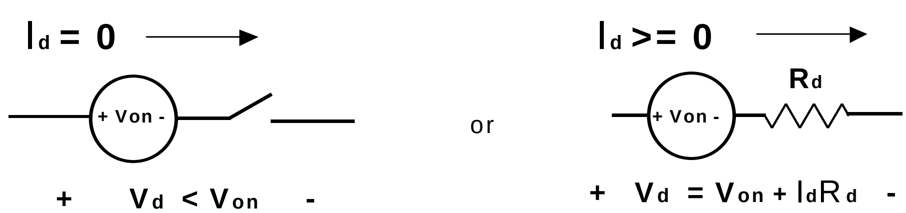


Figure 4 - Threshold voltage & resistor equivalent circuit

4. Piecewise linear approximation – The forward bias characteristic is approximated by a series of short straight line segments, with different, increasing slopes as the diode current increases. This model allows the "dynamic resistance" of the model to closely approximate that of a real diode, which decerases as diode current increases. This model is basically a "threshold voltage plus resistor" equivalent, where V_{on} increases and R_d decreases as a function of diode current.

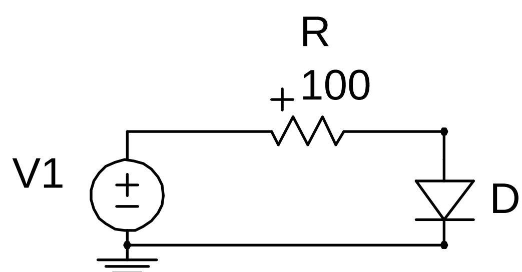
It's not always obvious which of the "states" of a particular linear equivalent model a diode will be in, so it's conventional to guess which state (conducting or not conducting) each diode will be in, and solve the resulting circuit, always checking after completing the analysis to see if there is any contradiction with the assumed state. Sometimes it's useful to find the boundaries between state transitions, in terms of the independent signal source exciting the diode circuit. For example, in the circuit of (h), below, using the threshold voltage plus series resistance equivalent circuit, the boundary between conducting and non conducting states occurs when $V_d = V_{on}$ where $I_d = 0$. At this point,

$$V_o = V_i = -V_B - V_{on}$$

When V_i is above this threshold, the diode is not conducting, and $V_o = V_i$. When V_i is below this threshold, the diode is conducting, so

$$I_d = \frac{-V_i - V_B - V_{on}}{R + R_d} \quad \text{and} \quad V_o = V_i\left(1 - \frac{R}{R + R_d}\right) - \frac{R}{R + R_d}\left(V_B + V_{on}\right)$$

PROCEDURE:



