ENEE 307 Laboratory#1 (Diode, Loadline, and n-MOSFET characteristics)


The purpose of these experiments is to familiarize you with the properties of diodes and MOSFETs and to let you see how an NMOS transistor amplifier works (Parts I, II and III). In the course of this you will learn something about analyzing noisy data (Part IV). This will familiarize you with the concepts of statistical and systematic errors in an experiment, and with means (averages) and standard deviations, which are a measure of how well a series of data points conforms to the average.

It is well known to anyone involved in experimental work that the subject of extracting data from noise is large and complicated, and it is worth saying a few words about it here. If, for example, you are trying to measure a DC voltage you would first reach for a digital voltmeter. You might notice that the last digit of the voltmeter occasionally fluctuates, especially if it is a four or four and a half digit meter. If you were to look at the voltage source with an oscilloscope, you would notice that there is always some random AC component in your measurement (small). This is what we call noise, and it spoils the measurement in the sense it makes it difficult to know what the true DC voltage really is. Noise has many sources – background electromagnetic fields from power lines and things that use electric power such as motors, transformers, fluorescent lights etc. It also occurs at the atomic level due to random collisions of electrons with atoms and sound waves as they pass through a conductor, which effect will depend on temperature. There are other sources of noise as well. An important aspect of noise signal is their frequency distribution. Fields due to power lines etc. fluctuate at 60 or 120 Hz. The voltage due to thermal noise usually falls off as 1/f, where f is the frequency of the AC voltage. Therefore, if you want to do a good experiment, you need to shield it from outside influences as much as possible and try to measure the noise power spectrum – the root-mean-square (\(\sqrt{\langle V^2 \rangle}\)) of the noise voltage as a function of frequency. It may be necessary, depending on the experiment, to make such measurements to very high frequencies (gigahertz) and with a sensitivity that depends on how large a signal you are measuring (volts, millivolts, microvolts...). The point is, it is a non-trivial task to make a reliable, high precision measurement (of anything).

Part I. The pn junction diode

The first three sections of Part I describe things; the actual experimental procedure is described in section 4. The purpose of this experiment is to measure some properties of a diode and to do a statistical analysis of your data to try to estimate how good your results are. A description of how to do the mathematical part of the latter is found in Part IV.

1. The following is a very brief description of a pn junction. You should read the description in Sedra and Smith and references therein, or go to the website http://www.ee.umd.edu/~jono/enee312/enee312/ for a more complete understanding.

Metallic conductors such as copper or aluminum carry electrical current via the motion of electrons. Since in a metal there are roughly as many free electrons that can move about as there are atoms – of the order of \(10^{21}\) per cubic centimeter – it is not surprising that
under ordinary conditions metal wires in our technology normally carry currents
equivalent to $\sim 10^{20}$ electrons per second (several amperes). Silicon is a very different
kind of material. Electrical current is carried by two kinds of particles: negatively
charged electrons and positively charged entities called “holes,” together called carriers.
An electron carrier is “created” when heat or light or some other form of energy ionizes a
Si atom, freeing the electron up so it can move between atom. When this happens, the
vacancy in the valence shell of the Si atom can move from atom to atom; it is equivalent
to a positive particle moving from atom to atom and is known as a hole (symbol $p$). The
motion of a hole to the right is equivalent, electrically, to the motion of an electron to the
left. If an electric field is applied to the Si, holes and electrons move in opposite
directions but together constitute a current moving in the direction the positive holes
move (electrons carry a negative charge). Pure silicon, although containing $\sim 10^{21}$ atoms
cm$^{-3}$, has very few free carriers, about $10^{10}$ cm$^{-3}$ at room temperature. For this reason Si
is a very poor conductor compared to Cu or Al. It is called a semiconductor. In
addition, unlike metals the resistivity of Si becomes very great (approaches infinity) as
the temperature approaches absolute zero because the density of carriers – holes and
electrons - is temperature dependent as $T^{3/2} \exp[-E_i/kT]$ where $E_i$ is a characteristic
energy.

