University of Waterloo
Electrical & Computer Engineering Department

ECE 331
ELECTRONIC DEVICES

LAB 1: THE PLANAR FABRICATION PROCESS AND TEST MEASUREMENTS

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Version 1.2

1. Prelab

1) One of your prelab assignments is to read and familiarize yourself with the lab. **Refer to Lab 1 reading document posted on LEARN.** Also, read this document to familiarize yourself with the terms and concepts.

   You'll find that many of the terms and concepts are completely new to you. Keep track of the things you find confusing, and then ask a teaching assistant or the lab instructor for clarification during the lab period.

2) With the hot probe apparatus, the voltmeter will read a positive voltage for V_h - V_c if the material is *n*-type, and a negative voltage for V_h - V_c if the material is *p*-type. Why? **Hint**: Neglect the minority carriers and consider what is left behind when the majority carriers move away from the hot probe.

Please note the highlight color code throughout the rest of the lab as follows:
The green color indicates in-lab data measurements
The yellow color indicates report work

2. In the Lab

In each of the exercises below, you will examine a different aspect of semiconductor device fabrication and characterization. For each exercise, there is a **description** and **questions**. Read the description, which contains all the background information you need, and then answer the questions.

2.1. Devices for this Lab

We followed the simplified planar process (outlined in the first part of section 3.1 in the lab 1 reading document, that is, the process illustrated in figures 3 and 4)

There are two wafers used in this lab. Wafer 4 is just **doped silicon**. Wafer 5 is the **completed wafer** with all devices on it as shown in Figure 1.

Each chip on the wafer 5 contains many more devices than you will actually use in this lab. Figure 1 shows the patterns you will probe. You will have to locate these when you look through the microscope at the probing station.

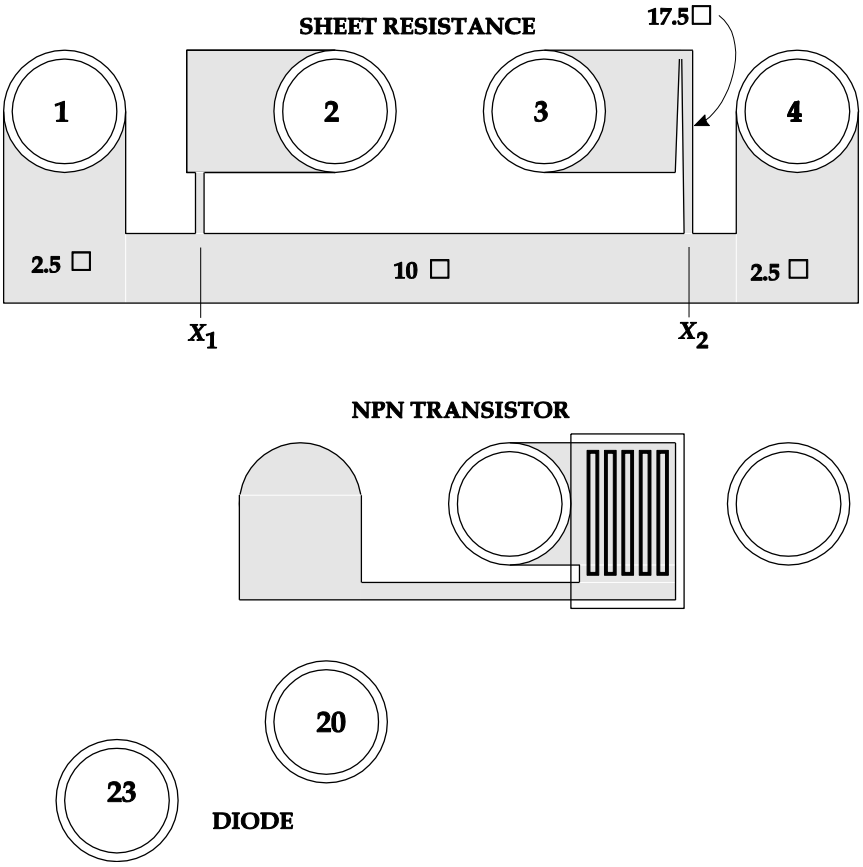


Figure 1: Patterns you will probe on the test chip (Wafer 5). Note**: The *npn* transistor is presently unavailable.**

2.2. Carrier Type by Hot Probe

Description

Silicon which has no impurities diffused into it is called *intrinsic*, and silicon with impurities diffused into it is called *extrinsic*. In intrinsic material, the free electron and hole concentrations are equal: $n = p$. In *n*-type extrinsic silicon $n > p$, and in *p*-type extrinsic silicon $p > n$. We call the carriers present in higher concentrations the *majority carriers*, and the other carriers the *minority carriers*; for example, in *n*-type material electrons are the majority carriers. The majority carriers in extrinsic material come from the impurity atoms: in *n*-type material, each impurity atom *donates* an electron, and thereby becomes a *positively charged ion*; in *p*-type material, each impurity atom donates a hole, and thereby becomes a *negatively charged ion*. Although the donated carriers are free to move through the material, the ionized impurities occupy fixed positions.

The *hot probe* method is used to determine the majority carrier type of a material. **Figure 2** shows a sketch of the hot probe apparatus. The point *h* is heated whereas the point *c* is kept at room temperature. Since *h* is hot, the majority carriers there are thermally excited. Therefore, on average, the majority carriers move away from *h*. Similarly, the minority carriers will also move away from *h*; however, their concentration is so small that we can neglect them. A voltage results between *h* and *c*, and the polarity of this voltage indicates the type of material.

