

## 4. $I$ - $V$ characteristics of electric conductors

### 4.1 Introduction

If an electric conductor is connected to a voltage source with voltage  $V$  a current  $I$  is produced. We define resistance being the ratio of the voltage applied and the current flowing through the conductor:

$$R = V/I \quad \text{unit: } 1 \text{ V/A} = 1 \text{ Ohm} = 1 \Omega \quad (4.1)$$

The resistance depends on the material and geometry of the conductor. In the simplest case the current is proportional to the voltage applied. Thus, in this case the resistance is constant and the conductor termed Ohmic resistor (or conductor). For such resistors, **Ohm's law** holds true:

$$R = V/I = \text{const.} \quad \text{at constant temperature } T. \quad (4.2)$$

Real conductors never behave like pure Ohmic conductors, and the dependence of the current on the voltage is far more complex. We represent such a current-voltage dependence graphically as so-called  $I$ - $V$  characteristic.

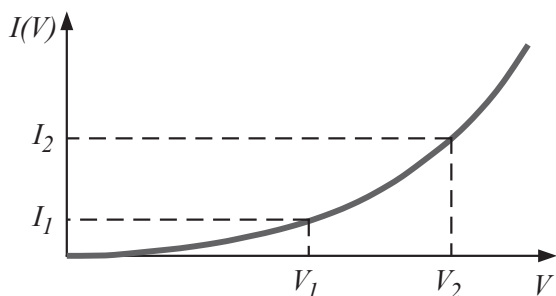


Figure 4.1:  $I$ - $V$  characteristic of some arbitrary conductor.

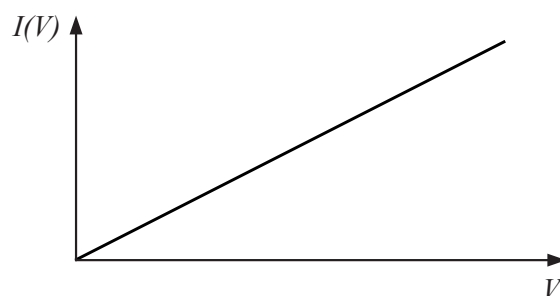


Figure 4.2:  $I$ - $V$  characteristic of a (Ohmic) conductor with constant resistance.

The characteristic shown in Fig. 4.1  $R = V/I$  is not constant; in this example  $R_1 = V_1/I_1 > R_2 = V_2/I_2$ . The resistance decreases with increasing voltage. If the characteristic is linear as shown in

Fig. 4.2, the resistance  $R = \text{constant}$  (Ohm's law).

In the present experiment we will investigate the characteristics of different types of conductors. The characteristics observed yield information about the physical mechanism of conductivity. Some keywords for this experiment:

- electronic circuits,
- Kirchhoff's laws,
- electric resistivity of various devices,
- Ohm's law,
- measurement of voltage and current, and
- *I-V* characteristics.

## 4.2 Theory

### 4.2.1 Metallic conductors

The conductivity of metals and alloys is a result of the presence of free electrons, which can easily move through the lattice of ions. At constant temperature the resistance does not depend on voltage and Ohm's law is valid. In contrast, if the temperature is not kept constant by active cooling, the voltage drop accompanying the current dissipates power (Joule's heat)  $Q = I \cdot V \cdot t$  and, thereby, heats the conductor. As a consequence the resistance increases in general.

In the simplest case,  $R$  depends linearly on temperature  $T$ . For  $T$  being the absolute temperature we obtain:

$$R = R_0 (1 + \alpha T)$$

The temperature coefficient

$$\alpha = \frac{1}{R_0} \frac{dR}{dT} \quad (4.3)$$

gives the relative change in resistance upon a change in temperature of 1 K.

For pure metals,  $\alpha = 1/273 \approx 0.4\%$  per degree Kelvin. By using alloys  $\alpha$  can be reduced to values of typically 0.002% per degree Kelvin.

