Experiment 3 Resistivity and Circuits

> "Look for knowledge not in books but in things themselves."
>
> W. Gilbert

OBJECTIVES

To learn the use of several types of electrical measuring instruments in DC circuits. To observe the I-V characteristics of some devices. To see how resistivity is measured.

THEORY

Because electrical devices and measurements are so pervasive, some knowledge of them is essential to all technical disciplines. In this experiment we will introduce several instruments and use them to measure the electrical characteristics of some common components and circuits. We will also measure a fundamental property of materials, the resistivity.

One of the most basic properties of any electrical device is the amount of current I which flows when a known voltage V is applied to the device. A plot of the current as a function of the voltage is usually called the "I-V characteristic" of the device. The I-V characteristic is often a complicated curve, which may change as the temperature of the device changes, as light hits the device and so on. Sometimes these changes are used to sense temperature, light level or some other variable, but at other times any change is a nuisance. Whatever the I-V curve looks like, it is customary to define the ratio V/I as the resistance, R, of the device at a particular current, temperature, light level etc. When V is in volts and I in amperes, R is in ohms.

There are many situations in which the I-V curve is simply a straight line through the origin. In other words, $V = IR$, where R is a constant. Such devices are said to obey Ohm's Law, or to be "ohmic". If the curve is also reasonably independent of external influences the device becomes particularly useful in electronics, and is simply called a "resistor". For example, in later experiments it will be convenient to use the voltage across a known resistor to infer the current in a circuit.

Resistance depends on both the geometry of the device and the material of which it is made. The resistivity is a more fundamental property of the material, since it is independent of the geometry of a particular specimen. Resistivity, ρ, is defined by

$$\rho = E/j \tag{3-1}$$

where j is the current density in response to an applied electric field E. More practically, the measured resistance of a sample of length L and area A is related to the resistivity by

$$R = \rho L/A \qquad (3\text{-}2)$$

This relationship assumes that the material has been shaped into a uniform cross-section and that the current is uniformly distributed across the area.

Turning now to circuits, it is clear that any combination of ohmic resistors is also ohmic, and could be replaced by an equivalent single resistor. Your text works out the effective resistance of series and parallel combinations of resistors R_1 and R_2, arriving at

$$R_{eff} = R_1 + R_2 \qquad \text{(series)} \qquad (3\text{-}3)$$

and

$$\frac{1}{R_{eff}} = \frac{1}{R_1} + \frac{1}{R_2} \qquad \text{(parallel)} \qquad (3\text{-}4)$$

More complicated combinations can be worked out by successive applications of these two results.

Figure 3-1 displays two representations of a circuit for measuring the voltage across a light bulb and the current through the bulb. On the left is a schematic diagram, as usually seen in text books. It shows the connecting wires, represented by solid lines between the various devices, each of which is represented by a special symbol. On the right is a pictorial representation of the same circuit as it might appear in the lab. Since the schematic is much easier to draw, it is usually used in preference to a pictorial representation. The mechanical details of the circuit are then left to the ingenuity of the experimenter. We will almost always work with schematics, so it is important for you to learn to translate them into hardware easily and correctly.

Recall that current is defined as the amount of charge that flows through a point in a specified time. To measure the current, we must therefore break the circuit and insert our ammeter at the point where we want to know the current. We can then think of current flowing in

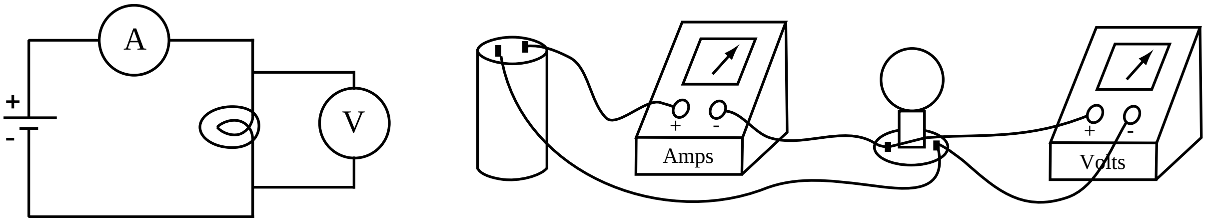


Fig. 3-1 Circuit for measuring the I-V characteristic of a light bulb, drawn as a schematic and as a pictorial.

the original circuit up to the desired point, taking a detour through the ammeter, and being returned to the original circuit. This is shown clearly in the schematic of Fig. 3-1, where the ammeter symbol is connected in series with the rest of the circuit. Since the ammeter must become part of the circuit, it is desirable for it to have zero resistance so that it does not change the properties of the circuit. Real ammeters do not, of course, have zero resistance, but they are designed to have as little resistance as practical. Incidentally, this means that if an ammeter is connected directly across a source of voltage, such as a battery, a very large current may flow. This is likely to damage both the source and the meter.

Voltage is defined as the difference in electrical potential between two points in the circuit. It does not make sense to speak of the potential at one point, without at least implicitly referring to some other point for comparison. A voltmeter must, therefore, be connected between points of the circuit, and there is no need to break the circuit to connect a voltmeter. This type of connection is shown in the schematic, where the voltmeter is used to measure the voltage between the two terminals of the light bulb. Because the voltmeter must connect two parts of the circuit which were not originally joined, it must have infinite resistance to avoid disturbing the current flow in the original circuit. As you might expect, this ideal voltmeter can only be approximated. If you happen to wire a voltmeter into one of your circuits incorrectly, the meter will not be damaged but its very high resistance will essentially prevent current flow, and your circuit will not work.