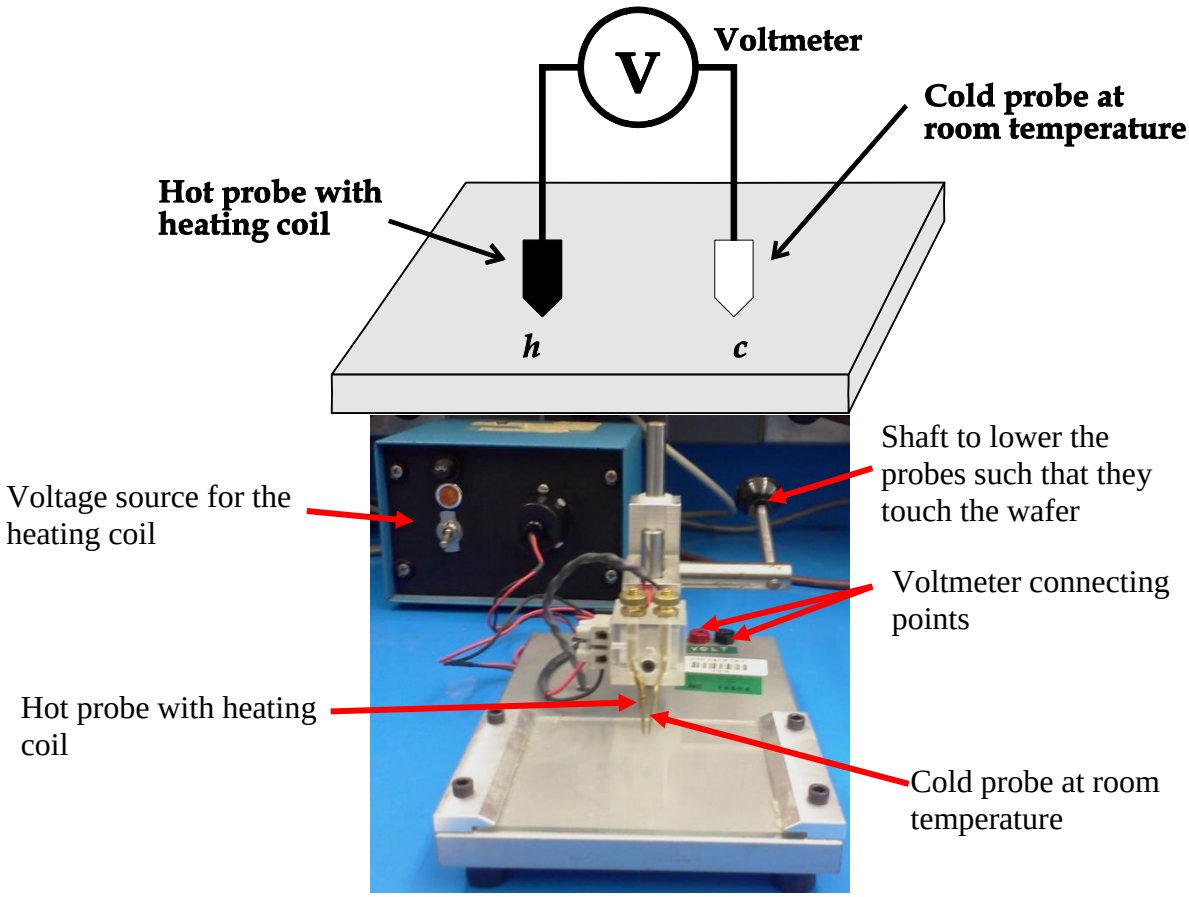


Figure 2: Hot probe apparatus.

Questions

a) Use the hot probe apparatus to determine whether wafer 4 is *n*-type or *p*-type.

- Set the power supply voltage connected to the heating coil to 13 V (Do not exceed that value!)
- Connect the Fluke 8808A DMM as a voltmeter
- Leave the coil to heat for ~ 30 seconds before putting the probes in contact with the wafer.
- Carefully use the shaft to lower the probes to make contact with the wafer (Watch the wafer you may break it if you do not pay attention!)
- Watch the trend and the sign of the voltmeter reading.
- Is the wafer n-type or p-type?

Disconnect everything specially the coil heat voltage.

2.3. Resistivity by Four-Point Probe

Description

A characteristic property of a doped semiconductor is its *resistivity*. The *four-point probe* apparatus, illustrated in **Figure 3**, provides a convenient way to obtain this quantity. Four equally spaced and colinear probes are lowered onto the surface of the material. A current I is passed through the outer probes while the inner probes measure a voltage V. If the impurity concentration is uniform throughout the material, and the thickness d of the sample is much less than the space s between probes, then it turns out that the resistivity is given by

$$\rho = \frac{\pi}{\ln 2}\frac{V}{I}d \approx 4.53\frac{V}{I}d \qquad \textbf{Equation 1}$$

For a sample of arbitrary geometry, the resistivity depends on both s and d in a more involved way.