In pure, or intrinsic, Si, the number density of holes is exactly equal to that of electrons
and current is carried in roughly equal amounts by electrons and holes (even though the
number densities are the same, electrons are more efficient carriers – they move faster in
a given electric field than do holes and so more current is carried by the electrons).
Intrinsic Si behaves like a metal in that its conductivity doesn’t depend on the voltage
placed across it. But this can be changed.

One of the most useful properties of Si is that it can be doped with certain chemicals
(“impurities”) at extremely low levels (parts per million or less) that have a huge effect
on its conductivity. Doped Si is called extrinsic Si; it can be doped with impurities that
increase the number density of electrons compared to holes (n-Si) or the reverse (p-Si).
Intrinsic Si becomes p-type where the conduction is due almost entirely to holes, or n-type
where the conduction is due almost entirely to electrons. Because only $\sim 1$ in $10^{12}$ Si
atoms is ionized at any given time, the addition of $10^{13}$ As or B atoms will increase the
number of carriers ten-fold, because in Si all the As and/or B atoms will be ionized at
room temperature. $10^{13}$ atoms out of $10^{21}$ is only one part in one hundred million: an
almost immeasurably small proportion, yet this will change the conductivity of the Si by
a factor of ten.

n and p type Si still behave rather like metals in that the conduction is independent of the
voltage placed across the Si. But, if a piece of n-Si and a piece of p-Si are made side by
side by doping one part of a piece of Si with As and the other with B, then the resulting
pn junction has radically different electrical properties. In particular, it passes electrical
current in one direction very well, but it doesn’t pass current in the other direction very
well at all. More precisely, a forward biased pn junction will carry milliamperes of
current with 0.6 – 0.7 volts placed across it, while a reverse biased pn junction will carry
$\sim 10^{-14}$ amperes with a similar voltage across it. The pn junction is what we call a diode
and can be used to convert ac current into dc current. When forward biased is has very
non-linear characteristics and the current through it is very well approximated by the equation \( I = I_S \left[ \exp \left( \frac{V_D}{V_T} \right) - 1 \right] \approx I_S \exp \left( \frac{V_D}{V_T} \right) \). \( I_S \) is called the *scale current* and \( n \) is called the *diode constant*. The approximation is extremely good when \( V_D > 5 \ V_T \).

\( V_T = kT/q \) is the thermal voltage; \( k \) is Boltzmann’s constant, \( q \) the electronic charge and \( T \) is the temperature in K. At room temperature \( V_T \) is about 26 millivolts.

2. In this first experiment you will measure the properties of a pn junction diode in a circuit with a resistor and a power supply. By analyzing this circuit you will be able to make an estimate of the scale current \( I_S \) and the diode constant \( n \). In order to get a reliable result it will be necessary to make a series of measurements and find the average value for these quantities and an estimate of the error in your results.

![Diagram of a circuit](image)

Figure 1. The “classical” circuit for measuring the properties of a diode using separate meters.

In order to find \( I_S \) and \( n \) it is necessary to find the slope of the I-V curve, \( \frac{dI}{dV_D} = I \left[ nV_T \right]^{-1} \) where we use the approximation \( I = I_S \exp \left( \frac{V_D}{V_T} \right) \). This implies that \( V_D \) is larger than about 0.15 volts. To find \( V_T \) you need to know the temperature of the environment, implying you don’t pass so much current through the diode that it heats up (how would you determine if that is the case?), using \( q = 1.602 \times 10^{-19} \) C and \( k = 1.381 \times 10^{-23} \) J K\(^{-1}\). The temperature in K is given by the temperature in C + 273.15 \( (\Delta T \text{ in kelvins} = \Delta T \text{ in Celsius}) \). The slope of the I-V curve is found by making an accurate determination of the current for a number of voltages and then plotting the data. You will need to measure the slope for at least ten (10) values of the current and you will need to make an estimate of the error in your measurement so that you can make a statistical estimate of the error in your values of \( I_S \) and \( n \), as described in Part IV, below.