A. Diode Characteristic

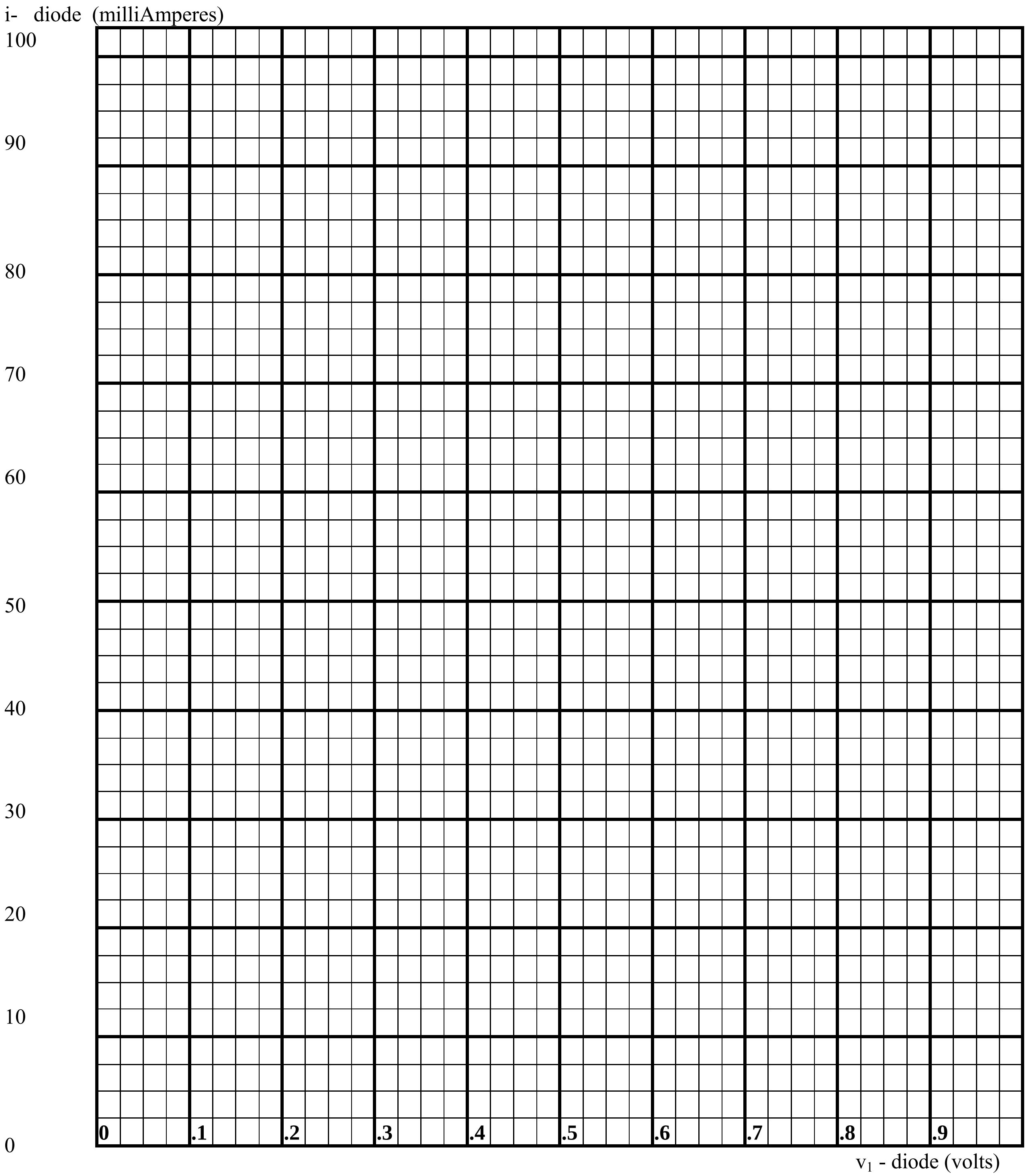
1. Connect the circuit in the figure above. (Note that the cathode end of your diode has a small stripe.) Use the power supply as V_1. Measure and record the actual value of the resistor, as it will be used to infer the diode current.

2. Change the value of the power supply so that I_D ranges from approximately 1 µA to 100 mA.. Use the DVM to measure the voltage across the dioder, and use it to calculate the diode current as $I_D=(V_1-V_D)/R$. Take enough data to plot a "smooth" curve, with more data in areas where the curve changes quickly. Increase R for low current measurements, to get more accurate control as you vary the voltage. (Use 100, 1k, 10k, and 100k.)

3. Plot I_D and $\log I_D$ versus V_D

4. For V_1 = 1 V determine the operating point of your actual circuit.

5. With R=100k, reverse the polarity of the supply voltage, and measure the voltage across the resistor instead. Calculate reverse V_D and I_D for V_1=5, 10, 15, 20 volts.