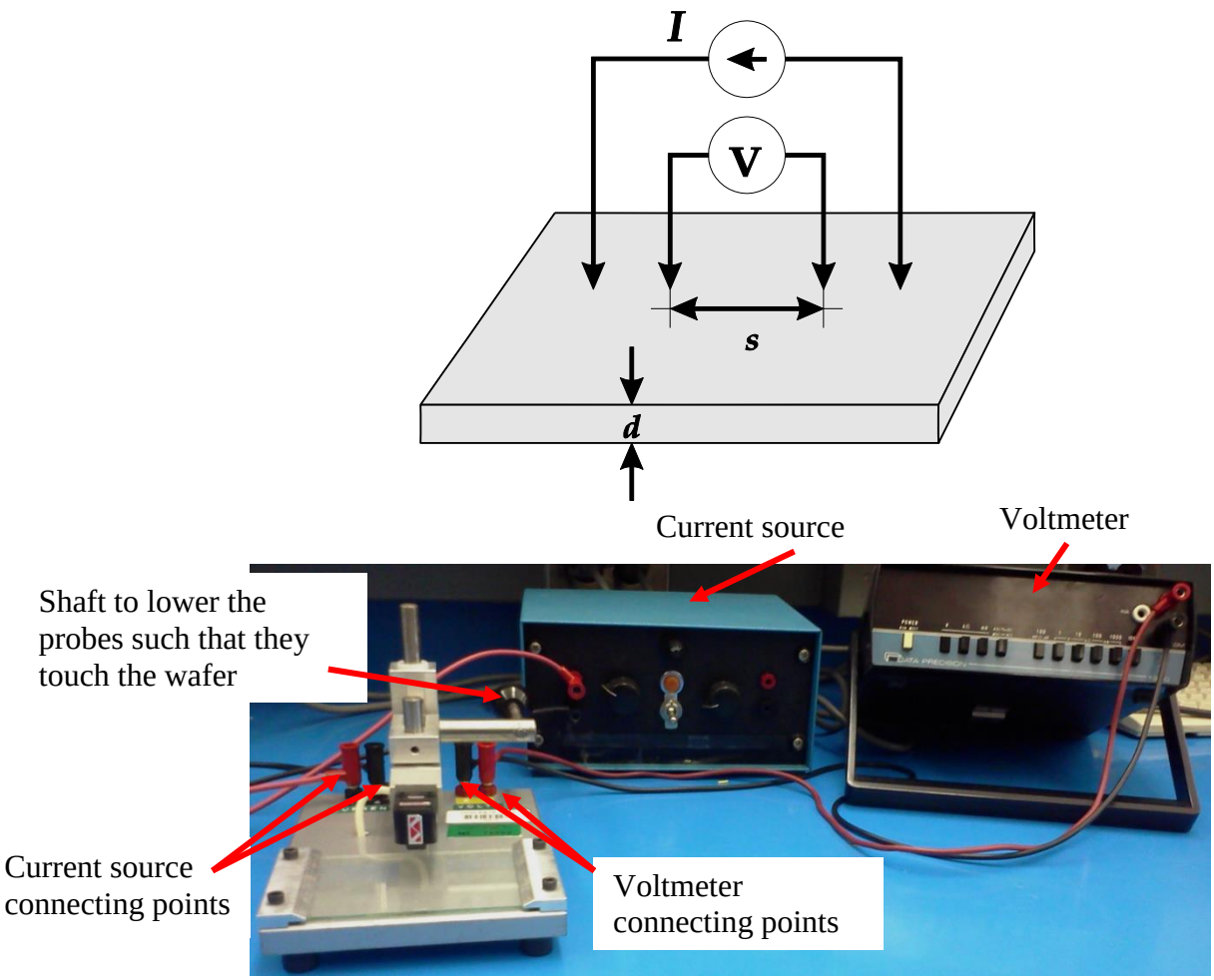


Figure 3: Four-point probe method to get resistivity.

Questions

a) Use the four-point probe apparatus to determine the resistivity of the material in wafer 4. Wafer 4 (***d* = 300 μm**) satisfies the conditions under which equation (1) is valid.
   - The current source is replaced with a power supply in series with 10KΩ (using the decade box), in series with an ammeter. All that is connected between point 1 and 4.
   - Set the power supply voltage between 5 and 10 volts
   - Connect the voltmeter between point 2 and 3
   - Record V (voltmeter) and I (ammeter) readings
   - Determine the resistivity in **Ω • cm (NOT Ω • m)**

V (Volts)	***I (Amps)***	***ρ (Ω• cm)***	***Impurity Concentration (cm^{-3})***

b) Using the value of resistivity that you obtain, your knowledge of the wafer type from part (b) of section 2.2, and the graph below.

c) Name one element which could have been used as the impurity for wafer 4.

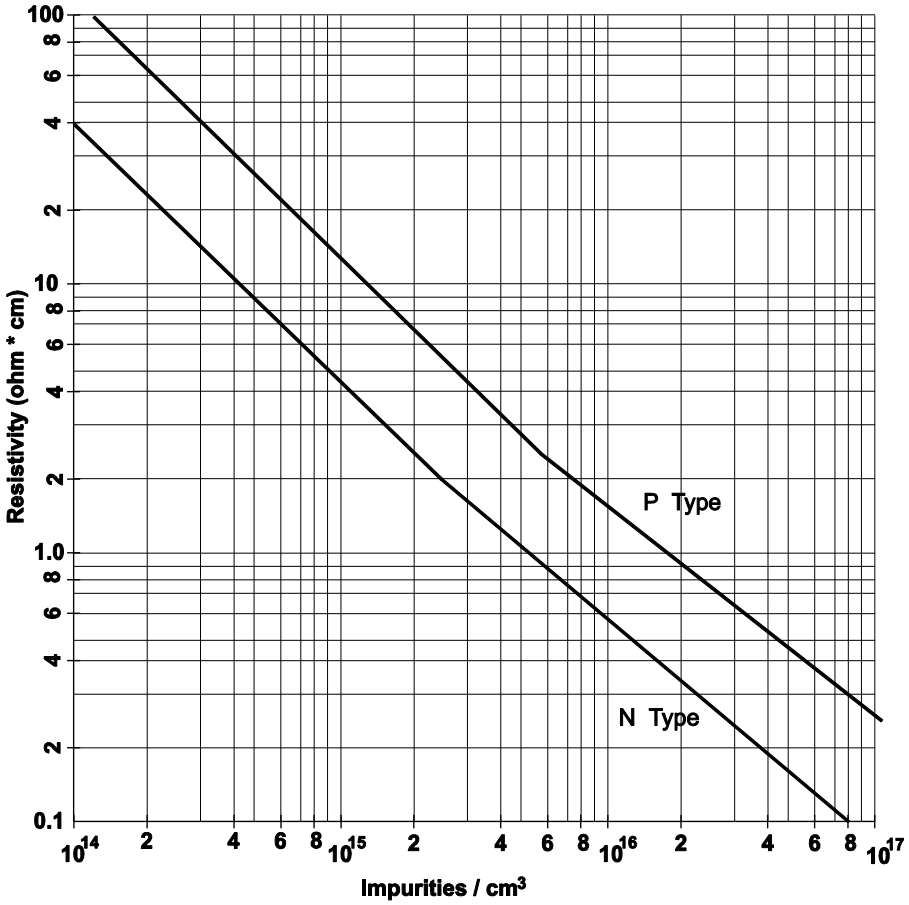


Figure 4: Resistivity versus impurity concentration in silicon.