Since \( I \) and \( V_T \) are known by measurement, when the slope is measured you can find the diode constant \( n \). Once \( n \) is known you can solve for the scale current \( I_S \). The problem is, the measurements of the current, the voltage, the temperature and especially the slope of the I-V\(_D\) curve, will be fraught with errors.
3. Somewhat extraneous information. The general shape of the I-V curve for a diode is this:

![I-V curve for a diode](image)

Figure 2. The I-V\textsubscript{D} curve for a diode (idealized).

while the I-V “curve” for a resistor is

![I-V relation for a resistor](image)

Figure 3. The I-V relation for a resistor. Note the resistance \( R \) is the inverse of the slope.

We see from Figure 1. that as the current through the diode circuit increases the voltage across the resistor will be \( V_{PS} - V_D \), where \( V_{PS} \) is the power supply voltage, so the current through the resistor (and the diode) will be \( I = (V_{PS} - V_D)/R \). Since \( V_D = V_T \ln(I/I_S) \), there is no analytical solution for the current: it must be obtained graphically or by approximation.

It we plot the diode current and the resistor current on the same graph as in Figure 4, the current through the resistor \( R \) would be a maximum when \( V_D = 0 \).
4. **What to do.**
(A) Wire up the circuit where a diode and a resistor (less than 1kohm) are in series. 
Apply a voltage across. Use the digital voltmeter to measure the voltage across the diode, and, separately, across the fixed resistor. 
(B) Verify that the voltages are consistent with the power supply voltage. 
(C) Vary the power supply voltage, and record the voltage drops across the diode and the resistor. 
(D) Plot the resulting data --- diode current versus its voltage drop --- by computer. 
(E) Fit the data by the exponential expression, and assume a room temperature of 300K, your fitting should generate (i) the diode constant; and (ii) the ideality factor. 
(F) Explain the loadline concept using the circuit shown in Fig. 5.

![Figure 4](image_url) **Figure 4.** The load line for the circuit in Figure 1. The slope of the load line is -1/R. 

and the current through the resistor would fall to zero when $V_D = V_{PS}$. These conditions give the load line for the circuit. The solution for the current is the intersection of the load line with the I-$V_D$ curve. The usefulness of a load line is perhaps not obvious for a diode circuit, but it is very useful in determining the operating point for a transistor amplifier, as will be shown below.

![Figure 5](image_url) **Figure 5.** Your actual circuit for measuring the diode properties. The voltmeter measures $V_D$ and the current $I$ is read on the precision power supply.
The precision power supply will tell you the current flowing through the circuit quite precisely and the voltmeter will give you the voltage with equal precision. To estimate the error you will need to connect the oscilloscope and to estimate the noise in the data, trying to take into account the noise in the oscilloscope itself by shorting the probe to ground.

Set up the circuit in Figure 5 on a breadboard using the diode and resistor supplied. Make sure all the connections are mechanically and electrically solid so you can rely on your measurements. Make sure the power supply is off before you make any connections. The maximum voltage across the diode will be less than about 0.7 volts at maximum current. Set the limiter for the current to 10 mA. Make sure the polarity of the power supply is correct:

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|   +   |
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the actual diode will have a band near one end to indicate the polarity. If you have the diode in backwards no measurable current will flow when the voltage across the diode is 0.7 volts.

Check the polarity again. Make sure the voltage of the power supply is set to zero. Turn the supply on and slowly increase the power supply voltage. Take measurements of $V_D$ and $I$ for ten values of $V_D$ between about 0.25 volts and about 0.7 volts.