### 4.2.2 Semi-conductors

The conductivity of semi-conductors ranges between that of metals and that of insulators. Modern technologies allow parameters like the number of carriers and their mobility to be varied over a

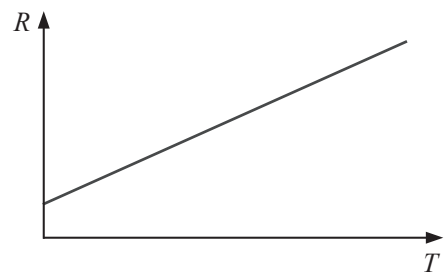


Figure 4.3: Linear dependence of the resistance on temperature.

wide range. By doping with different elements or addition of impurities the conductivity can be increased by orders of magnitude. We distinguish:

- **n-doped material:** Atoms of an element of valence 5 are added to a pure elemental semiconductor of valence 4 like e.g. Si or Ge. The additional valence electron of the dopant is mobile and contributes to the free carrier density. Elements adding an electron are termed donors.
- **p-doped material:** Some lattice atoms are replaced by atoms of a 3-valent element. The hole in the carrier density is filled by an electron from a neighboring atom. The displacement of the electron re-creates the hole at a different site, which in turn will be filled by another electron. So, in p-doped semi-conductors, a net positive charge (hole) is moving. Such dopant is called electron acceptor.

In the following some example applications of semi-conductors are described, which will be topic of the present experiment:

### Thermistor

Thermistors are semi-conductors which act as a temperature-dependent resistors. For instance, the so-called NTC resistors (NTC=negative temperature coefficient) are often oxides of transition metals like Cr, Mn, or Fe. As an example, the oxide  $\text{Fe}_2\text{O}_3$  can be doped either by changing the iron-oxygen stoichiometry leading to the presence of divalent Fe atoms, or by doping with tetravalent  $\text{Ti}^{4+}$ -ions. In the former case, the  $\text{Fe}^{2+}$  ions release the excess electron with increasing temperature thus generating negative carriers (n-doping); as a result, the resistance of the material decreases with increasing temperature. Such resistors can be used for temperature measurement because typical temperature coefficients are of the order of -2% to -6% per degree. In Fig. 4.4 some typical  $I - V$ -characteristics and the temperature dependence are shown.

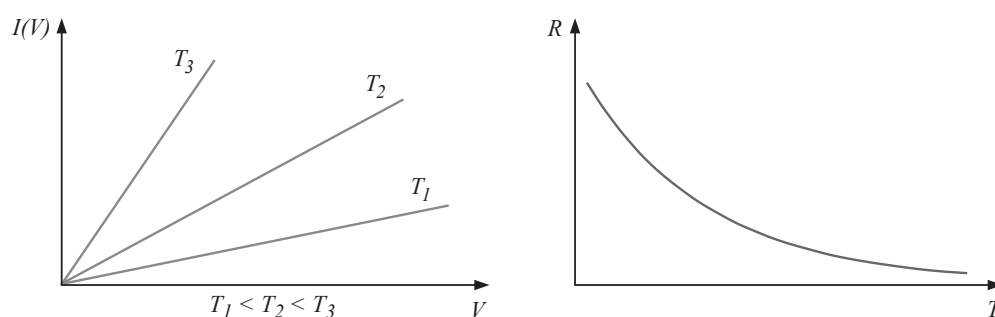


Figure 4.4:  $I - V$ -characteristic (left panel) and the temperature dependence (right panel) of a thermistor with negative temperature coefficient (NTC).

### Semi-conductor diodes

A semi-conductor diode is made of n- and p-doped material, which are in contact. The contact area is called the **pn-junction**. The junction has very special characteristics which are typical

for semi-conducting diodes. The typical application of such a diode is a rectifier of currents of alternating polarity.

A typical characteristic of a semi-conductor diode is shown in Fig. 4.5. While in the so-called forward bias direction the current increases exponentially with the voltage applied over the junction, the (leak) current in the opposite - reverse bias - direction is very small and due only to intrinsic minority carriers. At a certain threshold in reverse bias, however, the reverse voltage exceeds the breakthrough voltage and the current increases extremely fast (avalanche effect). Typical breakthrough voltages lie between -10 V and -10 kV depending on the type of diode used.

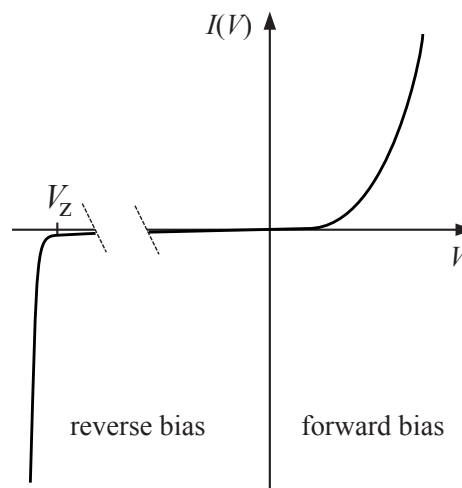
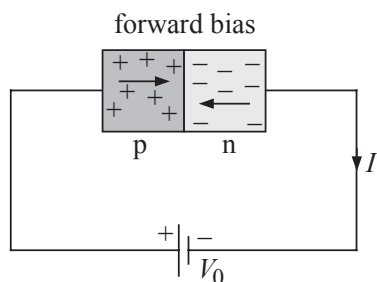