2.4. Sheet Resistance

Description

Consider the *p*-type regions in the diode and transistor of figures 1 and 5 in the lab reading document. For a given chip with several diodes and transistors, the *p* region in every device is created at the same time by the same processing steps. Therefore, the **vertical** characteristics of each and every *p* diffusion on a chip must be the same. On the other hand, the **lateral** dimensions of the *p*-type region in a given diode or transistor are determined by the mask diagram, and an engineer may specify different lateral dimensions for different devices on a chip depending on their intended use.

A *p*-type region of arbitrary lateral geometry is illustrated in **Figure 5**. For this region, we may write the resistance as

$$R = \frac{\rho l}{wt} = \frac{\rho}{t}\frac{l}{w} \qquad \textbf{Equation 2}$$

However, for the *p* region in every device on a chip, the resistivity ρ and thickness *t* are the same; only the length *l* and width *w* vary from device to device. With this in mind, we **define** the quantity $\boldsymbol{R_{\square} \equiv \rho / t}$, and rewrite equation (5) in the form

$$R = R_{sq}\frac{l}{w} \qquad \textbf{Equation 3}$$

The quantity $\boldsymbol{R}_{sq}$ (or $\boldsymbol{R}_{\square}$) is called ***sheet resistance***. Provided the ratio *l*/*w* is known, the resistance of any *p* region may be calculated using $\boldsymbol{R}_{sq}$ in equation (6). $\boldsymbol{R}_{sq}$ is said to have units of **Ω**/□ read "ohms per square", since it is equal to *R* for a square: $R = \boldsymbol{R}_{\square}$, when $l = w$. Correspondingly, the ratio ***l*/*w*** in (6) is called the *number of squares*, and taken to have units denoted by the symbol '□'.

Ideally, the ratio *l*/*w* is determined by dimensions on the mask diagram; in practice, the actual *l*/*w* ratio in a fabricated device is somewhat smaller. To see this, refer back to the planar process description in section 3.1 in the lab reading document. Suppose an engineer specifies a *p* diffusion mask diagram with a long, thin region of length *l* and width *w*. Ideally, this would correspond to a region with an area of *l*/*w* squares. However, in step 2 of the processing, etching can *undercut* to expose an area of width greater than *w* at the surface of the silicon; moreover, in step 4, diffusion proceeds *laterally* as well as downward. The result is that the actual *p* region which is formed will have a width greater than *w*, and the number of squares will be less than the value *l*/*w* obtained from the mask dimensions. Note that the larger the value of *w* on the mask diagram, the smaller the effect that undercutting and sideways diffusion will have on the ratio *l*/*w*.

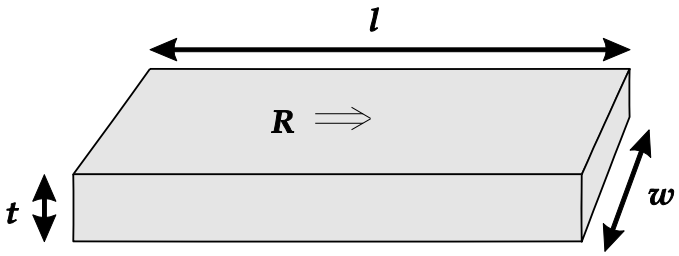
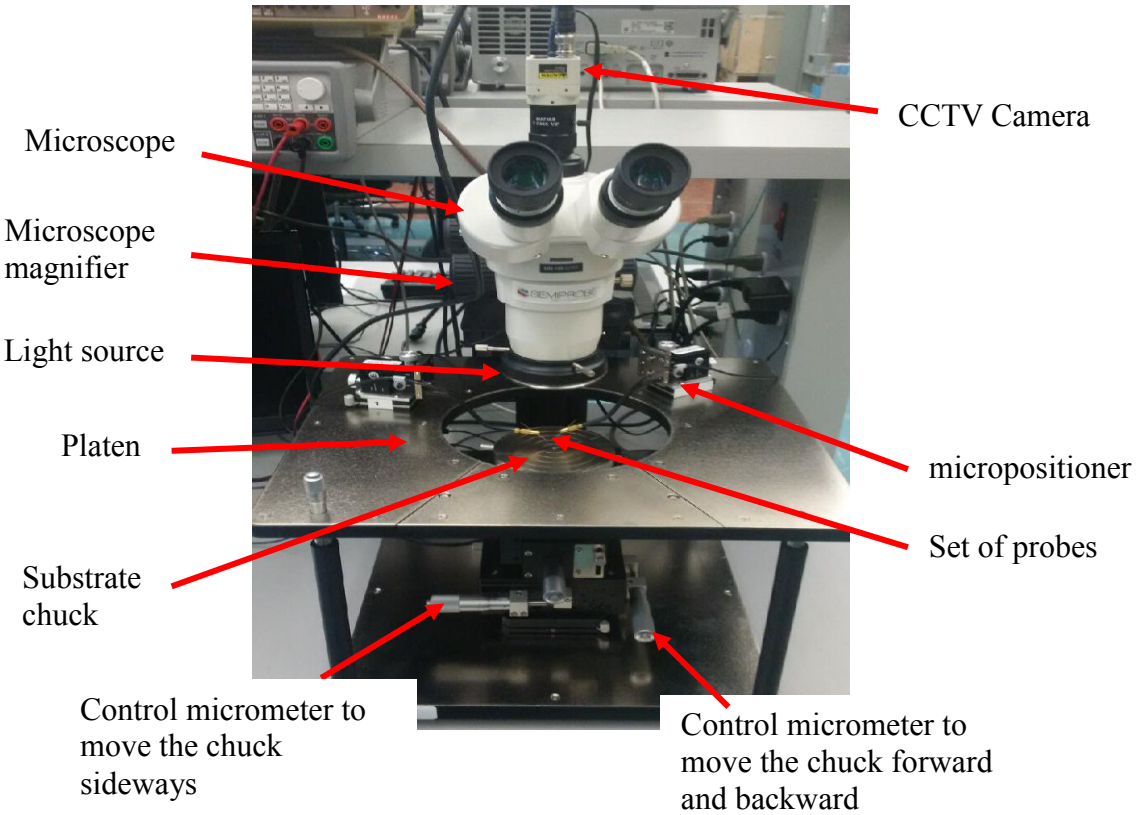