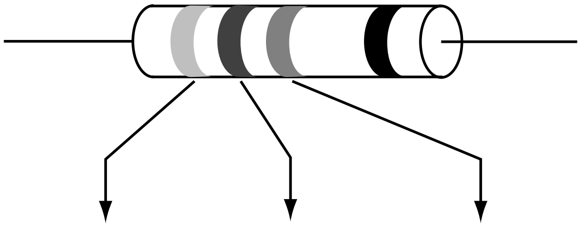
Before going on to the experiment, we need to talk about one more instrument. The ohmmeter is used for measuring resistance directly. It consists of a voltmeter, an ammeter and a current source properly connected to a pair of external terminals. When you attach an unknown resistance to the terminals, the ohmmeter automatically measures the ratio of voltage to current and displays the result. Since the ohmmeter measures the effective resistance of whatever you connect to its terminals, you must remove components from the circuit to measure their individual values. Also, any other voltage source in the circuit may damage or at least confuse the instrument, so you must be sure that all other sources are disconnected before using the ohmmeter.

EXPERIMENTAL PROCEDURE

Your lab station is equipped with a panel of mounted components, an adjustable voltage source, an analog ammeter, a digital multimeter and wires for easily connecting things. For this experiment we will use only the light bulb and the resistors on the panel. Connections are made to the terminals beside each component. The resistors are identified by their values in ohms, using an archaic color code which is explained in Fig. 3-2, and posted at the front of the lab room. The voltage source is usually referred to as a power supply. It contains circuitry which converts household power to an adjustable DC voltage. Connections are made through the terminals on top, and the desired output is set with the multi-turn knob. The ammeter is essentially self-explanatory.

The digital multimeter or DMM can be used as an AC or DC ammeter or voltmeter, or as an ohmmeter. With the instrument in front of you, the set-up procedure is reasonably logical. As an example, we want to use the DMM as a DC voltmeter for our first measurements. Simply set the large knob to point at the V with the straight line beside it (the other symbol denotes AC voltage) and connect the circuit to the terminals labeled V and Com on the meter. The DMM automatically chooses a range and displays the voltage. Other functions are set up in a similar fashion. (The other input is used only for the current ranges, which we will not need at the moment.)

The first experiment you should try is the measurement of the I-V characteristic of a resistor. Wire up the circuit of Fig. 3-1, replacing the light bulb with a 150Ω resistor and the battery with the power supply. Use the DMM to measure the voltage across the resistor. By varying the output of the power supply you will vary the current through the resistor. Plot current vs voltage as you go along to avoid the tedium of tabulating and then plotting data. Is the inverse



Color	Digits		Multiplier
Black		0	10^0
Brown	1	1	10^1
Red	2	2	10^2
Orange	3	3	10^3
Yellow	4	4	10^4
Green	5	5	10^5
Blue	6	6	10^6
Violet	7	7	10^7
Gray	8	8	10^8
White	9	9	10^9

Fig. 3-2 The resistor color code. The last band specifies the relative accuracy of the value: Gold ±5%; Silver ±10%; No band ±20%. A 51kΩ, 10% resistor would be marked Green-Brown-Orange-Silver.

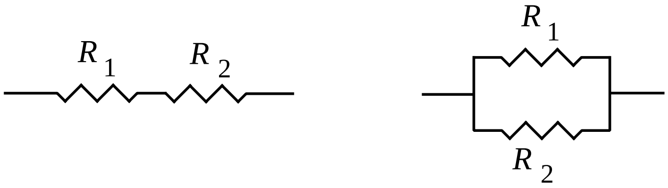


Fig. 3-3. Series and parallel connections of two resistors

of the slope of your line reasonably close to 150Ω?

When you finish with the resistor, replace it with the light bulb, and make a similar plot. The resistance of the bulb varies with the temperature of the filament and the temperature varies with the current, so we might expect some strange things to happen. Is the lamp ohmic?

Next you should use the ohmmeter capability of the DMM to check the rules for series and parallel combinations of resistors, Eq. 3-3 and 3-4. Disconnect the power supply and dismantle the previous circuit. Arrange the DMM for resistance measurements by setting the switch to the **Ω** symbol and connecting leads to the same terminals you used for voltage. Pick any two resistors from the left-hand column on the panel to be R_1 and R_2. Measure their values with the DMM. Are they within the specified tolerance of their marked values? Using the measured values, calculate the effective resistances for the series and parallel combinations of the two resistors. Measure the actual series and parallel resistances. Do the measurements agree with the calculation?

As a last exercise, we will determine the resistivity of some Play-Doh™. Because it does not come with wires attached, we will need to make our own connections. This is a bit complicated because chemical reactions between metal and Play-Doh may cause the contact resistance to change as current flows. To get around this problem, we will make a “4-probe” measurement as follows. Roll out a circular cylinder of Play-Doh, keeping the diameter as uniform as possible, and press the ends onto the two copper plates provided. Make the specimen long and skinny so the voltage will be big enough to measure easily. Connect the copper plates in series with the ammeter and power supply so you can pass current through the sample. Measure the voltage between two points a convenient distance apart on the cylinder surface, taking care not to deform the material. Changes in resistance at these contacts cannot affect the voltmeter reading since there is no current flow through the voltage contacts. Knowing the current, voltage and geometry you can derive the resistivity from Eq. 3-2. Try several shapes and areas to see if the resistivity as defined in Eq. 3-3 is indeed a constant of this material. Is Play-Doh ohmic?

REPORT

This lab has many small bits of data and scattered questions. The write-up will be shorter than usual, but be sure all the pieces of your work can be identified by the instructor.