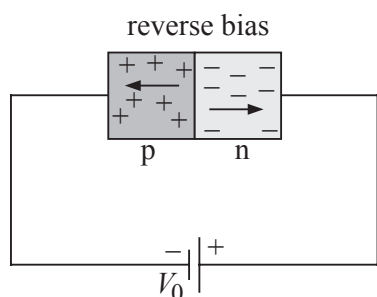
Figure 4.5: Characteristic of a diode.  $V_z$  is the maximum voltage the diode stands in reverse bias.

The behavior of a pn-junction can be explained as follows:



Free electrons are moving from the n- into the p-doped layer (or holes in the opposite sense). The resistance of the junction is low and there is a steady current flowing.

Figure 4.6: Carrier motion in forward bias.



Due to the field applied, holes and electrons are moving away from the junction in the p- and n-doped layers, respectively. A non-conducting layer is generated at the junction, there is no current flowing after the buildup of this layer (technically speaking: the depletion layer at the junction is growing with increasing reverse voltage).

Figure 4.7: Carrier motion in reverse bias.

In technical drawings of electronic circuits, diodes are represented as arrows as shown in Fig. 4.8. Forward bias corresponds to the voltage applied in direction of the arrow, and the arrow then points into the technical direction of the current:



Figure 4.8: Symbol of a diode in forward and reverse bias.

Due to these characteristics diodes can be used to rectify an electric current: if an alternating voltage is applied to the circuit, the current is only flowing if the voltage drop over the diode corresponds to the forward bias direction. Otherwise, no current flows through the circuit.

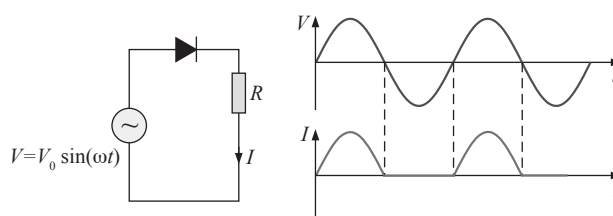


Figure 4.9: Diode used as rectifier.

### 4.2.3 Photosensitive resistors

In photosensitive resistors, free electrons and holes are generated by absorption of light. Thus, the resistance of the material decreases when the device is exposed to light. CdS is a technologically important example of such a material.

## 4.3 Experimental part

### 4.3.1 Goals of the experiment

- Measurement of the  $I - V$ -characteristics for the following devices:
  - Ohmic resistor,
  - light bulb,
  - semi-conductor diode.
- Qualitative observation of the resistance changes of a photosensitive resistor upon illumination.
- Measurement of the temperature dependence of a thermistor.

### 4.3.2 Experiment

#### Read before you start !

- Do not change the scale of measurement devices during data acquisition.
- The current may not exceed 200 mA (fuse)!

#### Measurement of the characteristics

- The characteristics are recorded using the circuit given in Fig. 4.10. The voltage can be set by means of the potentiometer  $R_p$  in the range 0 V...  $V_0$ .  $R_p$  is part of the voltage source.
- **Ohmic resistor:** Using the value for the maximum power dissipation  $P$  given on the resistor and the maximum voltage provided by the source, calculate the maximum current expected and choose the range of the amperemeter accordingly. Measure the characteristics over the full range in steps of 5 V, recording the current as function of voltage.
- **Light bulb:** The maximum voltage is given. Slowly increase the voltage and watch the current until either the voltage limit or a current of 200 mA is reached (whatever comes first). Optimize the range of the measurement devices. Measure the characteristic starting at 0 V up to the limit found above in steps of 5 V and record the current as function of voltage.

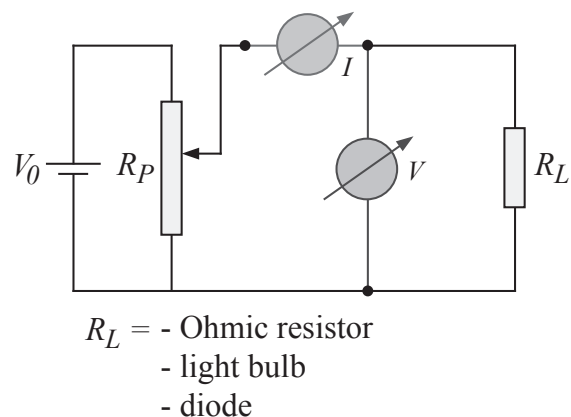


Figure 4.10: Electric circuit used for the measurement of the characteristic.