Figure 5: A *p*-type region of a diode or transistor. Length of the region is *l*, its width is *w*, and its thickness is *t*.

Of course, the concept of sheet resistance can be applied to **any** layer of material which has identical vertical characteristics all over a chip, or even all over a wafer for that matter, and not just the *p* regions discussed above. For example, one might speak of the sheet resistance of the *n*-type diffusions used to create the emitters of all bipolar transistors on a chip.

Questions

Consider again Figure 1. Note the sheet resistance test pattern. This pattern is just a large *p* diffusion made in the starting *n*-type material. Circular metal contacts, or *pads*, are made to the diffusion at the surface. The pattern will be used to study the sheet resistance of the *p* diffusions made during the creation of the diodes and transistors on your wafer. Locate the test pattern on a chip on wafer 5 by looking through the microscope at the probing station shown below.



For each of the following exercises we use the probing station to make contact to appropriate pads. **Please Note: Take Care: Ask a TA to position the probes gently so there is no damage to the wafer.**
Then, **before taking any readings, turn off the microscope light**! The light from the microscope is quite bright, and it can cause many electrons and holes to be *generated* in the silicon. These generated carriers could interfere with your measurements. Of course, the ambient light in the room will also generate a few carriers; however, this light won't cause enough generation to significantly affect any results.
Note, the contact pads on the wafer are numbered 1 to 4, the probe tips on the probe station are numbered 1 to 4 and the red female banana plugs on the probe station are numbered 1 to 4. We are not using the black female banana plugs on the probing stations.

a) Wire up the circuit with red and black banana cables, and two meters (one as Voltmeter and one ammeter):
Apply a voltage V using a power supply and measure the resulting current I using a DMM between pads 1 and 4. Connect voltmeter between pads 1 and 4 to measure voltage. **Hint**: For an accurate measurement, use a voltage V yielding a current ***I* of at least one milliampere (You can use 1 mA current, should not go too high either).** Then calculate the resistance $R_{1,4}=V/I$ between pads 1 and 4. You will need to draw a little circuit diagram using Figure 1 showing the connections of your meters and power supply.

b) If the lateral area of the p diffusion between pads 1 and 4 is equivalent to **15□ (sq),** calculate its sheet resistance $\boldsymbol{R}_{\square}$ using the value of $R_{1,4}$ you got in part (a).

$V_{1,4}$	$I_{1,4}$	$R_{1,4}$	$R_{\square}$

c) Use pads 1 and 4 as *current pads*, and pads 2 and 3 as *voltage pads*; in other words, cause a current I to flow from pad 1 to pad 4, and measure the voltage V between pads 2 and 3. **Again,** for an accurate measurement, use a current I of at least 1 mA. This will make the effects of any generated carriers from the ambient room light negligible.

d) Do you see that the voltage between the points $x1$ and $x2$ (probe between pads 2 and 3) is due to the current I flowing from pad 1 to 4? Hence, calculate the resistance $R_{x1,x2} = V/I$ of the p diffusion between the points $x1$ and $x2$.

e) If the equivalent area between $x1$ and $x2$ is **10□ (sq),** calculate the corresponding value of sheet resistance $\boldsymbol{R}_{\square}$ for the p diffusion. Strictly speaking, the value you get is more accurate than that in part (b) because, by using different pads for current and voltage, you eliminate the effects of *contact resistance* from your measurement.

$V_{2,3}$	$I_{1,4}$	$R_{x1,\,x2}$	$R_{\square}$

f) How does the value you get compare with that in part (b)? Would you say that contact resistance significantly affected the result you got in part (b)?

2.5. Measurement of the Finished Diode

Description

Figure 6 shows the current-voltage characteristics for a diode. For forward voltages $V_D > 0$, the current ideally rises exponentially with voltage, as predicted by equation (1). For reverse voltages $V_D < 0$, the current is approximately equal to $-I_S$, but slowly increases in magnitude with increasing reverse voltage. If the reverse voltage is increased far enough, *breakdown* will take place. At this point, occurring for a critical voltage called the *breakdown voltage* $-V_B$, the reverse current drastically increases in magnitude. Given the physical properties of a diode, you'll learn later in this course how to calculate I_S and V_B.