You will need to plot your data as you do the experiment. You will be measuring the slope of the $I-V_D$ curve, as described above, so you will want to make sure that the data is falling on a pretty smooth curve. You also need to put error bars on your measurements of the voltage $V_D$ based on the precision of your measurements as indicated by the oscilloscope. For current measurements you can measure the voltage across the resistor and estimate the current noise from the voltage noise. An example of this is shown in Figure 6. Since the maximum current through the diode won’t be very large at low voltage (say around 0.25 volts), the fractional errors in your current measurements will be more significant there.
Part II. The MOS transistor

1. The experimental procedure in the first part of this will be similar to that for the diode: you will measure voltages and currents, plot the data to determine the transistor constant (see below). In the second part you will determine the gain of a MOS amplifier and compare it with a calculated value.

An accurate description of the operation of the MOS transistor is extremely complicated, but under the conditions met for a simple amplifier there is a simple yet accurate pair of equations that describe the operation well. There are three modes of operation we will consider here: 1) off; 2) on and triodic; 3) on and saturated. In addition, there are two kinds of MOS transistors – PMOS where current is carried by holes, and NMOS where current is carried by electrons. We will consider the NMOS transistor in this experiment. Before proceeding you need to study section 1 (pp 235-248) of the text (Sedra and Smith, 5th ed.).

The MOS transistor has four terminals: the gate (G), the drain (D), the source (S) and the body (B). In this experiment we will connect the body of the transistor to the source and consider the transistor as a three-terminal device:

![Figure 1. The schematic of an NMOS FET with the body connection not shown.](image)

Because the gate is separated from the body of the transistor by an oxide insulator, there is no gate current at low frequencies (the capacitance between the gate and the body is very small). Thus source current is equal to drain current: $I_S = I_D$.

1. The off mode. To conduct electricity the gate must be at a positive potential $V_{GS} > V_T$ with respect to the source. $V_T$ is called the threshold voltage and its value ($\sim 1$ volt) is determined by the structure of the transistor and the way it is doped. If $V_{GS} < V_T$ the transistor is effectively off (current drops off exponentially with voltage).

2. The conducting modes.
   a. The triodic mode. If $V_{GS} > V_T$, as the voltage $V_{DS}$ across the transistor – between the drain and the source – is increased the drain current is given by the expression $I_D = k_n (W/L) [(V_{GS} - V_T)V_{DS} - \frac{1}{2} V_{DS}^2]$. Here $W$ and $L$ are geometrical parameters – the width and length of the transistor – $k_n$ is a parameter dependent on the way the transistor is fabricated and $V_{DS}$ is
the drain–source voltage. When \((V_{GS} - V_T) \gg V_{DS}\) the current is linear with \(V_{DS}\) and the transistor behaves as a voltage-controlled resistor.

b. The saturated mode. When \(V_{DS} = V_{GS} - V_T\) the current becomes almost constant with a value \(I_D = \frac{1}{2} k_n (W/L) [V_{GS} - V_T]^2\).

2. In this experiment you will measure the parameters \(V_T\) and \(k_n(W/L)\) of a MOS transistor in a simple, common-source amplifier configuration as shown in Figure 2. As in the diode experiment you can measure the current directly in the power supply. Since the power supply has dual outputs. That is, you can generate (and independently verify by a digital ohmmeter) the gate voltage \(V_{GS}\) with one channel, while produce another different voltage at the second channel \(V_{DD}\).

![Figure 2](image.png)

Figure 2. A common-source amplifier with individually adjustable gate and drain power supplies. The drain supply is called \(V_{DD}\). Both sets of voltages will be generated by the precision power supply, which has dual outputs. The ammeter is actually on the power supply. \(V_{GS}\) is measured with the meter in the power supply. The voltmeter measures the drain-source voltage \(V_{DS}\).