- **Diode:** Record the characteristic of a diode for positive and negative voltages by changing the polarity of the diode. be careful as the current rises exponentially in forward bias direction and keep the current below the maximum current given! Make small voltage steps of 0.02 V in the range where the diode starts to conduct.
- Compile all data in a table.

### Photosensitive resistor

- Observe qualitatively the change of the device resistance with changing light intensity: Keep the voltage constant at  $V = 3$  V, cover the resistor by your hand and watch the current change.

### Thermistor

The setup is shown in Fig. 4.11. The resistance of the thermistor is to be measured as function of temperature at constant voltage.

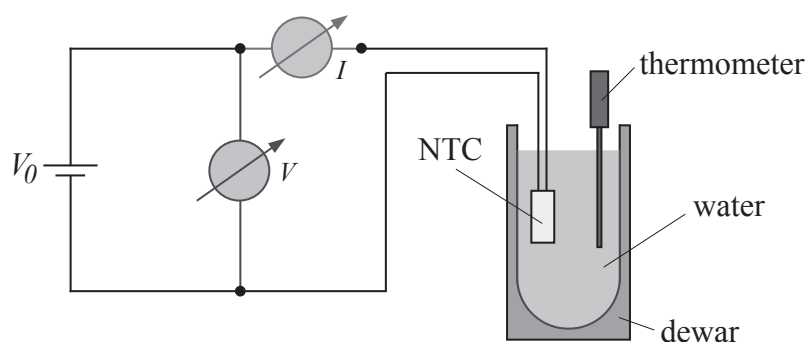


Figure 4.11: Setup for the measurement of the thermistor characteristic (NTC).

- Set the voltage to 10 V.
- Measure the current at five different temperatures between 10°C and 90°C. **Important:** Wait for the temperature to stabilize in order to measure in thermodynamic equilibrium.

### 4.3.3 Analysis and report

#### Characteristics of resistor, light bulb and diode

- Report the three characteristics on graph paper.
- Calculate the resistance  $R = V/I$  for each measurement ( $V$ ,  $I$ ) and plot  $R$  as function of  $V$  (4.12).

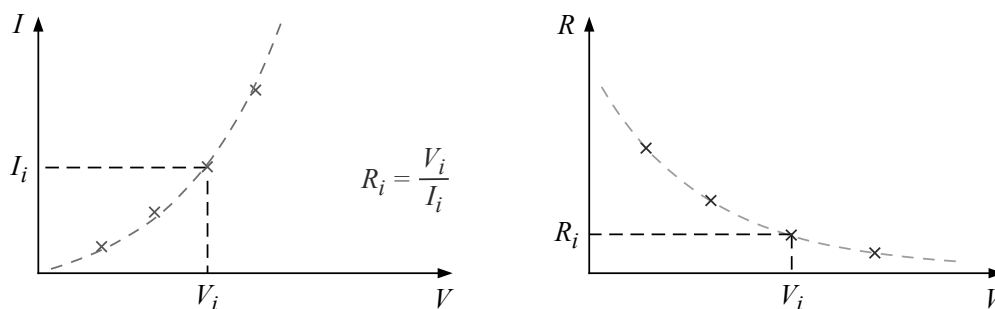


Figure 4.12: Representation of the characteristics.

### Thermistor

- Calculate the resistance of the thermistor for every temperature value measured and plot the resistance as function of temperature on linear graph paper.
- The resistance of the thermistor used depends exponentially on temperature:

$$R(T) = A e^{B/T}, \quad (4.4)$$

where  $A$  and  $B$  are constants and  $T$  the temperature measured in Kelvin. Logarithmizing yields (see experiment Capacitors as well):

$$\ln R = \ln A + \frac{B}{T}. \quad (4.5)$$

Calculate and plot  $\ln R$  as function of  $1/T$  on *linear* graph paper. Determine the parameters  $B$  and  $A$  from the slope and the intersection of the fitted line with the axis  $1/T = 0$ , respectively.