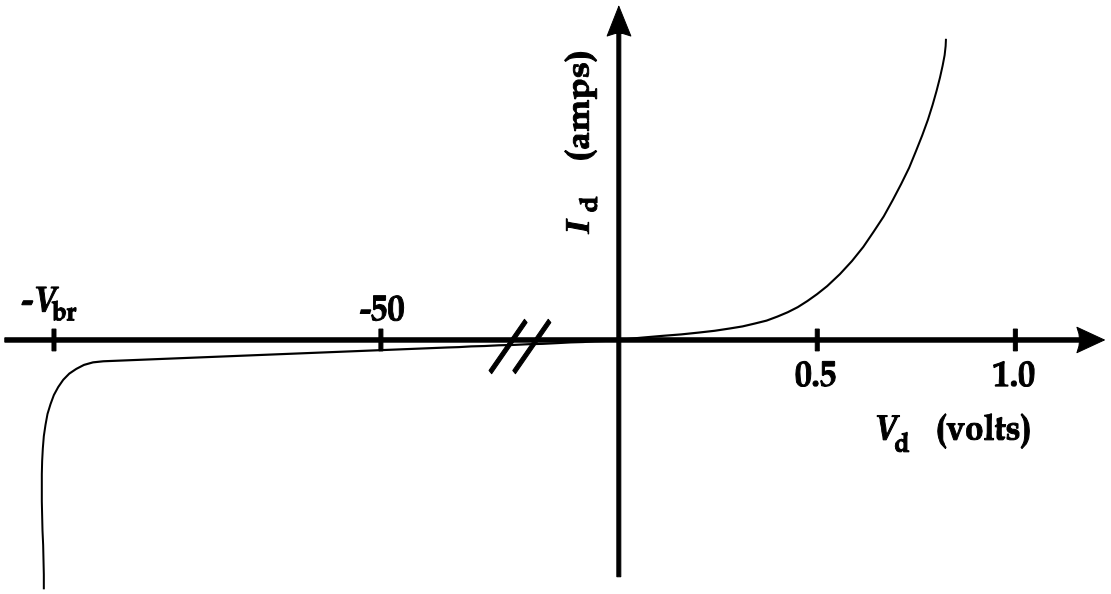


Figure 6: Current-voltage characteristics for a diode.

Questions

Refer back to Figure 1. Note the patterns for the diode and resistor. Locate these on a chip on wafer 5 by looking through the microscope at the probing station. In this exercise, you'll examine the characteristics of the finished devices using a Parameter Analyzer. The Parameter Analyzer is a tricky piece of equipment to use, so please ask a teaching assistant or the lab Instructor for help. Remember to turn off the microscope light prior to making any measurements!

The Lab Instructor/TA will connect:

Probe pads 23 and 20 of the diode, connecting pad 23 and pad 20 to the Keysight semiconductor parameter analyzer. The connections will be made by the lab Instructor but you will need to follow the instructions as given in the appendix for these parts.

a) Plot the diode forward characteristics for V_D between 0 and 1 V. Refer to the Appendix. Be sure to label and scale the axes on your sketch.

b) Plot the diode reverse characteristics, for V_D between 0 and -4 V for all the cases (light off, light intensity of "45 mark", and light intensity of "90 mark"). Refer to the Appendix. Observe that incident light has the effect of essentially shifting the characteristics vertically by an amount I_L. This occurs because of the holes and electrons generated by the incident light. It turns out that these generated carriers flow in the reverse direction, creating a *light current* I_L, which subtracts from the normal diode current. Show I_L on your sketch. Generate four Light Intensity measurement lines. Be sure to label and scale the axes on your sketch!

2.6. Switching of a Diode

Description

One of the most important things to know about a semiconductor device is its potential switching speed. This is because the fastest rate at which a diode or transistor can turn on and off ultimately determines the speed of the circuits, and hence the systems, in which they are used. The first step in understanding what limits the speed of a semiconductor device is to study the switching of a diode. In this exercise, you will look briefly at the *turn-off characteristics* of a diode under *current drive*.

Consider the simple circuit and waveforms in **Figure 7**. A generator is connected to the series combination of a diode and a resistor R. The generator switches from a positive voltage V_f to a negative voltage $-V_r$.

If V_f and V_r are both much larger than the forward diode voltage drop V_d, the diode is said to be under *current drive*; that is, the generator is attempting to *drive* currents of approximately V_f / R in the forward direction and V_r / R in the reverse direction through the diode.

When $V_g = V_f$, the diode is forward biased, and as you might expect, a current of approximately V_f / R flows. Now, when the generator switches to $V_g = -V_r$, you might think that the diode is immediately forced into a reverse bias condition, and hence that the current should immediately become $I_D = -I_S$ = tiny. But that's not what happens! In reality, when V_g switches to $-V_r$, a current $I_D = -V_r / R$ flows for a finite time t_S, called the *storage time*, and only then does it decay rapidly towards $-I_S$!