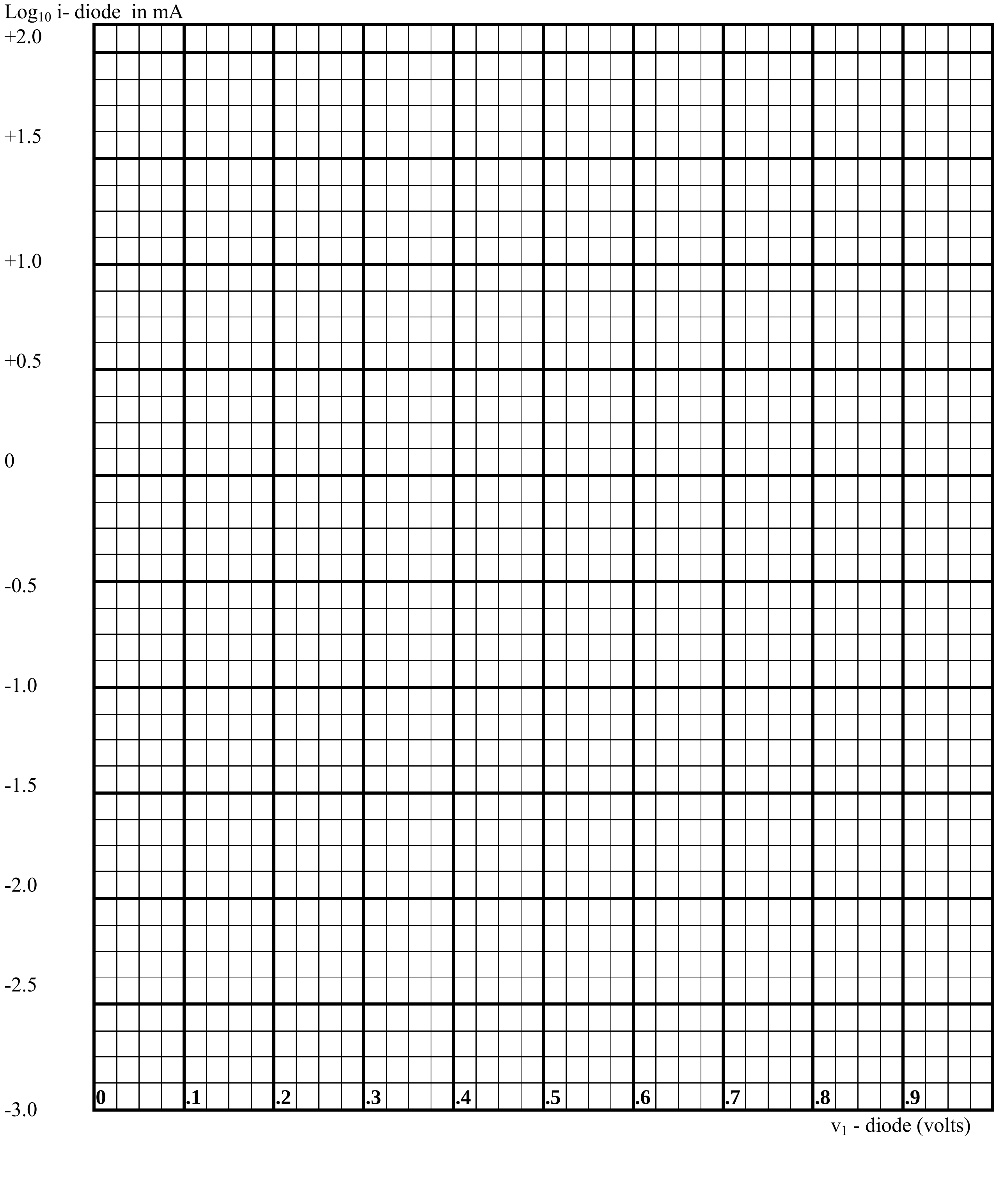


Diode operating point for V_1 = 1 volt: V_D = ________________________ I_D = _________________________

Reverse diode values:

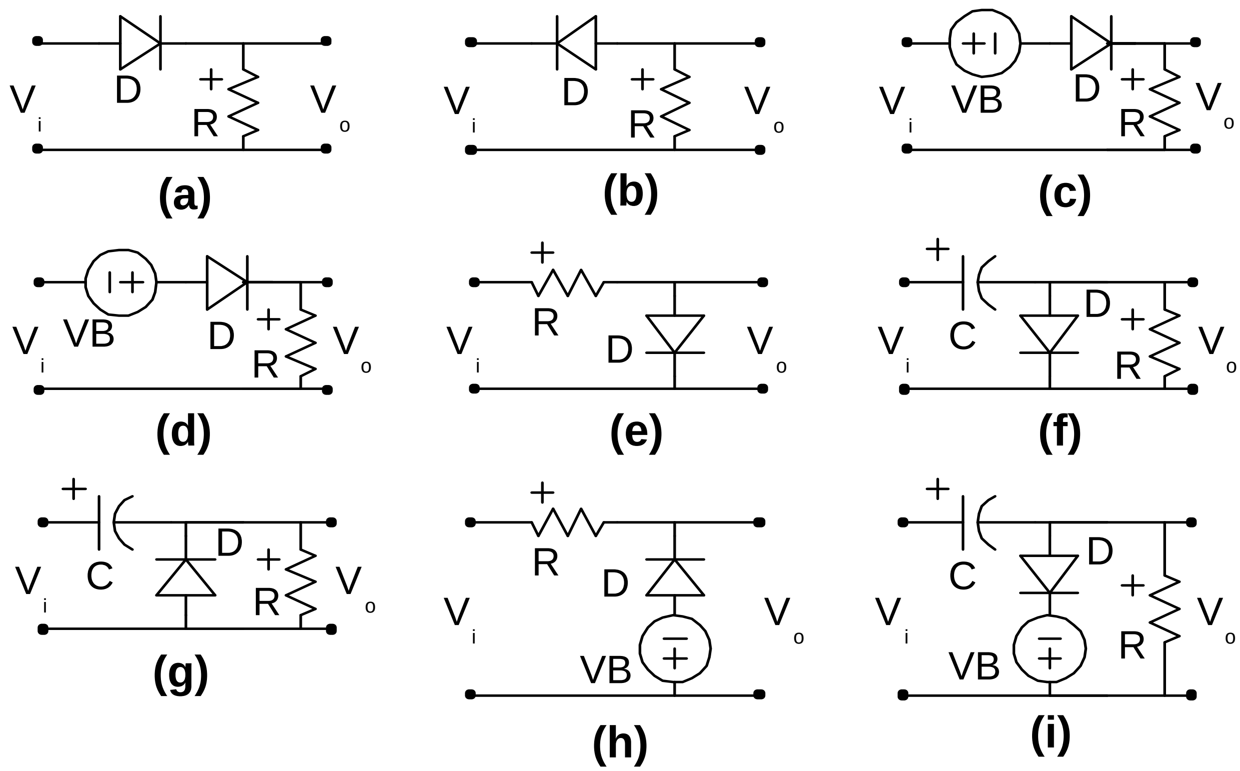
V_D = ____________volts ____________volts ____________volts ____________volts

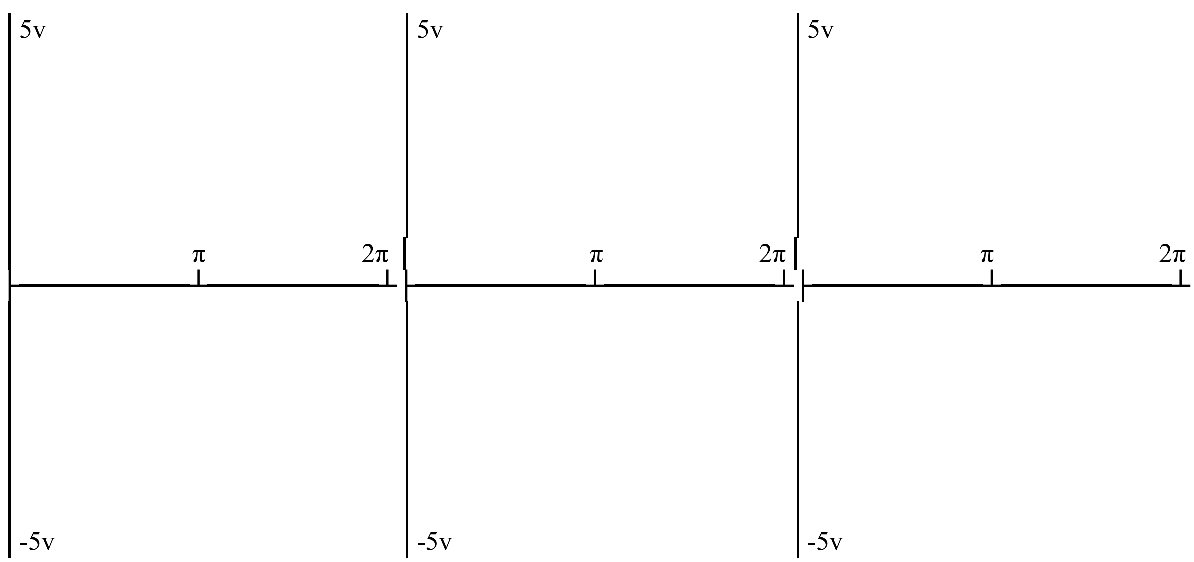
I_D = ____________amps ____________amps ____________amps ____________amps