The voltmeter allows you to measure \(V_{DS}\). To determine \(k_n(W/L)\) for the MOS you will need to make several (ten) measurements of \(I_D\) in the saturated mode for several (5) values of \(V_{GS}\), to get a statistically meaningful result. The current-voltage relationship will look like Figure 3 for \(V_{GS} > V_T\).
Figure 3. The $I_D - V_{DS}$ relationship for an NMOS transistor for three values of the gate-source voltage $V_{GS}$ (schematic). Note $I_D$ is essentially constant in the saturated region.

3. The load line for the circuit is shown in Figure 4 (see section 4.4 of the text).

Figure 4. The load line for the MOS circuit. Note one would not want to pick an operating point too close to the voltage $V_{DD}$ or the amplifier’s voltage swing would be limited (the point where the load line crosses $V_{GS2}$ is good). It might be necessary to choose a different load resistance, for example..

Normally an amplifier is designed so the transistor is always in the saturated mode. As you can see in this drawing, you wouldn’t want to go much above $V_{GS3}$ to meet this criterion. If the change in $V_{GS}$ is small compared to $V_{GS} - V_T$ then the amplifier is pretty linear (see p. 288 of the text). By finding the intersection of the load line with the $I_D - V_{DS}$ curves you can determine the output voltage swing at the drain and thus the amplifier...
gain $A_v = \delta V_{DS}/\delta V_{GS}$ (measured in volts per volt, i.e., how many volts output per input volt).

3. What to do.
(A) Make and change your wiring when the power supply is off. If not, you can be electrocuted. Or, the power supply might be damaged by a shorted output.
(B) Connect up the IRF 510 MOSFET in the circuit configuration shown in Figure 2 using a resistor (less than 1kohm).
(C) Fix the gate voltage at 0V. Slowly change the power supply voltage from zero to a few volts, at 0.1V steps, and record the voltage at the power supply, across the R, the gate, and across the drain-source. Calculate the drain current, and plot the drain current versus the drain voltage, under a fixed gate voltage.
(D) Change the gate voltage to 1V, and repeat the above procedure. Record the data and convert the voltage reading to drain current.
(E) Change the gate voltage to 2V, 3V, 4V, and 5V, and repeat step (C).
(F) Plot by computer the MOSFET current versus voltage characteristics measured in the common source configuration. Label the gate voltages, drain voltages, and the drain current clearly.
(G) Estimate the threshold voltage $V_T$. First, in the saturation mode. Set $V_{DS}$ to 5volts (by choosing a proper $V_{DD}$). Increase $V_{GS}$ from 0 volts to 5volts in 0.05 volt intervals. Find the range where $V_{GS} - V_T < V_{DS}$. Plot by computer the transfer relation, drain current versus the gate voltage under a fixed drain voltage, and find where $I_D$ goes to zero by extrapolating your data using a parabolic fitting: $I_D \sim (V_{GS} - V_T)^2$.
(H) Then, measure the threshold voltage in the triode mode. Set the drain voltage in the triode regime. In the triodic mode, measure $I_D$ vs. $V_{GS}$ for values of $V_{DS} < V_{GS} - V_T$. Plot your data and find by fitting the value of $V_T$ by a linear relation: $I_D \sim V_{GS} - V_T$.
(I) Compare results for both ways of finding $V_T$ and compare with your initial estimate.
(J) Find the transistor constant $k_n(W/L)$ Start with $V_{DS}$ high enough to ensure the transistor is in the saturated mode, say 5 volts. Start with $V_{GS} = 0.5$ volts and increase it in 0.5 volt increments up to about 5 volts. For each value of $V_{GS}$ measure $I_D$ and then calculate $k_n(W/L)$, using your previously found value of $V_T$.
(K) Study the loadline concept. Now that you have obtained the MOSFET characteristics. Continue to apply the previous circuit. Fix $V_{DD}$ at 5V. Measure the drain current and the drain voltage when the gate voltage is at 0V. Repeat this procedure for gate voltage = 1V, 2V, 3V, 4V, and 5V. On your computer plot that shows the transistor characteristics, label the measured operating points. They should be aligned on the loadline.