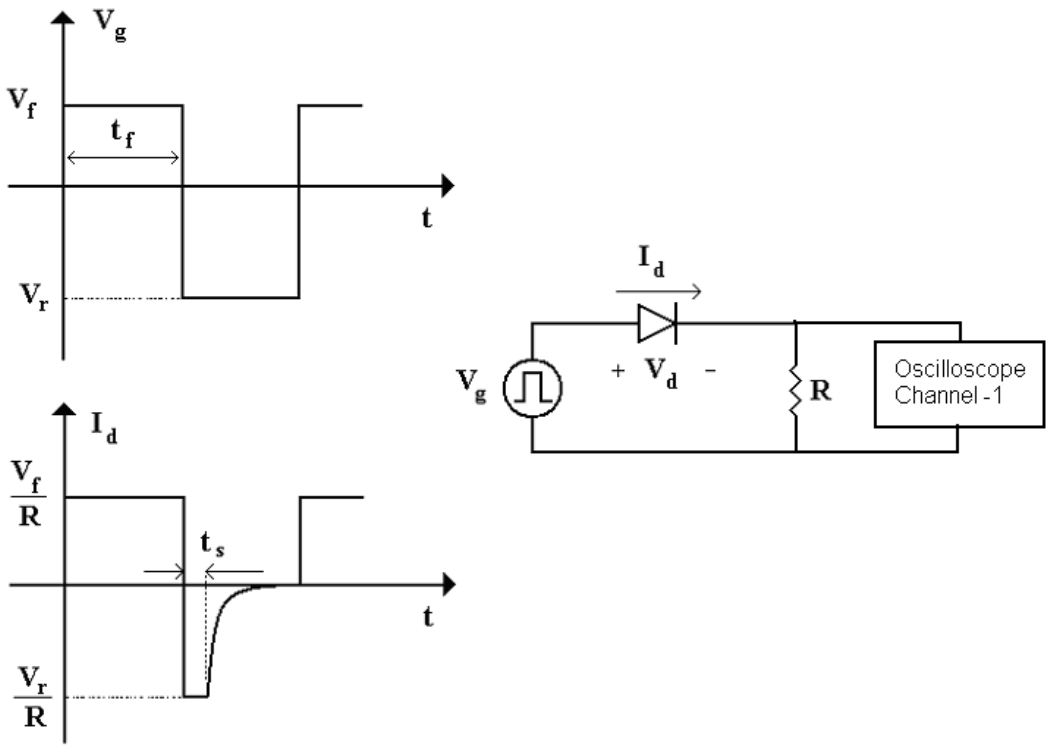


Figure 7: Simple diode switching circuit and waveforms. For this lab, a 1N4003 diode and R = 2.2 kΩ will be used.

What gives rise to the diode storage time? You'll learn later that in a *pn* junction diode, the current I_D through the diode is carried by holes and electrons which are *injected* from one region to the other: holes are injected from the *p* side to the *n* side, electrons are injected from the *n* side to the *p* side, and the amount of injection increases with the forward current. When the generator switches from V_f to $-V_r$, these carriers have to be *evacuated* before the diode is reverse biased; that is, the injected holes have to be pulled back to the *p* side, and the injected electrons to the *n* side. Until the carriers are all pulled back, they will carry the forced reverse current $-V_r/R$ in the diode, and this occurs for the storage time t_S.

Questions

Connect the diode switching circuit as shown in **Figure 7**. You will display the waveforms on your oscilloscope. Connect Ch 1 across the resistance to measure the signal proportional to I_d. Set the function generator to HiZ (Utility>output termination> HiZ) and to a square waveform.

The waveforms will be displayed for four cases:
(Note that the t_f is half the period.)

1. V_f = 5 V, V_r = -5 V, t_f = 50 μs;
2. V_f = 9 V, V_r = -1 V, t_f = 50 μs;
3. V_f = 3 V, V_r = -7 V, t_f = 50 μs;
4. $V_f = V_r$ = -5 V, t_f = 5 μs.

Watch the demonstration and do the following:

a) Write down the measured value of t_S from the oscilloscope display for each of the four cases.

	V_f (V)	V_r (V)	t_f (μs) "half the period"	t_s (μs)	$\lvert V_f / V_r \rvert$	τ_{p0}
1	5	-5	50			
2	9	-1	50			
3	3	-7	50			
4	5	-5	5			

b) Using your observations from cases 1 to 3, explain qualitatively how t_S varies with the ratio V_f / V_r. Explain why this behavior ought to be expected.

c) For the diode used in this demonstration, and **assuming that the diode is fully turned on initially**, it works out that t_S is given by

$$t_S = \tau_{p0} \ln (1 + |V_f / V_r|) \qquad \textbf{Equation 4}$$

where τ_{p0}, called the *hole minority carrier lifetime*, is the average length of time an injected hole survives in the *n* side before *recombining* with an electron. Using your observations from cases 1 to 3, calculate τ_{p0}, which is an important diode parameter. Are the values you get from the three cases similar? What would you quote as the approximate value of τ_{p0}?

d) Cases 1 and 4 use the same values of V_f and V_r. Yet, you will find that t_S in case 4 is less than t_S in case 1. How can you explain this? **Hint**: Note that equation (4) is not valid for case 4.Why is the equation not valid for case 4, explain?

3. Conclusions: What You Learned!

In this lab, you have been introduced to many important ideas in the study of semiconductor devices, including: the planar fabrication procedure; conductivity type; *pn* junctions; real diodes and transistors junctions; resistivity; sheet resistance; and diode switching. As the term progresses, you will study each of these topics, and others, in detail.

Make sure you got all measurements and screenshots. Please tidy up your station.
Submit you "data1.pdf" file to learn before leaving.

Report Submission "Report1.PDF" should include prelab, inlab and postlab in PDF Format.
A penalty will be applied for otherwise.

References

1. Donald A. Neamen. *Semiconductor Physics and Devices, 3ed edition*, McGraw Hill, Toronto, 2003.

2. Ben G. Streetman and Sanjay Banerjee. *Solid State Electronic Devices, 5 th edition.* Prentice Hall, Upper River, New Jersey, 2000.
Chapter 5 covers the p-n Junction.

3. David H. Navon. *Semiconductor Microdevices and Materials*. Holt, Rinehart and Winston, New York, 1986.
Chapter 11 contains an overview of the fabrication procedure for integrated circuits.

4. R. Runyan and K. E. Bean. *Semiconductor Integrated Circuit Processing Technology*. Addison-Wesley Publishing Company, Reading, Massachusetts, 1990.
This book contains far more information than you need for this lab. However, if you're interested, chapter 1 offers a nice historical perspective on the invention of the transistor and integrated circuits, and chapter 2 contains a nice overview of the integrated circuit fabrication process.