Log$_{10}$ i- diode in mA
+2.0
+1.5
+1.0
+0.5
0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
v_1 - diode (volts)

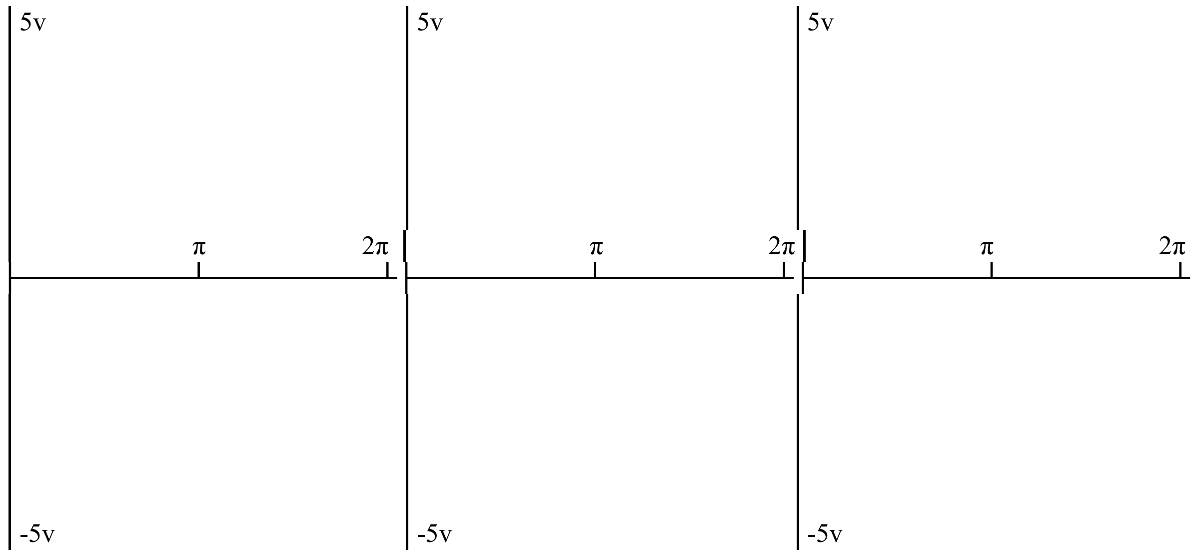
B. Diode Circuits: Rectification, Clipping, and Clamping

Construct each circuit in the figure below. For each circuit using a dual trace setup for the oscilloscope, sketch both $V_i(t)$ and $V_o(t)$ waveforms at the circuit input and output. Use the 1N4001 diode, R = 100kΩ, C=0.1μF, V_B = 3V *dc* source and the input is a sinewave with an amplitude of 5V (10V pk-pk) and a frequency of 10 kHz.Remember that the waveforms have *dc* components: use the *dc* coupling on the oscilloscope inputs. For Circuit (a), ALSO add capacitors C = 0.001, 0.01, and 0.1 μF in parallel with R, and sketch each waveform.