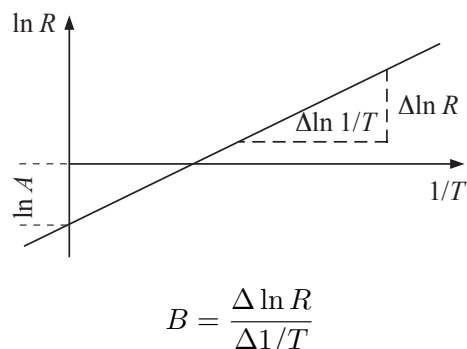


Figure 4.13: Best line fit.

- The temperature coefficient  $\alpha$  is specified as the relative change in resistance per unit change (one degree) in temperature. It can be calculated by differentiating Eq. 4.4 with respect to the temperature  $T$ :

$$\begin{aligned} \frac{dR}{dT} &= A e^{B/T} \left( -\frac{B}{T^2} \right) \\ \frac{1}{R} \frac{dR}{dT} &= -\frac{B}{T^2}. \end{aligned}$$

The term on the left-hand-side equals  $\alpha$ . Therefore:

$$\alpha = \frac{1}{R} \frac{dR}{dT} = -\frac{B}{T^2}. \quad (4.6)$$

Calculate  $\alpha$  for  $T = 300$  K.



## 4.4 Appendix

### 4.4.1 Influence of the measurement devices on the measurement

Each measurement device (voltmeter, amperemeter) has an so-called internal resistance. When measuring small resistances  $R_L$ , the resistance of the amperemeter  $R_{iA}$  cannot be neglected with respect to the one being measured. Therefore, taking the internal resistance into account the electric circuit can be optimized as follows:

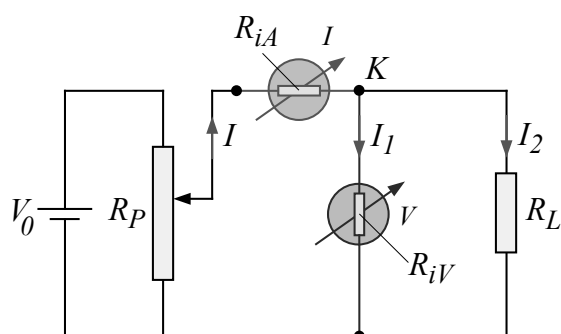


Figure 4.14: Setup for the measurement of a small resistance  $R_L$ .

The total current splits at point  $K$  in parts  $I_1$  and  $I_2$ , which flow through the voltmeter and the resistor  $R_L$ , respectively.

$$\begin{aligned} I &= I_1 + I_2 \\ V &= I_1 R_{iV} = I_2 R_L \end{aligned}$$

Ergo:

$$I_1 = I_2 \frac{R_L}{R_{iV}} \rightarrow 0 \quad \text{for} \quad R_{iV} \gg R_L$$

If the internal resistance of the voltmeter is much larger than  $R_L$ , the fraction of the current flowing through the voltmeter  $I_1$  will be very small and the current  $I_2$  through the resistor  $R_L$  can be well approximated by the total current:  $I_2 = I - I_1$ . Thus, a voltmeter should have a high input resistance (typically  $10^7 - 10^8 \Omega$  for a DVM). If, in turn, the resistance  $R_L$  to be measured is large, the internal resistance of the voltmeter  $R_{iV}$  and, thereby, the current  $I_1$  can not be neglected. For large resistance  $R_L$ , the setup is done in the following way:

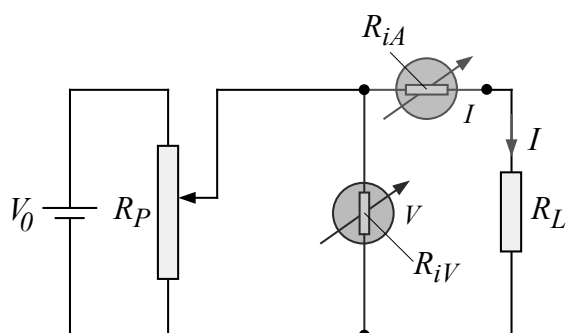


Figure 4.15: Electric circuit for measuring a large resistance  $R_L$ .

Here, the voltage measured corresponds to the sum of the voltage drop at amperemeter and resistor:

$$V = I R_{iA} + I R_L$$

Ergo:

$$R_L = \frac{V}{I} - R_{iA} \rightarrow \frac{V}{I} \quad \text{for} \quad R_{iA} \ll R_L$$

The internal resistance of an amperemeter should be as small as possible. For the amperemeters used here the resistance is of the order of  $1 \Omega$  for the current range of 200 mA.