5. J. Roulston. *Bipolar Semiconductor Devices*. McGraw-Hill, New York, 1990.
This book contains more information than you'll need for this course; however, it's a great one to keep in mind as a general reference when you study diodes and bipolar transistors. Chapters 1 to 3 present the basics of semiconductor physics, p-n junctions, and diodes; chapter 4 investigates diode switching; chapter 7 looks at the basic theory of operation of the bipolar transistor; and, if you're interested, chapter 14 has information on the fabrication of advanced technology bipolar transistors.

6. Adel S. Sedra and Kenneth C. Smith. *Microelectronic Circuits*. Holt, Rinehart and Winston, New York, second edition, 1987.
Appendix A has a nice, concise overview of the fabrication procedure for integrated circuits.

7. Edward S. Yang. *Microelectronic Devices*. McGraw-Hill Book Company, New York, 1988.
Not particularly useful for this lab, but good to keep in mind as a general reference.

8. Adir Bar-Lev. *Semiconductors and Electronic Devices*. Prentice Hall, Englewood Cliffs, New Jersey, 2nd edition, 1984.
Chapter 16 gives an overview of the fabrication procedure for integrated circuits. Chapter 5 contains a little information on the hot probe method, resistivity by the four-point probe, and sheet resistance

Appendix

Instructions for the Section 2.5 (Diode characteristics measurements):

2.5(a) Silicon Diode I-V Characteristic Curves

Read the question 2.5(a) in the lab manual first and then follow the instructions.

1- Ensure that "Force" in Keysight or Agilent B2912A/2902A unit is connected to "Pad 23" on the wafer, this is the anode of the PN junction, and that "Low" in Keysight or Agilent B2912A/2902A unit is connected to "Pad 20" on the wafer, this is the cathode of the PN junction.

2- Go to Start →Programs→ Keysight B2900A Quick IV Measurement Software → Quick IV Measurement Software

3- From the top right corner pane that "Channel Communication" do the following:
   a. Select "Search Channel" icon.
   b. In the opened window do the following:
      i. Set "Select interface type" to "USB".
      ii. Press "Search" icon.
      iii. The software should be able to locate the address of the connected Agilent B2912A/2902A unit.
      iv. Select "Close"
   c. Set "Address" to address found in the previous step.
   d. Set "Channel" to Channel 1.
   e. Edit "Name" to be "Diode"

4- From the top right corner pane, select "Channel Setting" and adjust the following.
   a. Select "Function" to be VAR1.
   b. Set "mode" to "V".
   c. Set "Shape" to "DC".
   d. Set "Source Delay" to auto. You may put some delay around 0.005 S if needed if the graph does not come out right.
   e. Set "Sweep" to "Linear Single".
   f. Set "Start" to 0 V.
   g. Set "Stop" to 1 V.
   h. Set "Compliance" to 3E-3 A.
   i. Set "Source Range" to Auto.
   j. Check "Voltage Measure".
   k. Check "Current Measure".
   l. Set "Range" to "Auto".
   m. Set "Measure Delay" to auto or 0.0005 s if needed.
   n. Set "Measure speed" to "Long"

5- In "Common Sweep Setting" adjust the following (at the bottom left of your screen)
   a. Set "VAR1 (Primary Sweep) Count" to 50. You can increase this count if needed.
   b. Set "VAR2 (Primary Sweep) Count" to 1.
   c. Set "Repeat" to 1.
   d. Set "Trigger" to Auto.
   e. Uncheck "Specify Minimum Auto Trigger Period".

6- Press the "Graph" icon.

7- In the "Quick Setting" tab, set the following:
   a. Set "X Data Type" to Voltage.
   b. Set "Y1 Data Type" to current

8- Now press the "Measure" icon to start measurements.

9- Right click on the resulting figure and select "Dump" to save the graph.
10- If your plot is very noisy then try with some delay. Set "Source Delay" and "Measure Delay" to 0.005 sec or 0.25 S in Channel settings and then repeat steps 8 and 9.

Include the resulting figure in your report.

2.5(b) Effect of Light on Carriers in Reverse bias mode of the diode

Read now question 4.8 (b) in the lab manual and then follow the instructions.

1- You will be plotting reverse current for different light conditions in this section by overlaying the plots in Excel. Please follow the instructions as below.
2- Press "Setting" icon.
3- Keep the same setting as in steps 3-10 in 4.8(a) except for the following:
    a. Set "Stop" to "-4 V".
    b. Set "Compliance" to 1E-5 A.
    c. Set "source Delay" and "Measure Delay" to 0.05 sec and 0.25 sec.
4- Turn off the light of the microscope on the probing station.
5- Press the "Measure" icon.
6- Press the "Table" icon.
7- Right click on the resulting Table and select "Export as csv" or "Excel Navigation → Export" or copy –paste the columns of "Diode voltage and "Diode current" in the excel sheet. You can also save the file if you want.
8- Turn ON the light of the microscope and set its light intensity to be at the mark of "45" on the dial.
9- Repeat Steps 5-7, however if you are copying in the excel sheet directly then now you need to copy only "Diode current" column as voltage is the same.
10- Set the light intensity of the microscope to be at the mark of "90" on the dial.
11- Repeat Steps 5-7.
12- Save the Excel file under your N: drive in a secure folder. You need to plot from these data as asked in this question , however you can do the plot either for your in-lab report or submit later on for your post-lab report depending on your time availability in the lab. If you do not have enough time in the lab to do the plot then submit only excel sheet of data file in your "in-lab report" and mention that the plot will be submitted later on. You need to plot the voltage vs. the resulting current for all the cases (light off, light intensity of "45 mark", and light intensity of "90 mark") in one figure using Excel and include it in your report. You can format the axis/labels if you want.

13- **Make sure to "log off" after you are done so other group can log in to this computer.**