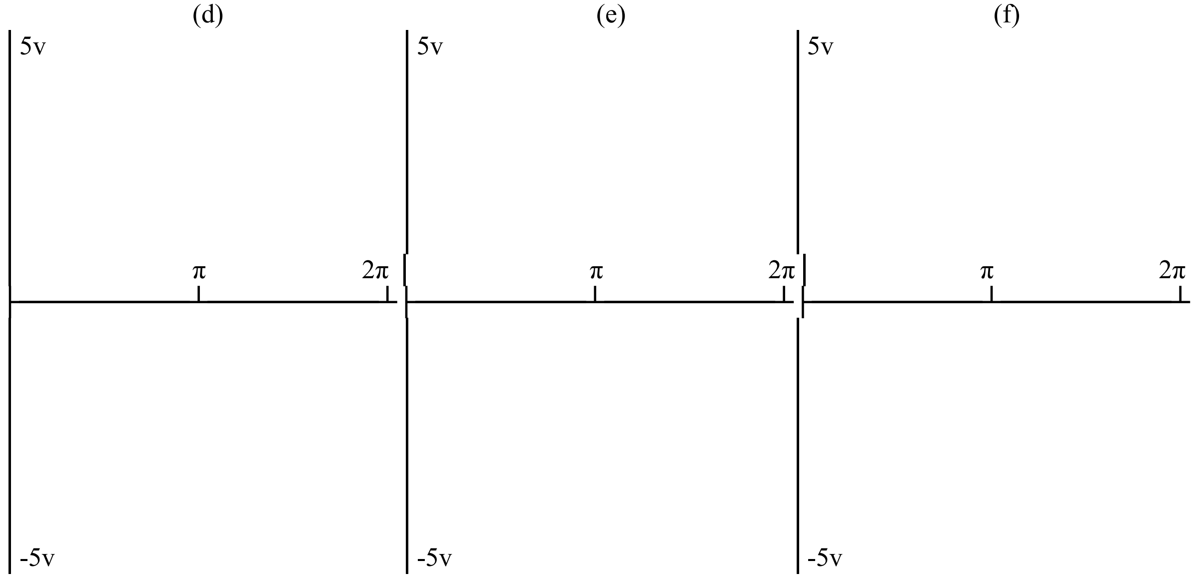




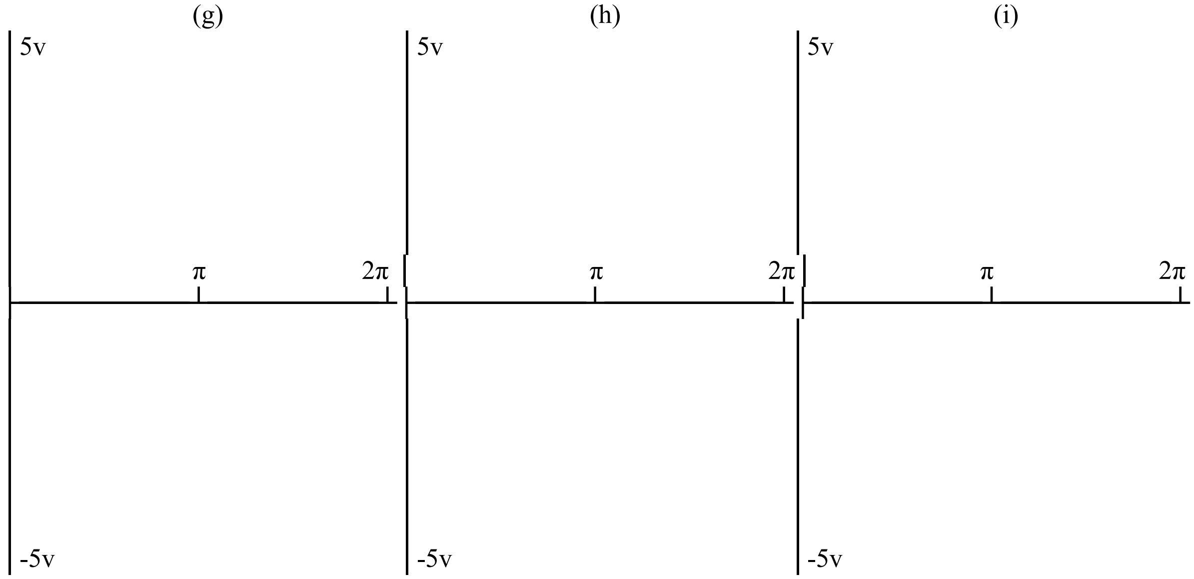
(a) No C (b) (c)



(d) (e) (f)



(g) (h) (i)



(a) C= 0.001μF (a) C= 0.01μF (a) C= 0.1μF

<u>SUMMARY:</u> (To be completed at the end of lab)

What is the shape of the v-i characteristic of a diode with current in the forward direction?

What is the order of magnitude of the diode resistance in the reverse current direction?

Explain the effect of the capacitors in circuit (a) in terms of time constants.

Explain the operation of clipping circuits. Which circuits act as clippers?

Explain the operation of clamping circuits. Which circuits act as clamps?

Briefly discuss what you learned from this experiment. Were there any surprises?

What facts do you need to remember?

HOMEWORK

For the diode characteristic shown in Figure 1 and Figure 2, calculate n_e, I_S and R_S assuming the characteristic was measured at T = 300 K.